Advanced Cockpit Interface Design

Through Multiple Levels of Hierarchical Visual Representation

(MLHVR)

A Thesis Submitted to the Faculty of the Interactive Design and Game Development

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Dedication

Dedicated to my wife and son who have given me unconditional love and support throughout my pursuit to further my education.

Acknowledgments

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Table of Contents

List of Figures and Tables

Abstract

Advanced Cockpit Interface Design Through Multiple Levels of Hierarchical Visual Representation (MLHVR)

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Modern flight deck displays from private aircraft to commercial airliners are getting more informative and sophisticated to help pilots acquire more information and make decisions to enhance flight safety. However, recent studies conducted by cognitive scientists reveal that such advanced cockpit interface would increase the workload of the pilots while a poorly designed one may negatively influence their ability to respond to urgent situations. The chance of severe airplane accidents caused by the confusing multi-functional displays of the current generation of flight deck systems can be decreased, if not eliminated through the adoption of a touch-enabled user interface of flight decks. Specifically, the state-of-art flight deck system splits the control information from status information, allowing the pilot to navigate over many interfaces. To address this issue, aerospace divisions recently introduced touch-based user interfaces for aircraft flight decks. While they provide superior control and status information to pilots, they are generally not well-organized and fail to present the most crucial information promptly. An existing theory from Ergonomic Design dictates that the negative impacts caused by excessive information flow can be alleviated by establishing the balance between information desirability (how much information is needed) and accessibility (how much information is being presented or is quickly accessible) in the flow. Based on this theory, this thesis introduces an innovative touch-oriented visual hierarchical representation first and then employs it to build an intuitive screen interface of the flight deck. It begins by defining six layers, namely Background, Airplane Skeleton, Electronic Components, Electronic Wires (Physical information), Buttons (Controls), and Text (Status). The first four layers provide physical information, the following layer provides control information, and the last layer displays status information. This thesis establishes a hierarchy of touch-based interfaces which allows the pilots to navigate along the related components over the layers following the user-verified scenarios. As a result, the pilots will be exposed only to essential information at any moment to promptly make a crucial decision. In summary, the proposed display system not only minimizes distraction when presenting complex and dynamic status information but also reduces the chance of pilots' operational errors.

Keywords: Flight Deck Display; Flight Deck Design; Synoptic System; Cockpit Interface; Touch-Based User Interface; Hierarchy Visualization; Interactive System; Interaction Design

Statement

This thesis presents a novel design framework to design displays for better pilot reaction in the flight deck where multiple levels of hierarchical visual representation are linked together and operated from an efficient system level rapid prototyping environment.

1. Introduction

For over forty years, the flight industry has used electronic displays to transmit critical information to pilots. Due to the intricate nature of aircraft systems, the flight deck display has been an essential constituent in dealing with the vast amount of flight data and presenting it in an intelligible manner. For years, intense research and the constant improvements in computerized systems have resulted in a widespread acceptance of the cockpit interface concept in all types of aircraft and even flying vehicles, ranging from massive commercial airliners to small private aircraft.

In comparison, the automobile industry has fallen far behind the flight industry both in the usage of flight deck technology and simulator-based design even though it is always searching for what will be the next trend in Urban Air Mobility (UAM). However, in recent years several manufacturers have started incorporating advanced computerized systems for relaying information to the drivers. These systems involve touch screens, heads-up displays, and other information displays combined with some physical and virtual interaction devices such as haptic, gesture, and voice controls. Nowadays the industry seems to focus on how our digital lives can be integrated into our vehicles and what features the vehicle can provide within infotainment. As new concepts and systems are continuously introduced into new UAM models, model systems improve and touch interfaces are inherently more common. Much is still to be done, and the full potential of the glass cockpit in an air transportation environment has not been reached.

In this context, Uber Elevate recently introduced the concept of on-demand aviation which has the potential to radically improve urban mobility, giving people back time lost in their daily commutes. Just as skyscrapers allowed cities to use limited land more efficiently, urban air transportation will use three-dimensional airspace to alleviate transportation congestion on the ground (Holden 2). A network of small, electric aircraft that take off and land vertically (called VTOL aircraft for Vertical Take-off and Landing), will enable rapid, reliable transportation between suburbs and cities and, ultimately, within cities. Uber believes VTOL aircraft need to be safer than driving a car on a fatalities-per-passenger-mile basis. Federal Aviation Regulation (FAR) Part 135 operations for commuter and on-demand flights, on average, have twice the fatality rate of privately operated cars, but it is believed that this rate can be lowered for VTOL aircraft at least to one-fourth of the average Part 135 rate, making VTOLs twice as safe as driving (Holden 4-8).

Distributed electric propulsion (DEP) and partial autonomy for pilot augmentation are critical pieces of the safety equation (Holden 6). VTOL services could be deployed to hundreds of aviation vehicles through air traffic control (ATC) systems that rely on voice communication between the aircraft pilot and air traffic control operators. Under visual flight rules (VFR), pilots are able to fly without the ATC, and when needed, they can fly under instrument flight rules (IFR) by taking advantage of existing ATC systems (Holden 7). However, a well-optimized on-demand urban VTOL operation will require a much higher frequency and airspace density of vehicles operating over metropolitan areas. To handle this daunting complexity, it is necessary to develop new ATC systems with innovative communication interfaces. VTOLs will necessarily utilize digital fly-by-wire systems and adapt these systems to include pilot aids to significantly decrease failure modes (Holden 18). Pilot aids will become fully autonomous, which will likely have a marked positive impact on flight safety. Significant advancements with augmentation technology to support pilots should alleviate their skill set requirements that could subsequently reduce training periods.

As the air transportation sector continues to advance, the UAM market surges ahead with initial steps for automated flying. Implementation of both lateral and longitudinal controls are currently permissible through aviation regulations, citing specified flight situations (e.g., ATC). During these circumstances, the role of the pilot changes from actively operating the air mobility to supervising the system. Remotely placed from the control-loop, vigilance, and over-reliance, performing supervisory tasks is something humans are typically not very good at. For this reason, Human Factors and Ergonomics experts have often raised concerns about the implementation of semi-automation. The design of the appropriate interaction between pilots and automation, remain limited.

The purpose of this research is to apply the concept of the flight deck display to a greater extent in a semi-autonomous air transportation environment, and at the same time, present the potential benefits of simulator-based design and interactive prototyping as concept development tools on desired pilot-flight deck interaction. The most important design considerations are: (a) how to avoid the confusion caused by the alteration of display modes by informing the pilot appropriately about system state; (b) how to improve support situational awareness of the system's operational envelope, and (c) how to provide instructions to the pilot. From the user testing results, it is concluded that interfaces representing informational depth through multiple levels of hierarchical visual representation, while depicting elements relevant for system functioning. It provides practical solutions to support pilot's awareness of the system's operational envelope.

Nonetheless, there has been no unequivocal understanding of what the best interface mechanism should look like, or consensus of the appropriate ways to communicate mode-changes and to effectively instruct pilots when a role-change is required (i.e., retrieving control).

Because confusion might readily occur when needing to interpret mode-information in time-critical situations and revealing the associated pilot's role, this thesis strongly recommends more focus on pilots' instructions in the development of future interfaces.

1.1 Background

In winter 2017, a project originating from Gulfstream Aerospace was conducted in the Collaborative Learning Center (CLC) at the Savannah College of Art and Design (SCAD). The title of this project was Synoptic Redesign for Advanced Flight Deck and focused on enhancing the cockpit environment with touch-based interfaces, incorporating system status and system control. A total of twenty students worked in three project groups, separately focusing on the synoptic interface with its main instruments as well as on the overhead switch panel. As members of the synoptic interface design group, we created a touchscreen-based synoptic interface concept controlling all the primary functions that one could find in a premium private aircraft of today and implemented the solution in the simulator cockpit. This thesis work revolves around the main instruments area with the support of new interface design concepts representing informational depth through multiple levels of hierarchical visual representation (Figure 1).

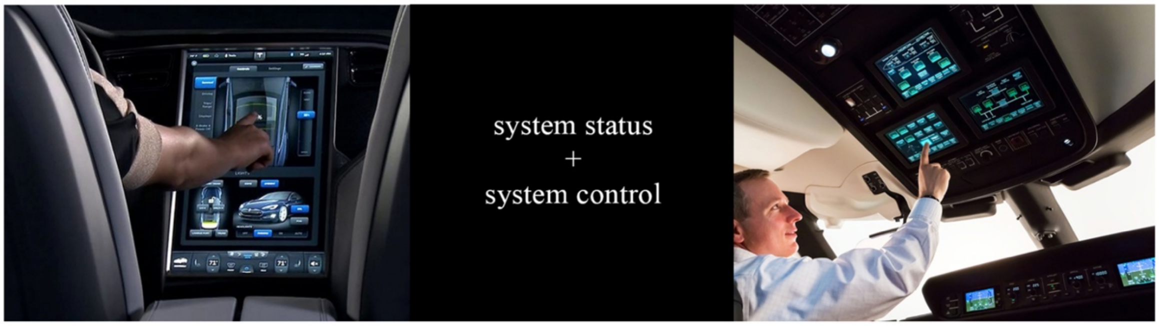


Figure 1. “Gulfstream project overview for the touchscreen interface”

While designing touchscreen interfaces is becoming an essential issue for the aviation industry, the Gulfstream Aerospace’s cockpit system needs to consider incorporating touch-screen navigational interface and system control. The current flight deck interface has used the same visual representations for decades, and an update was needed to bring the interface up to a higher level, meeting Gulfstream Aerospace’s impressive branding style. There were also discrepancies in the representation of components, especially the icons, that diminished the usability of the cockpit interface and could cause uncertainty while controlling the system.

This project also sought to streamline the visual and navigational components of the digital flight deck. The director of Gulfstream Aerospace’s Advanced Flight Deck department, Jeff A. Hausmann, joined in the research and development of innovative concepts for the digital flight deck system. A high level of importance is placed on the advanced flight deck to incorporate system status and system control and to design the major components of the current flight deck interface for improving usability and situational awareness while maintaining a significant level of safety.

Given the proven necessity of touchscreen-based interface for various aviation systems, this thesis represents the creation process of a unified interface for the flying vehicle which is an aircraft as well as a vehicle. The proposed interface is applicable to autonomous operations.

1.2 Problem

Existing in-flight procedures require complex human-machine interaction and have devastating consequences for pilot errors, prompting a small margin for human mistake operating the aviation system. However, abstract information or inadequate peripheral feedback on the condition of aircraft systems require a higher mental workload, which can be the cause of conflict between pilot and aircraft operation. The mental workload encountered during the follow-up of the navigation belonging to the aviation cockpit can be the direct causes of the accident (Harris 111-117). Aircraft navigation and controls are aspects of the cockpit system that need improvement. Most of the current flight deck interface lacks touchscreen control integration, and its navigation has too many steps, which often led the pilot through an unnecessarily lengthy process. According to the PlaneCrashInfo database, more than 50% of the fatal aviation aircraft accidents were caused by pilot errors including those accidents in which weather or a mechanical fault was a substantial contributing factor (see Table 1).

Table 1

Accidents by Causes

Cause	1960s	1970s	1980s	1990s	2000s	All
Pilot Error	60%	55%	54%	60%	60%	58%
Mechanical	21%	16%	18%	15%	18%	17%
Weather	6%	5%	6%	6%	7%	6%
Sabotage	5%	11%	11%	8%	9%	9%
Other	8%	13%	11%	11%	6%	10%

Source: "STATISTICS." *Accident Statistics*, www.planecrashinfo.com/cause.htm.

In 1989, Boeing 737 crashed into the side of the runway near Kegworth, UK, because pilots shut down an engine with no abnormality when another engine problem began. In *Whos Who*, Cooper illustrates how and why this severe accident occurred:

> As the aircraft was climbing through 28,300 feet, the outer panel of one blade in the fan of the left engine detached. This resulted in airframe shuddering, ingress of smoke and fumes to the flight deck and fluctuations of the left engine parameters. Believing that the right engine had suffered damage, the crew throttled that engine back and subsequently shut it down. Then, the crews initiated a diversion to East Midlands Airport and received radar direction from air traffic control to position the aircraft for an instrument approach to land on a runway.

> The approach continued normally, although with a high level of vibration from the left engine which was malfunctioning, until an abrupt reduction of power, followed by a fire warning. The aircraft initially struck a field adjacent to the runway and then suffered a second severe impact on the sloping ground. Thirty-nine passengers died in the accident, and a further eight passengers died later from their injuries. Of the other 79 occupants, 74 suffered severe injury (1-2).

Unfortunately, the pilots had the impression that the normal engine was at fault and turned it off. At one point during the flight, the dial indicating the vibration in the left engine rose to the maximum and stayed there for three minutes; however, the pilots never saw it because it was too tiny (Figure 2).

Figure 2. Showing hybrid electromechanical LED counter instruments used for display of engine parameters with vibration indicators arrowed. *British Midland Airways*. Appendix of Aircraft Accident Report No: 4/90.

In the current generation of instrumentation, data and information overwhelm the crew. Conversely, limited or misleading information is given to the pilots. NASA's Aviation Safety Reporting System found that 70 percent of all the incident reports cited "information transfer" as a leading cause (Parke 71). The underlying issue is that the cockpit displays need to provide a quick indication to the pilots that all is well and good for the current phase of flight.

1.3 Purpose

The proposed display system not only minimizes distraction when presenting complex and dynamic status information but also reduces the chance of pilots' operational errors. With pilot safety and error avoidance at the forefront, a visual update is imperative.

The goal is to analyze the future implications of the digital flight deck system and to increase the pilot's confidence of this system. By utilizing visual displays, this study develops guidelines and visual design principles for the flight deck display. The proposed design concept has stated that information is not displayed until something goes wrong and, in turn, contributed to separate system status from system control. Today's pilots are becoming "system monitors," suggesting humans do not make decisions very well (Paul 44). In order to address the problem, this study presents a framework to design displays for better pilot reaction in the flight deck where multiple levels of hierarchical visual representation are linked together and operated from an efficient system level rapid prototyping environment. The proposed framework is accomplished with careful consideration to the hierarchical representation of multiple levels of information organization—Background, Aircraft Skeleton, Components, Wires, Buttons/Controllers, and Texts/Status—and the interactive interface rapid prototyping with Origami Studio.

The notion of ‘Multiple Levels of Hierarchical Visual Representation (MLHVR)’ is a verbalization of the framing of this dissertation. This framework leads to the layering scheme for the information architecture, visual hierarchy, and viewing modes. The goal of the layering scheme is to enhance the clarity of the synoptic and to display solid information directly, thus reducing the visual cognitive load of pilots, which in turn reduces error rates.

When designing each synoptic, this project explored different viewing modes to convey helpful information more efficiently through progressive disclosure. The project also designed the crew-alerting system (CAS) and checklist panels to follow this contextual model so that the new system was as consistent and intuitive as possible. This research also addressed the misleading iconography found in the current synoptic interface by redesigning each icon to better represent its function. All the iconographies had numerous iterations that were user tested to choose the schemes with the best clarity and discoverability in the new touch-screen interface.

2. Literature Review

2.1 Situational Awareness

During a flight, a pilot constantly acquires information displayed on the flight deck. Depending on the condition and context, the information that the pilot intends to obtain from the deck changes. In *Flight Operations Briefing Notes: Human Performance, Enhancing Situational Awareness,* Airbus describes the recognition of events and environmental elements with respect to space and time, the understanding of their meaning, and the projection of their status after situation and/or condition has changed (1-2). This means that a pilot who can maintain situational awareness (SA) tends to be effective and ready to deal with unknown and unforeseen events, which frequently results in saving lives. Naturally, the concept of SA plays an important role in building an efficient flight deck display system. SA-oriented flight deck display systems can help a pilot to effectively handle massive information flow from the display and recover the pilot from chaotic situations in a timely manner. In Figure 3, a model of SA includes several key parts of the process which influence the pilot's decision- making and allows them to stay ahead of the flight. It illustrates the model of the structure which is between SA and the distribution of visual attention. Consequently, on the decision-making process, SA is an important factor which influences designing the flight deck interface.

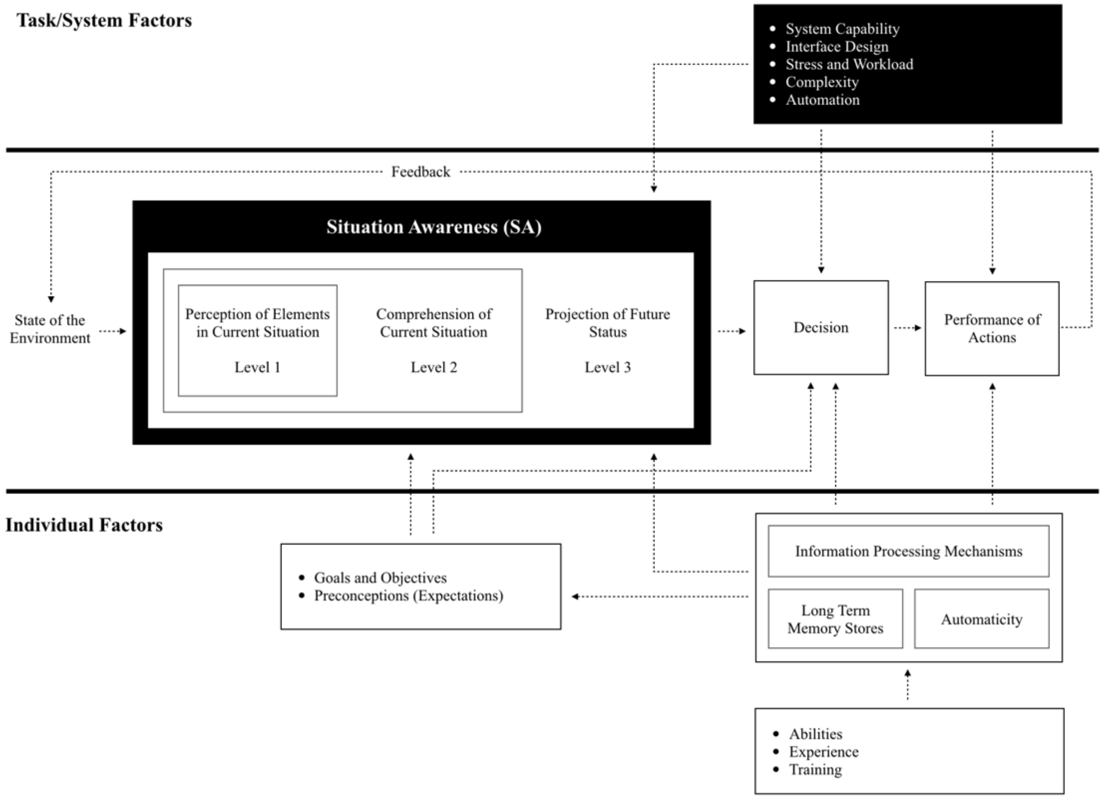


Figure 3. Model of Situational Awareness and decision making. Airbus. *Flight Operations Briefing Notes: Human Performance, Enhancing Situational Awareness*. 2007, p. 5.

In the case of Airbus flight deck display system, the following factors must be considered to build an effective SA-oriented flight deck display system:

(1) Perception, comprehension, and projection as three levels of SA.

(2) The role of goals and goal-directed processing in directing attention and interpreting the significance of perceived information.

(3) The simultaneous role of information salience in "grabbing" attention in a data-driven fashion.

(4) The importance of alternating goal-driven and data-driven processing in processing information in the environment.

(5) The role of expectations (fed by the current model of the situation and by long-term memory stores) in directing attention and interpreting information.

(6) The heavy demands on limited working memory restricting SA for novices and those in novel situations, but the tremendous advantages of mental models and pattern matching to prototypical schema that largely circumvent these limits.

(7) The use of mental models for directing attention to relevant information, providing a means for integrating different bits of information and comprehending its meaning (as relevant to current goals) and allowing people to make useful projections of future events and states.

(8) The use of Q-morphisms in mental models to provide defaults, providing reasonable SA with even limited and missing information, and a context model providing for the representation of uncertainty in the situation representation.

(9) A process for building and updating mental models over time.

(10) Pattern matching to schema, prototypical states of the mental model, that provide rapid retrieval of comprehension and projection for the recognized situation through critical cues and, in many cases, providing single-step retrieval of appropriate actions for the situation. (Airbus 4-11)

While factors introduced by Airbus can be used as a nice starting reference to build an effective SA-oriented flight deck display system, it is not sufficient as the factors were not specific to the flight deck display system. For instance, according to Eddie Haskel, who served as an Airforce pilot for twenty years and a civilian pilot for another sixteen years, a pilot needs to maintain the SA on the environment outside the airplane, not only the airplane itself (Figure 4).

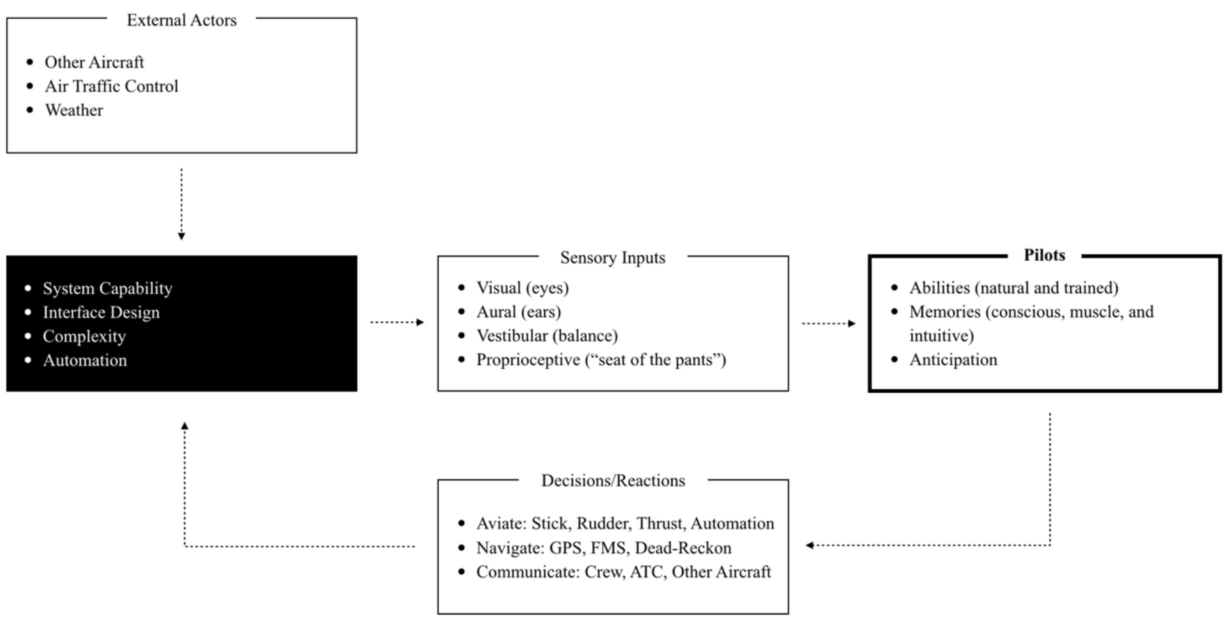


Figure 4. A pilot's situational awareness model. Haskel, Eddie. *Psychology: Situational Awareness*. 2016, http://code7700.com/sa.htm#references.

Nevertheless, none of the factors described above concerns this issue. Haskel also emphasized the importance of new technologies, such as enhanced vision systems, heads-up displays, radar, synthetic vision, and flight management systems. However, to the best of our knowledge, these have never been considered in flight deck display systems. To improve SA, crews also need to ensure channels of communications from their sensory inputs are unimpeded:

Visual. Pilots visually acquire aircraft attitude, performance, navigation, and spatial information, which can be improved by using technology, such as enhanced vision systems, heads-up displays, radar, synthetic vision, and flight management systems.

Aural. Pilots use their ears to listen to the noise level of the cockpit to identify volume regarding airspeed, altitude, thrust settings, and aircraft health.

Vestibular. Pilots' ears do for a sense of balance from the vestibular system. Their ears' semicircular canals derive attitude and rate of turn information.

Proprioceptive. The proprioceptive system reacts to the sensations resulting from pressures on joints, muscles, and skin and changes in the position of internal organs. It is associated with the vestibular system and, to a lesser degree, the visual system. Forces act upon the seated pilot in flight. With training and experience, the pilot can easily distinguish the most distinct movements of the aircraft by the pressures of the system seat against the body. (Haskel)

2.2 Law of Conservation of Complexity

The law of conservation of complexity dictates that the complexity of interface is in contradiction to the complexity of the system (Figure 5). For instance, a highly-sophisticated device such as an iPad has a very simple touch-based interface, while a calculator is equipped with an interface with various buttons. Similarly, old flight deck display systems tend to have lots of gauges, displays, levers, pedals, and handles, and thus are very complicated. It is noteworthy that the complexity of modern air flights has reduced significantly thanks to the technological development over recent years, but many of them still have flight deck interface with relatively high complexity even though they can afford an interface with a lower complexity such as touch screen. This means that there is huge room to simplify the flight deck pilot interface of modern aircraft by exploiting simple but powerful and elegant interface technologies.

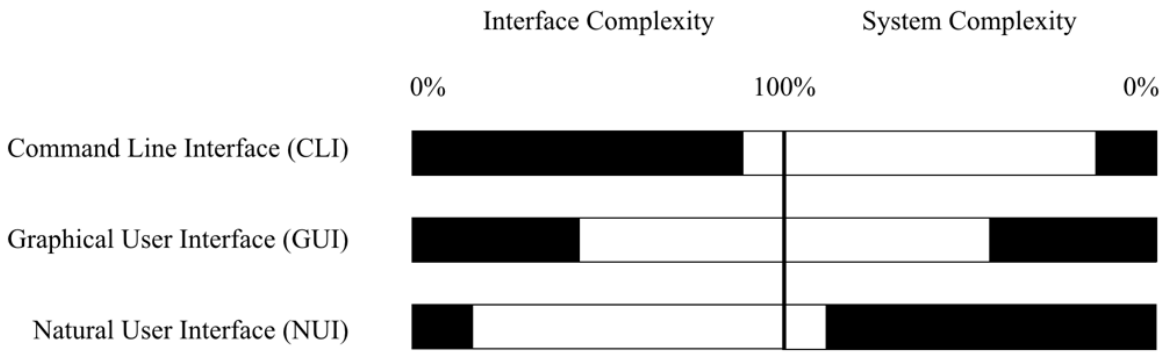


Figure 5. Law of conservation of complexity. Choi, Billy. "Zero Effort & Connected(ZEC) UI/UX Strategy." *LinkedIn SlideShare*, 10 Dec. 2014, www.slideshare.net/BillyChoi/zero-effort-connectedzec-uiux-strategy.

2.3 Hierarchical Information

Visual hierarchy is a useful method for the arrangement and presentation of information elements that make it more comfortable for the pilots to recognize the importance of each component (Figure 6). Visual hierarchy dictates the order of the number of elements which the pilot perceives. In the perceptual view of visual psychology, visual contrast determines the order among the combined use of points, lines, numbers, symbols, text, and color. Gestalt psychological theory proposes that the brain of a human has unique innate organizing tendencies that "structure individual elements, shapes or forms into a coherent, organized whole" ("Visual Hierarchy"). The theory explains how a user can perceive individual elements and illustrates how people perceive a group of the visual elements as a consolidated whole. This thesis demonstrates the relationships among various applications of Human-Computer Interface while recognizing that the tasks of a pilot to operate an airplane are not neat and straightforward. The connection among areas such as pilot selection, pilot training, flight deck design and safety management is continuously emphasized within layouts.

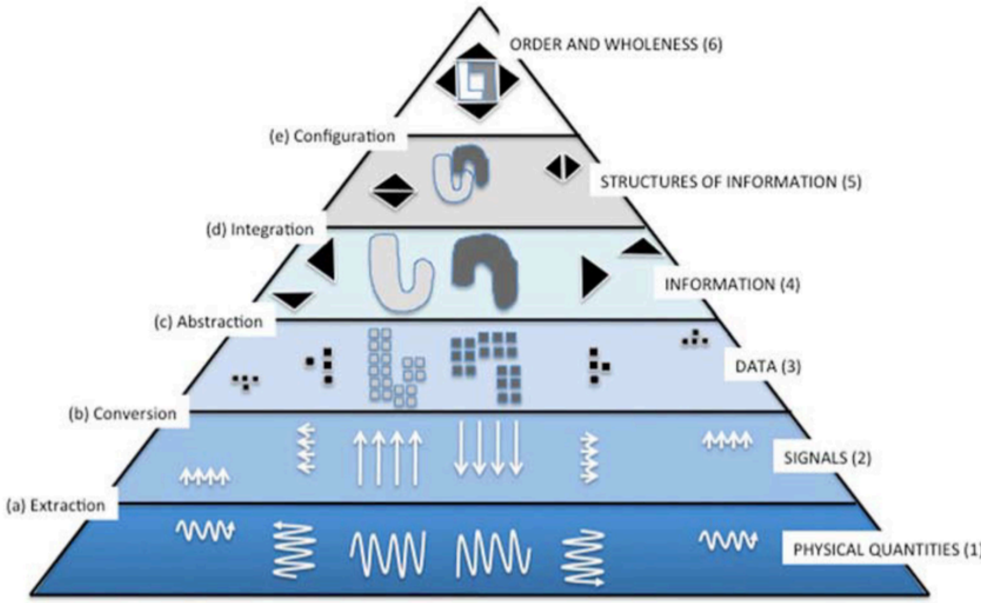


Figure 6. Hierarchical representation of the six levels of information organization. Degani, Asaf, et al. "Information Organization in the Airline Cockpit." *Journal of Cognitive Engineering and Decision Making*, vol. 7, no. 4, 2013, pp. 337., doi:10.1177/1555343413492983.

2.3.1 The Visual Display of Quantitative Information

In many fields, graphic visualization of data possesses much more expressive power than small statistical tables. Most importantly, graphics are important tools to understand and evaluate quantitative information. In *The Visual Display of Quantitative Information*, Edward Tufte introduces the concept of motivating display which can prevent distraction from data visualizations through revision and editing. The book focuses on the design of statistical visualization with the consideration about design and statistics. Utilizing visual displays of quantitative information in the field, the theory suggests that new types of graphics lead to changes and improvements in design. Figures 7 and 8 illustrate two abstract, non-representational pictures which demonstrate the importance of the diversity of fields to build a better display, in this case, visual art and mathematics. Frequently, the most effective way to describe, explore, and summarize a set of numbers—even a very large set—is to look at pictures of those numbers. Among various methods for analyzing and communicating statistical information, well-designed data graphics are usually the simplest and at the same time the most powerful.

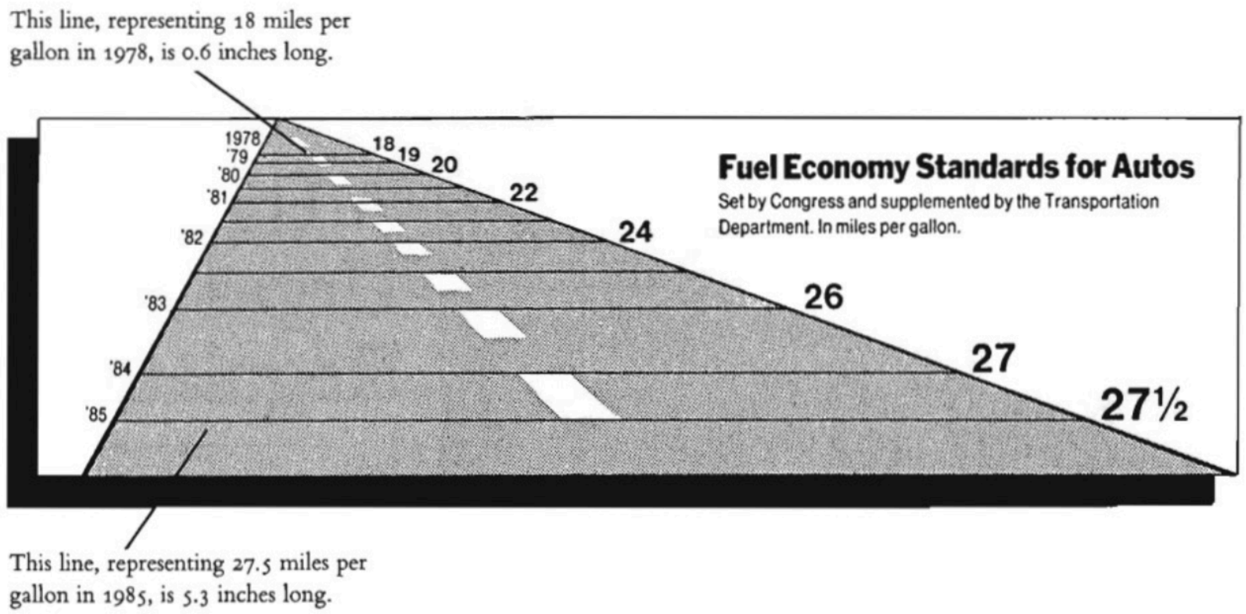


Figure 7. Fuel Economy Standards for Autos Rolf from Tufte, Edward. *The Visual Display of Quantitative Information.* Second, 2001. p. 57.

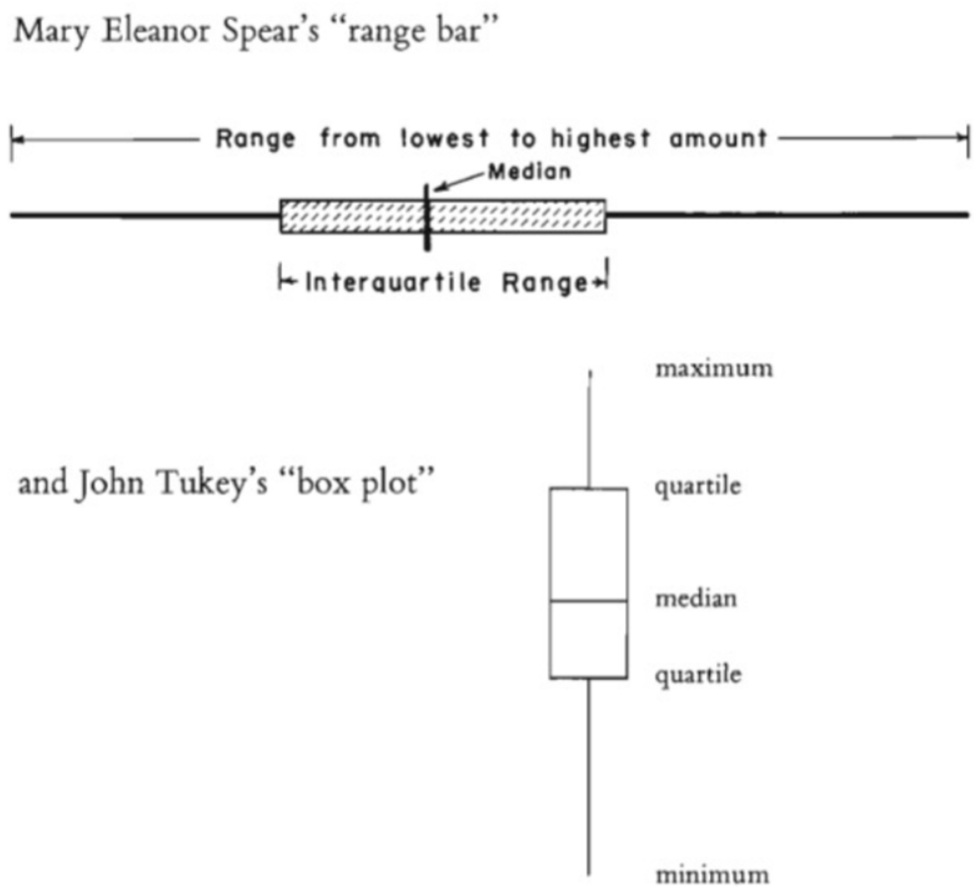


Figure 8. Mary Eleanor Spear, *Charting Statistics* (New York, 1952), p. 166; and John W. Tukey, Exploratory Data Analysis (Reading, Massachusetts, 1977). RolfTufte, Edward. *The Visual Display of Quantitative Information*. Second, 2001. p. 118.

2.3.2 InterRing

The advantages of Radial, Space-Filling (RSF) techniques for hierarchy visualization over traditional flat node-link diagrams have been very well-recognized. RSF techniques are highly efficient to use the display space and at the same time effectively present the hierarchy structure. Over the years, RSF has been adopted to develop several systems and tools. Among those, InterRing is known to provide the complete set of necessary operations on hierarchical structures such as multi-focus distortions, interactive hierarchy reconfiguration, and both semi-automated and manual selection, in addition to supporting traditional interactive operations such as navigation and selection (Yang 16).

2.3.3 Material Design

By presenting a design principle of unified user interfaces, Elevation in Google's Material Design is developed by models of hierarchical information (Figure 9). The design principle provides interactive information on the relative depth or distance between component surfaces along the z-axis. To specify, the distance from the front of one Material surface to the front of another is measured along the z-axis and depicted using shadows. Therefore, it allows users to effectively control the user interface on the liberal use of responsive layouts.

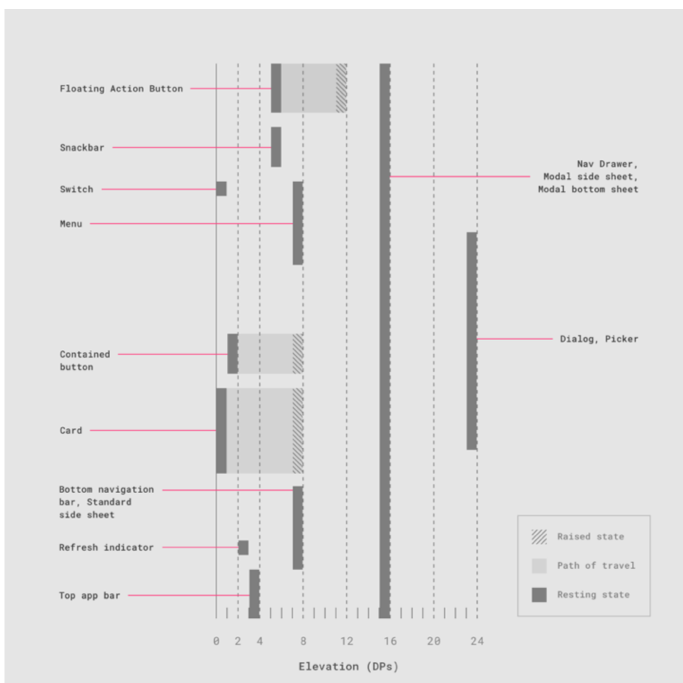


Figure 9. Elevation values for graphical user interface. “Elevation.” *Material Design,* material.io/design/environment/elevation.html#default-elevations.

2.4 Touch Interface Guidelines

In order to maximize the touchable area for larger fingers and to minimize errors from turbulence or unsteady hands, a single touch target on a small screen like the overhead screen should be large enough in order to properly function as a touchable display. One of the pilots at Gulfstream explains that there are certain circumstances in which the touch-screen is not the best interface and that a trackpad and a controller are more suitable for situations under certain circumstances. Specifically, a small button on a touch-screen is not so easy to recognize under an urgent situation.

Larger buttons which are imposed or unnecessarily scaled, may occupy too much space on the display and will make the display less effective. In the paper entitled “The Fat Thumb,” Sebastian Boring, David Ledo, Xiang ‘Anthony’ Chen, Nicolai Marquardt, Anthony Tang, and Saul Greenberg introduce an interaction method that uses the finger's touch size as a form of simulated pressure and volume. The authors compared the fingertips with three alternative techniques where people have to accurately pan and zoom to a predefined area of the screen and found that the touch interaction technique could better help users to handle control information flow from the display in Figure 10. For this specific reason, this project also considers the differences among fingertips based on the finger's limited operational range.

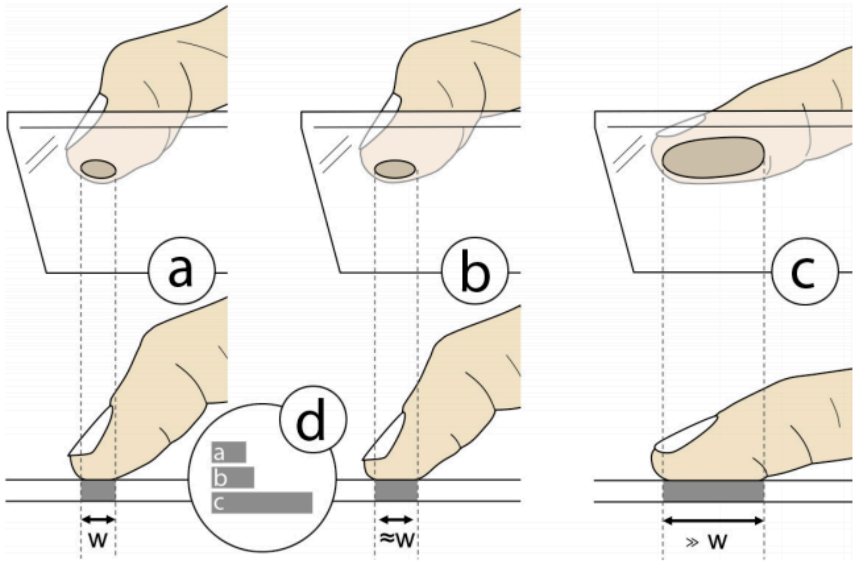


Figure 10. The thumb's contact size for single-handed mobile interaction. Boring, Sebastian, et al. “The Fat Thumb.” *Proceedings of the 14th International Conference on Human-Computer Interaction with Mobile Devices and Services Companion - MobileHCI 12*, 2012, p. 4., doi:10.1145/2371664.2371711.

Figure 11, shown below, represents both the touch zone and the area obstructed by the finger. The real touch zone (i.e., the part of the finger that is in contact with the screen) will be smaller and a bit more precise, unless pilots smash their finger against the screen. When designed for touch elements, it is safer to overestimate the size needed for touch targets than underestimate them.

Figure 11. Small touch targets lead to big problems. "Finger-Friendly Design: Ideal Mobile Touchscreen Target Sizes." *Smashing Magazine*, 21 Feb. 2012, www.smashingmagazine.com/2012/02/finger-friendly-design-ideal-mobile-touchscreen-target-sizes/.

There is no perfect size for touch targets. Different sizes work for different situations. Operations under turbulent conditions or frequently used actions require large touch targets with components that have enough area between them to avoid any mishaps.

A mouse pointer is precise to operate buttons or elements, yet fingers are not, and small targets require higher precision than larger ones. Considering the size of the touch targets, it allows pilots to distinguish between swiping and touch on the display. They can access items quick and easy because the entire item is a target for selection.

2.5 Color Theory

A well-constructed user interface design should be easily recognizable and clearly understandable under any circumstance. As a safety perspective, the Federal Aviation Administration (FAA) also emphasizes that no more than six colors should be used for color-coding on the screen display. The perception of colors is usually subjective, not standardized, yet when it comes to a work environment, certain principles should be followed. Another important characteristic of user interface elements is that visual displays primarily present status information using intense brightness and color characteristics for various aircraft performance parameters. According to Gulfstream Senior Test Pilot, Jim Phillips, “airspeed and angle of a climb have to be consistently displayed to pilots.” On the other hand, in case of an altitude indicator, there is no need for pilots to keep monitoring this parameter. Still, it is desirable for this information to be constantly displayed for the sake of timely awareness of deviation from clearances. As significant advancement in interface technology surges ahead, color remains one of the most important factors when it comes to the construction of displays to ensure compatibility and intuitive usability. To better understand how a basic color structure can establish a clear visual hierarchy, Professor Dennis M. Puhalla visualizes three distinctive properties of color to emphasize the present principles of saturation (tints and shades) and the value scale of hue (color) in Figures 12 and 13. Understanding the full color spectrum and how it can be manipulated to enhance or distinguish equal degrees of value contrast can employ interface displays with proven formulas to achieve specific criteria.

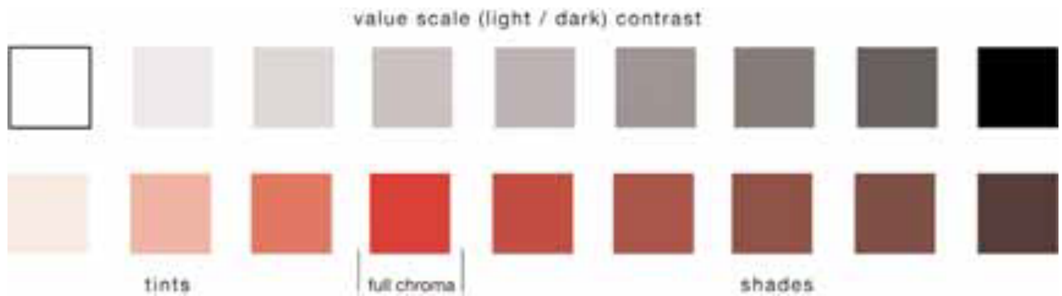


Figure 12. Value scale defined. Puhalla, Dennis M. “Perceiving Hierarchy through Intrinsic Color Structure.” *Visual Communication*, vol. 7, no. 2, 2008, p. 204., doi:10.1177/1470357208088759.

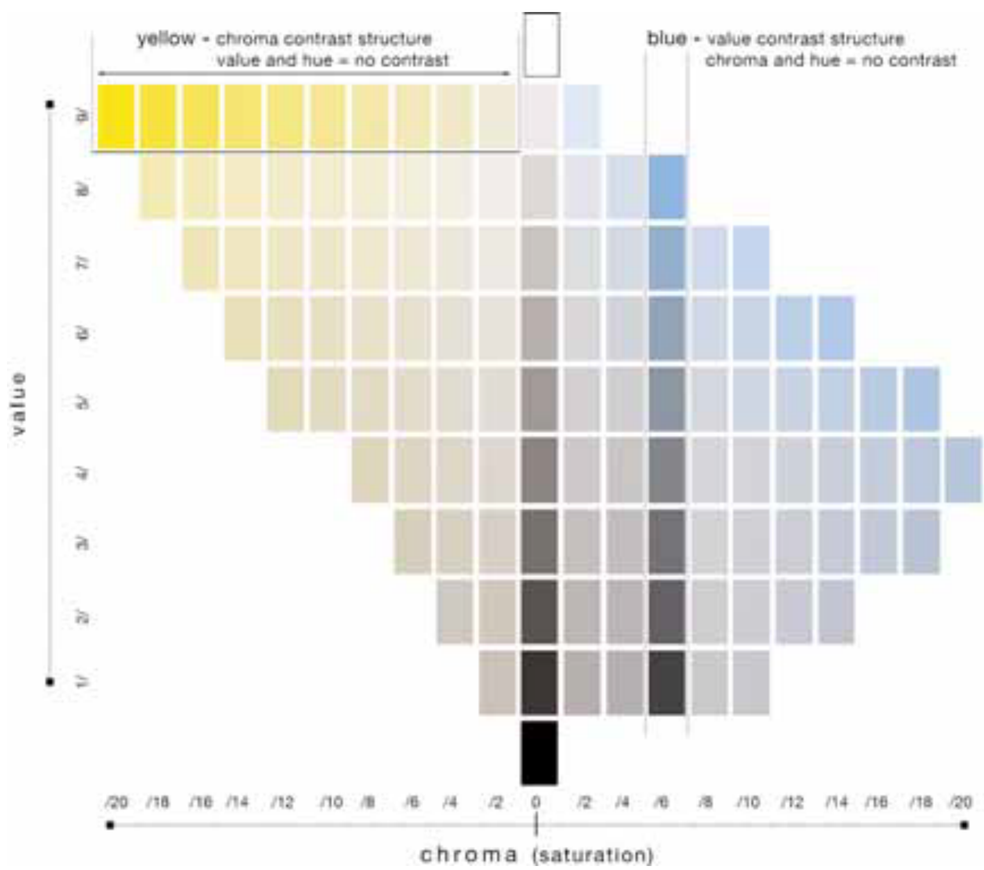


Figure 13. Color structure rationale. Puhalla, Dennis M. “Perceiving Hierarchy through Intrinsic Color Structure.” *Visual Communication*, vol. 7, no. 2, 2008, p. 206., doi:10.1177/1470357208088759.

3. Methodology

3.1 Design Process

This methodological approach relies on the design process, and the project which is the topic of this thesis is conveyed and processed in four steps. The different phases of the working process are shown in Figure 14: discover/research, define/synthesis, develop/prototype, and deliver/integration phase. In particular, the development phase is divided into specific stages: ideation, concept development, and visualization. When the initial concept was defined to the development stage, it was organized into a detailed functional layout of the flight deck display.

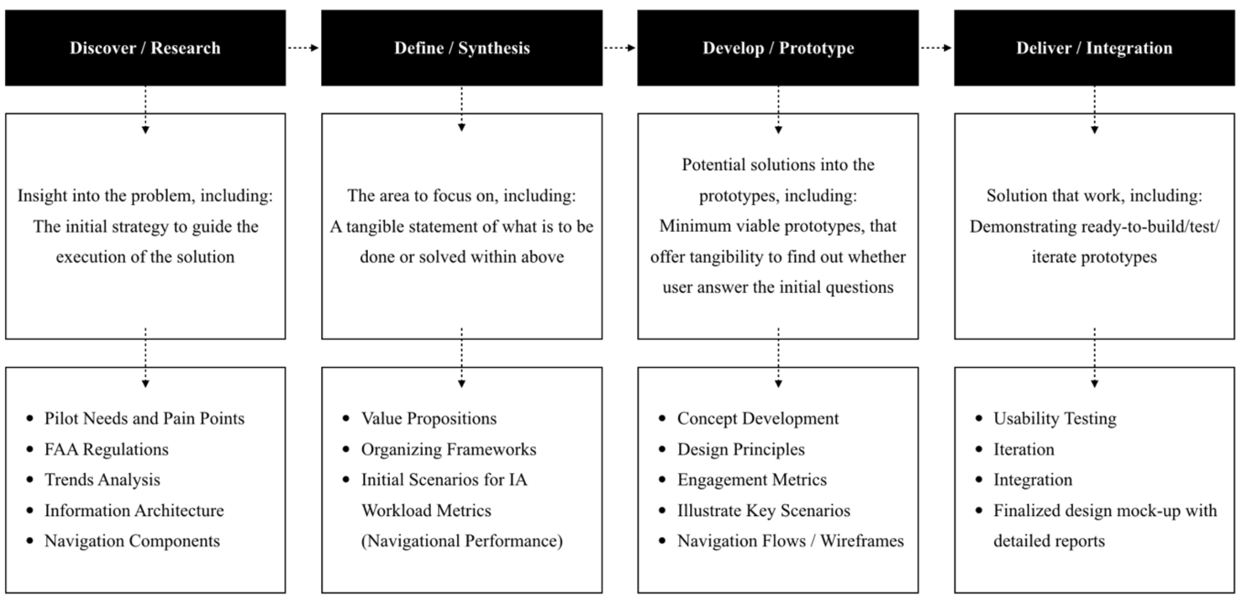


Figure 14. "Design Process"

The discover and define phase focused on the extraction of information required by pilots using the design arrangement method shown in Figure 15. At visualization state, aesthetic requirements were considered to visualize the MLHVR framework with the focuses on the touch-screen display. The deliver phase involved setting up pilot's operational tasks to evaluate the interface which provided constructive feedback. When it comes to the simulated task with the system display, temporary interface testing was conducted to refine their previous operational rules. By specifying rules to follow in the MLHVR framework, the step of interface specification that interacts between the system interface and the pilot were designed according to the significant use case chosen. This thesis focuses on concept development and the visualization step (Figure 16).

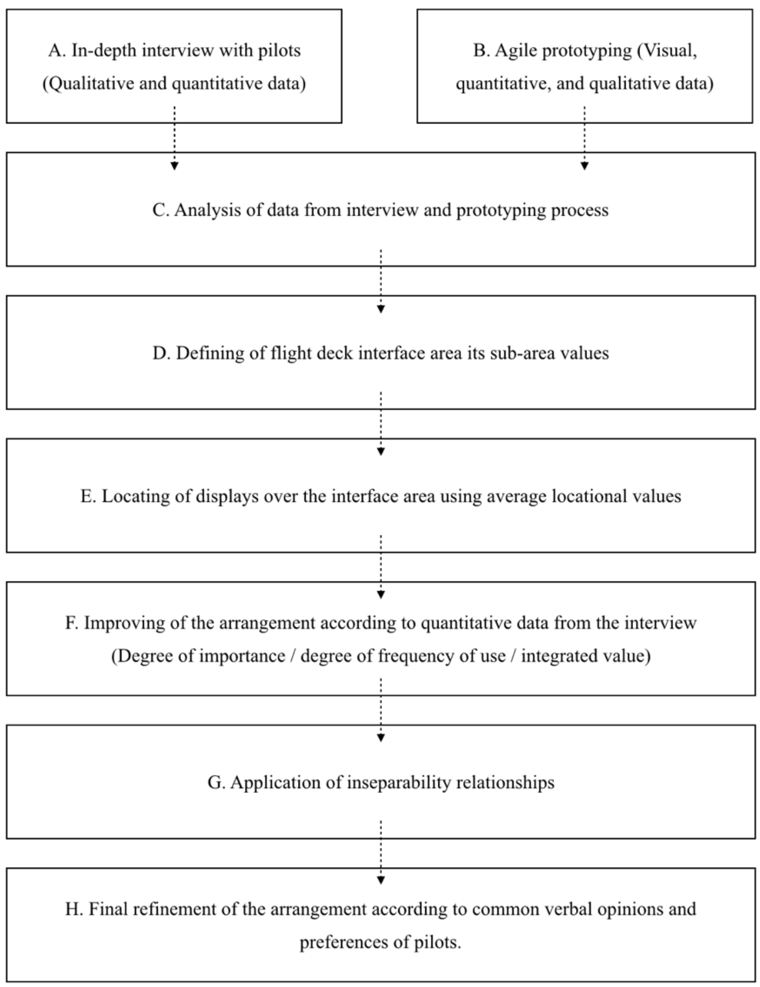


Figure 15. “Design Arrangement Method”

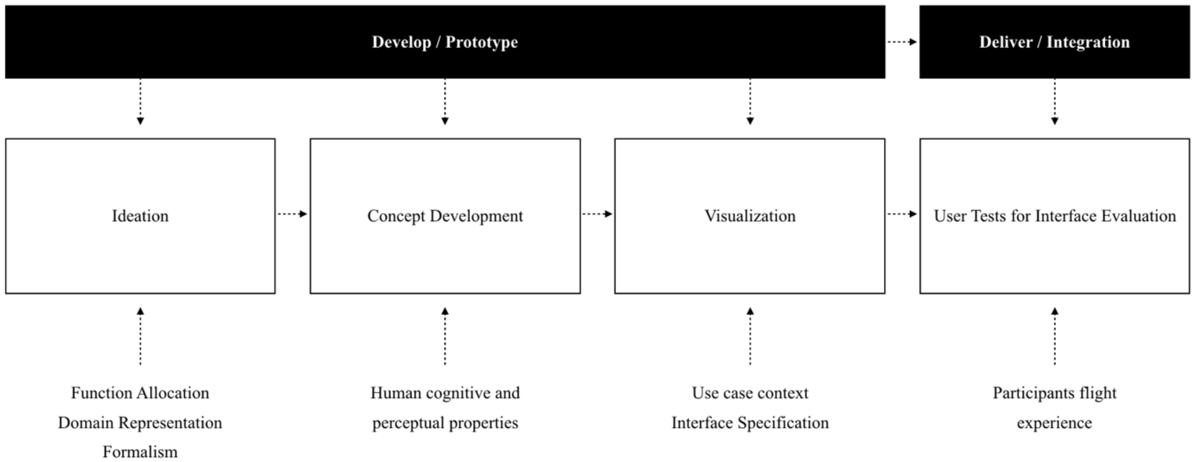


Figure 16. “Concept development and visualization step throughout design methodology”

3.2 System Description

This project started with qualitative research by collecting objective and subjective data to understand how and why pilots make decisions and what improvements can be made to the current system to support all the interactions between interface and pilots. At the beginning of the project, two test pilots in the laboratory flight deck of the G450 were observed in Figure 17 at the Gulfstream facility.

Figure 17. Gulfstream G450 Flight Deck Displays. “Gulfstream G450 Long-Range Business Jet.” *Aerospace Technology*, www.aerospace-technology.com/projects/gulfstream2/.

Field observations initiated the primary research phase and resulted in an overall understanding of how the current cockpit in the flight deck responded as pilots performed operations. The pilots spent the majority of the visit explaining the cockpit layout, synoptic pages, associated controls, and functions of the display units and discussing their pain points when interacting with the current system interface. In addition to the initial field trip, there were multiple meetings conducted with experienced Gulfstream pilots, engineers, designers and project managers throughout the project. These meetings resulted in a greater understanding of the synoptic system architecture, component functionality, phase-of-flight relevance, troubleshooting issues, and pilot behaviors.

Previously, the primary means of system control were through two cursor controller devices (CCD) located on the sides of the pilot and co-pilot. These CCDs were used to interact with the system interface, but it was slow and often frustrating for pilots to drag the cursor. It provides the opportunity to transfer their functionality into a touch-enabled interface with valid usability for pilots. Moreover, Gulfstream Aviation specifies that flight crews need to immerse themselves in a flight deck system that is more an extension of aviating, navigating, and communicating. Therefore, the flight system leverages active control sidestick, CCD, and touch-screen technology and is designed to accept continual upgrades and incorporate future navigation advancements:

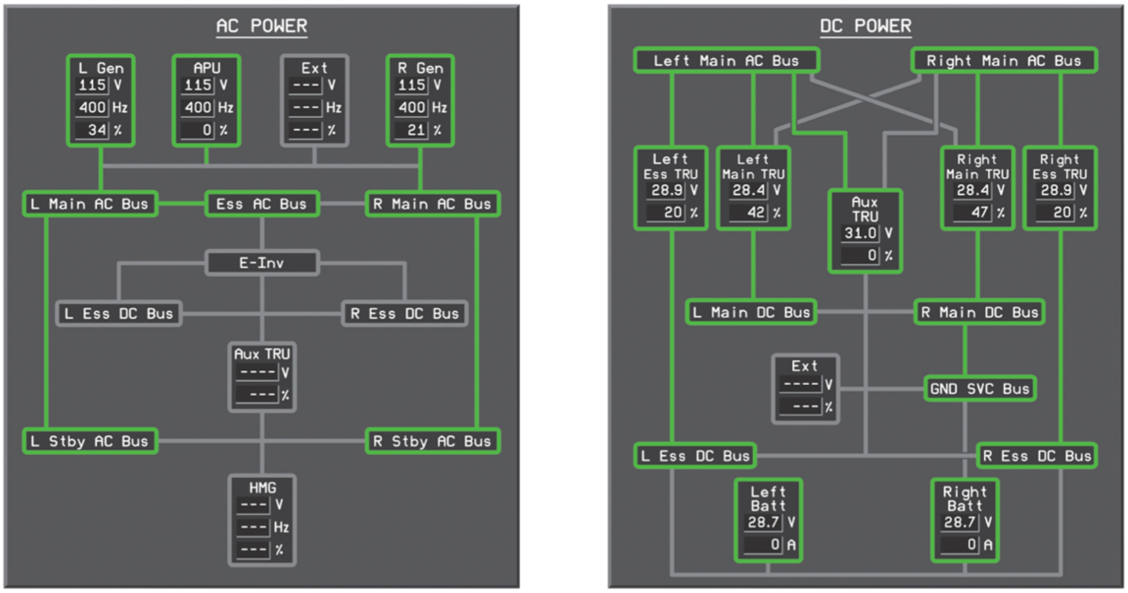
> Pilots will be drawn to the active control sidesticks. The controls replace the traditional pedestal-mounted yoke and provide increased visibility of the avionics suite and improved pilot comfort. Unlike other sidesticks on the market, Gulfstream's active control sidesticks are digitally linked to provide visual and tactile control inputs in concert to improve situational awareness. The active control sidesticks are ergonomically mounted where a pilot's arm and hand naturally rest and angled for more natural use. The ten touch-screen controllers vastly reduce the number of switches on the flight deck. The tablet-based interfaces intelligently and intuitively structured avionics input options to match only the tasks appropriate to the phase of flight the aircraft is in at that point in the mission. Moreover, the controller panels are equipped with ergonomic frames to stabilize the pilot's hand while he or she uses the touch screens. The flight deck is an office conducive to the work pilots perform. The absence of control columns

> frees space for foldout work desks and the adjustable perforated leather crew seats. (Gulfstream Symmetry Flight Deck)

3.2.1 Layering Analysis

Gulfstream's hydraulic pump, fan, valve, and power transfer unit (PTU) icons were redesigned for discoverability in the new touchscreen environment. The new icons also corrected visual discrepancies across the synoptic pages that represented form and function. It was implemented through a grid system, optimizing distinctive clarity and visual organization of each synoptic.

One of the central insights is that the airplane's delayed feedback loops prompt pilots to feel a lack of control, which provides the opportunity to integrate feedback into the designing of the flight deck. It was also discovered that pilots rely heavily on muscle memory for navigation. This study considers this insight as an opportunity to design the information architecture to be more intuitive to support quick decision making. Based on a mental mapping exercise conducted with several pilots, they prefer to think of the alternating current (AC) and direct current (DC) system cockpit interface contextually rather than technically (Figure 18). This insight leads the project to minimize divided attention by grouping information, encouraging holistic processing by presenting the bigger picture, and filtering information when required by only giving pilots the most relevant information. Specifically, the project designs the electrical information to represent both AC and DC systems in one synoptic.



AC POWER SYNOPTIC 2/3 DC POWER SYNOPTIC 2/3

Figure 18. Gulfstream G450 AC/DC Power Synoptic. Haskel, Eddie. "Electrical System." *G450 Electrical System*, code7700.com/g450_electrical.htm.

3.2.2 Phase of Flight

In the current generation of instrumentation, data and information are pushed onto the crew. Unfortunately, sometimes not enough, or misleading, information was given to the pilots. Providing statistical data in leading causes of major incidents, NASA's Aviation Safety Reporting System revealed 70 percent of the incident reports cited "information transfer" (Paul 44). The underlying issue is that the cockpit displays need to provide a quick indication to the pilots that all is well and good for the phase of flight in Table 2.

Table 2

Phase of Flight Synoptics

Taxing	Take Off	Cruise	Descent
1.Charts 2.Video 3.Flight Controls 4.Engine Status 5.Fuel 6.Brakes 7.ECS / Pressure 8.Engine Startup	1.Flight Control 2.ECS /Pressure 3.Map 4.Waypoints 5.Hydraulics	1.Flight Controls 2.Map 3.Radar 4.Fuel 5.Waypoints	1.Flight Controls 2.Brakes 3.Hydraulics 4.Chart 5.Waypoints 6.ECS / Pressure

This proposed display system has stated that information is not displayed until something goes wrong and, in turn, contributed to separate system status from system control relying on the phase of flight in Table 3.

Table 3

Phase of Flight Synoptic Relevance Analysis

Ground Check	Taxing	Take Off	Cruise	Descent	Landing
1.Checklist 2.Fuel 3.Flight Controls 4.Doors	1.Flight Controls	1.Flight Controls	1.Summary 2.Flight Management System (FMS) 3.Waypoints 4.Fuel 5.Map 6.Weather	1.Approach Charts 2.Airfield Chart 3.Fuel	1.Flight Controls 2.Brakes 3.Airfield Chart

Ground checking, Taxing, and Landing phases are not addressed due to having the ability to abruptly bring the aircraft to a quick stop on the ground (see Table 4).

Table 4

Phase of Flight Synoptic Relevance Analysis - Abnormal Circumstance

Ground Check	Taxing	Take Off	Cruise	Descent	Landing
		1.Flight Controls 2.Hydraulics	1.Summary 2.Flight Management System (FMS)	1.Flight 2.Fuel 3.Hydraulics	

3.3 Methodological Framework

Designing displays, interface elements, grid systems and modular layouts, are required separately based on the avionic interface system. Especially in occurrences of abnormal system status during cruise mode, when pilot instruction is specified through guided system prompts. For better pilot reaction, a design should use a purely visual user interface, using shape and color to provide context and numbers only when necessary. Figure 19, Multiple Levels of Hierarchical Visual Representation (MLHVR), is a proposed framework that involves the visual organization of information making it easy for pilots to access the flight deck display. The design framework led to the layering scheme for the information architecture, visual hierarchy, and viewing modes. The layering framework was to enhance the clarity of the synoptic and to display dense information in a simple manner, thus reducing the visual cognitive load of pilots, which in turn could help reduce error rates.

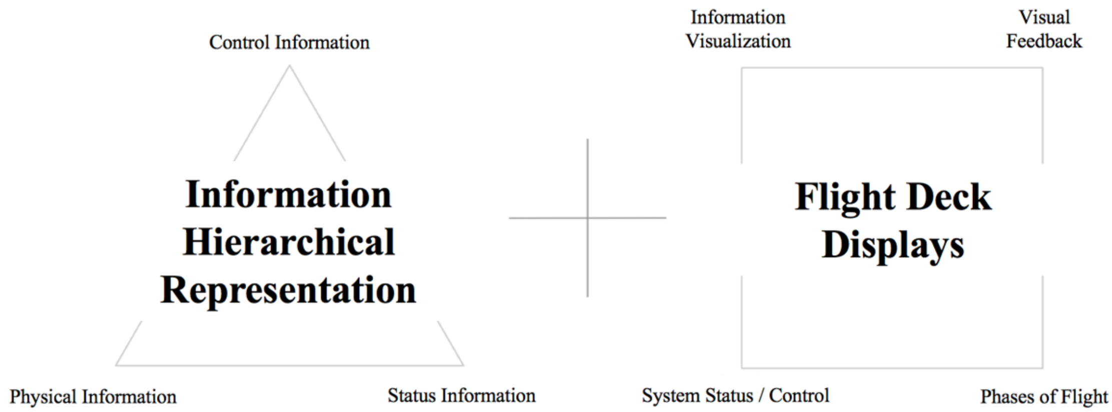


Figure 19. “Multiple Levels of Hierarchical Visual Representation (MLHVR) Framework”

From the definition of framework, main experience principles were utilized: status and control should be incorporated; how the pilots engage must be immersive; how the pilots interact must be seamless; fulfilling experiences must be synthesized with environmental conditions (Figure 20).

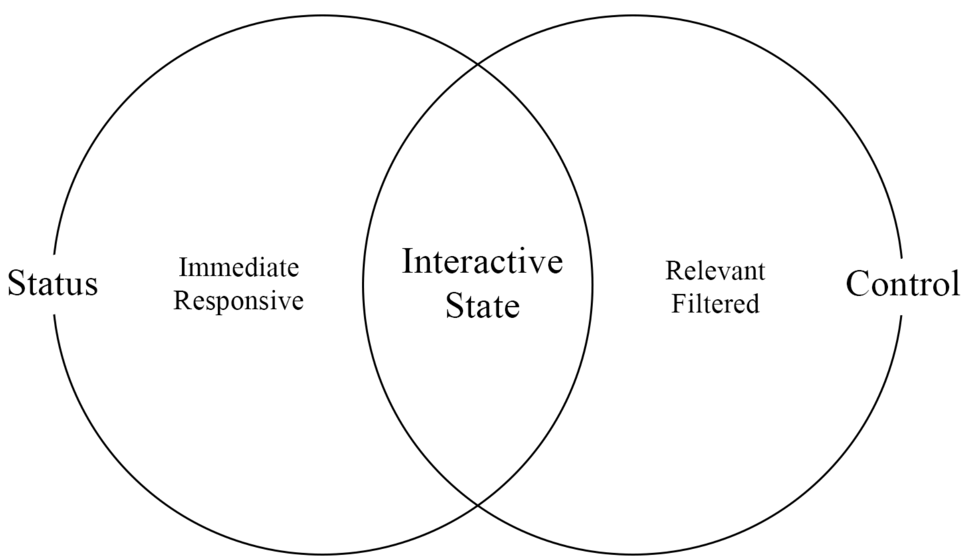


Figure 20. “Interactive state of the digital flight deck system”

The MLHVR framework aims to be in line with next generation expectations or assumptions about how it looks and behaves. If asked for a highly immersive environment with flight deck displays (Naturalized Interaction), pilots want to better visualize massive amounts of information (Flexible Information Visualization), but the reasoning has probably not been carefully thought out, but it presents an opportunity to show a more comprehensive solution which incorporates the qualities of MLHVR which will allow for structured user interface (Figure 21).

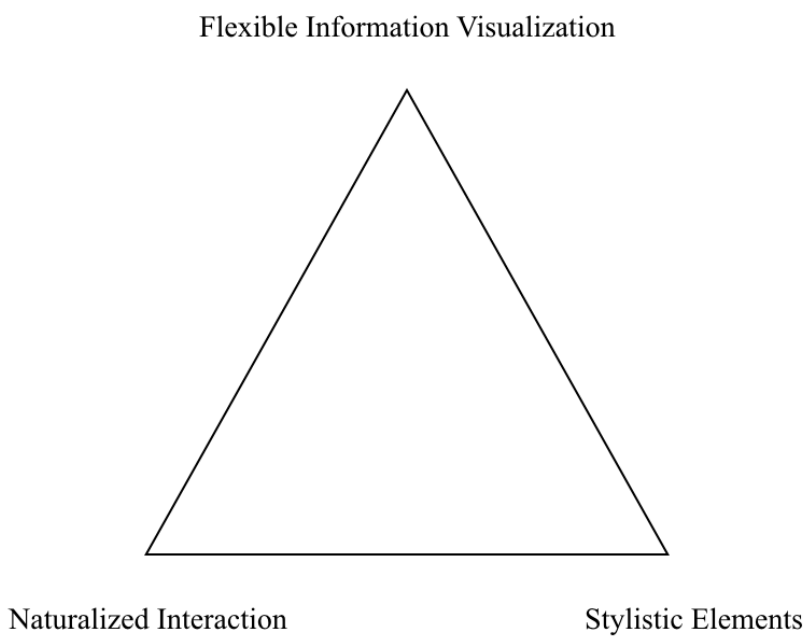


Figure 21. “MLHVR Framework”

The framework is a tool for orienting an interface project in the conceptualization and development phases. It offers a means to recognize the needs of cabin displays and relates them to general aspects and benefits of visual hierarchy in touch-based user interface solutions. It also serves as cockpit environments for immersive interaction with Gulfstream around the subject of 3D, helping them map their intents towards concrete action points or design directions for the next generation of technological possibilities.

3.3.1 Flexible Information Visualization

A scalable user interface to organize datasets ranging from small to endless amounts of Multiple Levels of Hierarchical Visual Representation (MLHVR) can be used to create more extensive overviews and exploit various navigational metaphors. Flexible Information Visualization describes the elements of visual components which allow a user interface to better display large amounts of data in simple ways relevant to a pilot and to an interface being used. It provides the possibility of scalable and movable user interface to organize data-sets ranging from small to endless amounts. In contrast to a traditional user interface, which thrive by displaying small amounts of data or utilizing search functions, MLHVR can give scalable overviews and exploit various navigational metaphors.

3.3.2 Naturalized Interaction

Naturalized Interaction is a systematic method to create meaningful engagements between man and machine that are enriched by purposeful and identifiable traits. This aims to further the users understanding of spatial elements and the material of physical objects. Relative to interface development, the objectives surrounding Naturalized Interaction are achieved with an intuitive and immersive design that can reduce the cognitive load of the user.

3.3.3 Stylistic Elements

Visual Style Elements describe how MLHVR can be made a product and better differentiate itself from competitors. As a stylistic element, multiple layering components offer the possibility of product differentiation and an enriched visual language that proposes both functional and aesthetic appeal.

Visualizing high-dimensional labeled data on a two-dimensional plane can quickly result in visual clutter and information overload. To address this problem, the data usually needs to be structured, so that only part of it is displayed at a time. It presents a hierarchy-based approach that projects labeled data on different levels of detail on a two-dimensional plane, whilst keeping the user's cognitive load between the level changes as low as possible (Figure 22).

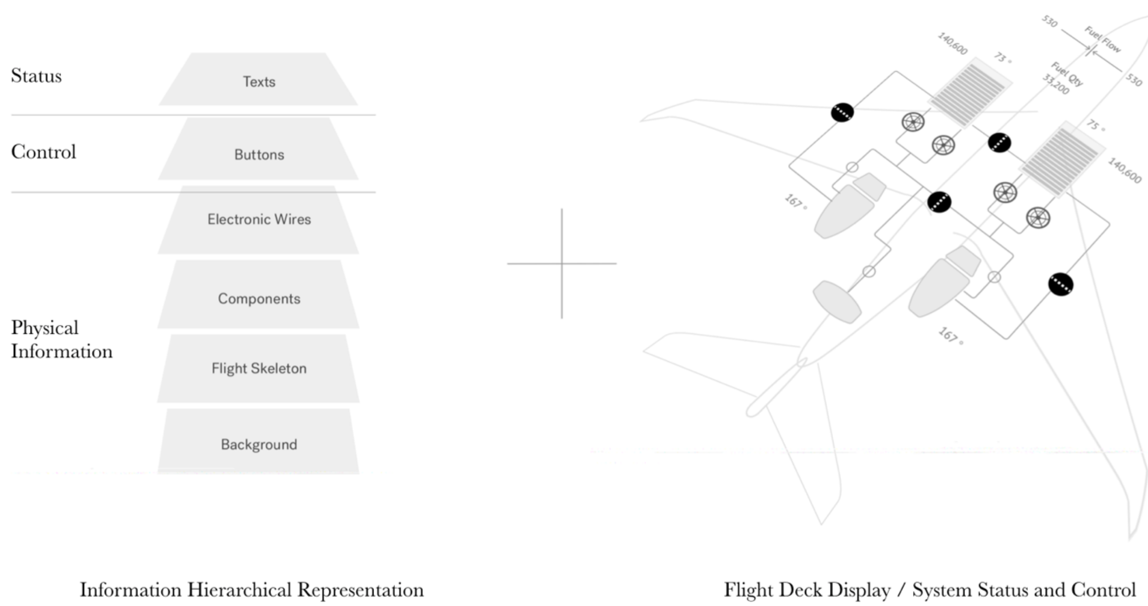


Figure 22. “Hierarchy-based flight deck interface”

The approach consists of three steps: (1) the data is hierarchically clustered; (2) the user can determine levels of detail; and (3) the levels of detail are visualized one at a time on a two-dimensional plane. Animations make transitions between the levels of detail traceable, while the exploration on each level in Figure 23 is supported by several interaction techniques, including halos, a darts view, and a magic lens.

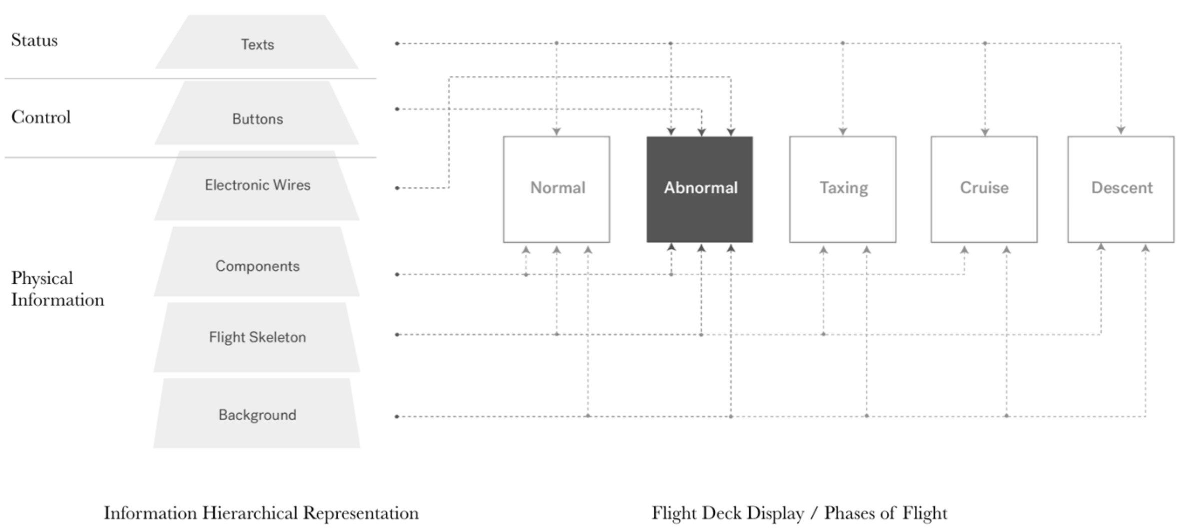


Figure 23. “Example of hierarchical view mode of abnormal state”

3.4 Brainstorming

In the brainstorm session, work was directed at generating ideas for a design concept and developing various methods to explore potential solutions. Combinations of the best and worst cases were developed to improve visualizations of the synoptic display (Figure 24).

Figure 24. “Project Brainstorming”

4. Historical Review

In the historical review, flight deck technology trends, flying car trends, and the future of mobility trends were investigated through secondary research. The publications from aviation manufacturers were analyzed to predict the mature technologies in the near future. Especially, designing flight display systems that create enthusiasm in the aviation industry with the opportunities that touch-based user interface technology supports for cockpit design integration, functionality, and ergonomics.

This framework also demonstrates the principles to understand cumulative knowledge in research by addressing how the overall quality of a flight deck interface is formed. Before moving to the methodology phase, this project had to explore the overall flight deck experience which includes how pilots engage and interact with flight status, control, and environmental conditions. These principles helped form the design requirements, which established a unified approach to guide the project in Table 5.

Table 5

Interface guideline for the Gulfstream project

Color should be used to convey component states.
Shape should be used to convey component function, using symbology familiar to user.
Synoptics should be simple, intuitive, and clean.
Synoptics should only employ spatial positioning of components if the position is both accurate and increases the understanding of the function of the system.
Conveying understanding of the system operation is more important than conveying spatial positioning of the system.

In general –L and R – placed either on the L or R of a symbol – should be used to convey ‘handedness’ of a component if needed for clarity.
Synoptics are used to convey both system state – and to permit control of some components in a system.
Component shape should readily confer understanding of whether that component only depicts component state – or whether that component can be controlled (e.g., a hydraulic line that is either pressurized or not – versus a generator that can be turned off or on).
(For discussion) Eliminate clutter by only displaying component parameters (e.g., battery voltage – generator V/A/Hz – Hyd pressure) if that component is out of its normal range.

4.1 Interface and Technology Trends

4.1.1 Bombardier Vision Flight Deck

Bombardier, in collaboration with avionics partner, Rockwell Collins, set out to deliver groundbreaking advancements with the assembly of their innovative Vision Flight Deck. Core objectives to deliver a complimenting convergence of advanced technology with exceptional aesthetics would present pilots with a completely new and enhanced cockpit experience. This meant a key focus of single control and comfort in the Bombardier Global aircraft which would guide the approach of design and development. The Vision Fight Deck completion yielded aviation breakthroughs by integrating the first synthetic vision imagery system on a head-up display (HUD). Additionally, incorporating the Rockwell Collins Pro Line Fusion avionics suite into the four t-shaped 15-inch diagonal active LCD displays would ensure unified interface operability between systems. Customization opportunities would also prove possible by creating personalized display information, electronic checklist as well as graphical navigation and weather maps for informative flight planning. These notable advancements would create pointed interactions and communications to improve collaborative cockpit controls among pilot personnel which surpassed initial expectations behind the intended objectives and outcome of the Bombardier Vision Fight Deck (Figure 25).

Figure 25. Bombardier Vision Flight Deck. Keller, John. “Bombardier Delivers First Vision Flight Deck Avionics on Company’s Global 6000 Business Jet for Enhanced Situational Awareness.” *Intelligent Aerospace*. 16 Apr. 2012, https://www.intelligent-aerospace.com/articles/2012/04/vision-flight-deck-on-bombardier-global-6000.html.

4.1.2 Dassault Flight Deck

Dassault's EASy cockpit system in Figure 26 focuses on intuitive usability between two pilots with advancements aimed to eliminate any paper correspondence or interactions virtually. Such progress has been made possible by utilizing the Primus Epic System, a flexible hardware platform developed by Honeywell. Customization opportunities were realized through close collaboration and Dassault's role as lead system architect. EASy cockpit was a product of detailed attention towards integrating Dassault's ideology and philosophy to create an intelligent and interactive avionic system. Goals to equip the cockpit environment with a user-centered, human-machine interface would prove vital to enhancing a pilots' situational awareness. Honeywell's contributions to the project enhanced reliability and delivered vast improvement to the visual display.

Figure 26. Dassault's EASy cockpit system. "The Award-Winning EASy Flight Deck Makes Your Private Jet Unique ." *The EASy Flight Deck Meets the Safety Needs of Private Jet Pilots*, www.dassaultfalcon.com/en/Technology/PilotBenefit/Pages/Flight-deck.aspx.

Upon entering the EASy cockpit, identifiable consideration was applied to the configuration and placement for visual displays. The central location of the four larger 14.1” screens convey and link pilots to the informative data they need to obtain. This visual information highlights communications, navigation, and aircraft sensors affecting systems and flight management.

4.1.3 Thales Flight Deck

Thales consistently challenges what is perceived as possible through their revolutionary approach towards the next generation of aviation cockpits. Signature seamless design with their angled single glass display unit is just one of the identifiable aesthetic examples of pure elegance and first class detail. Intuitive interface usability takes the system to another level using swipe, zoom, point, drag and pinches gestures to navigate the desired information efficiently (Figure 27). Pilots are guided by programmed intelligence making decisive prompts to advance one screen to the next. Clear visualization is projected through organized advanced graphical assets, responsive color configurations and a clear hierarchy of informative contextual data. Thales is on track to negate all physical buttons and control panels in their current cockpit configuration by the end of the decade by relocating their functions by virtualization into the interface capabilities (Clark).

Figure 27. A Pro Line Fusion flight deck with touchscreen capability. Clark, Nicola. "Touch Screens Are Tested for Piloting Passenger Jets." *The New York Times*, The New York Times, 19 Oct. 2018, www.nytimes.com/2013/07/06/technology/passenger-jets-testing-touch-screen-technology.html.

4.2 Market and Trend Forecast

4.2.1 The Future of Mobility

In Deloitte's *The Future of Mobility*, Derek Pankratz, Philipp Willigmann, Sarah Kovar, and Jordan Sanders describe a framework for the future of personal mobility developed by the extent to which autonomous vehicle technologies become pervasive and the extent to which vehicles are personally owned or shared (Figure 28).

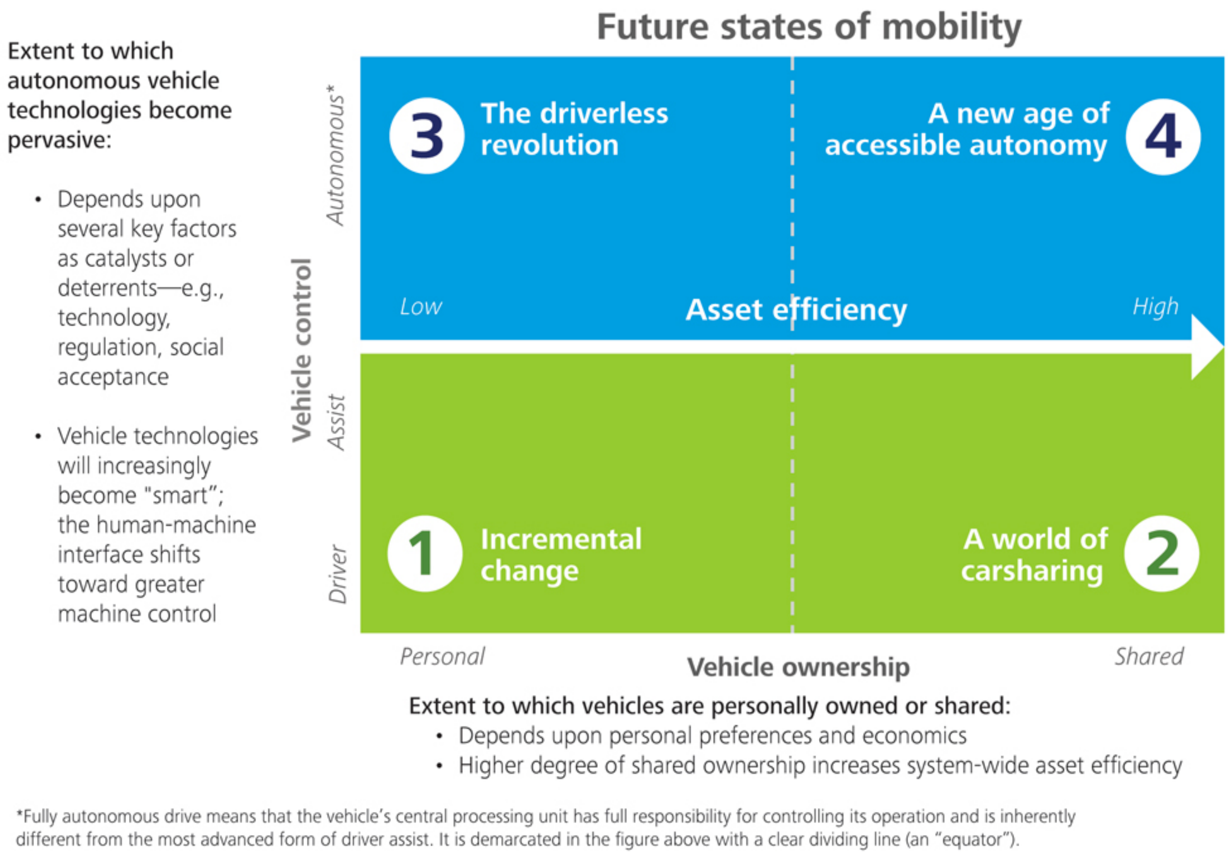


Figure 28. Future states of mobility. "Framing the Future of Mobility." *Deloitte Insight*s, https://www2.deloitte.com/insights/us/en/deloitte-review/issue-20/overcoming-consumer-resistance-to-future-of-mobility-behavioral-economics.html.

4.2.2 Semi-Autonomous Vehicle

Artefact developed a concept of a semi-autonomous vehicle that would have the capability to drive itself. John Brownlee, a design writer at Fast Company & Inc., illustrated that drivers would push the handing of the wheel in the transportation then turn on the autonomous mode. When the vehicle toggles between driving and self-driving mode, the entire user interface adapts, exposing only the information that is needed (Figures 29 and 30). It is important not to burden a driver with too much information, making the idea of turning over the wheel and user interface to the car intimidating ("How UI/UX Design Will Map The Future Of Self-Driving Cars"). As situational awareness increases, the driver is able to quickly respond, integrate, and interpret information from the driving system.

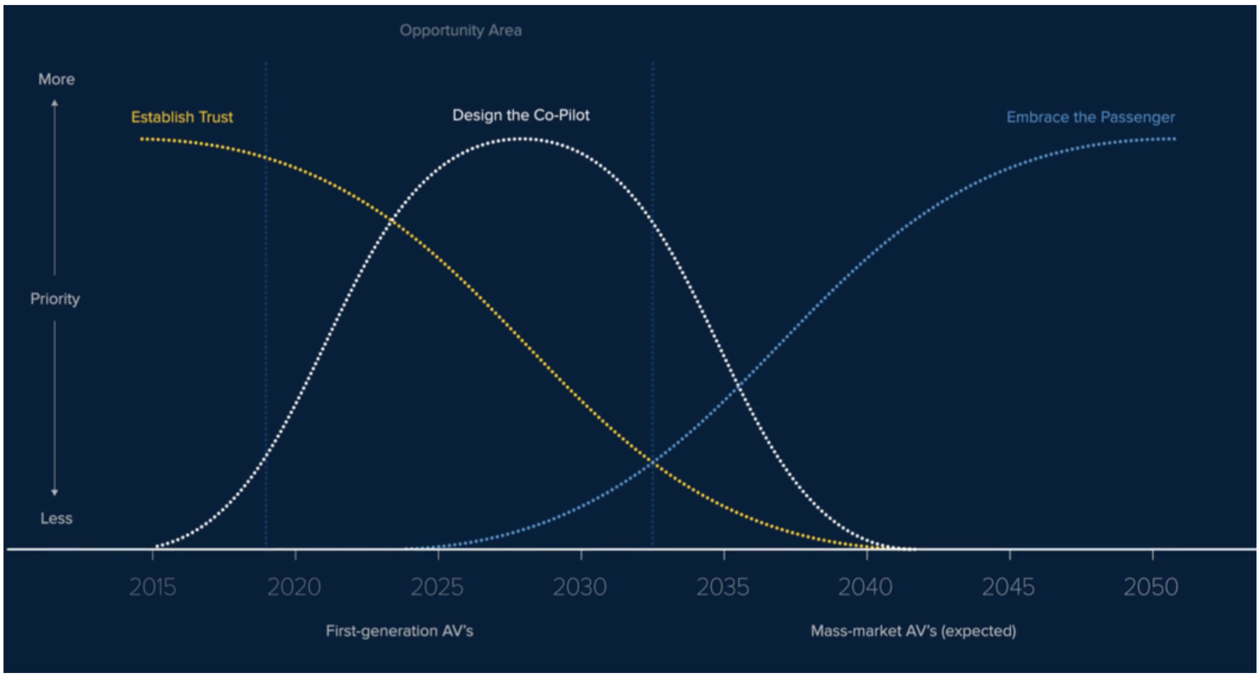


Figure 29. Human transition in three phases. "Hyundai: Are We There Yet? Exploring the (Near) Future of Driving." *Artefact*, www.artefactgroup.com/work/hyundai-a-vision-for-semi-autonomous-cars/.

Figure 30. Guideline of the semiautonomous vehicles by Artefact. Brownlee, John. "How UI/UX Design Will Map The Future Of Self-Driving Cars." *Fast Company*, Fast Company, 23 Aug. 2018, www.fastcodesign.com/3052738/how-ui-ux-design-will-map-the-future-of-self-driving-cars.

4.2.3 Uber Elevate (Vertical Take-Off and Landing, VTOL)

Uber envisions electric and fixed-wing vehicles with the flying taxi, even though they have yet to perfect the technology that is reliable for transportation between suburbs and cities avoiding ground-based difficulties (Figure 31).

Figure 31. Expected time for traveling from San Francisco's Marina to work in downtown San Jose. Holden, Jeff, and Nikhil Goel. *Fast-Forwarding to a Future of On-Demand Urban Air Transportation*. 27 Oct. 2016, www.uber.com/info/elevate/.

They consider it is feasible in the coming decade if regulators, vehicle designers, communities, cities, and network operators collaborate in the VTOL ecosystem. Then, the system will ultimately use the technology of vehicles to reduce pilot's error. In Uber's current model, the drivers are contractors who are in charge of each of their transportation environments. Therefore, the interface of this air mobility needs to be determined on flight information to suit every user's needs. It also needs to include temperature, infotainment experiences, and a method of displaying information relative to the trip. In the paper "Fast-Forwarding to a Future of On-Demand Urban Air Transportation," Jeff Holden and Nikhil Goel emphasize that autonomous VTOLs will improve the safety of pilot's operations:

Users and regulators become more comfortable with the technology and meet statistical proof that vehicles provide greater levels of safety than human pilots. Since this level of control system software is new in small aircraft, it raises the question of how these systems will be certified for safety and how long that process will take. Recognizing the potential benefits of automation to the primary causes of accidents in general aviation, they also saw that the FAA Small Airplane Directorate has initiated efforts to explore more affordable approaches to implementing these type of systems. Ground-based operators—just like the pilots who will initially fly these VTOLs—will need to be trained and licensed. As part of certification of a new vehicle, manufacturers will need to define ways an operator can monitor vehicle air worthiness and its ability to make flight safety decisions remotely. This move to remote piloting will likely need close coordination with the FAA Unmanned Aircraft Systems efforts as they address similar issues with large drones in civilian airspace. (42)

5. Design

5.1 Ideation

When designing each synoptic, it explored different viewing modes to convey relevant information more efficiently through progressive disclosure. The display system was designed using the crew-alerting system (CAS) and checklist panels to follow the contextual model so that the new system was as consistent and intuitive as possible. This interface also addressed the misleading iconography found in the current synoptic interface by redesigning each icon to better represent its function. All icons had numerous iterations, from pencil to digital, that was user tested in order to choose the designs with the best clarity and discoverability in the new touch-screen interface (Figure 32).

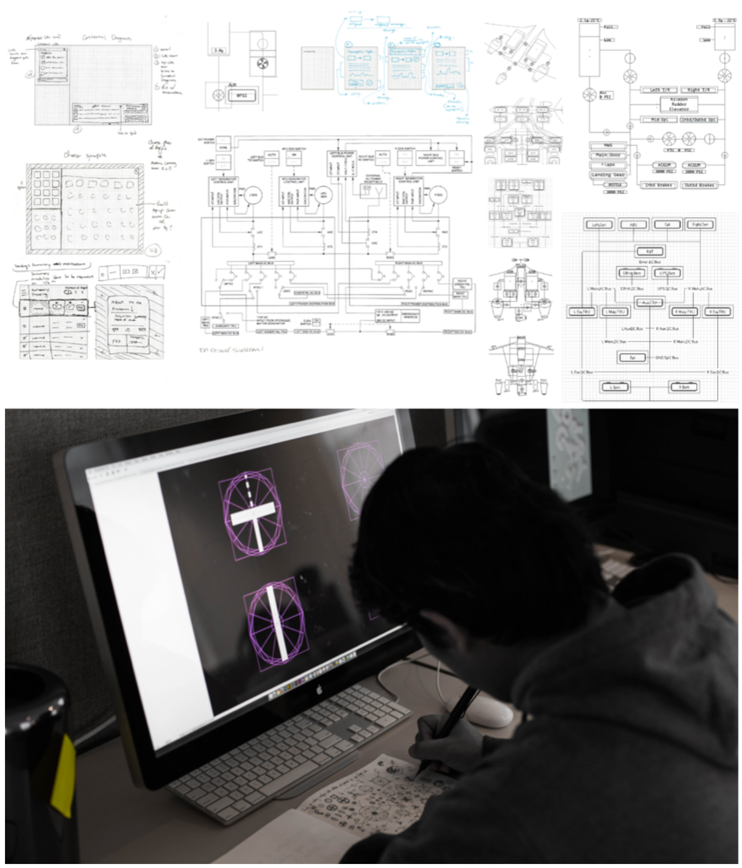


Figure 32. “Generating ideas and formulating concepts”

5.2 Concept Development

In the concept development phase, the user interface of the synoptic system was further implemented to incorporate control and the flow between them in order to improve the pilot's flying experience. In addition, design principles of the concepts (Table 6) were created to illustrate each idea within the context of the system environment so that the concepts could validate its design criteria during the development (Figures 33 and 34).

Table 6

Design principles of display system

Attributes	Principles
Instant	Prioritize situation over interface to give user a sense of instant gratification with each screen
Relevant	
Personal	Let users take control of the information they watch, making their synoptics as unique and personal as their mobile
Controllable	
Connected	Facilitate connections to related content, information, and users with similar interests
Focused	Optimize navigation for quick access to user's preference and situational context
Scalable	
Discoverable	
Iconic	Keep the interface quiet but distinctive, using progressively to reveal unique interactive elements as the user dives deeper into information
Invisible	
Intuitive	Use gestures to define a clear and memorable spatial model, and to reduce dependency on visible interface elements

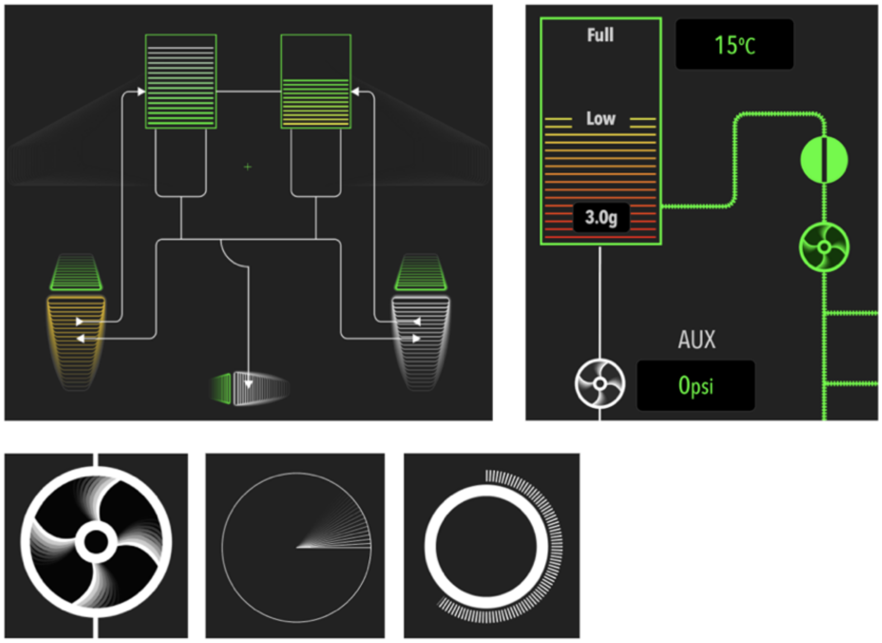


Figure 33. “In-between states of interface elements through design framework principles”

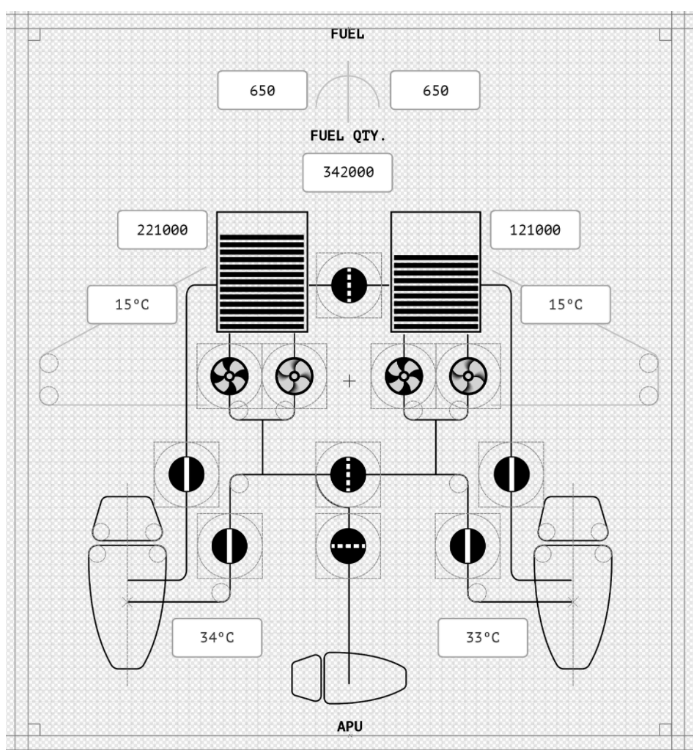


Figure 34. “Interface guideline through design framework principles”

5.3 Visual User Interface Design

To incorporate control, the project designed each of the new interactive icons to have both visual feedback and a touch target surrounding each element to minimize error. By highlighting the affected components and integrating a contextual control panel, the pilot's navigation during an abnormal state would be efficiently directed on a path for correction. In Figure 35, these initial sketches and concept work were an essential step as the project explored each opportunity before focusing their efforts on refining their design decisions based on feedback.

Figure 35. “Basic principal of the user interface design”

5.3.1 Status Mode

The Status Mode holds only the most relevant information when all systems are functioning normally. This viewing mode supports the “quiet/dark” flight deck philosophy, and the pilot can infer that everything is well within normal parameters provided that the status synoptic mode is green and dark. Only the background, graphics, and some of the component layers are shown in the status mode in Figure 36.

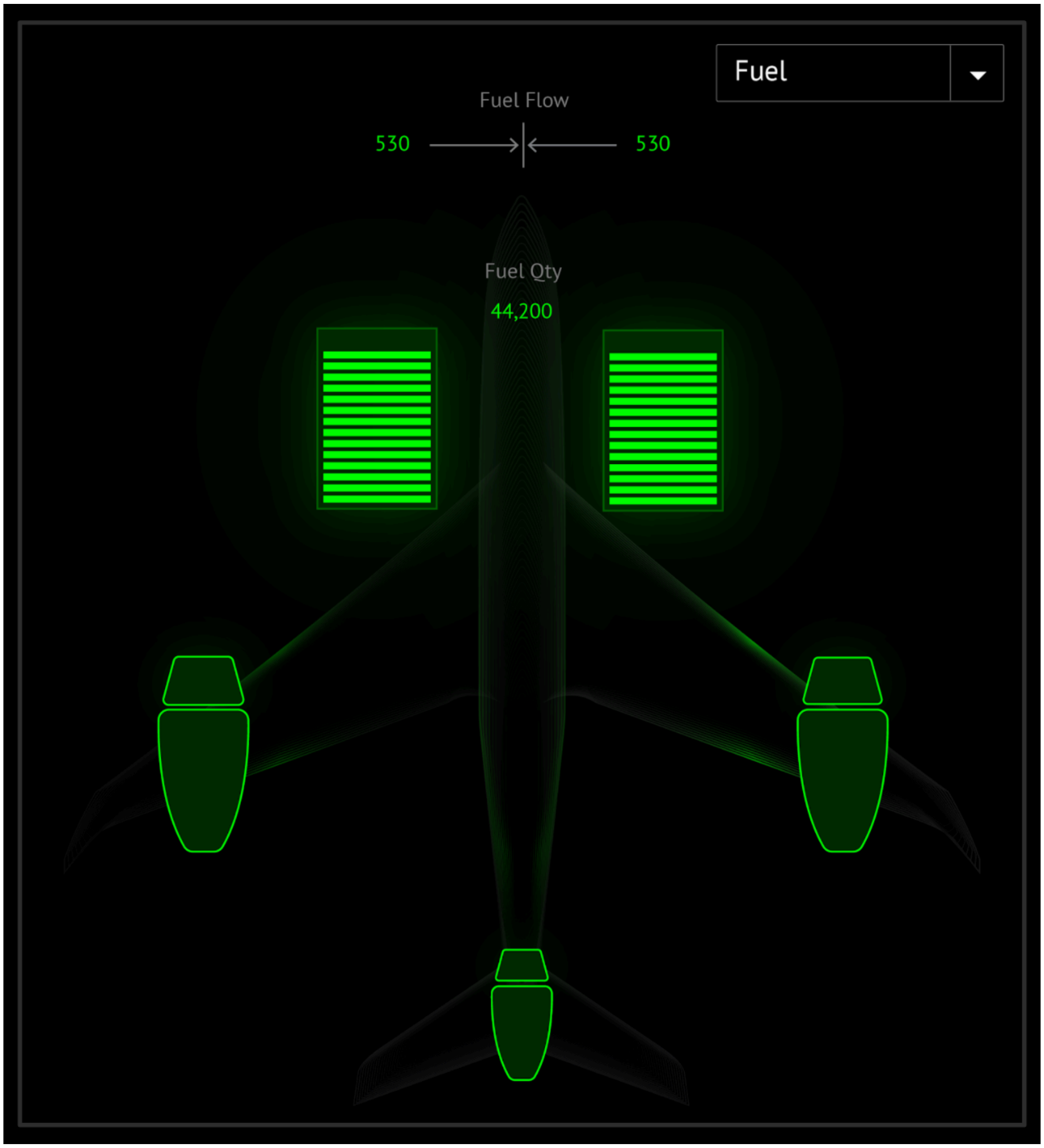


Figure 36. “Status mode for fuel synoptic”

5.3.2 Magnified Mode

The Magnified Mode shows all of the extended information and element parameters for the synoptic and contains all of the interactive components such as buttons and icons in Figure 37. The pilot can swipe between the two modes at any time, but the magnified mode is brought up automatically in an abnormal situation so that the pilot immediately has all the information needed to address the problem efficiently. The magnified mode has all the detailed information in the current synoptic, allowing for complete control from this mode.

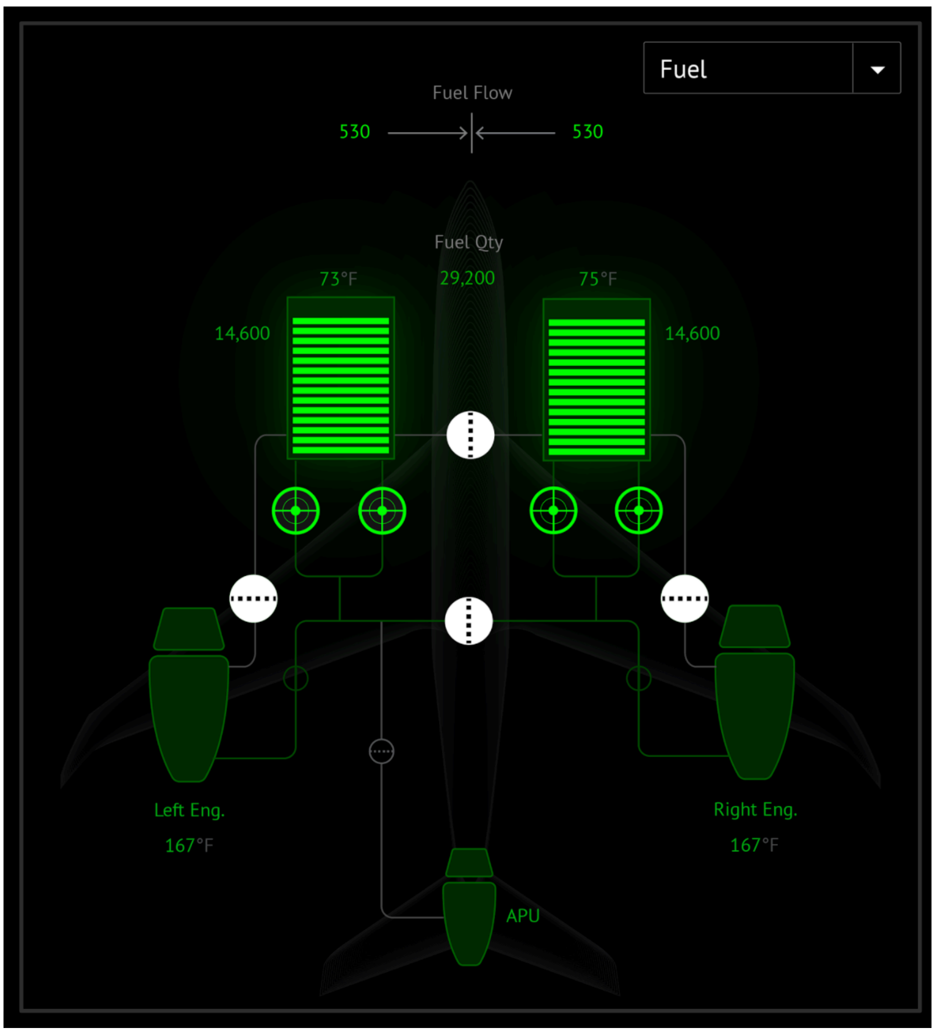


Figure 37. “Magnified mode for fuel synoptic”

These multiple layers (also called viewing mode) can be restructured into two groups, and these groups become the following viewing modes in Figure 38. The Status mode is the simplest, and the lack of clutter makes it easy to comprehend. The pilot can instantly infer that system is functioning normally when everything is green and dark.

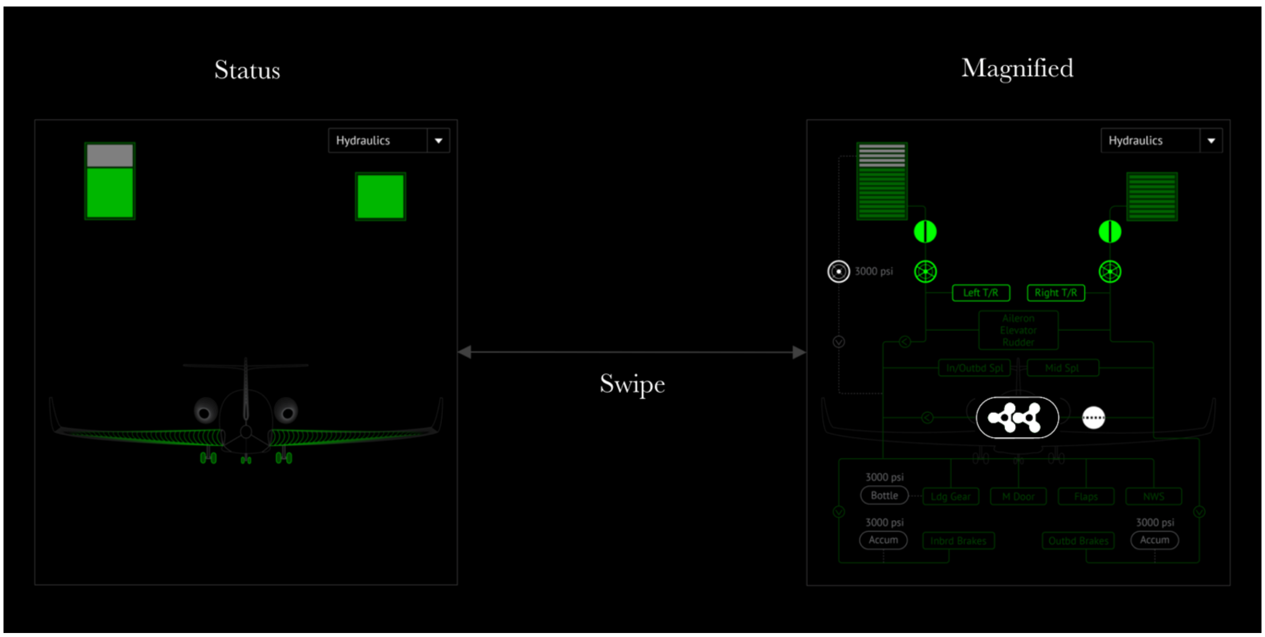


Figure 38. “Switching hydraulics modes by finger swiping on the screens”

The pilot can quickly swipe between these two modes on any screen, and in the case of an abnormal state, magnified is brought up automatically, so the pilot has all the information he needs to address the problem efficiently in Figure 39.

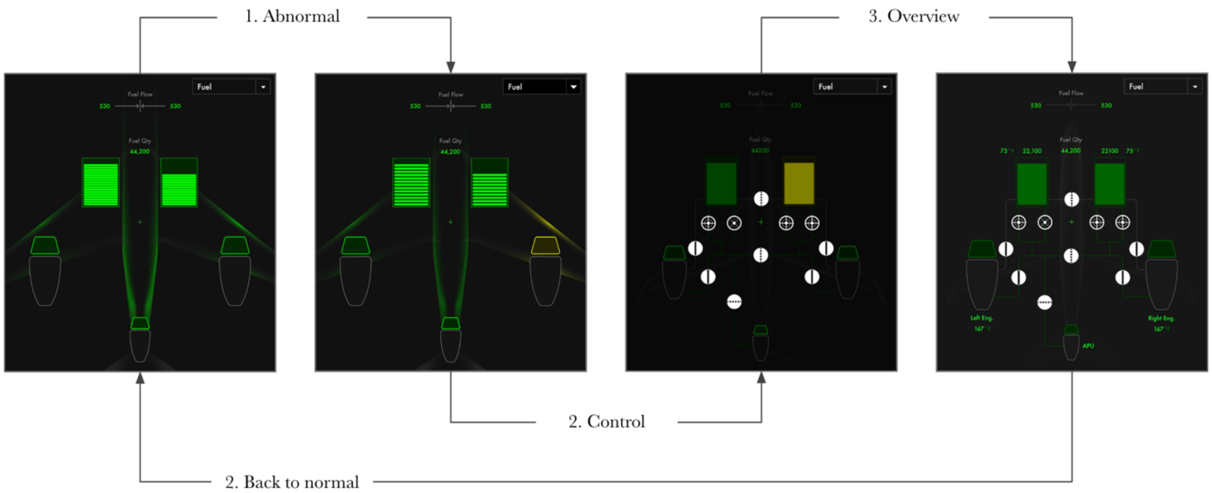


Figure 39. “Four stages of interaction for abnormal states”

5.4 Refinement

Following the designing of research, Gulfstream’s Project Manager of Advanced Cockpit Programs, Nick Kershaw, gave constructive feedback that contributed to the progress throughout each stage of the project. During the research review, Gulfstream was impressed by the quantity and quality of research collected by the project, providing insights to the concept as they moved forward into the design phase. During the concept review and user testing, detailed feedback was issued regarding individual elements of the concepts. The quantitative feedback from Gulfstream includes type size, color saturation and visual weight of interactive icons, and the proposed viewing modes.

5.5 Design Guideline

The design guideline led to layering schemes for the information architecture, visual hierarchy, and viewing modes relying on the Federal Aviation Administration (FAA) regulations. It optimizes the distinctive clarity and visual organization of synoptic information (Figure 40). Any visual elements should align with the overall look and feel of the aircraft and should support the pilot's comprehension and the functions of the aircraft in Figures 41 and 42.

Figure 40. "Basic design guideline for synoptic"

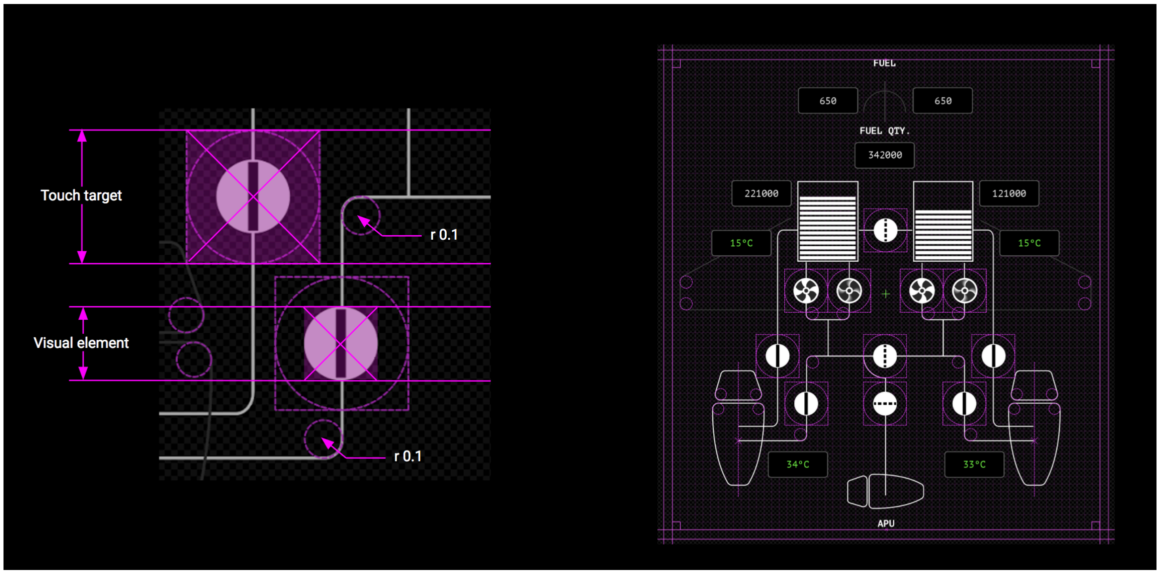


Figure 41. “Example of user interface guideline for designing fuel synoptic”

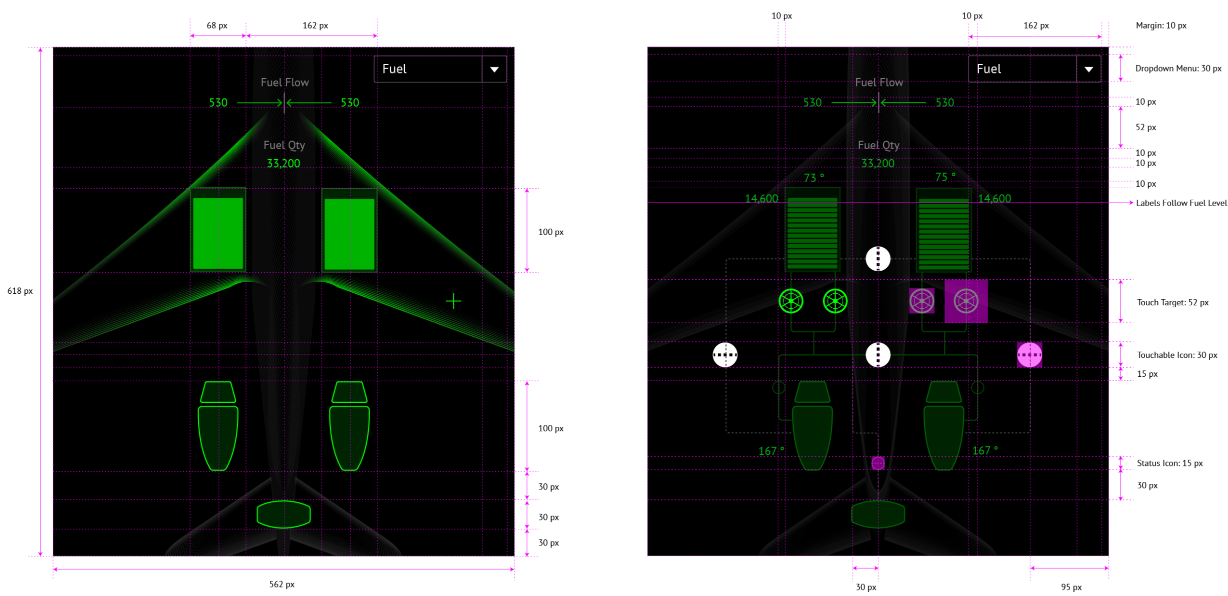


Figure 42. “User interface guideline for fuel synoptic”

The current synoptic was the established language of color green meaning good/normal, amber meaning warning, and red meaning emergency. The FAA limits color to six hues, and this concept of the interface has followed that requirement but pushed the boundaries by including tints and shades of the six hues. There are distinguished controllable/interactive elements from the purely status parts of the synoptic. More saturated icons elevate up to the front visually, and the lower contrast colors recede into the background so as not to distract the pilot from what is most important on the interface. It addressed the visual problem of inconsistent and misleading icons. From the research, the icon for a fan and a hydraulic pump are identical, even though those elements have vastly different functions, so these elements were designed to distinguish the two (Figure 43).

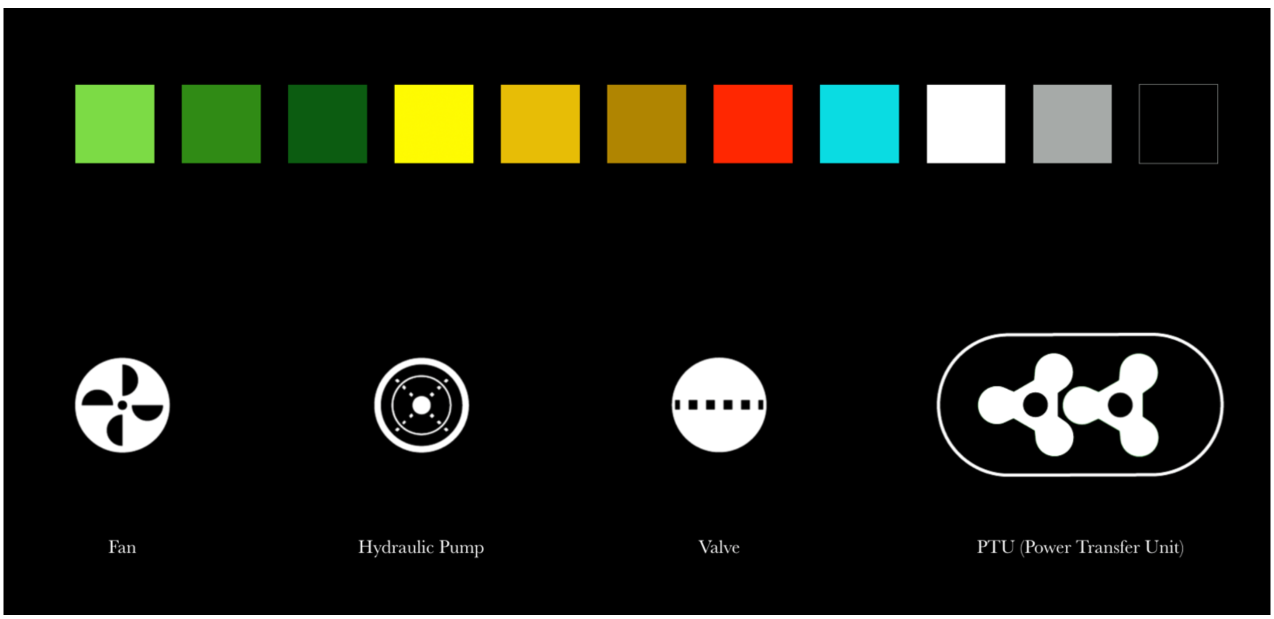


Figure 43. "Basic design principles of color and iconography for proposed synoptic"

The applicant should follow a design philosophy for the display system that supports the intended functions to be readily available. In order to avoid the ambiguity of hierarchy and navigation, the design philosophy should include a high-level description of

(1) The general philosophy of information presentation – for example, is a "quiet, dark" flight deck philosophy used or is some other approach used?

(2) Color philosophy on the electronic displays – the meaning and intended interpretation of different colors – for example, does magenta always represent a constraint?

(3) Information management philosophy – for example, when should the pilot take action to retrieve information or is it brought up automatically? What is the intended interpretation of the location of the information?

(4) Interactivity philosophy - for example, when and why is pilot confirmation of actions requested? When is feedback provided?

(5) Redundancy management philosophy – for example, how are single and multiple display failures accommodated? How are the power supply and data bus failures accommodated (Aviation)?

5.6 Mockup Design

The synoptic interface with the Digital Mockup (DMU) is inspired by key data discovered in the research and design phases. The result incorporates all the elements from the research data integrated into Gulfstream's Advanced Flight Deck, with emphasis on emerging technologies, presenting a more contextual and personalized cockpit experience for pilots in Figures 44.

Figure 44. “DMU for Gulfstream flight deck in cruise mode”

6. Validation

At the beginning of the validation session, all participants were deeply familiar with the associated terminology of the flight deck interface and briefed on the full scope of the scenario presented in Figure 45. Pilots navigated through the new user interface on the first attempt, issuing feedback to scripted questions and offered comments supporting confirmation and opportunity points. The testing flow was seamless and presented a definitive starting point to identifying an evidence-based understanding of the prototype content.

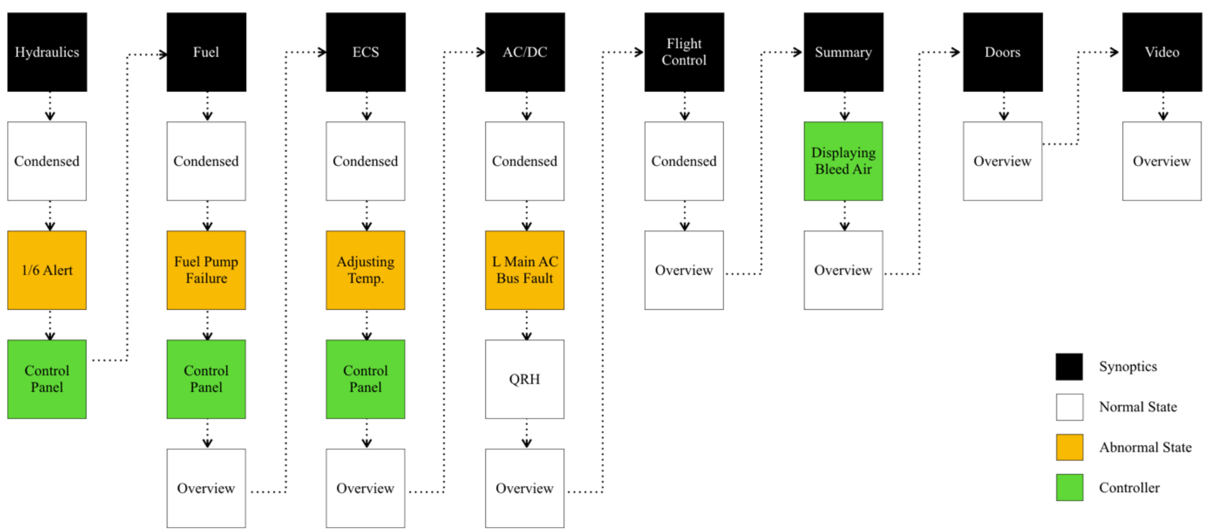


Figure 45. "Validation scenarios for the new flight deck interface"

Working prototypes were created to display the configuration of MLHVR elements within the context of their environment to validate the design outcome with user testing. Pilots were prompted to perform task-specific actions with little or no guidance to observe and evaluate the efficiency of the MLHVR interface with completed tasks. These tasks involved ameliorating abnormal situations and navigating through specific areas of the synoptic system. The prototype was displayed in an environment which mimicked the current synoptic interface.

To provide the pilot with context when interacting with the synoptic interface, a testing environment was configured which mirrored the current flight deck. This included a cockpit seat, as well as touch-screen and display monitors (Figure 46). The touch-screens displayed the synoptics in their interactive state, and the display monitors were used to replicate the environment as it would be seen outside of the cockpit windows.

Figure 46. “Evaluation of visual clarity for the MLHVR framework”

User testing covered navigation layouts with different information arrangements which were subsequently analyzed by a demonstrative example of pilots to access the required information. Although the MLHVR framework was created to display synoptic pages within the context of the flight deck environment, it required high-fidelity interaction prototyping. Pilots were prompted to perform task-specific actions to interact with the physical touch screens through probable situations using the MLHVR interface (Figure 47).

Figure 47. “Simulation environment for the evaluation of the developed flight deck interface”

Gulfstream pilots participated in user testing of this solution in the flight simulated environment. Participants offered feedback regarding the components of the synoptics as well as navigation. Overall, pilots intuitively navigated through the screens and controlled various components with minimal instruction. Pilot #1 vividly described the concept during testing, confirming the organization of MLHVR elements enhanced clarity and displayed dense information in a simple manner, thus presenting the future opportunity to reduce the visual cognitive load and error rates of pilots (Figure 48). Pilot #2 explained that displaying three fuel tanks in the summary synoptic was unnecessary, suggesting only the outside two fuel tanks be shown. When introduced to the video synoptic, Pilot #3 explained that while the aircraft was on the ground, pitch, stabilization, and roll were not necessary for the flight controls synoptic. However, stated that it would be quite helpful if they appeared once the plane was in flight. Pilot #4 provided necessary feedback regarding the functions of the environmental control system (ECS) and Anti Ice system, guiding the restructured information and design of those pages.

Figure 48. “Testing abnormal states of the flight deck interface”

The next step considered evaluation methods with simulation environments; the proposed design framework was tested with some ambiguity between the status information and control buttons (resolved by changing the iconography, distinguishable hue contrast, scale, and position on the screen). Gulfstream´s hydraulic pump, fan, valve, and power transfer unit (PTU) icons were evaluated for discoverability in the new touch-screen environment in Figure 49.

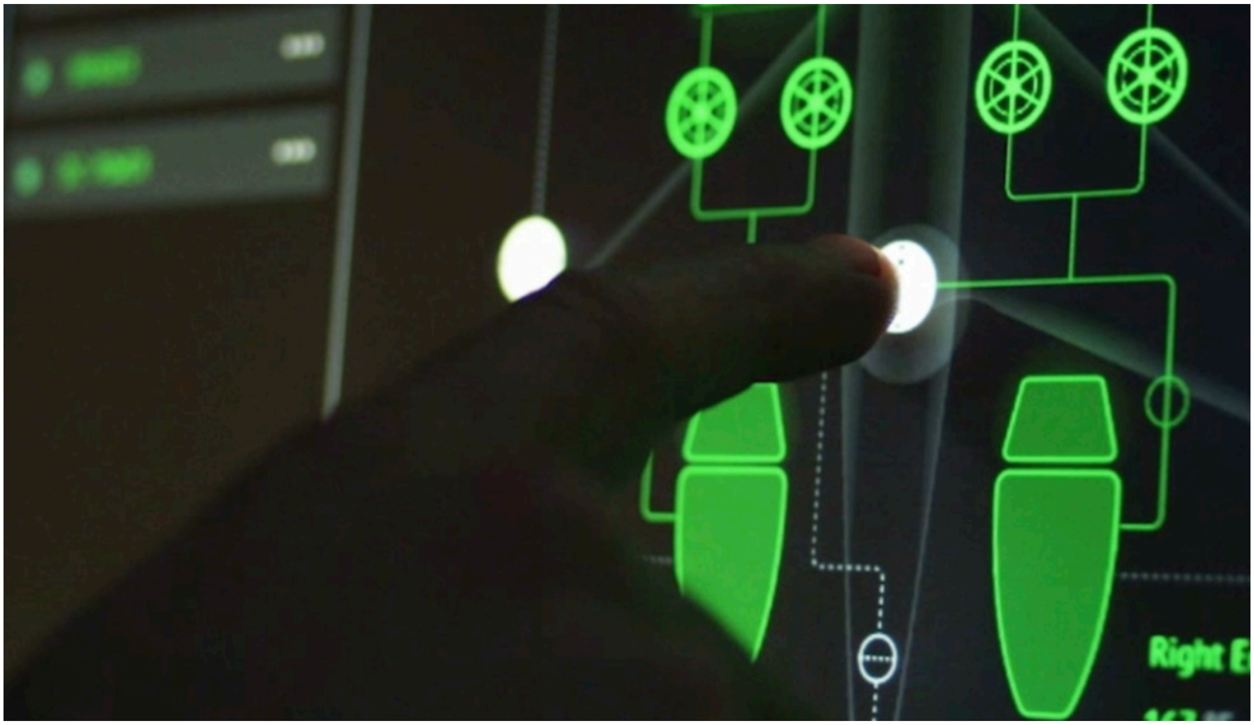


Figure 49. “In-context testing for graphic representation of iconography”

Testing participants resoundingly agreed the proposed iconography corrected the visual discrepancies across the synoptic pages that better-represented form and function. The hierarchical structure of the design framework was able to resolve the immediate problems brought to attention by the pilots. Following extensive design iterations, progressive disclosure, and user testing, MLHVR identified decisive advancement in display quality through visual and graphic representation that enabled the elimination of inconsistencies with organized hierarchical levels of status and control.

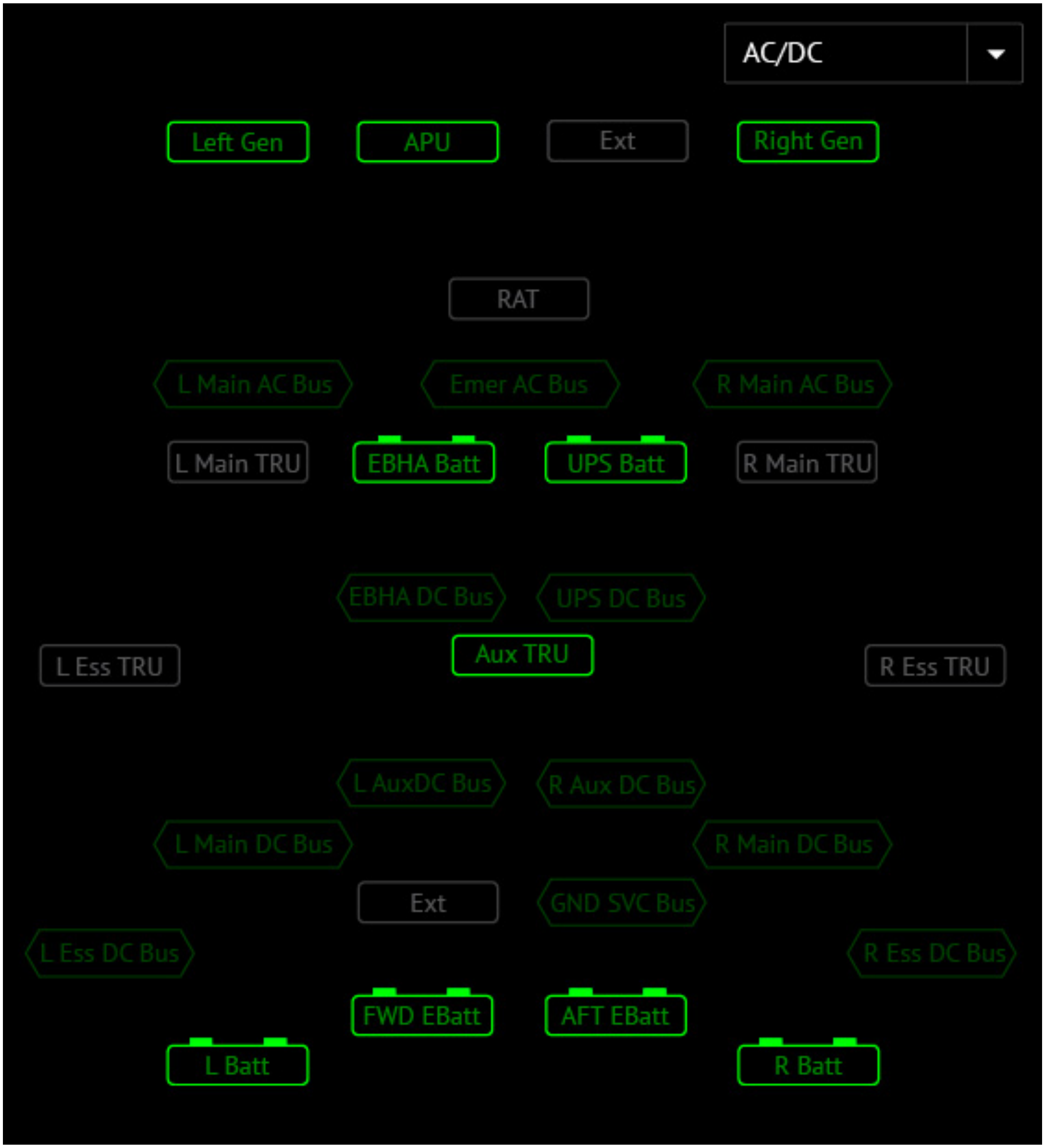
7. Conclusion

Connecting a carefully considered balance of humanistic and technological interactions will allow me to integrate and advance interactive design. Aside from elegant interactions that are both purposeful and personal, how I curate flow and experience will determine the rate of change and acceptance in my interactive design solutions. There needs to be a clear and meaningful insight that cultivates interpersonal connections between objects. Obtaining the foundational framework of object relations will produce empathetic products that better represent the users' intended outcome. This means shifting the delivery process to a more unique and meaningful direction. In the creative design process with interactive elements, global humanitarian efforts, actions, reactions, and access become inherently more powerful. Speeding up these processes will continue to evolve further the connection between societies and technological colonies to shape the next progression.

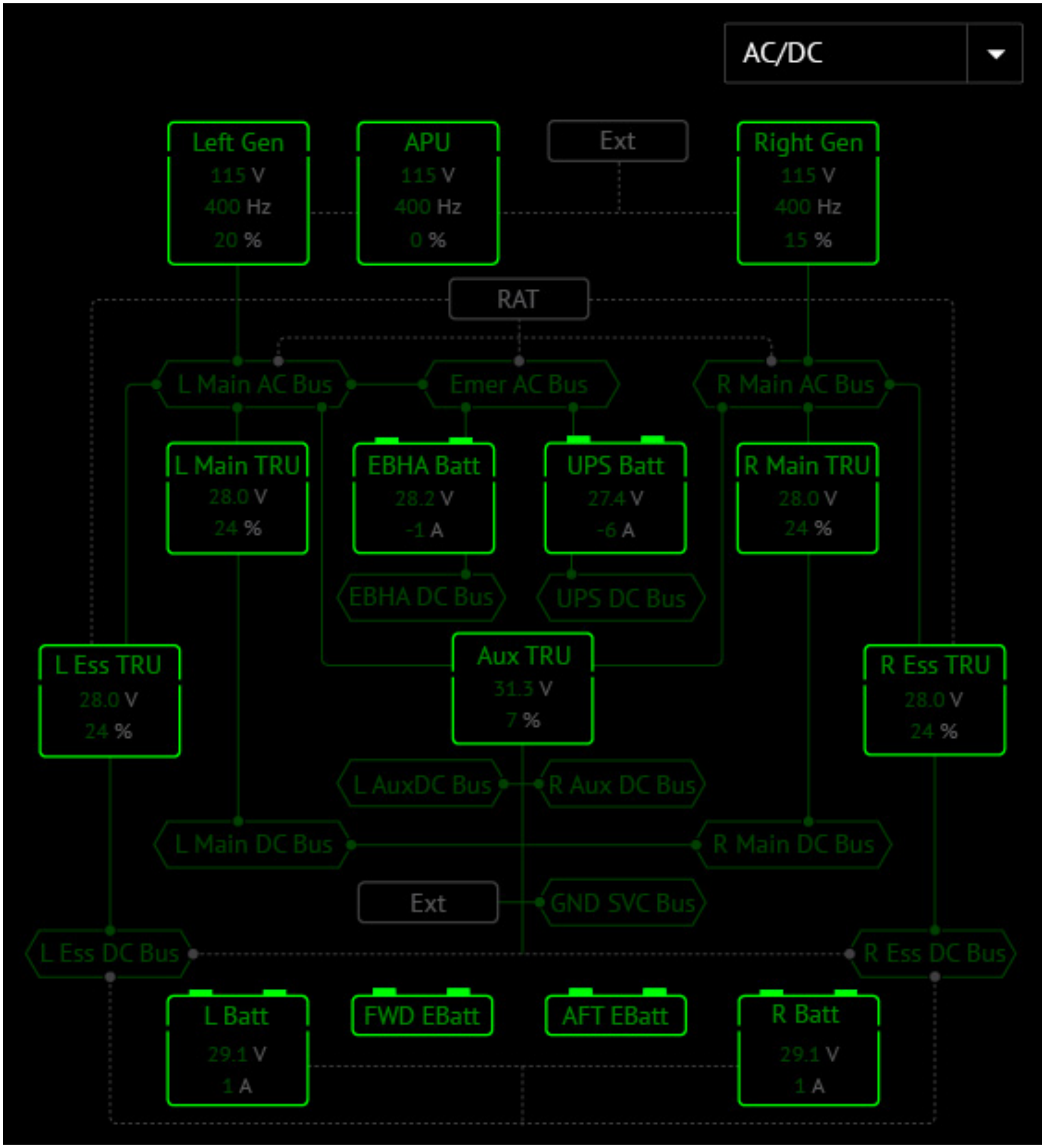
Appendix

Appendix A: Touchscreen Synoptic Display

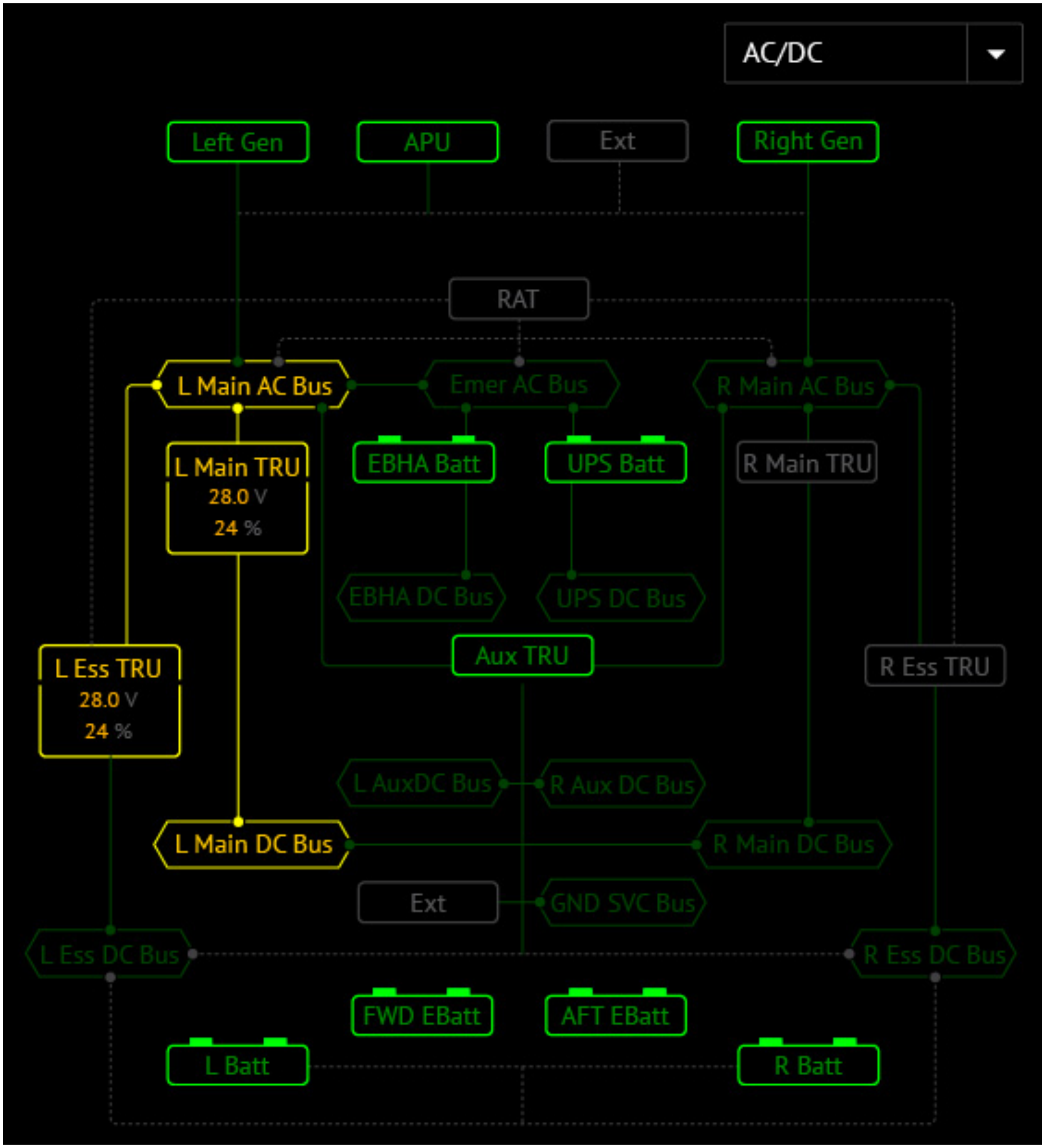
AC/DC—Status mode



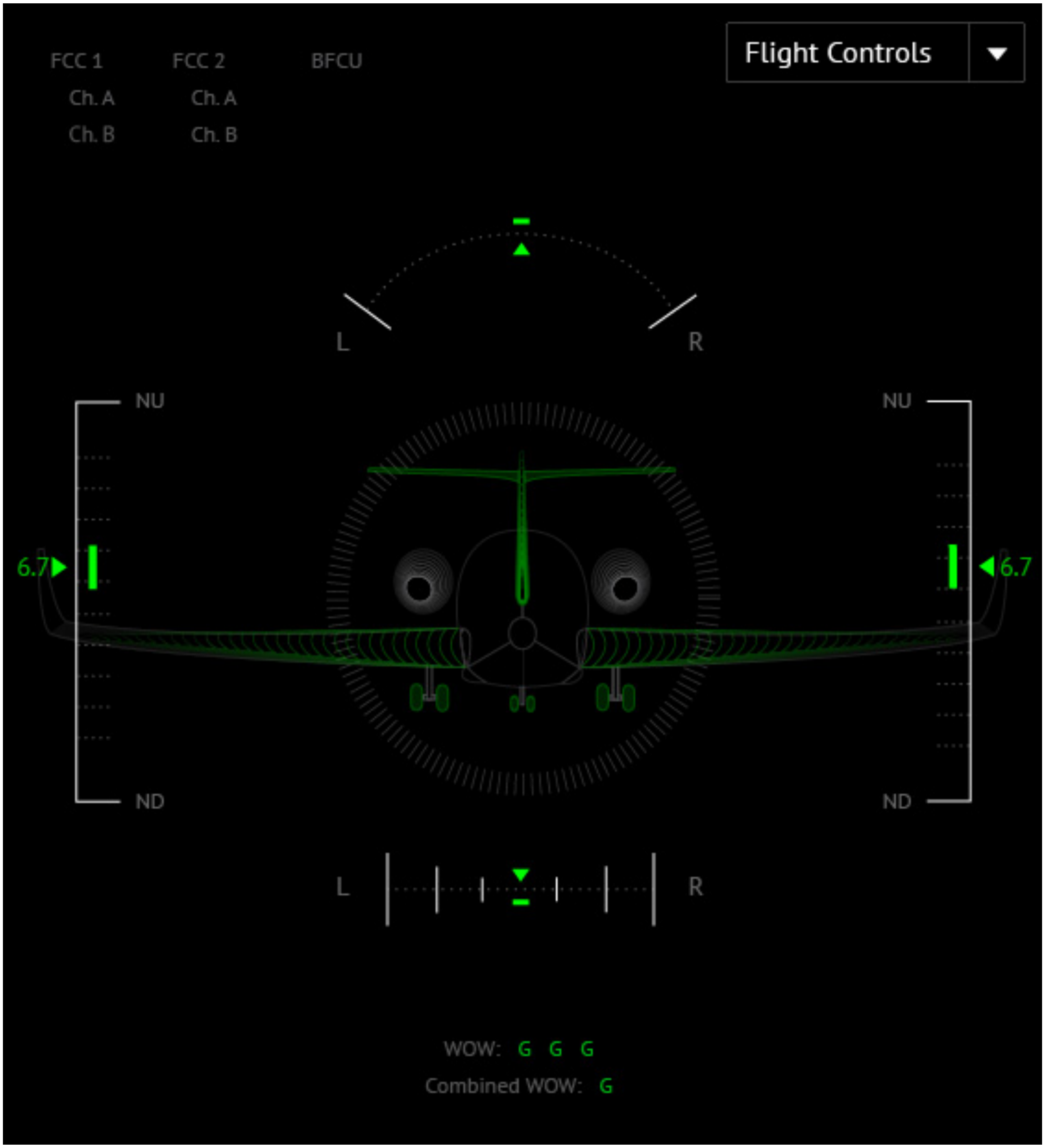
AC/DC—Magnified mode



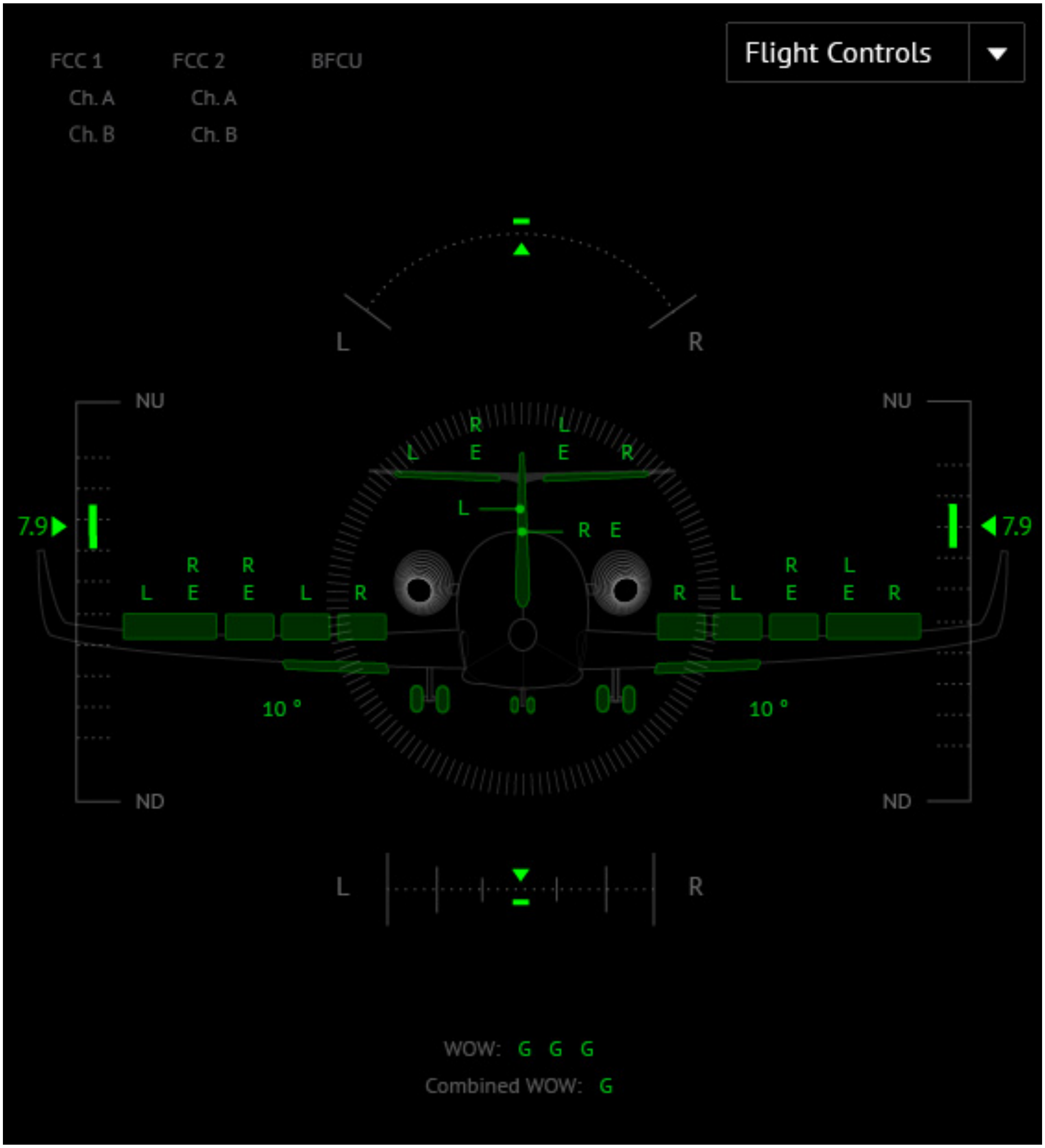
AC/DC—Abnormal Status



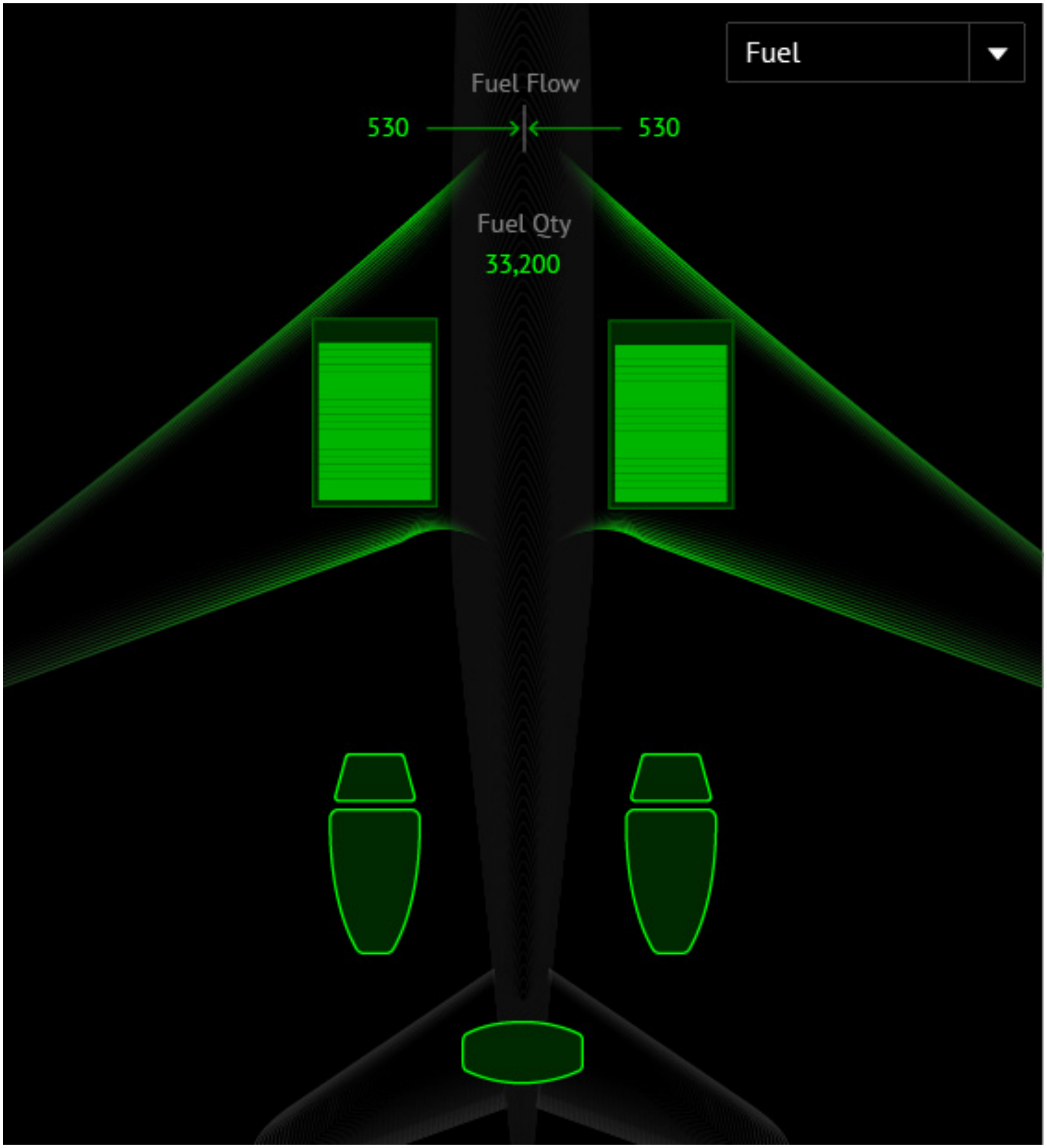
Flight Controls—Status mode



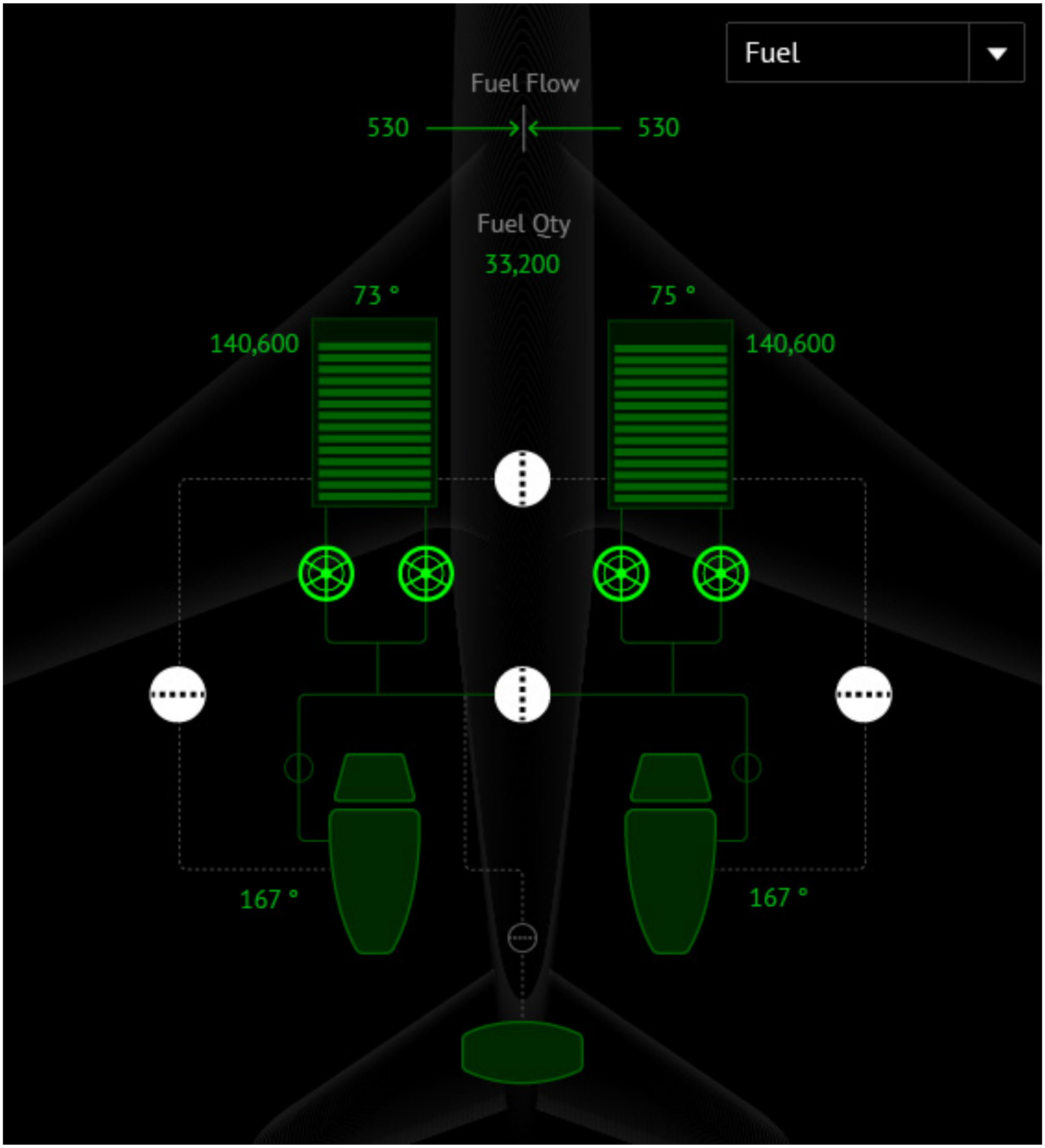
Flight Controls—Magnified mode



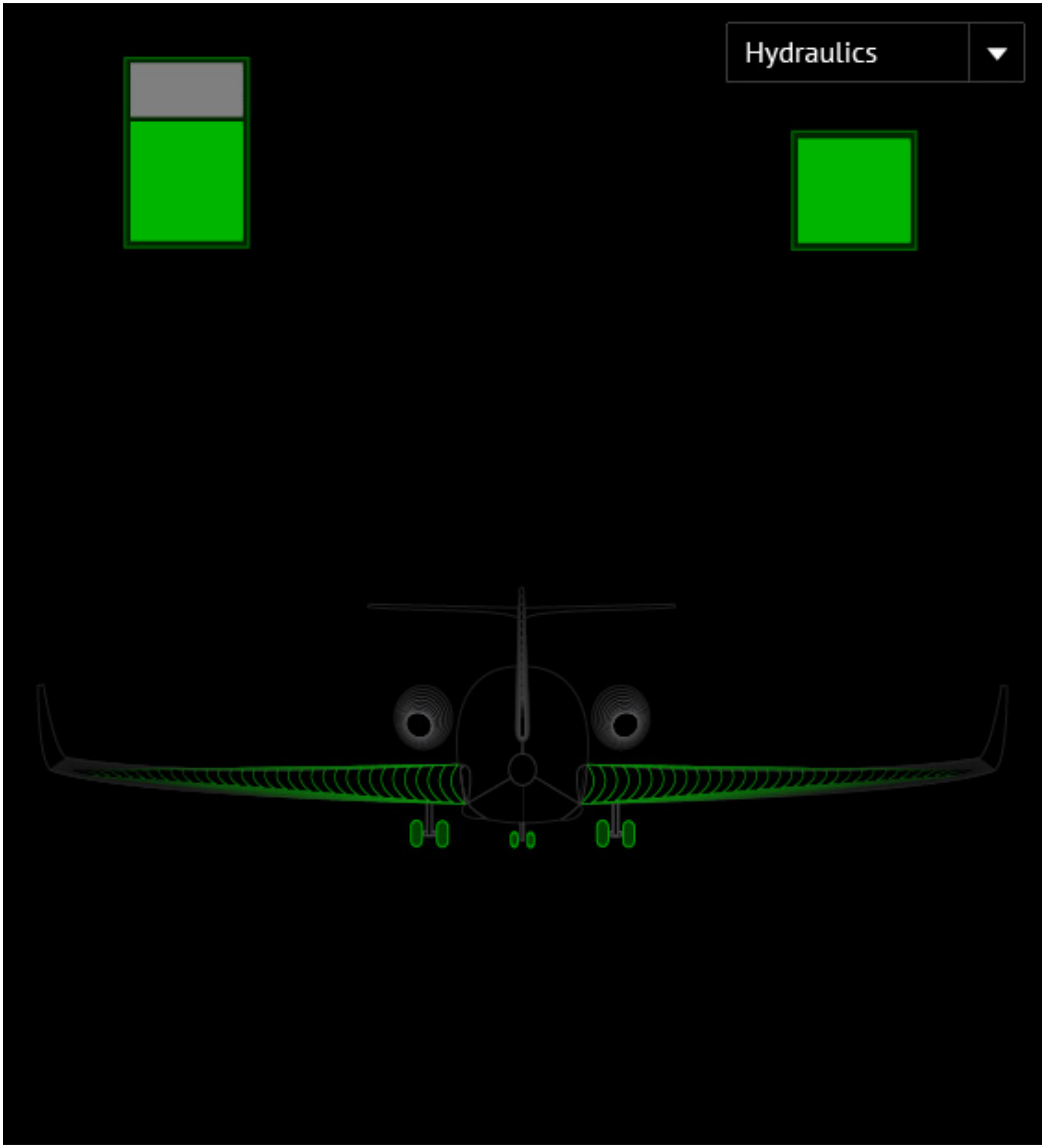
Fuel—Status mode



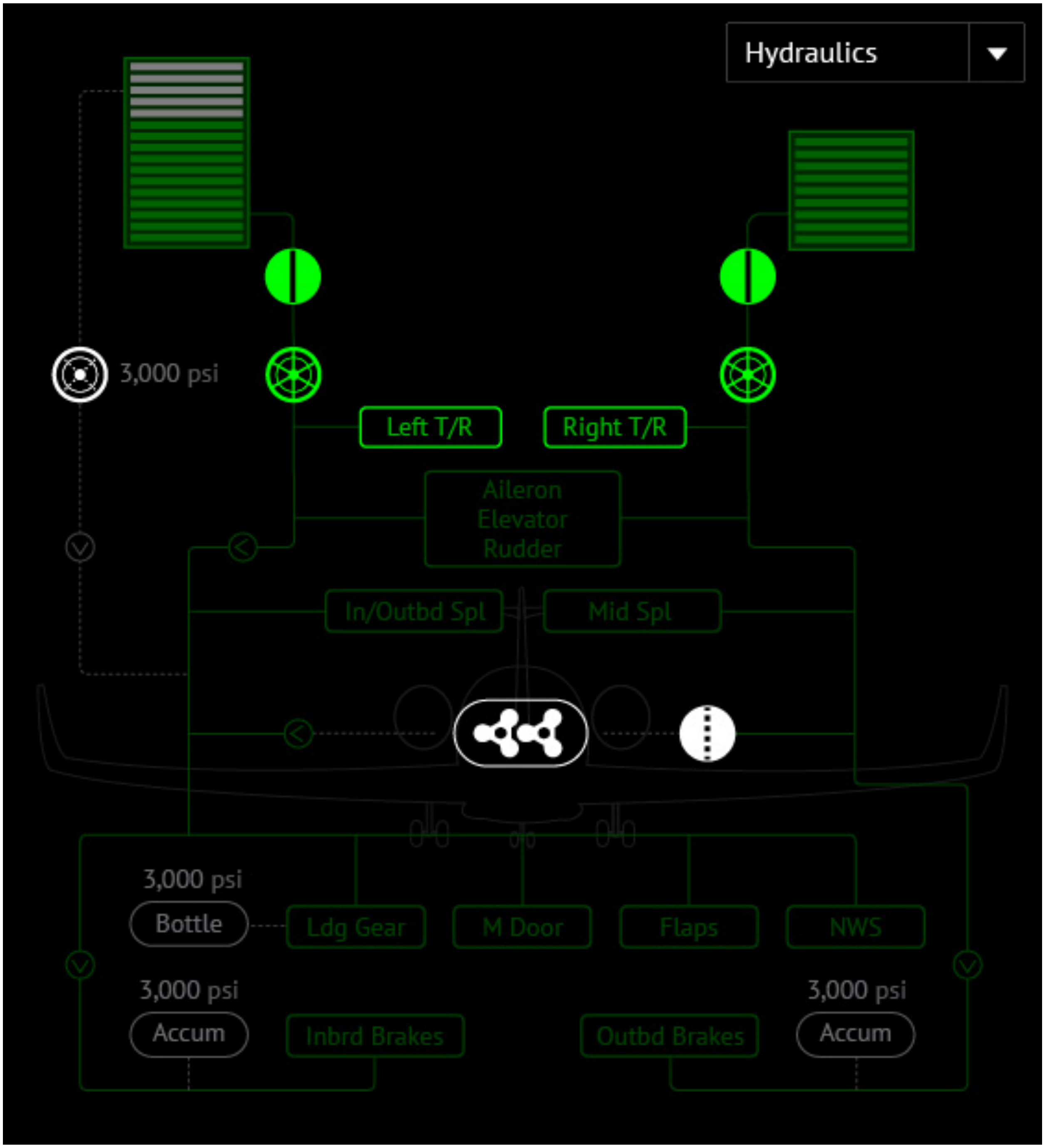
Fuel—Magnified mode



Hydraulics—Status mode



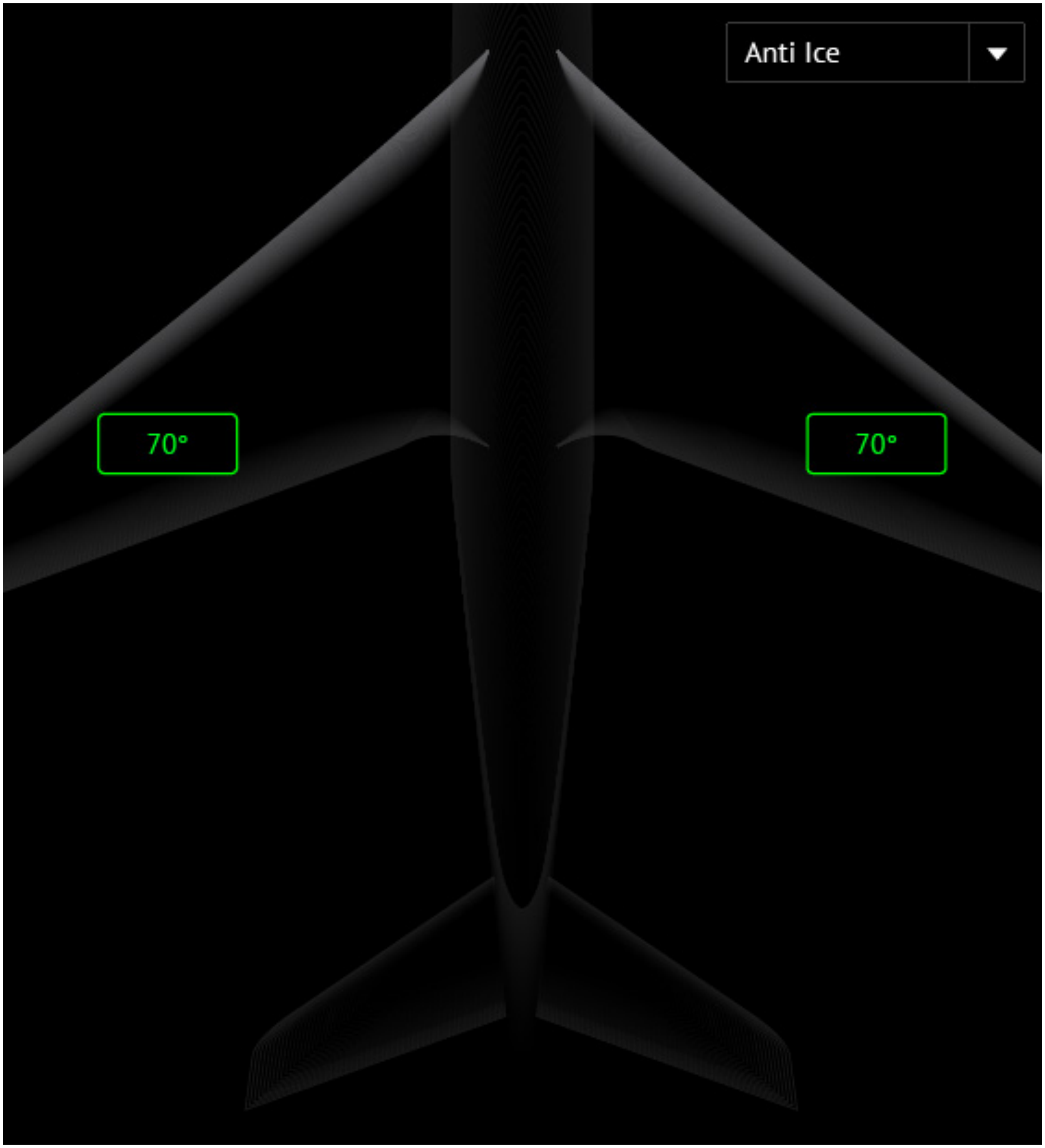
Hydraulics—Magnified mode



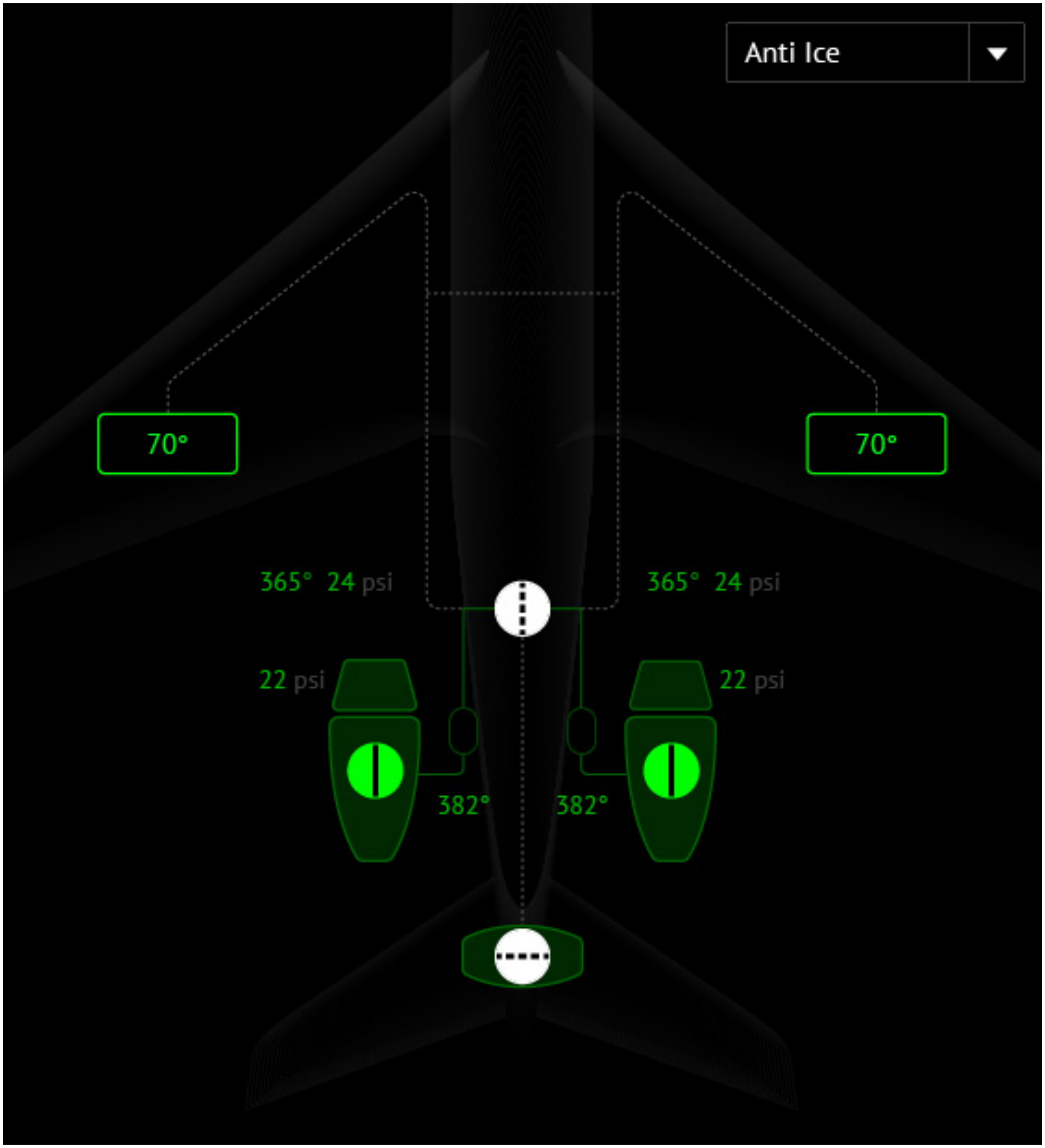
Summary—Status mode

Summary—Magnified mode

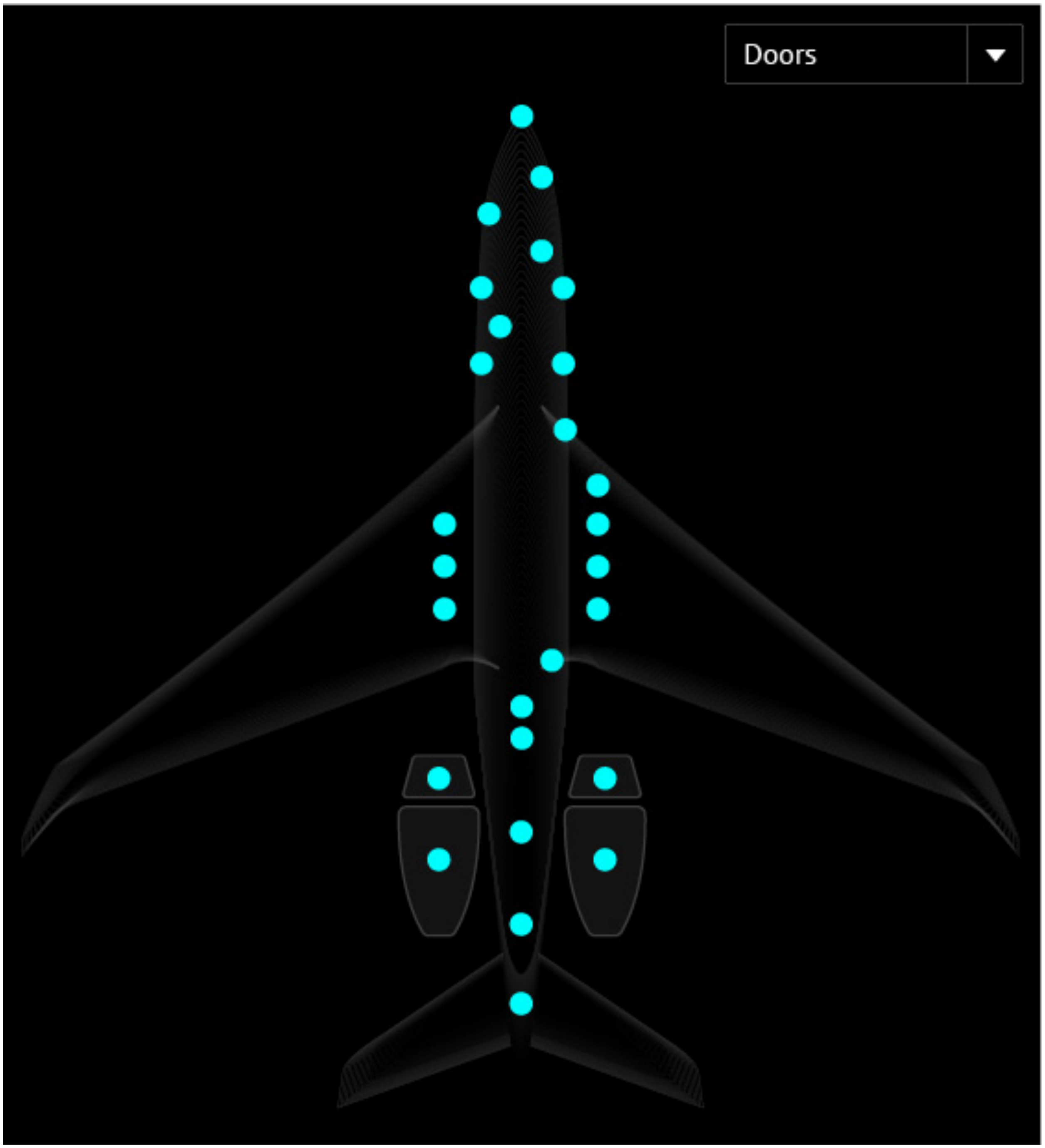
Anti-Ice—Status mode



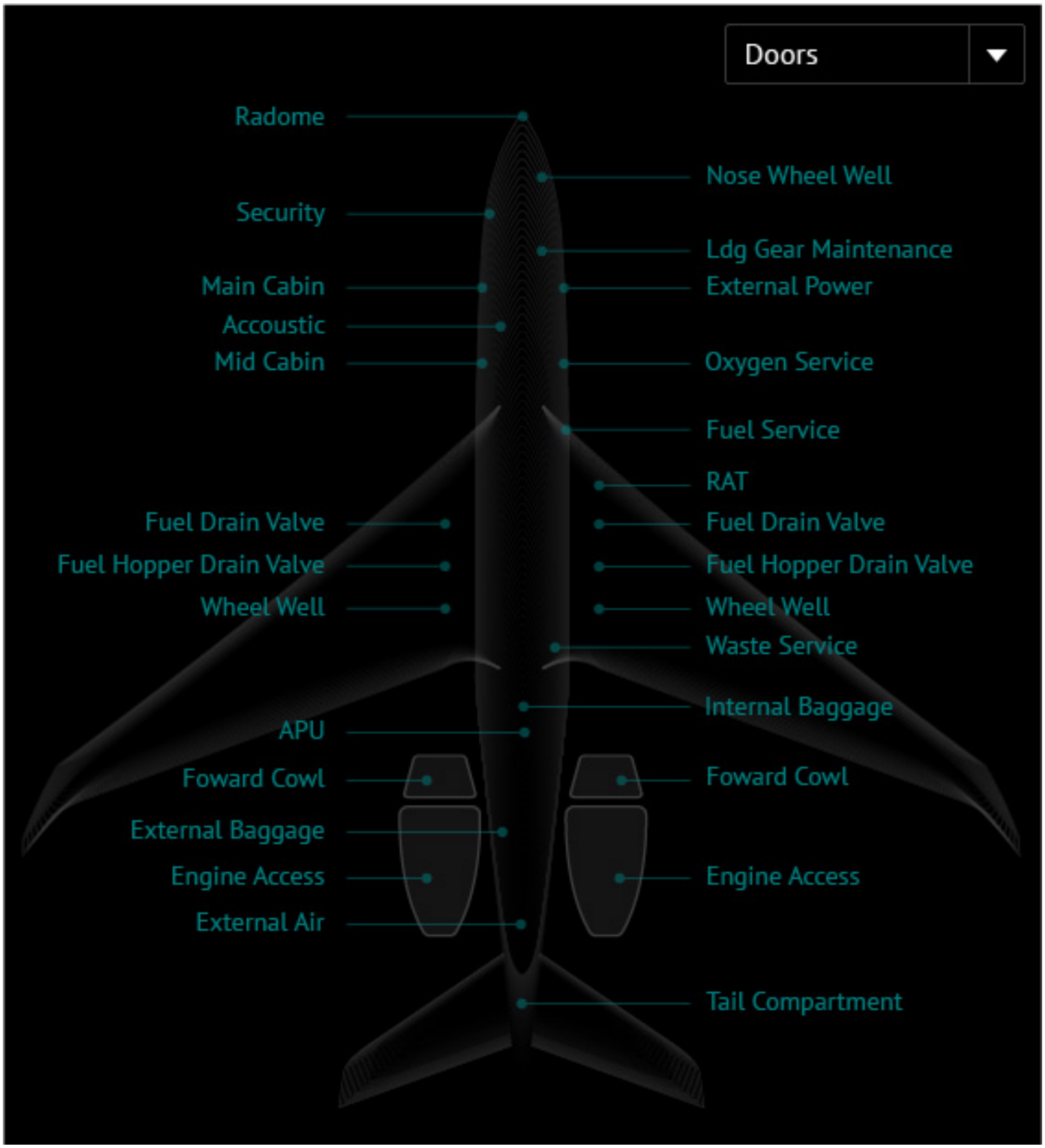
Anti-Ice—Magnified mode



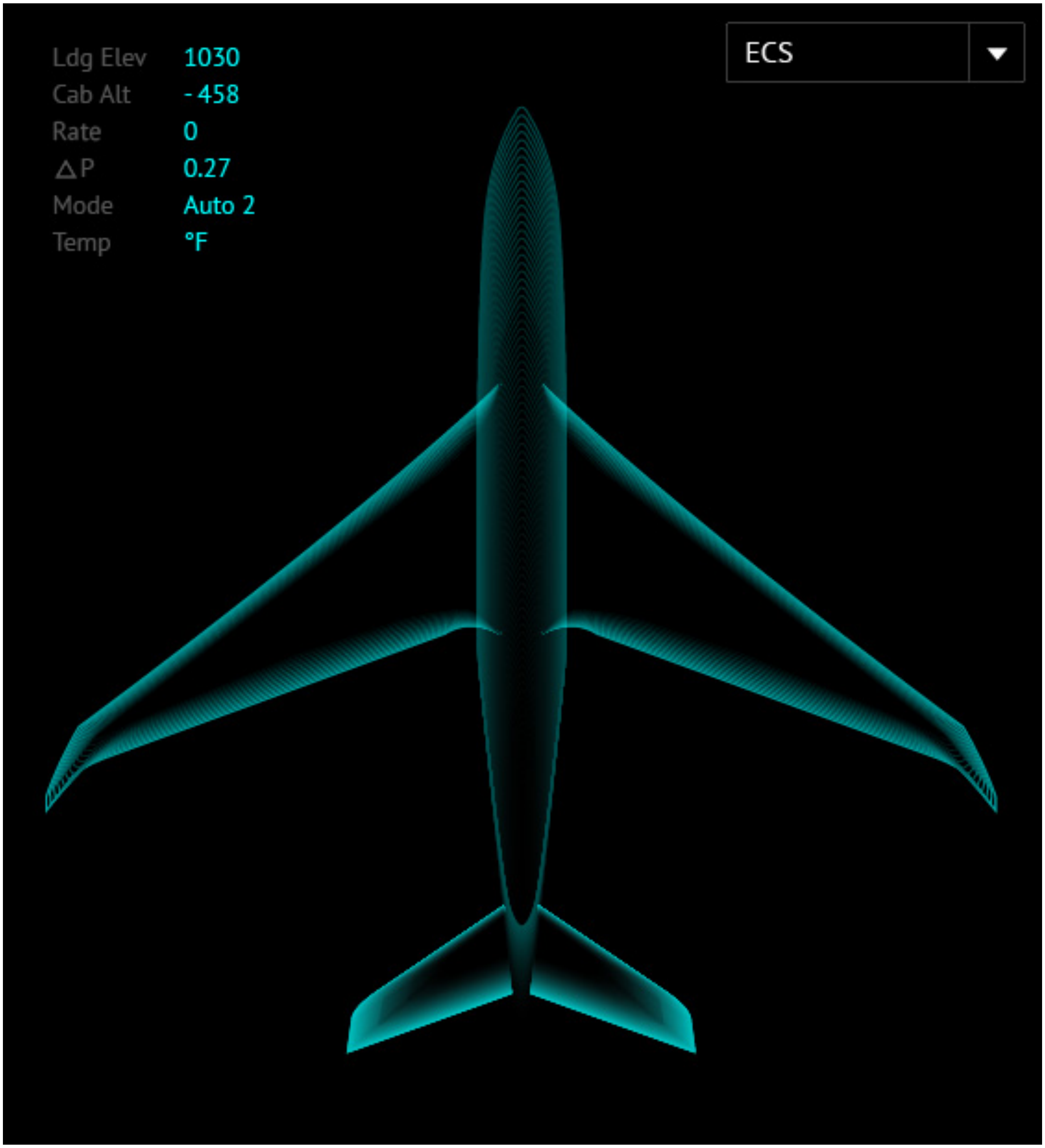
Doors—Status mode



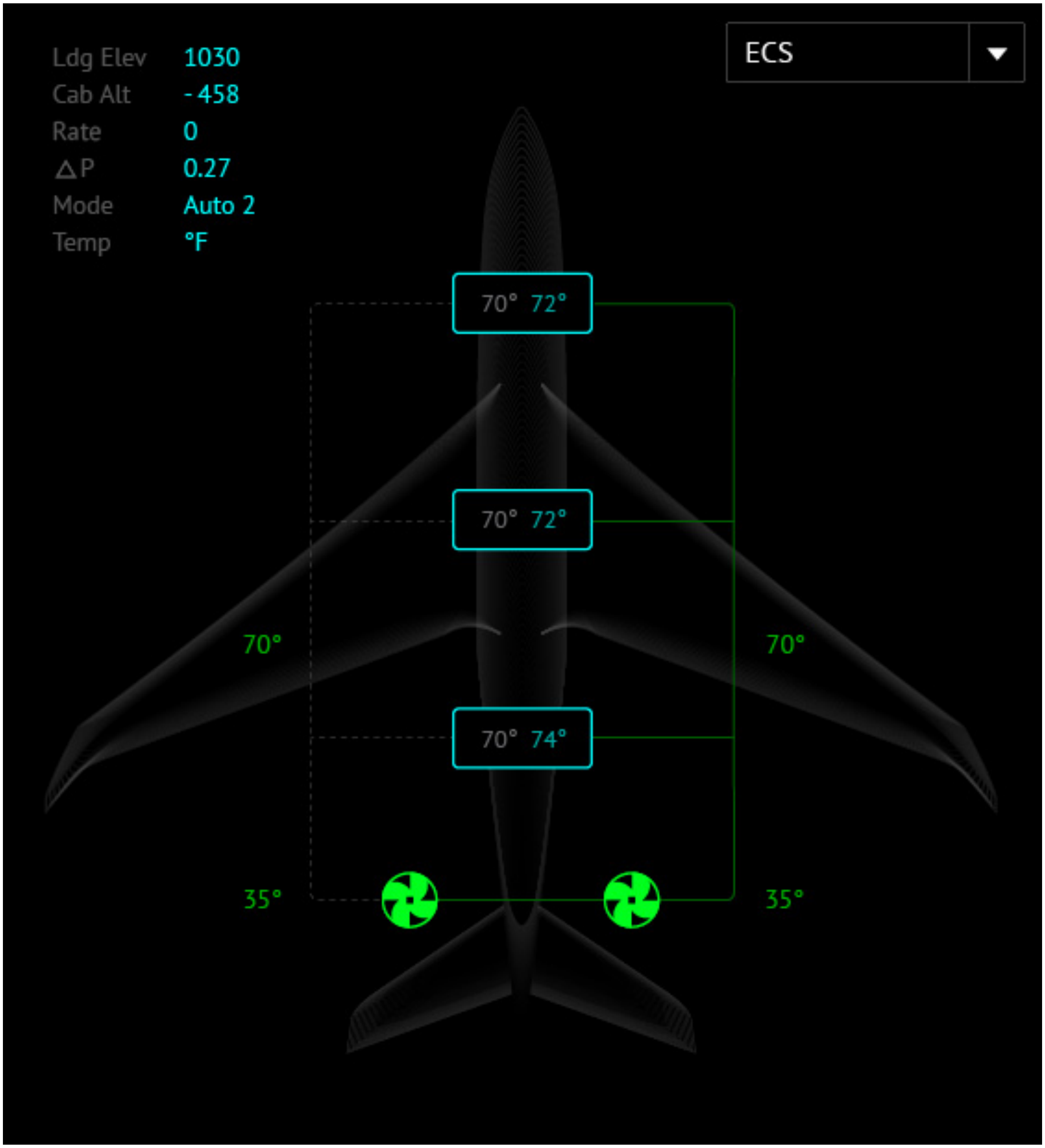
Doors—Magnified mode



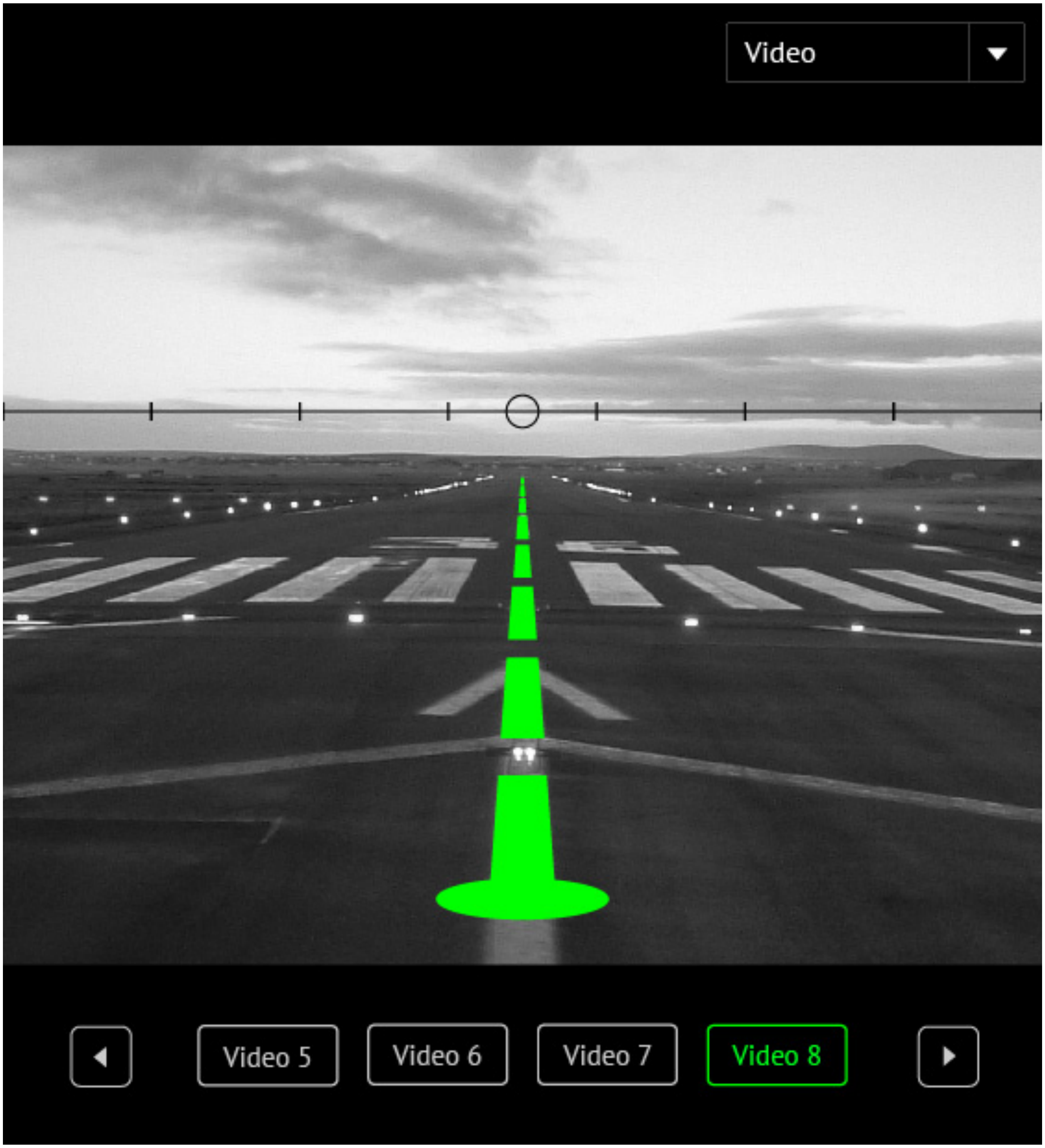
Environmental Control System (ECS)—Status mode



Environmental Control System (ECS)—Magnified mode

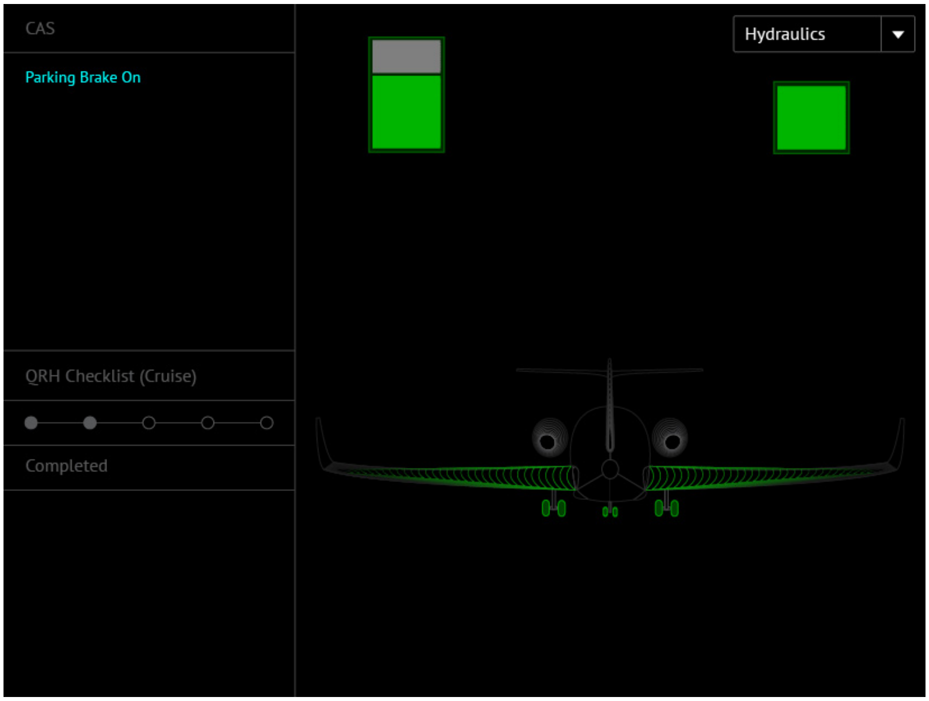


Video—Status mode

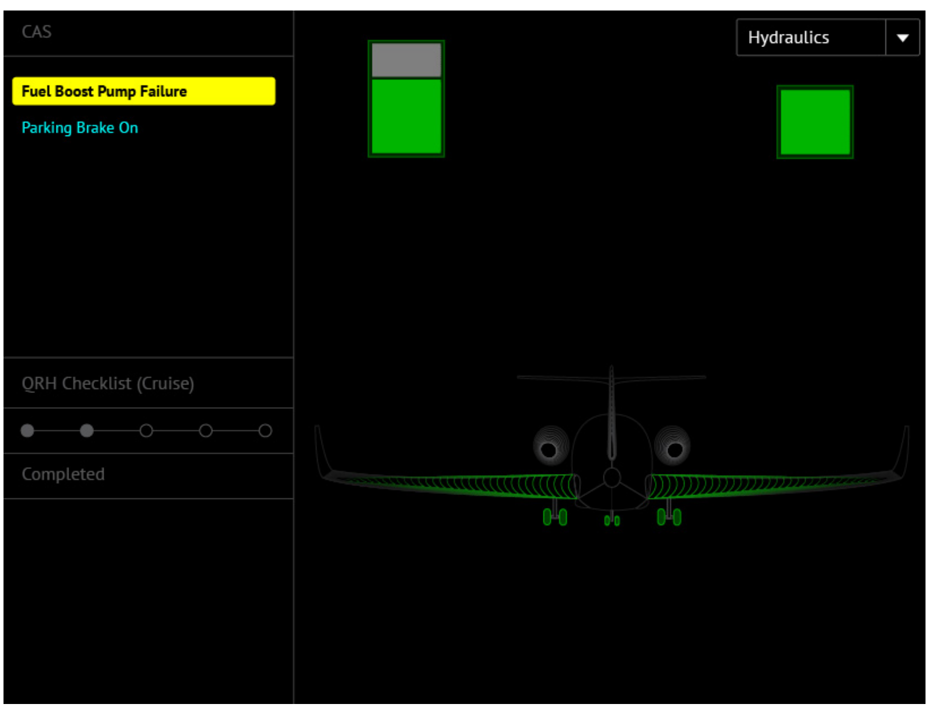


Appendix B: Synoptic Display for Rapid Prototyping

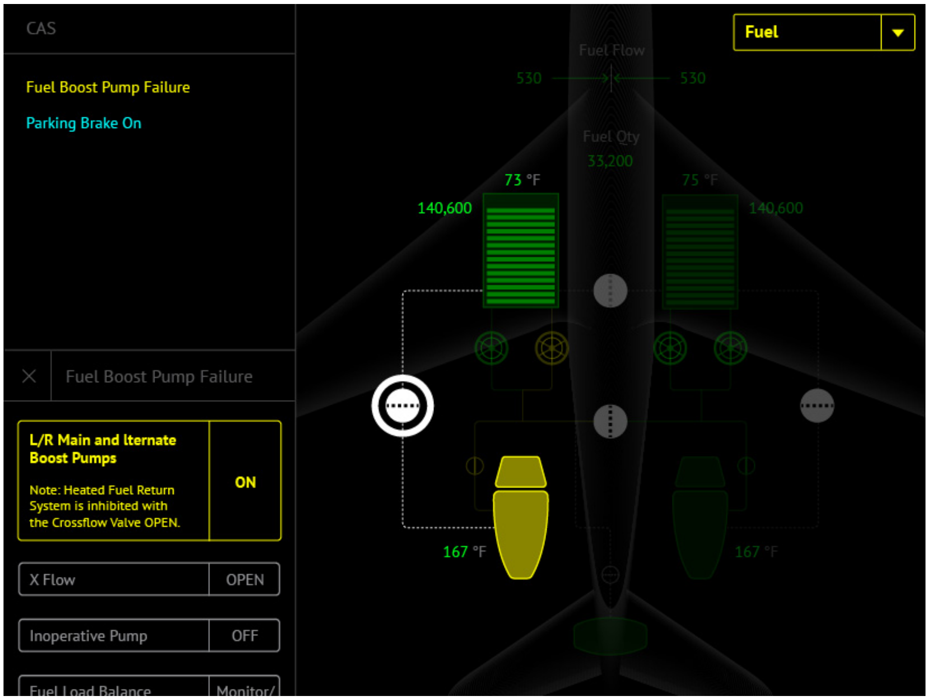
1. Hydraulics



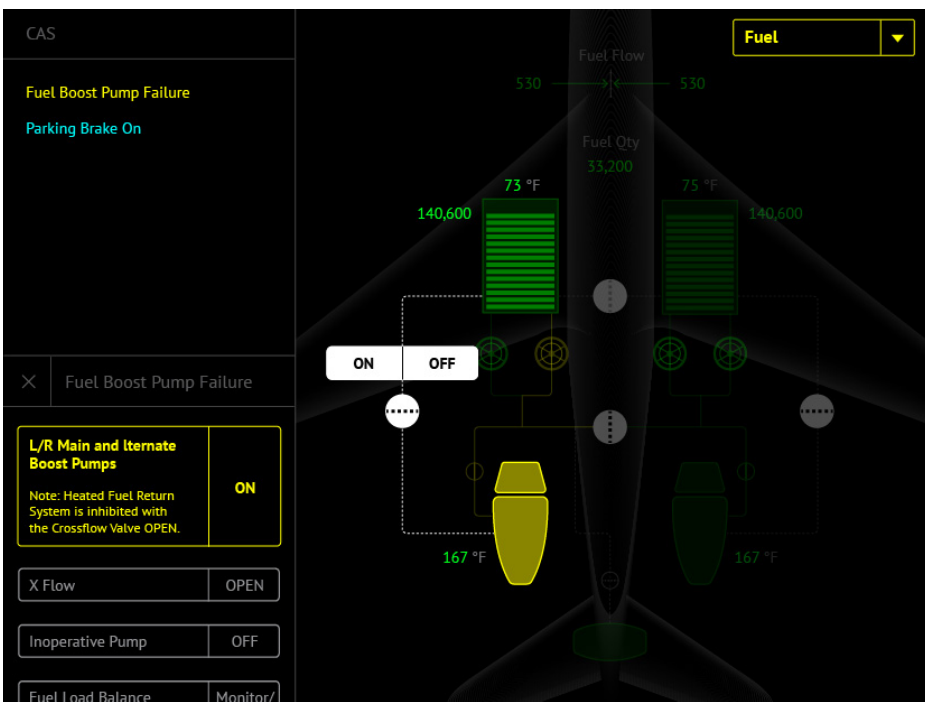
2. Hydraulics—Alert—Fuel Boost Pump Failure



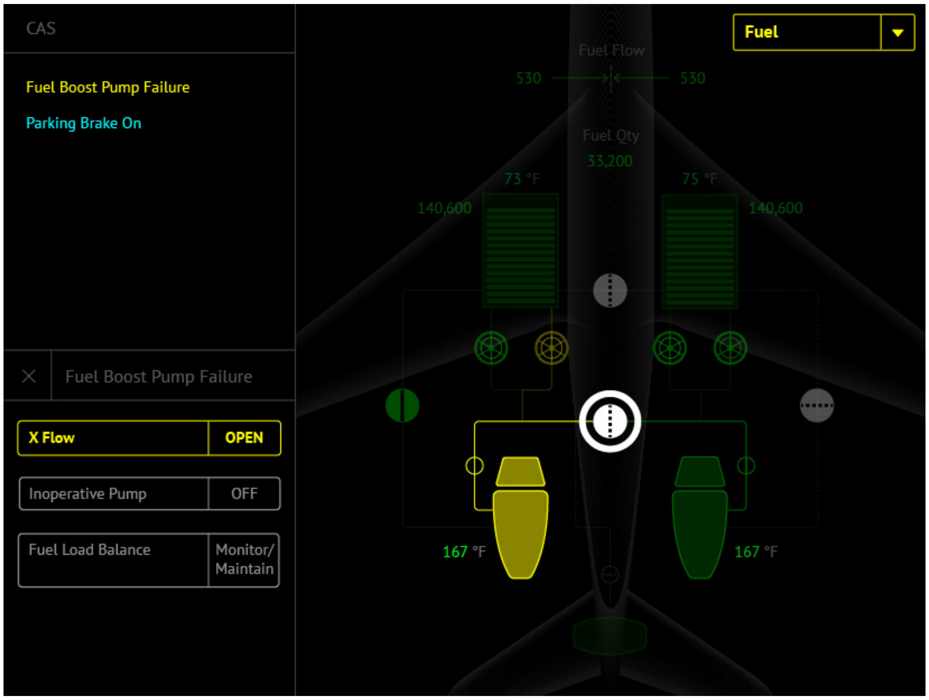
3. Fuel—Alert—L Main Boost Pump



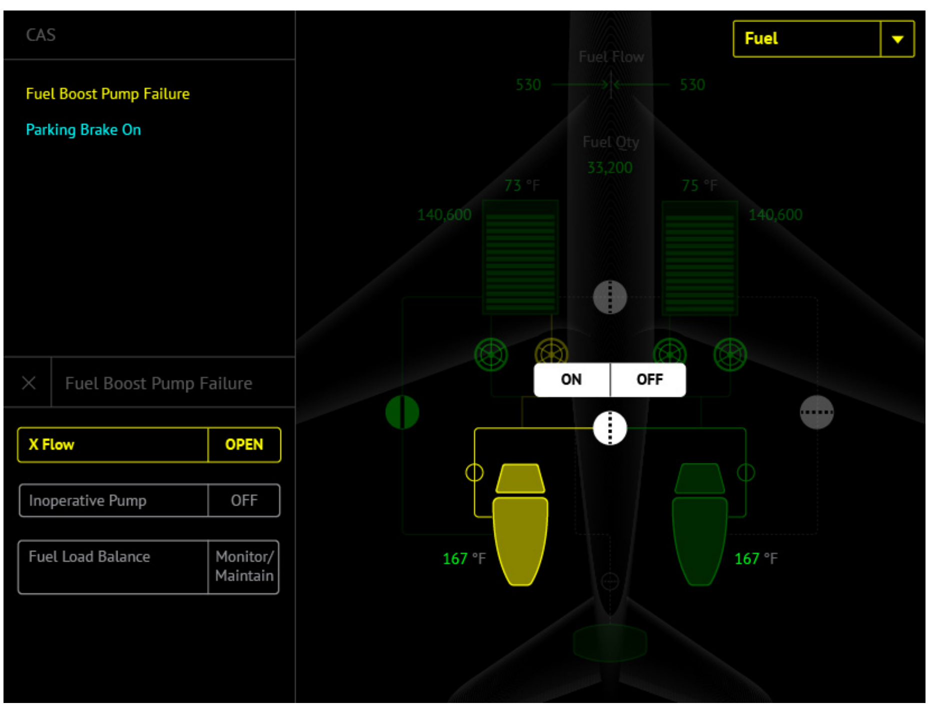
4. Fuel—Alert—L Main Boost Pump—Vale on



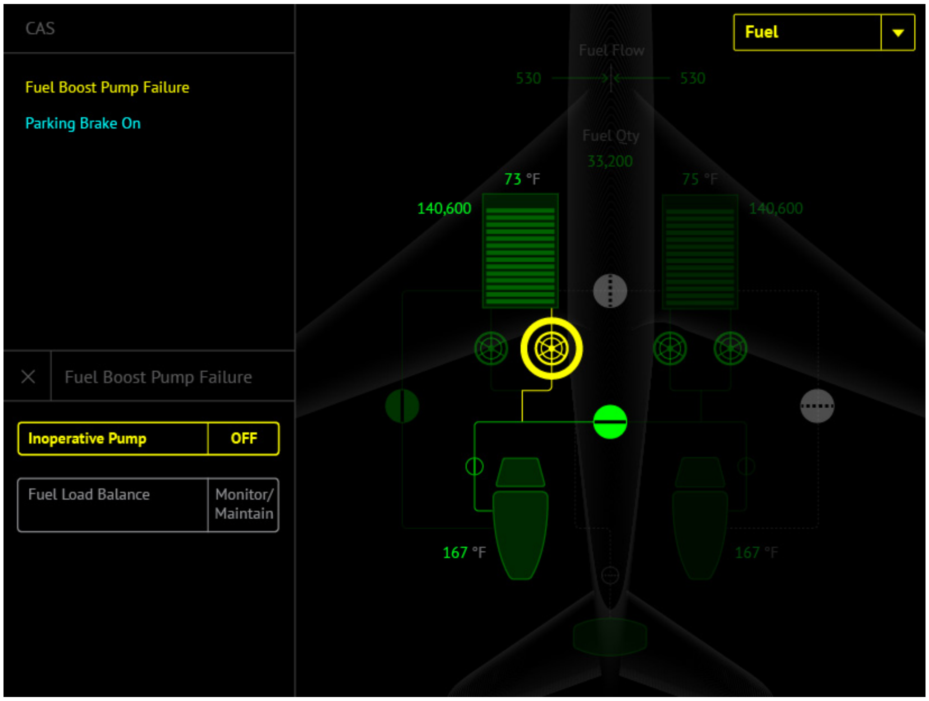
5. Fuel—Alert—X Flow



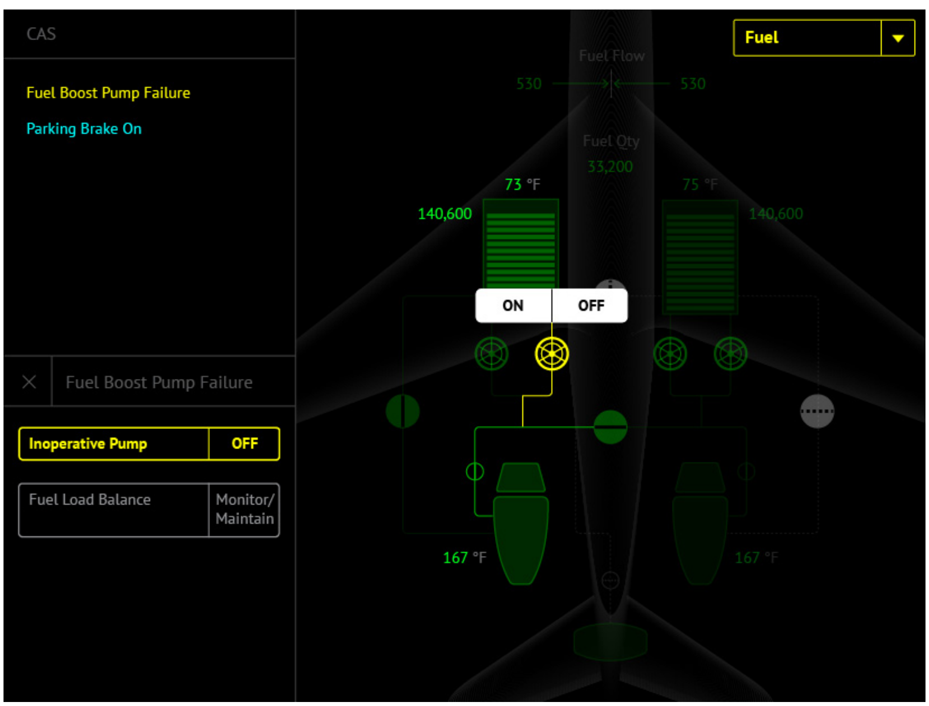
6. Fuel—Alert—X Flow—Valve on



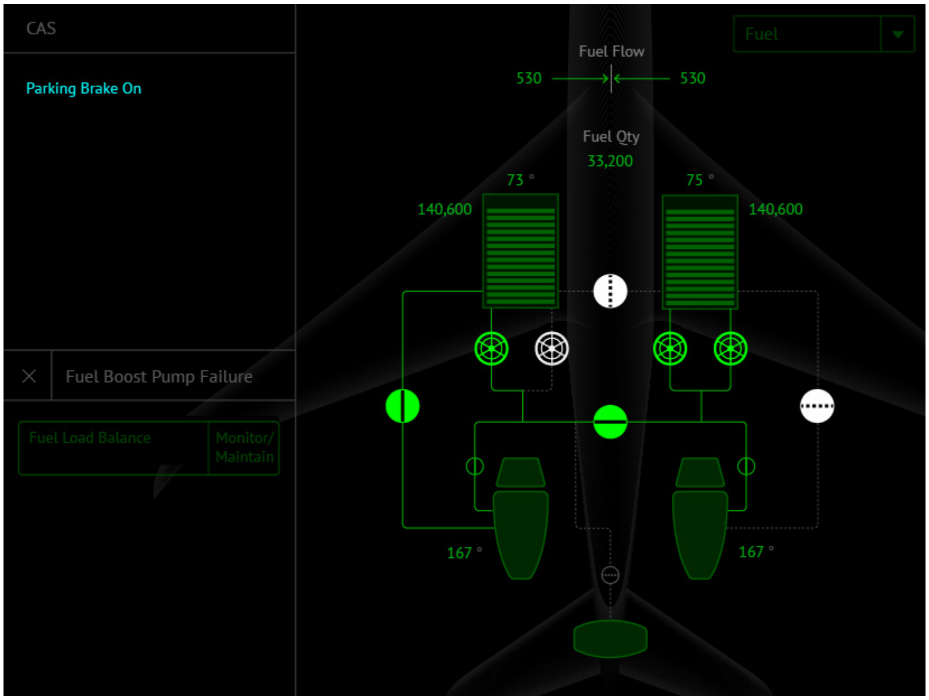
7. Fuel—Alert—Inoperative Pump



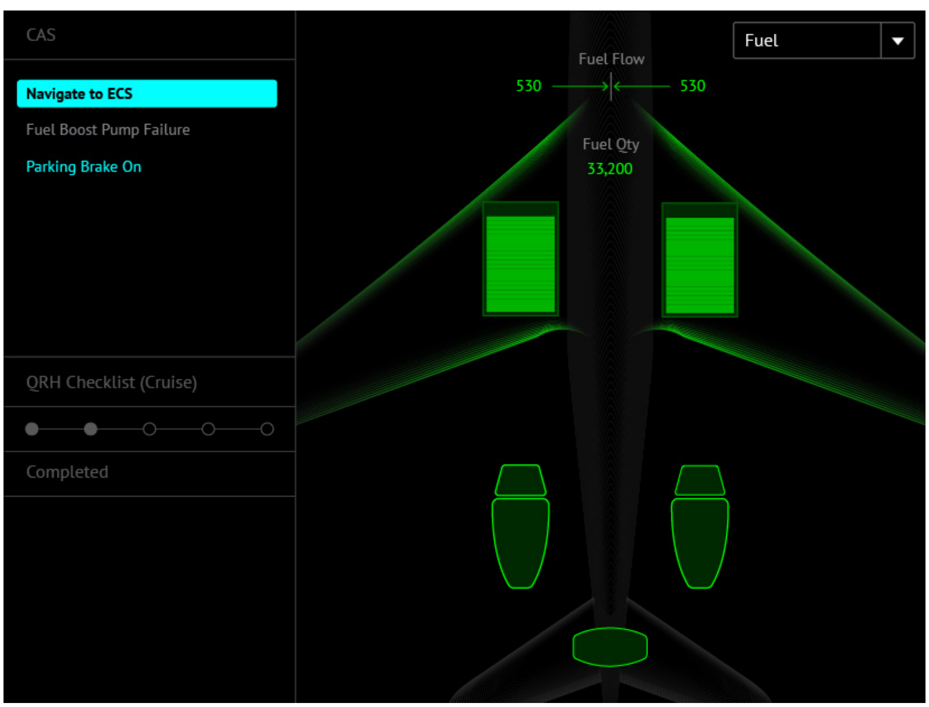
8. Fuel—Alert—Inoperative Pump—Fan off



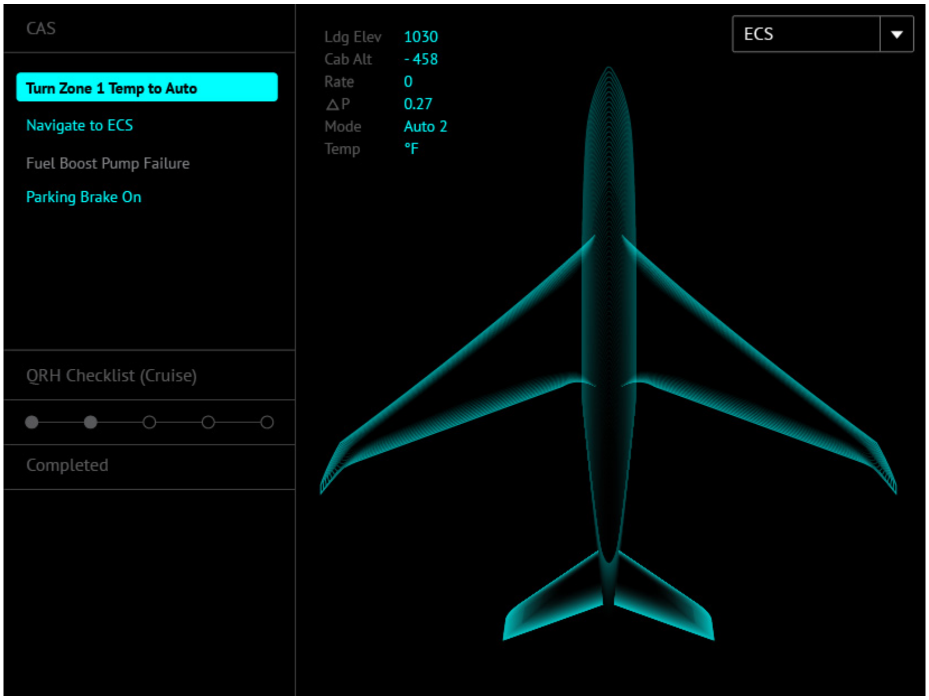
9. Fuel—Normal—Magnified mode



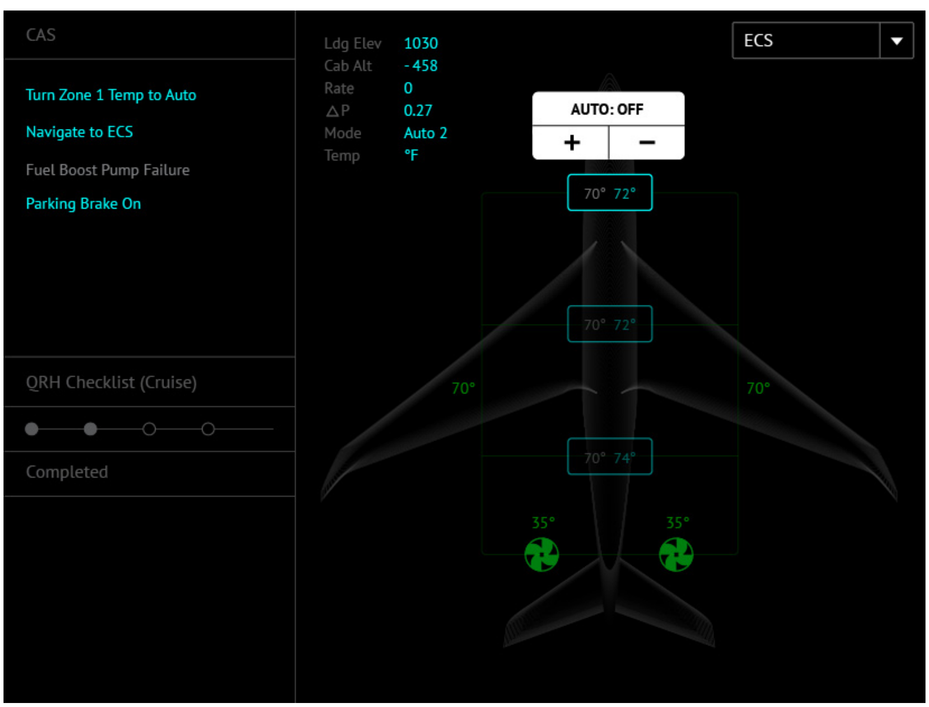
10. Fuel—Normal—Status mode



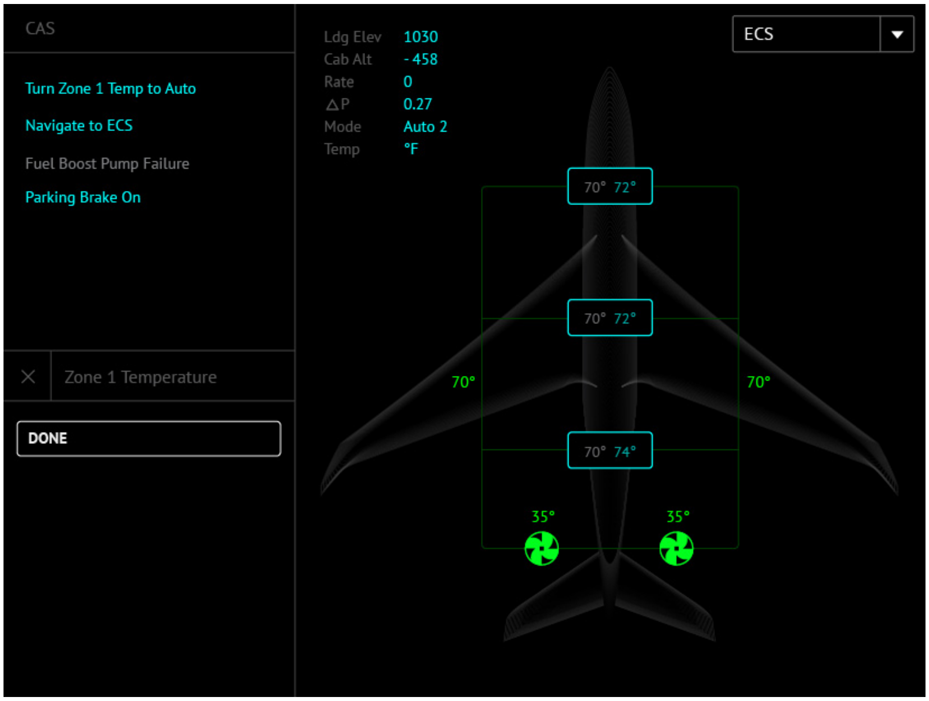
11. ECS—Status mode



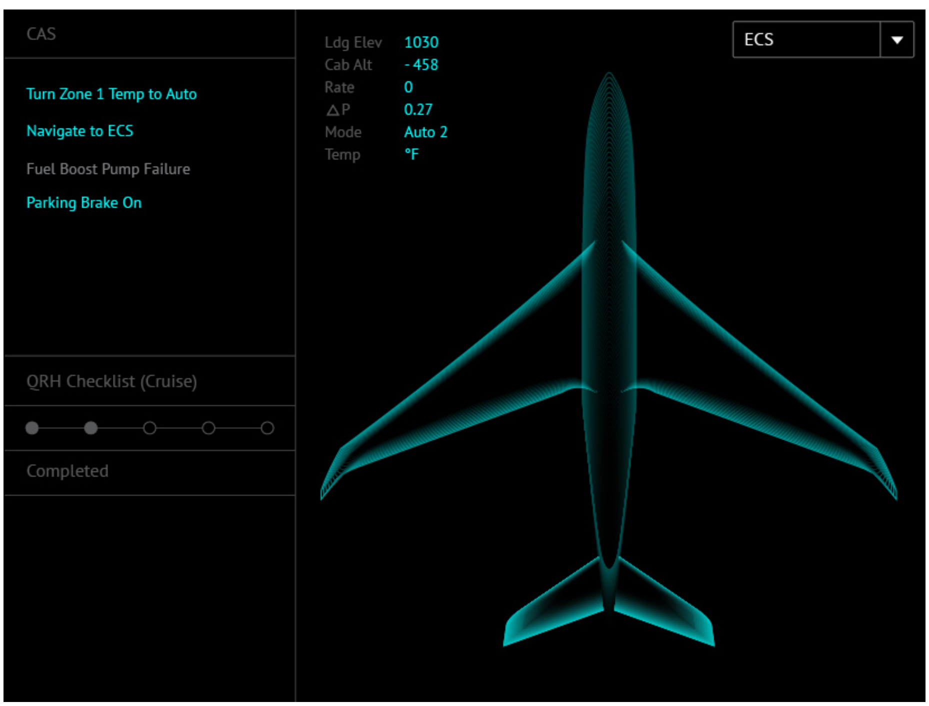
12. ECS—Temperature change



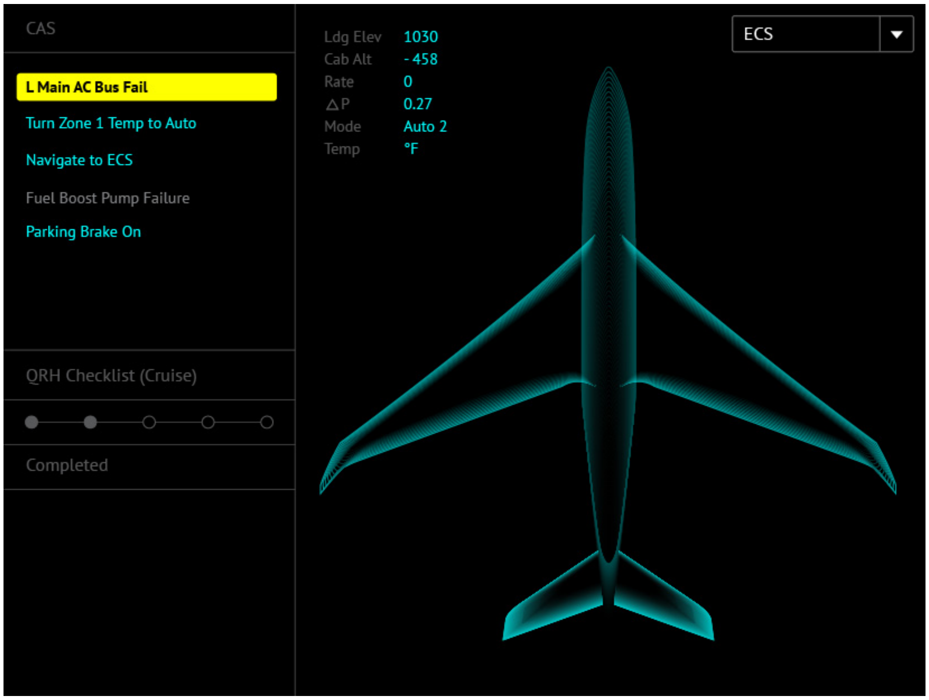
13. ECS—Magnified mode



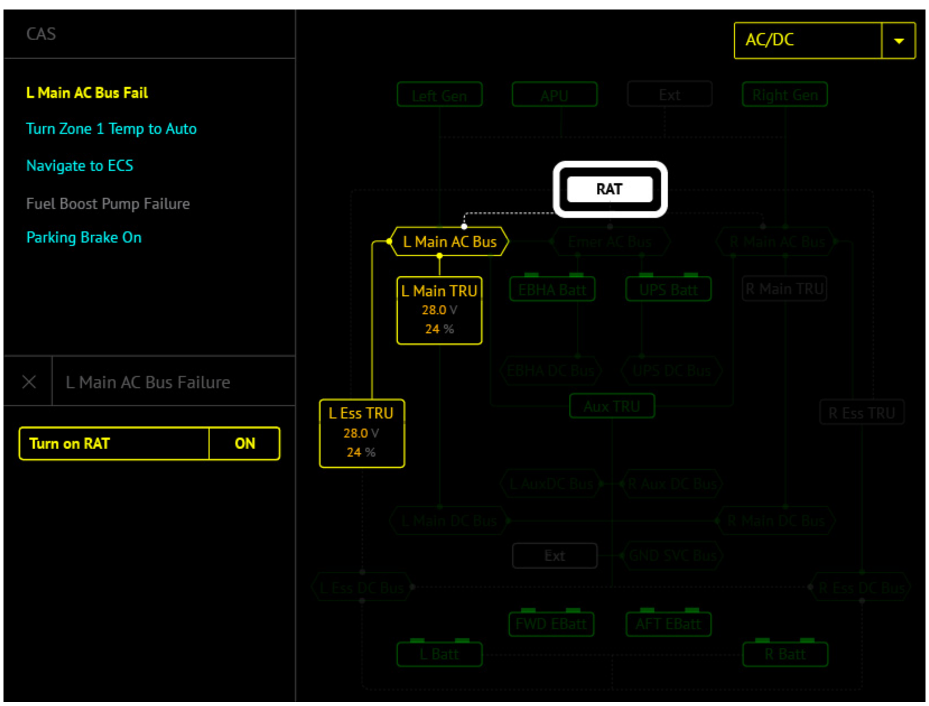
14. ECS—Status mode



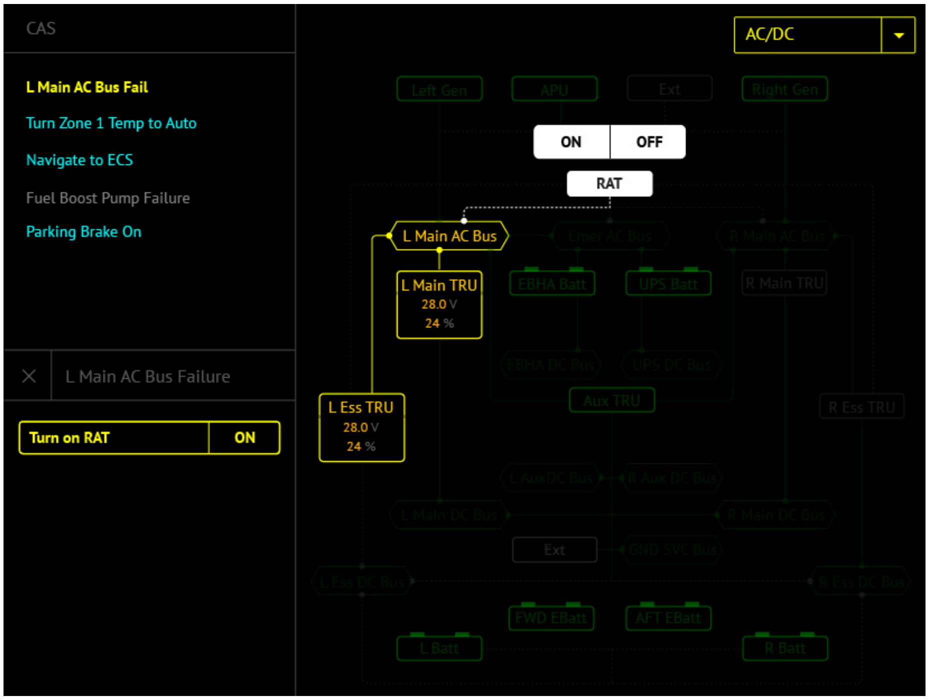
15. ECS—Alert—AC/DC Fail



16. AC/DC—Alert—Augmented



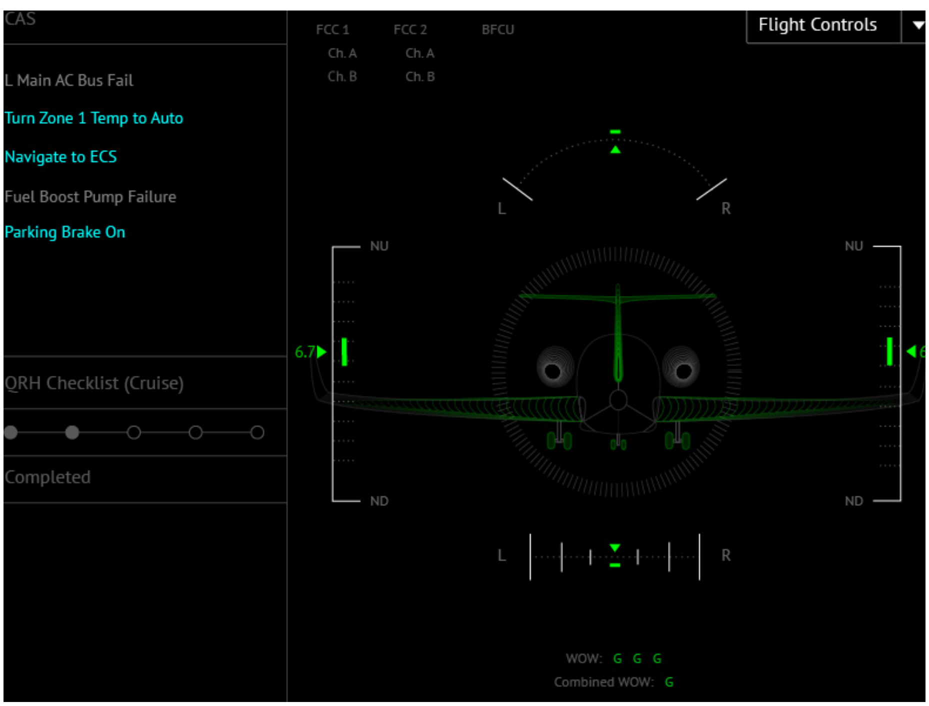
17. AC/DC—Alert—Control off



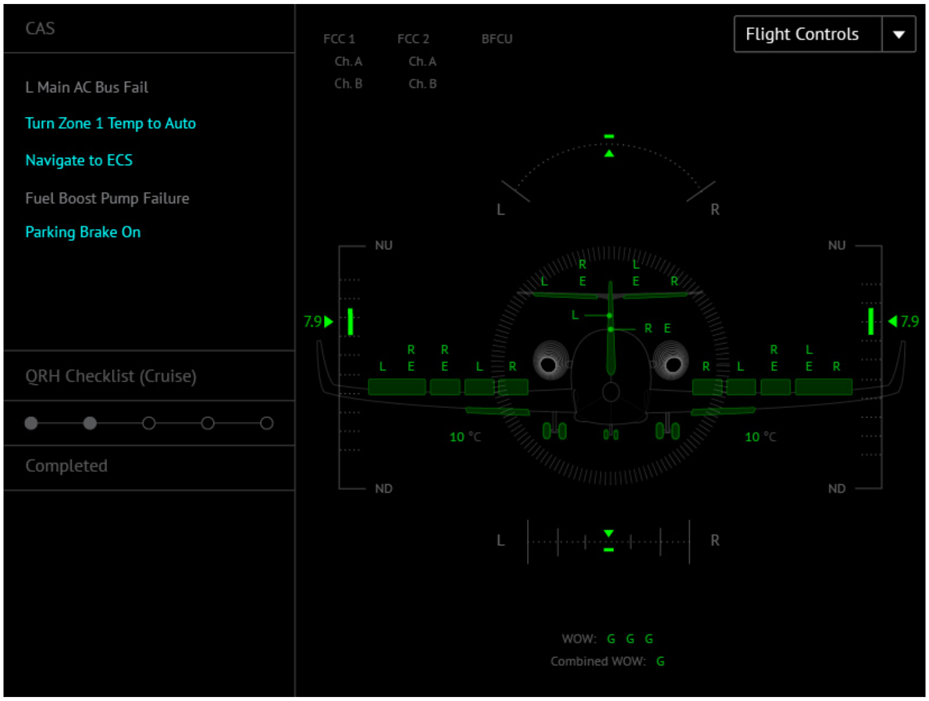
18. AC/DC—Magnified mode

19. AC/DC—Status mode

20. Flight Control—Status mode



21. Flight Controls—Magnified mode



22. Doors—Magnified mode

Appendix C: Pilot Testing Requirements

Consideration	Displays
Create adequate synoptic environments to provide design direction	$2/3^{rd}$ Displays: AC Power, DC Power, Doors, Summary, Hydraulics, Flight Controls, Fuel, ECS/Pressure, Video, Checklist
Design incorporates system status and system control	$1/6^{th}$ Displays: Waypoint List, Engine Start, Video, Ground Service, APU/Bleed, AC/DC Power, CAS, ECS/Pressure, Flight Controls, Brakes, Traffic, Primary Engine, Secondary Engine, Compacted Engine, Alternate Engine
Consider screen real-estate of the $1/6^{th}$ displays to incorporate control	
Choose where to eliminate clutter within the synoptic (e.g. Battery Voltage-generator V/A/Hz/Hyd pressure) if that component is out of its normal range	
Need to define the certain contexts in which examine typical pilot's flows	
Consider controls that can incorporate (Battery, Generators, Power receptacle, Pump, Valve)	

About Pilots	Pilot Behavior	Pilot Needs
They enjoy the view - because they earned it. (freedom)	Error free flight	Safety of passengers and staff
Up to 250k Spent on education (8-12 weeks)	Double Check	Checklist review
Must renew their license every 6 months (1 plane at a time)	Smooth flight	Constant communication
Never alone - Co-pilot (50/50)	Ability to react to errors	Flexibility, Familiarity, and Similarity
Requires confidence (ego), responsibility, and authority	Maintain	Access to information
Simulator practice required	Accessibility to settings	Training frequently
Pre-generated decision	Task switch, Situation awareness	Short learning curve
Must stay active to be current & relevant	Avoid severe weather	Knowledge
Improved by the Data Concentration Network (DCN)	Motivated by freedom	Phases of flight requirements
		Overall control
		Punctual
		Collaboration
		Large Font (Accessibility)
		Less technology drive, trust in their own intuition

Social Norms	Shared Beliefs	Rituals	Unwritten Rules
Long travel times	Sense of freedom	Auto-pilot	Hold each other accountable
Away from home	Sense of control	Validation	Individual reactions to problems
Self-Confident	Believe in the process	Eat in cockpit	Cover each other
Healthy	Cockpit familiarity	Phases of flight	Respect shared environment
Enculturation	Pilot syntax	Checklist*	
References & cross checking	Communication	15 hours of fly max	
Educated	Trust in technology	Renew their license	
Military Background	Safety first		
Napping			
Prone to change			

Pain-Points	Opportunities
Navigating through tasks is clunky and takes too long Paradox of choice, too many options at once Multifunctional displays can be very confusing Not many symbols and iconography to identify status and controls. Weather Long flights Updrafts (worse than turbulence) Multiple step process (solving error messages)	Linking CAS alerts to relevant synoptics Linking checklist activities to synoptics with relevant controls through touch interaction Providing Help information on the MCDU Dynamic 1/6th modal can provide controls according to the synoptic being viewed Quiet display (show a synoptic when it is in an abnormal state) Intelligent data-link (weather and news etc.) communication on the MCDU Tap into the renewal of license process to foster improved habits & alter behavior patterns Create new synoptics to enhance pilot & co-pilot communication

Display demo

1. Tabbing (AC/DC synoptics in particular)
2. Notifications (noninvasive)
3. Informed notification (LEFT wing, RIGHT fuel pump)
4. Notification redirects (clickable notification windows that link and open related synoptics)
5. Menu interaction (possible use of thumb scroller for tactile response and to eliminate item skip-overs)
6. Menu UI (circular "GTA style")
7. Moveable windows (free windows with an exploded view)
8. Scaleable windows (responsive synoptic menu to scale as the window resizes) 9. Denote power source amongst systems

At the basis synoptics systems are strictly information oriented, being that they lack input opportunities for the user other than yes/no or off/auto in some circumstances.

1. Tabbing for synoptics menus that have a close relation to each other or that pilots find themselves using frequently may improve viewing time and ease. Similar to the function that having multiple tabs open in a browser window serves a user needing information from various sources.

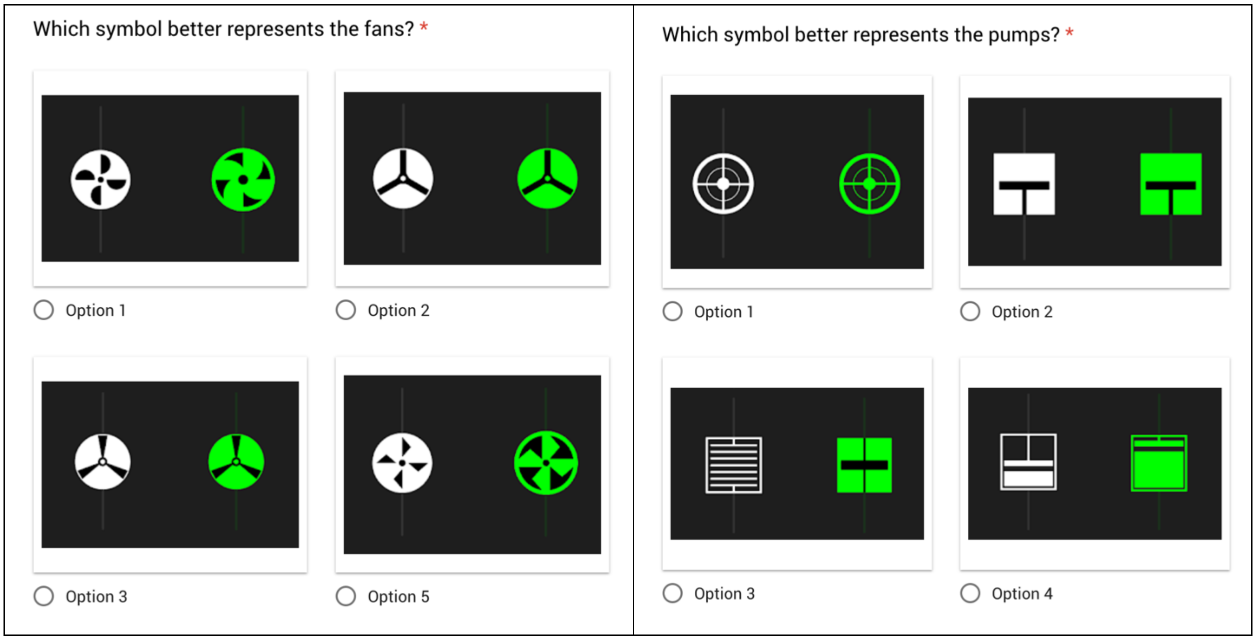
2/4. Non - invasive and clickable (touchscreen integration needed) for system changes in synoptics menu. Examples from multiple phone OS can be viewed as an example. Notifications would have to be concise and clickable.
Redirecting to the appropriate synoptics page automatically

3. Informed notification would only involve adding an extra layer of information to notifications already presented in the system.
i.e. denotations of sides (Left, Right) in notifications or any other information along those lines.

5. Current menu interaction is a multi-step process that while learnable can allow for room for error. The controllers being used in cockpit currently are equipped with thumb toggles that can be scrolled. Allowing that hardware to control the menu scroll and highlight of the synoptics menu would add physical response and structured scrolling to the menu.

6. Denoting power sources among the various systems is important. There are some small discrepancies in the synoptics system that needs refinement.

Appendix D: Questions for Pilot Testing



<u>Questions for pilot showing the new flight deck interface:</u>
Delineate what is an interaction with the interface as opposed to the other cockpit.
What physical controls can we incorporate, what is off limits and why?
Describe the forms of the controls, and reasoning behind the form.
Identify what states can be hidden when normal
Pain-points from the pilot's point of view
Create a priority list of what is needed by the pilot

- In Normal state vs Abnormal state
- During what phase of flight
- What are the most important controls to incorporate?
- Reasons for controls spatial positioning within the cockpit

<u>Questions for phases of flight:</u>

1. Taxi
    a. Normal states
        i. What is the most important info during this phase of flight to accomplish your task?
        ii. What is the most important control during this phase of flight to accomplish your task?
        iii. What could be hidden as long as its status is normal?
    b. Abnormal states
        i. What do you need easy access to during an abnormal situation?
        ii. What is the most important information during an abnormal taxi situation?
        iii. How is that information conveyed?
        iv. What is the most important control during this phase of flight in an abnormal state to accomplish your task?
        v. How is that control conveyed?
2. Take-off
    a. Normal states
        i. What is the most important info during this phase of flight to accomplish your task?
        ii. What is the most important control during this phase of flight to accomplish your task?
        iii. What could be hidden as long as its status is normal?
    b. Abnormal states

        i. What do you need easy access to during an abnormal situation?
        ii. What is the most important information during an abnormal taxi situation?
        iii. How is that information conveyed?
        iv. What is the most important control during this phase of flight in an abnormal state to accomplish your task?
        v. How is that control conveyed?

3. Flight
    a. Normal states
        i. What is the most important info during this phase of flight to accomplish your task?
        ii. What is the most important control during this phase of flight to accomplish your task?
        iii. What could be hidden as long as its status is normal?
    b. Abnormal states
        i. What do you need easy access to during an abnormal situation?
        ii. What is the most important information during an abnormal taxi situation?
        iii. How is that information conveyed?
        iv. What is the most important control during this phase of flight in an abnormal state to accomplish your task?
        v. How is that control conveyed?
4. Landing
    a. Normal states
        i. What is the most important info during this phase of flight to accomplish your task?
        ii. What is the most important control during this phase of flight to accomplish your task?
        iii. What could be hidden as long as its status is normal?
    b. Abnormal states
        i. What do you need easy access to during an abnormal situation?
        ii. What is the most important information during an abnormal taxi situation?
        iii. How is that information conveyed?
        iv. What is the most important control during this phase of flight in an abnormal state to accomplish your task?
        v. How is that control conveyed?
5. Landing Taxi
    a. Normal states
        i. What is the most important info during this phase of flight to accomplish your task?
        ii. What is the most important control during this phase of flight to accomplish your task?
        iii. What could be hidden as long as its status is normal?
    b. Abnormal states
        i. What do you need easy access to during an abnormal situation?
        ii. What is the most important information during an abnormal taxi situation?
        iii. How is that information conveyed?
        iv. What is the most important control during this phase of flight in an abnormal state to accomplish your task?
        v. How is that control conveyed?

Appendix E: Gulfstream Crew Quotes During Testing

"Blue is you"
- Jim

"Design with purpose"
- Alex

"Eliminate steps"
- Nick

"Pilot's want to know"
- Jeff

"Visual elements should move to their respective locations"
"Establish familiarity"
"Tutorials are critical"
"Trend basis"
"Phase of flight oriented"
"While you're looking you mine as well be gathering information"
- Felix Bonds (while trying the testing)

"Very intuitive"
- Felix Bonds (while trying the testing)

"I like that I can go separately and then see a detail"
- Felix Bonds (while trying the summary page)

"The things we carry in our pockets have elevated our expectations for the flight deck"
"The best part of the job is the view"
"I want to know I have a problem before it happens"
"Not flying manual it's like landing a video game."
"Don't touch anything on my side, and I won't touch anything on your side."
"They expect me to do what is part of the plan, but I have emergency authority."
"I don't need to know actual numbers, just show me limits"
"Sometimes we need to save pilots from themselves"
- Justin

"My job gives me the freedom to fly"
"Design to anticipate pilot & system errors."
"Color can become a crutch; design is more important."
"Pilot proof it."
-Unknown

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