

Power System Human Machine Interfaces for the X-57 Mod II Aircraft

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The transition from a Tecnam (Costruzioni Aeronautiche Tecnam srl) (Sapua, Italy) P2006T twin-engine aircraft into the fully electric X-57 Modification II (Mod II) configuration required the development of cockpit displays and controls to allow the pilot to properly monitor and interface with the research electric system. This paper describes the machine interfaces developed to interface with the X-57 Mod II traction battery system and the unique considerations of developing interfaces and monitoring tools for electric aircraft. The key design philosophy during the X-57 cockpit development was to retain or make minor modifications to the stock P2006T aircraft wherever possible and to use highly reliable commercial displays for monitoring of safety critical parameters. From these efforts, development of accurate estimates of battery state of charge and energy meters designed specifically for flight applications for future electric aircraft development is recommended.

I. Introduction

The X-57 “Maxwell” all-electric experimental aircraft is a NASA flight demonstrator concept for distributed electric propulsion (DEP) technologies where distributed electrically driven propulsors are strategically placed along the wing to yield aero-propulsive benefits. The X-57 subproject encompasses three major phases of development for the transition from a stock general aviation Tecnam (Costruzioni Aeronautiche Tecnam srl) (Sapua, Italy) P2006T twin-engine aircraft to the X-57 DEP demonstrator: Mod II, Mod III, and Mod IV. Modification II (Mod II) focuses on the installation and integration of electrical power systems, replacing traditional gas powered propulsors and fuel systems; Mod III replaces the stock P2006T wing with an optimized wing for efficiency at cruise flight conditions and relocates the cruise motors to the wing tips; and, finally, Mod IV integrates the DEP motors along the wing.

To operate the research electrical systems safely and effectively, it was necessary to develop cockpit interfaces that allowed the pilot to monitor the energy state of the batteries, control the cruise motors, and maintain situational awareness of critical components within the research systems. The stock P2006T avionics systems, however, were unmodified when appropriate with the goal of retaining as much of the pilot familiarity with the P2006T aircraft as possible. Modifications were made to the cockpit gages, throttle levers, and power switches based on inputs from test pilots, subsystem experts, ground operations personnel, human system integration engineers and safety personnel. The X-57 simulator was used as a tool to test and iterate on potential cockpit modifications in a simulated flight environment. Due to the X-57 aircraft being a one-off flight demonstrator, human machine interface principles were only implemented as necessary to safely operate the aircraft and were not included throughout the entire design process.

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Flight operations for the X-57 Mod II aircraft consist of a single pilot in communication with a control room performing real-time monitoring of the experimental system. Accordingly, the pilot cockpit is designed so that the sole pilot can monitor the overall status of the research power system and be immediately alerted of any potential safety hazards while relying on the control room to monitor more in-depth system performance.

This paper describes the cockpit machine interfaces developed to operate, control, and monitor the experimental battery system in the X-57 Mod II configuration, the rationale for developing those interfaces, and provides recommendations for improved power system human machine interfaces.

II. Aircraft Description

A. Tecnam P2006T Twin-Engine Aircraft

The X-57 Mod II aircraft is a modified version of the Tecnam P2006T aircraft - a high-winged, twin-engine aircraft built by Costruzioni Aeronautiche Tecnam srl (Sapua, Italy). The pilot controls the aircraft using a control yoke, rudder pedals, throttle levers, and propeller pitch levers. The yoke and rudder pedals are connected to each control surface by pushrods, cables, and pulleys. The control surfaces include a single unit stabilator, stabilator trim, ailerons, aileron trim, rudder, and rudder trim. The trim settings for the stabilator and rudder can be adjusted in flight via a dial located in the cockpit, however, aileron trim tab settings can only be adjusted while the aircraft is on the ground. Deployable slotted flaps are used for takeoff and landing operations. The flaps are adjustable via a momentary down, locking-up flap switch on the instrumentation panel.

B. Overview of Mod II Changes

The Mod II changes to the aircraft are primarily to the internal electrical system and the engines. The Tecnam stock Rotax (BRP-Rotax GmbH & Co KG, Gunskirchen, Austria) engines have been replaced with Joby Aviation (Joby Aviation, Inc., Santa Cruz, California) JM-57 72 kW electric cruise motors powered by an experimental battery system located in the aft portion of the cabin. The experimental battery system is referred to as the traction battery system because it provides power to the electric motors. These battery modules also provide low voltage power to the avionics system, as described in Section III, C. The cockpit avionics, as described in detail in Section V, A, have been modified to provide situational awareness of safety critical parameters related to the traction power system to the pilot and customized for visual and aural alerts during emergency scenario. The throttle and propeller pitch levers have been modified to send torque and propeller pitch commands to the electric motors, as described in Section V, C. The copilot seat, yoke, and rudder pedals have been removed to allow for space to install the research instrumentation pallets. The Mod II configuration maintains mostly the same outer mold line (OML) as the stock Tecnam 2006T aircraft, with a major change added: a new research air data boom attached to the nose of the aircraft. The Mod II configuration is displayed in Fig. 1.



Fig. 1 The X-57 Mod II aircraft.

C. Avionics Power Architecture

The avionics power architecture, depicted in Fig. 2, is divided into seven total buses: the Essential Bus, Wing Avionics Bus A and B, Avionics Bus A and B, and Direct Current (DC) Converter Bus A and B. The A and B buses are each connected to the A and B side traction batteries, respectively. The components assigned to each bus are selected based on the safety criticality of the component, with the least critical components on the Avionics Bus and the most critical on the Essential Bus. The Essential Bus powers all the subsystems required to land the aircraft, including landing gear, torque and propeller pitch control, and flap control. This bus is meant to be the last remaining bus in the event of a power shedding emergency scenario. The DC Converter Buses power the left-hand-side instrumentation panel displays such as the trim, artificial horizon, and turn and bank indicators. The Wing Avionics Buses power the low-voltage connection to the cruise motor controllers (CMCs). The Avionics Buses power non-flight critical systems such as the instrumentation pallet. Note: Fig. 2 acronyms defined: Advanced Central Logger (ACL), Battery Control Computer (BCC), Battery Control Module (BCM), Battery Management System (BMS), Communication Data Acquisition Unit (CDAU), Flight Data Recorder (FDR), Fiber Optic Bus Extender (FOBE), Global Positioning System (GPS), Miniature Data Acquisition Unit (MDAU), Outside Air Temperature (OAT), Synchronous Versatile Input Module (SVIM), Transponder (TDR), Ultra High Frequency (UHF).

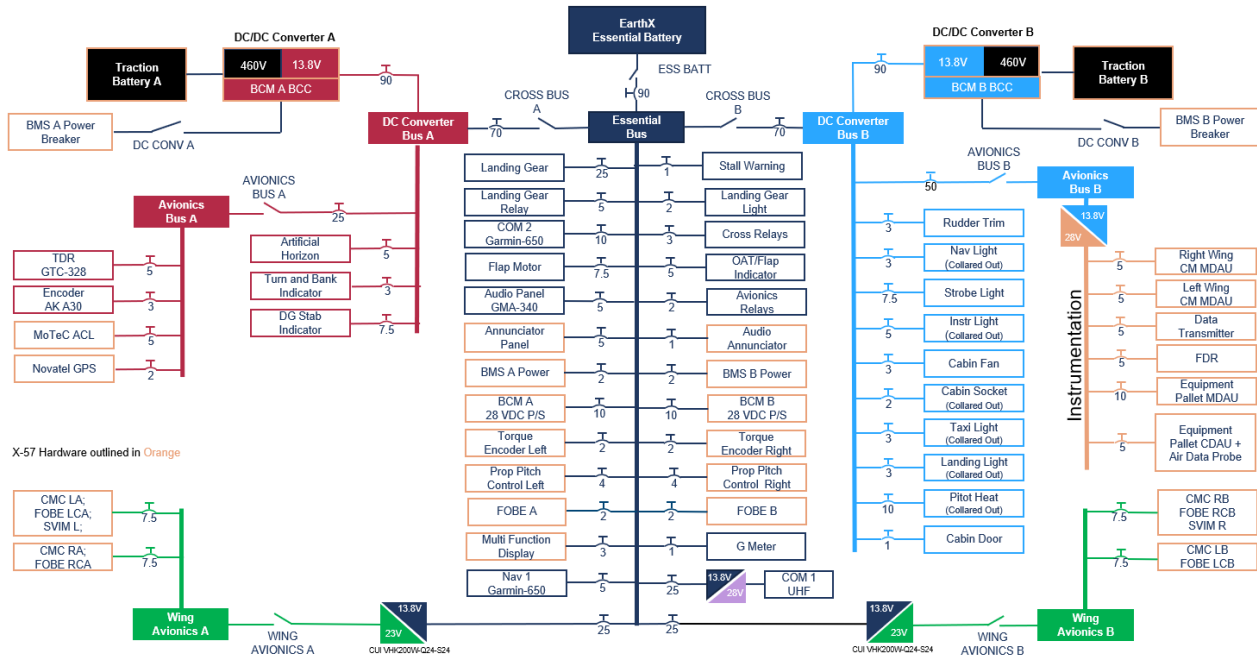


Fig. 2 The Mod II avionics power architecture.

Finally, two cross buses provide power to the avionics system if one of the DC/DC Converters fail. Each DC/DC converter is sized to provide power for the entire avionics system in the event of such a failure.

III. Simulator Description

The X-57 simulator is designed to provide a realistic simulation of the X-57 cockpit for pilot training, mission planning, and operational procedure development. The X-57 simulator was developed alongside the aircraft cockpit and served a role in the development of the X-57 gages and displays by allowing the pilot to use the displays in a wide variety of scenarios, such as takeoffs and landings, mission rehearsals, and emergency scenarios. Figure 3 shows the pilot-in-the-loop simulator at the National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (AFRC) (Edwards, California), which includes two touch screen displays to simulate the aircraft instrumentation panel gages; a multifunction display (MFD) in the center console that consists of hardware and software components that are identical to the MFD installed on the aircraft to provide the pilot with real-time information of the research electrical systems; and control inceptors with a force feedback feel system that has been tuned to simulate the stick forces of the P2006T aircraft.



Fig. 3 The Mod II simulator cockpit.

The X-57 simulator has locking switches that match the part number and relative locations of the aircraft cockpit. The simulator has been designed to accurately simulate the function of each of these switches such that the pilot can practice startup, shutdown, and emergency procedures.

The torque levers and propeller pitch levers match the location and feel of the aircraft levers, including detents for different torque and propeller pitch controller modes. Further details of the X-57 simulator development can be found in Ref. [1].

The simulator serves two major roles in the X-57 cockpit development process: 1) for displays and interfaces that are commercial-off-the-shelf (COTS) or in a mature state, such as the energy meters or the torque levers, the simulator serves as a training tool to familiarize the pilot with these interfaces through various nominal and emergency flight scenarios; and 2) for components that were in development throughout the project lifecycle, such as the MFD, prototypes are implemented in the simulator, evaluated by pilots for usability in a variety of flight conditions and aircraft states, then further iterated on before being finalized for on aircraft use.

IV. Cockpit Modifications

A. Cockpit Layout Overview

The X-57 cockpit, shown in Fig. 4, has been modified to provide situational awareness of safety critical parameters and includes customized visual and aural alerts for hazardous faults detected in the traction power system.



Fig. 4 The Mod II aircraft cockpit.

The left panel includes stock P2006T instruments (blue shading) and the annunciator panel (orange shading). The right panel includes tachometers (red shading); battery energy meters (green shading); and avionics power meters (yellow shading). The center panel includes the multifunction display (purple shading); the torque levers (light-blue shading); and propeller levers (dark-red shading).

The left-side panel, located directly in front of the pilot's seat, is designed to retain as much of the stock P2006T panel as possible. The primary driver for this design choice is to reduce the risk of a failure of flight critical indicators by using hardware that has already been flight certified. The stock P2006T gages, highlighted with the blue shading in Fig. 4, include the airspeed indicator, attitude indicator, altimeter, turn coordinator, vertical speed indicator, stall warning and a longitudinal trim indicator. A COTS g-meter was installed to assist in test points that required the capture of specific g-force levels. The annunciator panel, highlighted in orange shading, has been modified to provide caution and emergency alerts related to the traction power system, which is further described in Section V, F.

The right-side panel has been redesigned to incorporate X-57-specific displays that give real-time information on the critical components of the traction power system and includes the traction energy meter (green shading), as described in detail in Section V, E; the tachometer (red shading) to display propellor revolutions per minute (RPM) measurements; and avionics power meters (yellow shading) to provide voltage and current readings of the DC converters.

In the center panel, a customized MFD (highlighted in purple shading) has been installed to provide controller area network (CAN) bus outputs to the pilot for situational awareness. The CAN bus protocol is used to enable communication of performance parameters from the cruise motors and CMCs to monitoring devices such as the MFD and instrumentation pallet. The MFD display is described in Section V, D: the torque (light-blue shading) and propellor (dark-red shading) levers are modified from the stock throttle quadrant to send torque commands to the CMCs and RPM commands to the propellor pitch controller. These levers are described in Section V, C. Further information on the cockpit can be found in Ref. [2].

B. Cockpit Switches

The Mod II cockpit switch layout is meant to mimic the switch order of the stock P2006T cockpit. The switches are divided into two sections: the low-and the high-voltage switches. The low-voltage switches power the avionics systems, as previously described in Section III, C, and the high-voltage switches engage the traction battery contactors and arm the CMCs to provide power to the cruise motors. For each switch, there is at least one corresponding light or reading in the cockpit that allows the pilot to verify the switch has been engaged. Early in the cockpit design process, the decision was made to use lever locking switches instead of rocker switches, with the rationale that using lever locking switches will momentarily delay the pilot and provide them the opportunity to confirm that the correct switch is being activated. These lever locking switches were considered necessary because the X-57 aircraft is configured for a single pilot, where normally a two-pilot cockpit would use crew resource management to confirm switch positions.

The layout of the low-voltage switches is depicted in Fig. 5. The essential battery switch is intentionally a different type of lever locking switch compared to the other low-voltage switches and is used so that the pilot can easily determine when they are activating that specific switch purely by feel. The change in switch type is due to the criticality of the essential battery, which powers the components necessary for landing operations.

The startup procedure is kept simple by engaging the low-voltage switches from left to right. This procedure begins with powering the following switches in sequential order: ESS BATT, then DC CONV A and B, then CROSS BUS A and B to allow the DC converters to supply power and charge to the essential battery. WING AVIONICS A and B and AVIONICS BUS A and B switches are then engaged to allow the DC converters to power the remaining low-voltage system. When all low-voltage systems are powered, each switch is in the upward position. The switches are ordered such that the least safety critical systems on AVIONICS BUS A and B are powered up last and are powered down first if power load shedding is required.



Fig. 5 Low voltage switches.

Once the low-voltage system is fully engaged, the pilot begins powering the high-voltage traction power system via the overhead panel, depicted in Fig. 6. This process begins by engaging the traction battery contactors via the MAIN BATT A and B switches. Then the CRUISE TRACTION POWER LA, LB, RA, and RB switches are engaged to provide high voltage to each CMC. Upon powering each CRUISE TRACTION POWER switch, a light-emitting diode (LED) light next to the switch will illuminate green upon a successful engagement of the high-voltage system. If there is a fault during the engagement, The LED lights will turn red to notify the pilot. These LEDs are monitored during high voltage startup and shutdown, but during flight operations, the overhead panel is not within the pilot's field of view and the pilot must rely on visual and aural alerts from the annunciator panel, as described in Section V, F and G, for immediate notifications of any faults with the cruise motors, CMCs, or traction batteries.

The final step is to arm the LEFT CMC A and B and RIGHT CMC A and B switches, which allows the CMCs to begin accepting throttle commands. The right CMCs are armed first to allow for easier pilot egress from the cabin door (on the left side of the cabin) in the event of a motor emergency.



Fig. 6. High voltage switches.

The nominal shutdown procedure works in the reverse order of the startup procedure to safely power down systems. In an emergency shutdown scenario, certain switches are skipped and remain engaged to expediate the shutdown process. The high-voltage system is shut down first, with the torque levers brought to idle, the propeller levers to feather, and the MAIN BATT A and B switches immediately disengaged. Then, the pilot begins shutting down the low-voltage system by disengaging the following: CROSS BUS A and B, followed by the DC CONV A and B, and finally, the ESS BATT is shut down as soon as practical.

C. Torque and Propeller Pitch Levers

The torque and propeller pitch levers, depicted in Fig. 7, were selected to keep the same location and feel as the stock P2006T location but have been modified with the capability to activate unique modes of the research CMCs.



Fig. 7 Torque and propeller pitch levers.

The torque levers function similarly to how the stock P2006T throttle levers previously functioned; however, the throttle levers now increase fuel flow to achieve a thrust output, and the torque levers increase current draw to achieve a desired motor torque. The torque levers are connected to the CAN bus via an angle encoder for lever position with detents at idle and full torque. Past the detent located at the FULL torque lever position is the OVERDRIVE mode, which allows for up to a 30-percent increase in torque output for each CMC. This mode is meant for emergency situations where one CMC is inoperative, and the pilot requires additional torque to execute an emergency descent and landing procedure. At the bottom of the torque lever, beyond the detent located at the IDLE position, is the REGEN mode, where a negative torque is applied to the cruise motors to extract energy from the airflow and provide battery recharging in flight. The torque levers can only be moved across the detents using newly added finger lifts on the levers. These finger lifts were installed so that the pilot could not unintentionally activate the overdrive or regen functions.

The pilot can select between an automatic (AUTO) and manual (MAN) modes for propeller blade pitch control. In MAN mode, the pilot directly adjusts propeller blade angle via START or FEATHER switches on the right-hand side of the instrumentation panel. When toggled in the START position, blade pitch is commanded towards a finer pitch, and when toggled in the FEATHER position, blade pitch is commanded towards a coarser pitch. In the AUTO mode, the pilot sets an RPM command via the blue propeller pitch levers that is then sent to a constant speed controller that automatically adjusts blade pitch to achieve the desired RPM. The range of available RPM commands in the AUTO mode is 1,700 to 2,700 RPM. At the aft stop of the propeller pitch lever is a FEATHER switch that overrides all MANUAL or AUTO modes and drives the propeller pitch to the feathered position. Moving the propeller pitch levers forward, off the aft stop, restores the propeller pitch controller to AUTO mode.

D. Multifunction Display

The purpose of the MFD, depicted in Fig. 8, is to provide the pilot with situational awareness of parameters from the propulsion systems across the CAN bus [3]. The amount of information on this display was intentionally limited to avoid overloading the pilot. The primary parameters displayed are as follows: traction battery state of charge (SOC); estimated torque; torque lever position; propeller blade pitch angle; estimated motor power; motor voltage draw; and caution warnings for motor temperatures. The estimated motor torque and torque lever position are used during test points where specific torque settings are required. The propeller pitch position provides situational awareness on the behavior of the propeller pitch controller. The estimated motor power and voltage draw are driven by values calculated

in the CMCs. The pilot and ground crew would cross-check these estimates against the power and voltage readings from the battery energy meters on the right-hand panel to verify the accuracy of the CMC estimates. Across the top of the MFD are 10 green LEDs that signify valid CAN bus communication is occurring between each of the CMCs, battery control modules (BCMs), torque encoders, and data acquisition units. These LED indicators are primarily used to diagnose problems with the CAN interfaces during ground testing. If any of the LED indicators turn off in flight, the pilot immediately contacts the control room for more information and advice on next steps.



Fig. 8 Multifunction main display layout.

Because the CAN bus architecture driving the MFD is not certified as safety critical software for flight, the display is not the sole indicator for safety critical parameters. Critical parameters are available either on other displays within the cockpit or monitored from ground mission control via telemetered data from the aircraft; one example is temperature caution warnings. The pilot is alerted on the MFD when a motor temperature is exceeding a yellow or red temperature limit and immediately reduces power on the overheated motor. The pilot then queries the control room, which is monitoring safety critical temperatures concurrently, for additional information on the overheating motor and to discuss the appropriate in-flight response.

The SOC display is driven by an estimate of the battery energy capacity that continuously updates based on the output of traction battery current sensor. Due to the design of the BCM, not including a bus bar, the current sensor cannot achieve the manufacturer documented accuracy, and these inaccuracies are further increased at higher current settings. Because these current sensor inaccuracies are directly fed into the SOC estimates, the error in the SOC continues to increase over the course of a flight. These SOC characteristics were the primary factor in the decision to not rely solely on the SOC estimate for monitoring battery charge during flight and instead to use voltage readings from the traction energy meters as the primary energy monitoring parameter, as described further in Section V, E.

E. Traction Bus Energy Meters

The traction bus energy meters were chosen from COTS hardware to provide a high level of reliability because they acted as the primary battery energy reading for the pilots. As depicted in Fig. 9, the energy meters display voltage, current, and power readings that are output from the traction battery system.



Fig. 9. Traction bus energy meters displaying from top to bottom: voltage, current, power.

Simulation evaluations and on-aircraft testing revealed several quirks with these energy meters. The energy meters have an autoscale function that moves the decimal place reading for every order of magnitude increase in voltage, current, or power. Similarly, the autoscale function converts from watts to kilowatts when the power setting is over 1,000 watts, causing the decimal point to shift with only a small indication on the left side of the meter to denote that the units are now in kilowatts. This autoscaling feature required piloted sim training to properly familiarize pilots on how the energy meters behave in flight.

Because the energy meters are considered reliable COTS hardware, the voltage readings from the traction battery system are considered the truth source for determining the remaining battery energy. Voltage readings at a constant power setting, however, do not decrease linearly throughout the course of a flight and further fluctuate with changes to the power settings. To account for this problem, the pilot sets the torque and propeller levers to a predefined power state, such as idle or full power and 2,250 RPM, and compares the voltage readings from the cockpit meters to the voltage predictions derived from the X-57 battery model [4] at a target minimum SOC. This solution allows the pilot to use the most accurate battery information available in the cockpit for energy management and allows the flight-test planners to develop flight plans around linear SOC predictions.

F. Annunciator Panel

The annunciator panel, shown in Fig. 10, is a modified panel from the stock P2006T panel that provides the pilot with visual alerts of traction system failures and aircraft statuses that necessitate an emergency response.

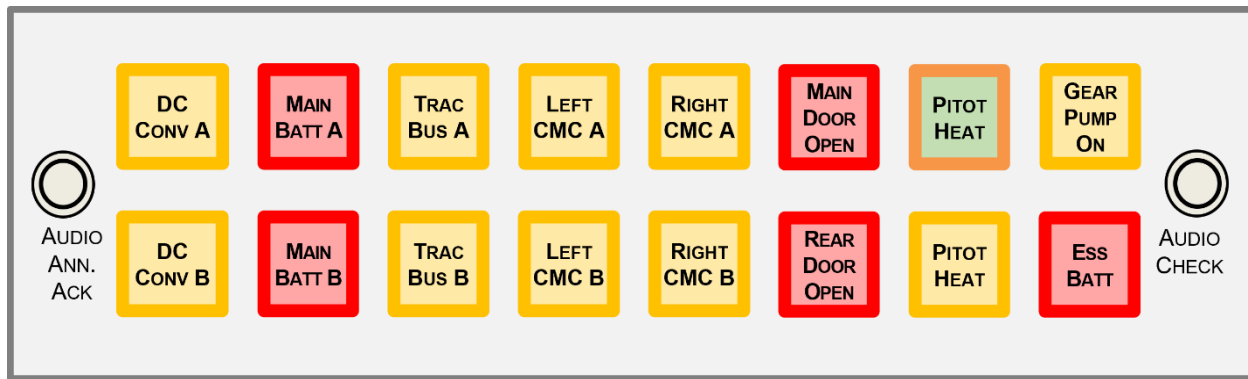


Fig. 10 Annunciator panel.

The MAIN DOOR OPEN, REAR DOOR OPEN, PITOT HEAT, and GEAR PUMP ON indicators retain the same functionality as the stock P2006T annunciators but have been moved to the far right of panel. The DC CONV A and DC CONV B indicators trigger from faults in the 13.8 Volts Direct Current (VDC) converter, primarily when the input voltage falls below minimum limits, or the output voltage exceeds expected values. The MAIN BATT A and MAIN BATT B indicators trigger from faults in the traction batteries and are primarily related to exceedance of temperature limits and sensor failures. The TRAC BUS A and TRAC BUS B annunciate an alert when the energy meters detect voltages below 350 volts. The four CMC visual alerts indicate that the corresponding CMC has reported a fault or has stopped receiving torque messages. The ESS BATT light is a visual only alert for faults related to battery temperatures, failing cells, or short circuits of the essential battery.

The colors of the failure annunciations were chosen to communicate the urgency of the failure. Red alerts denote an immediate pilot action, resulting in a Return to Base (RTB) or emergency descent. Yellow alerts signify a caution state, and if the alert cannot be resolved, a RTB is then executed. The lone exception is the green PITOT HEAT light that signifies when pitot tube heating is active.

For all the visual alerts (lights) except the ESS BATT light, these lights remain continuously illuminated and active if a fault is present. For the ESS BATT light, the light is red and continuous when short circuit protection is activated: flashing (five-second-on and -off) for battery voltage failures and a slower flashing (two-second-on and -off) for battery temperature exceedances.

G. Aural Annunciation System

In combination with the annunciator panel, a commercial-off-the-shelf (COTS) six-channel aural annunciation system is installed in the cockpit. This six-channel limitation required the project team to prioritize and combine alerts to best communicate failures to the pilot. Four visual alerts are set to trigger simultaneously with the annunciator panel: MAIN BATT A or B, DC CONV A or B, TRAC BUS A or B, and CMC faults. The two remaining aural alarms are related to propeller overspeed faults and propeller pitch controller faults. These six faults were selected by the project pilots as faults that would most likely impact take-off operations, which is considered the most critical phase of flight due to the aircraft being in a low-altitude, low-speed, high-power setting flight condition.

An omission from the list of aural alerts is an alert for the essential battery fault. The essential battery aural alert was excluded primarily due to the limited amount of available annunciation channels and because the DC converter aural alert will activate in the event of an undervoltage of the avionics power system, which would trigger with an undervoltage in the essential battery. This aural alarm combined with visual essential battery annunciation was deemed sufficient to alert the pilot. Pilot training with essential battery failures in the simulator was done to help further mitigate this scenario. In a production system, however, a separate essential battery aural alert is recommended due to the criticality of the component.

V. Discussion and Recommendations

Throughout the process of developing the cockpit displays and controls for the X-57 Mod II configuration, several design considerations helped shape the final cockpit layout. As noted by the project pilots, the X-57 simulator proved to be a critical tool in the development and verification of the cockpit displays, providing a means to test the displays in flight scenarios prior to the first flight of the aircraft. The effectiveness of the simulator was most evident in the design of the multifunction display (MFD), where several iterations of the display were first implemented into the simulator and evaluated prior to being implemented on aircraft hardware.

Significant consideration went into the design of the avionics power architecture. The key trait of this architecture was the decision to place all systems required for landing on the essential bus, which allowed the pilot to quickly determine which power loads to shed in an in-flight emergency and still maintain the capability to glide the aircraft to a safe landing. This architecture served as a primary safety mitigation in the event of failures of the research traction power system.

A design philosophy that worked well for the X-57 cockpit was to retain existing avionics displays where appropriate, allowing the pilot to maintain familiarity with operating the aircraft. In situations where possible, existing avionics were repurposed for the X-57 system, such as modifying the annunciator panel design to communicate high-priority warnings and alerts to the pilot.

An effective method for monitoring remaining battery energy is preferred for electric aircraft operations. An ideal solution would be the development of a parameter that could be used similar to how fuel gages are used on traditional combustion engine aircraft with a linear decrease at a constant power setting and predictable change in rate occurring with changes in power. Crucially, that parameter would also require a high degree of reliability and accuracy for all battery energy states. Due to the unreliability of the state of charge (SOC) parameter in the X-57 configuration, the primary indicator of energy states was voltage outputs, which were read directly from the battery system. This indicator required a more complex process of setting torque and RPM commands to predetermined values and comparing the resultant voltages to simulator model predictions to estimate the remaining battery energy.

For a production electric aircraft, it is highly desired to design energy meters specifically for aircraft operations. Autoscaling meters, such as the meters used on X-57, tend to be cumbersome for in-flight energy monitoring and place an unnecessary workload on the pilot reading the displays. Needle gages are preferred over the digital readouts used in the X-57 energy meters because the gages would allow the pilots to determine trend information when changing power settings. Caution and warning colors when voltage, current, or power readings are outside of the expected bounds would further improve the display.

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