X-57 Cockpit Display System Development and Features

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The X-57 Maxwell airplane employs a programmable, modified off-the-shelf data acquisition and display system to provide the pilot with real-time situational awareness of the status of the electric propulsion and energy storage systems. These data are also telemetered to the flight control room for secondary review in flight, stored in the onboard flight data recorder for post-flight analysis, and used during ground testing for immediate verification and validation as well as troubleshooting.

I. Introduction

The X-57 Maxwell airplane [1,2] cockpit display system includes multiple, pilot-selectable pages in a multifunction display with detailed statuses of critical parameters from each of the cruise motors (CMs), cruise motor controllers (CMCs), and battery control modules (BCMs), as well as air temperature measurements at reference locations in the passive ram-air cooling ducts for the motors, controllers, and auxiliary equipment. The user (pilot or ground-test crew) can select overview pages that are part of the standard instrument panel scan pattern or switch to a series of detail or debug pages as the system is operating using a rotary position switch in the cockpit. This paper presents and describes each of these displays, and gives an overview of the development and verification process. The critical data condensed for cockpit handling from each of the major electric propulsion and traction power systems are discussed.

Critical cruise motor parameters include stator winding temperature measurements with statistical summary data calculated in real time from the multiple redundant sensors embedded in the motor windings. Motor bearing temperatures proved to be necessary during the development process after ground testing revealed that the bearings were not ideally loaded, which resulted in accelerated wearing of the races. Temperature measurement of each bearing stator race provides some early indication of end of life so that maintenance can be scheduled prognostically.

Cruise motor controller performance is constrained by the temperature of silicon carbide (SiC) metal-oxide semiconductor field-effect transistor (MOSFET) modules that operate near their temperature limit but are packaged with the control circuitry and central processing unit (CPU), which has a much lower temperature limit, and are cooled using thermal pads inside the controller and heat sinks on the controller cases. These two heat rejection paths are compressed and have low temperature margins for the passive, air-cooled nacelle environments on the X-57 Maxwell airplane. The cockpit display system displays the internal motor controller temperatures collected from CMC telemetry messages along with air temperature data measured within the system. Thus the system is ensured to be operating within limits during static ground testing, when air might not be forced into the nacelles, as well as in flight.

The battery system reports temperature, voltage, current, state-of-charge, and fault data in controller area network (CAN) bus telemetry, which the cockpit display system processes and summarizes for the flight crew or ground-test vehicle operator. Individual sensor data and trend information would increase crew workload too much to review in detail, so it is critical that the relevant extremes and limits be summarized for the vehicle crew to enable immediate response to system faults or performance limits exceedances. The flight systems integration team reviews the battery data in real time during ground- and flight-testing with remote monitoring or control room stations, but this secondary

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review by remote engineering support cannot shut down a faulty system as quickly as the vehicle operator can, who can shut down individual components of the propulsion system if they exceed their thermal limits.

While the cockpit display system is not a primary flight instrument required for the moment-by-moment handling and maneuvering of the airplane, it provides important context and insight into the experimental electric propulsion system components that helps the pilot plan and configure specific test points as well as enabling faster troubleshooting during development and integration phases in ground testing.

II. Hardware

Early in the development of X-57 airplane predecessors such as the National Aeronautics and Space Administration (NASA) AirVolt [1], the CAN bus was determined to be a robust and noise-resistant communication protocol to be used for the command system. With an eye toward using this protocol, a MoTeC D175 Display (MoTeC USA, Mooresville, North Carolina) (a device that communicates by way of CAN bus) was selected. MoTeC USA creates displays, loggers, and data acquisition hardware primarily used in the automotive, marine, and industrial fields; the fact that these devices are designed for such rugged environments deemed them suitable for use in an electric airplane. It should be noted that the cockpit display system was not developed to meet safety-of-flight standards and is only used to display mission-critical data. After the display successfully passed environmental testing, additional MoTeC devices were acquired for the entire X-57 cockpit display system (CDS). The devices used are the D175 [3] display; the Advanced Central Logger [4] (ACL) (used as the display computer); and Synchronous Versatile Input Module (SVIM) (used for data acquisition).

A. Multifunction Display

The MoTeC D175 display is a full-color liquid-crystal display that is 125 mm (approximately 5 in) and has 10 color light-emitting diodes (LEDs) embedded in the top bezel, and one 22-pin connector. The D175 display communicates using the CAN bus protocol and is programmed to communicate at 1 Mbit/s. The display has eight analog inputs that are designed for use with a multi-position switch. In the X-57 airplane, the display consists of seven different pages that the operator can select using a switch. The display is installed in the center console of the X-57 cockpit, as shown in Fig. 1.

Fig. 1 The MoTeC D175 display (MoTeC USA, Mooresville, North Carolina) in the X-57 cockpit.

B. Cockpit Display Computer

The MoTeC ACL is used as the cockpit display computer and is the central device in the cockpit display system. The ACL receives data from each device transmitting on the CAN bus, performs calculations as programmed, and transmits the new values onto the CAN bus to be displayed on the D175 display. The ACL is required for communicating with the SVIMs and is installed in the equipment pallet to the right of the pilot's seat. The ACL is shown in Fig. 2.

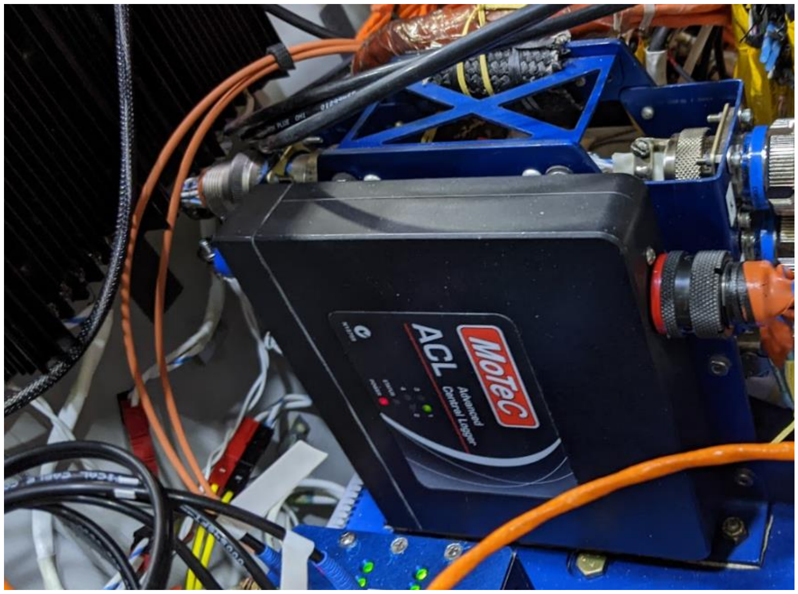

Fig. 2 The MoTeC Advanced Central Logger (MoTeC USA, Mooresville, North Carolina) in the X-57 airplane.

C. Data Acquisition Units

The MoTeC SVIM is a data acquisition device with 26 different inputs; two SVIMs are used in the X-57 airplane: one per motor in each nacelle of the airplane. The SVIM is shown in Fig. 3. As described in its datasheet, the "SVIM is a compact expander that works in conjunction with the ACL and ADL3 Data Loggers to facilitate the synchronized logging of high-speed, high-resolution inputs."[5] High-speed inputs are sampled at 5 MHz; high-resolution inputs are sampled at 1 MHz. The SVIM devices transmit data in accordance with the CAN bus protocol as well as with the manufacturer's design, making communication with the ACL synchronous. The SVIM is used in the X-57 airplane to acquire temperature data from CM windings and bearings, temperatures in the nacelles, temperatures of the electronics storage compartments in the wing, and the propeller pitch from each motor.

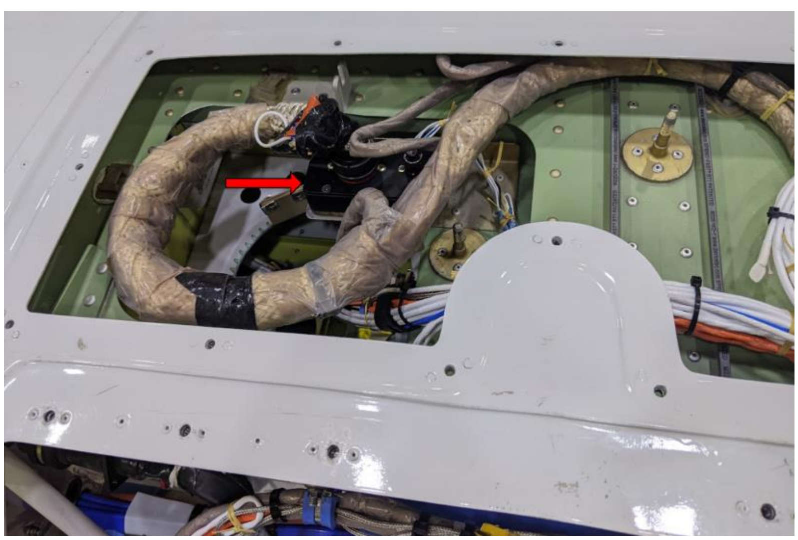

Fig. 3 The MoTeC Synchronous Versatile Input Module (MoTeC USA, Mooresville, North Carolina) in a nacelle of the X-57 airplane.

D. Harnessing and Filtering

The X-57 airplane is a high-electromagnetic-interference (EMI) environment, thus the CDS hardware requires wire harnesses that are designed to mitigate the effects of EMI. The electrical differences due to geometrical differences between the airplane and the laboratory environment made this mitigation especially difficult. Mitigations that were necessary to communicate with the motor in the laboratory were detrimental to communication on the airplane. Figure 4 shows the braided-shielded cable that was necessary for communicating with the motor in the laboratory, connected to both the motor and SVIM chassis (the motor connection is not shown in the figure). The CAN bus error rates that exceeded approximately 25 percent were too high for reliable communication if the harness shield was not connected to both the motor and the SVIM chassis. Conversely, with the same grounding scheme applied to the airplane, the SVIM was not able to transmit data to the ACL at all, so the shield had to be disconnected. The SVIM aircraft harness is shown in Fig. 5.

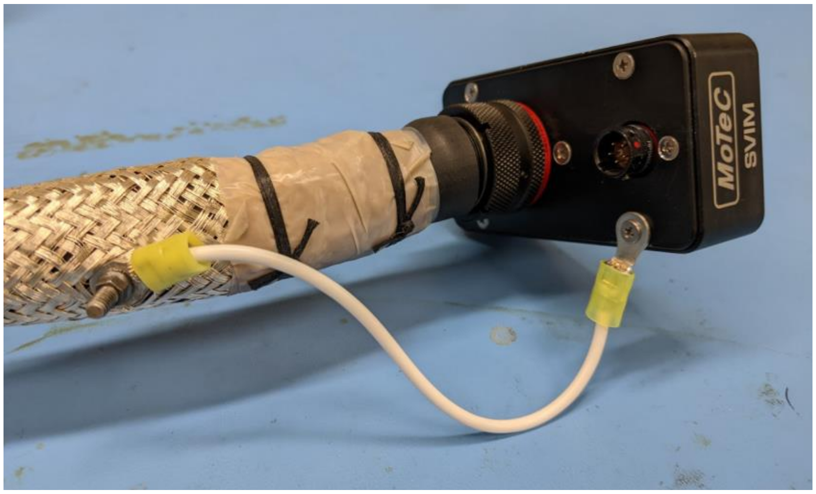

Fig. 4 The laboratory harnessing on the MoTeC Synchronous Versatile Input Module (MoTeC USA, Mooresville, North Carolina).

Fig. 5 The X-57 airplane harnessing on the MoTeC Synchronous Versatile Input Module (MoTeC USA, Mooresville, North Carolina).

III. Environmental Testing

The MoTeC devices were tested operationally for airworthiness in an environment as similar as possible to the anticipated X-57 flight environment, at both acceptance and proto-qualification levels. Nonflight assets were tested to proto-qualification levels to ensure qualification; each flight asset was tested to acceptance levels to test workmanship. The D175 display and the ACL are each installed in the cabin area and were tested at the same limits. The SVIMs are installed in the nacelle areas near the motors and were tested to higher limits than the other devices were. The environmental tests performed were temperature extremes and random vibration.

A. Temperature Extremes

The devices were tested in a thermal chamber to temperatures in accordance with Fig. 6, where T0 is the ambient temperature before the chamber is enabled. The acceptance temperature limits for the D175 display and the ACL were -15 °C and +60 °C for 12 cycles; the proto-qualification temperature limits were -20 °C and +65 °C for four cycles at 15,000 ft. The acceptance temperature limits for the SVIM were -45 °C and +70 °C for 12 cycles; and the proto-qualification temperature limits were -50 °C and +70 °C for four cycles at 15,000 ft. Each unit passed its temperature test.

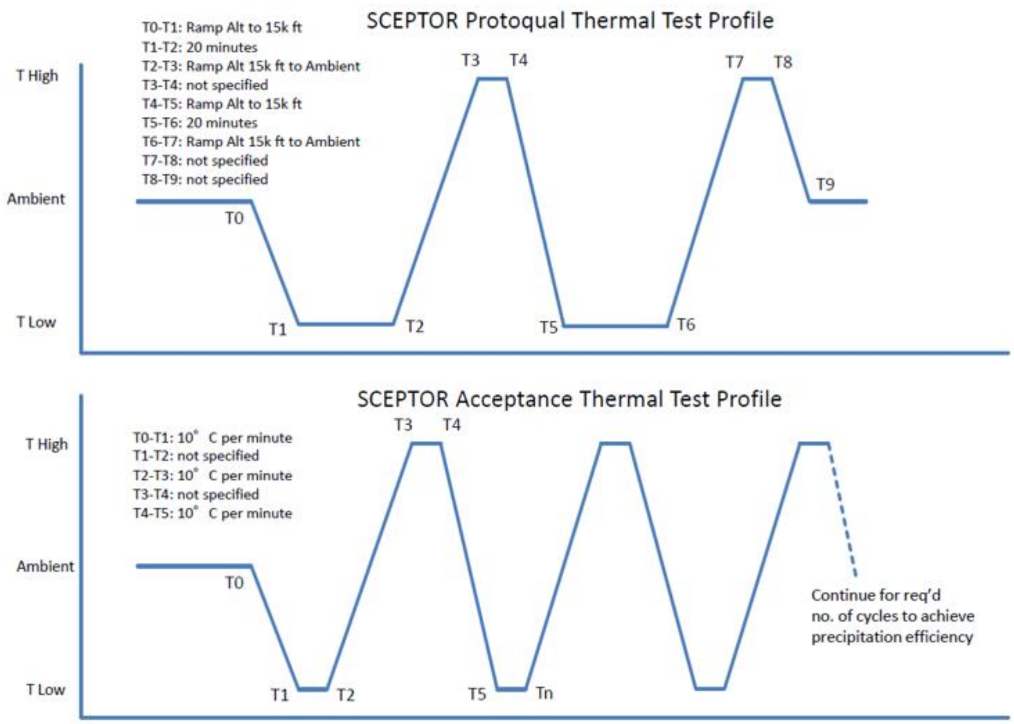

Fig. 6 Temperature profiles for proto-qualification and acceptance tests.

B. Random Vibration

The devices were tested on a random vibration table in accordance with Fig. 7. The vibration profile for acceptance testing the D175 display and the ACL was curve B1 4.13 Grms for 20 min on each axis; the vibration profile for proto-qualification testing was 5.84 Grms for 20 min on each axis. The vibration profile for acceptance testing the SVIM was curve A1, 7.71 Grms for 20 min on each axis; the vibration profile for proto-qualification testing was curve A2, 10.9 Grms for 20 min on each axis. Each unit passed its random vibration testing without incident. Cockpit devices were tested to curves A1 and A2, and devices in the nacelle were tested to curves B1 and B2.

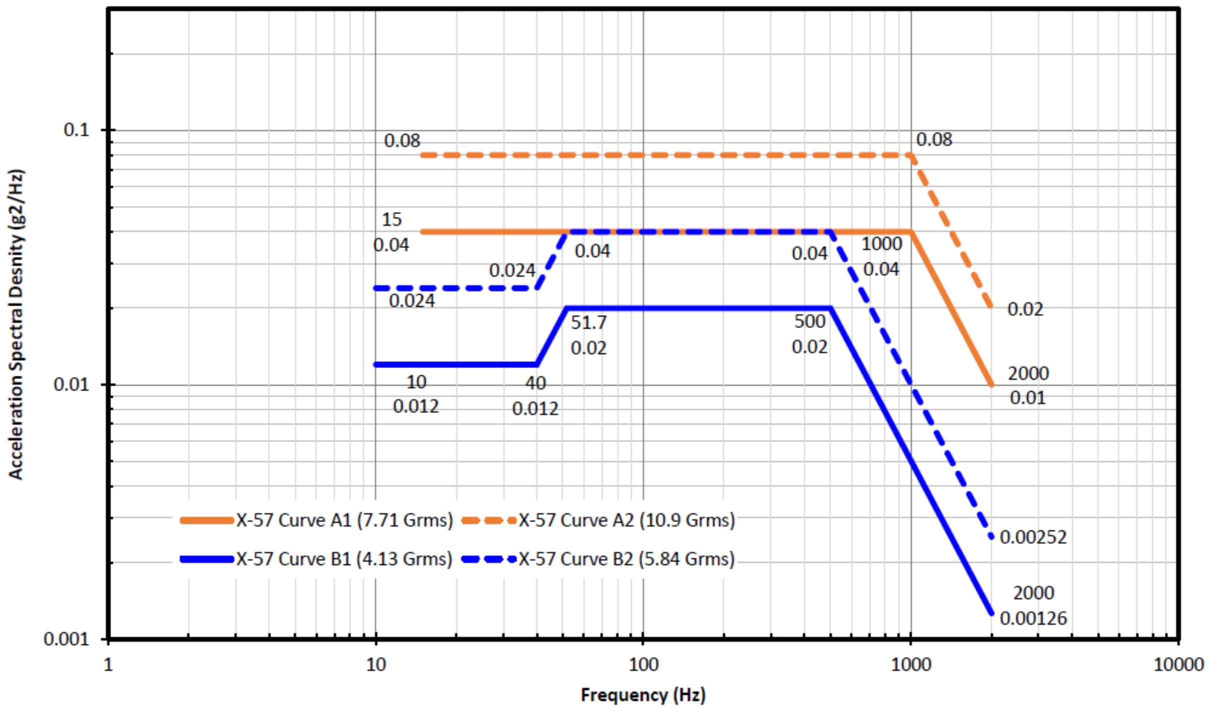

Fig. 7 Random vibration curves for proto-qualification and acceptance tests.

IV. Software

The CDS software is comprised of two parts: the ACL-SVIM build and the D175 build. The SVIM acts as an extension of the ACL and increases the number of inputs available. In the X-57 airplane, the SVIMs acquire temperatures from the motors and nacelles, and the propeller pitches. The ACL receives measurements from the SVIMs, torque lever encoders, CMCs, and BCMs. Due to the closely related nature of both software loads, they are discussed together.

A. Display Pages

The D175 Display Software was developed using MoTeC Display Creator [6] integrated development environment through an iterative process involving consultation with the X-57 project chief engineer and test pilots. Pages 1 through 3 of the flight candidate software load are designed for pilot use; pages 4 through 7 are to support verification and validation testing, troubleshooting, and other debugging activities. The page displayed is based on pilot input from an eight-position rotary switch. All values displayed in Figs. 8 through 14 (except those in Fig. 9) are estimates and are not representative of ground- or flight-test data.

The main page is shown in Figs. 8(a) and 8(b). The main page displays the estimated motor torque, the torque lever travel percentage, CMC and motor temperature alerts, motor power, battery voltage, and battery state-of-charge. The displayed values of motor torque, motor power, and torque lever travel percentage are computed by the ACL, which is configured using the ACL Manager [7] integrated development environment; battery voltage and state-of-charge are received directly from the BCMs. The temperature warnings shown in Fig. 8(a) indicate that a yellow temperature limit has been exceeded on the left-hand side and a red temperature limit has been exceeded on the right-hand side. Fig. 8(b) shows how the main page looks when there are no temperature warnings. These parameters were deemed to be the most important for the pilot to check when a limit had been exceeded. The values displayed are based on the estimated torque and power needed at takeoff and climb to cruising altitude.

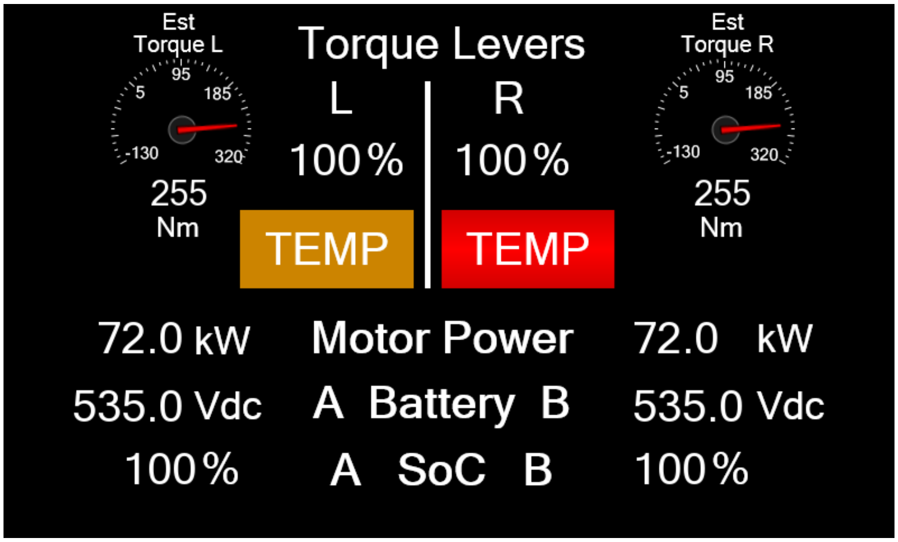

Fig. 8(a) Display page 1 showing warnings.

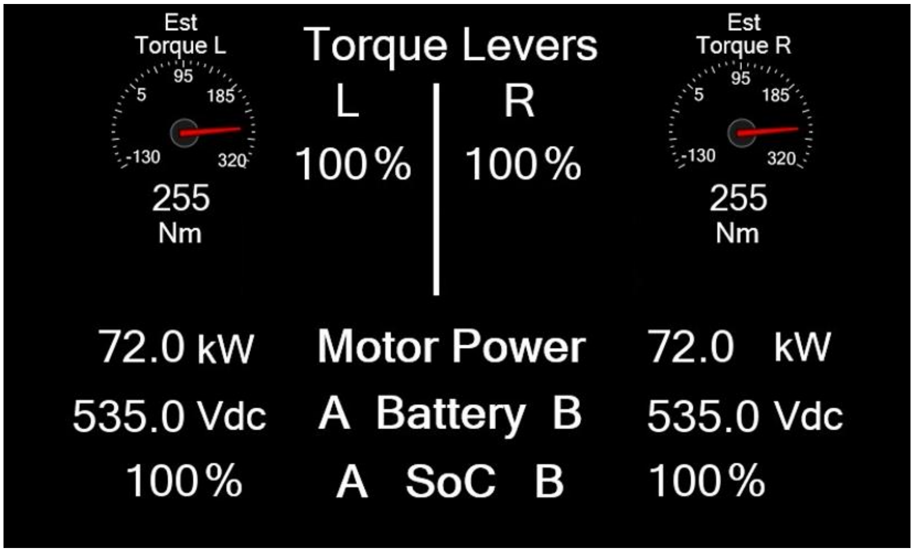

Fig. 8(b) Display page 1 showing no warnings.

The second display page is shown in Fig. 9, which is a photograph of the cockpit display in the X-57 airplane that displays the maximum temperatures from the cruise motor controllers. Due to the large number of measurements and the small screen size, only the hottest temperature of the set of values is displayed. The CMC with the hottest temperature is indicated by an A or a B beside it; if a letter is not displayed, then both controllers are producing the same temperature within 1 °C. If only its yellow limit is exceeded, then the background color displayed behind the temperature will turn to yellow. If both the yellow and the red limits are exceeded for the same metric, then the background behind the temperature display will turn red. If a temperature limit is exceeded, the corresponding color alert will flash on and off on the main page. The maximum temperature is calculated by the ACL and the D175 displays the highlighted background if a limit is exceeded, and an A or B is displayed to indicate which CMC is the source. All temperatures shown in Fig. 9 are within the nominal operating limits of the devices. The temperature alert limits are listed in Table 1.

Table 1 Cruise motor and controller temperature limits.

Parameter	Yellow temperature limit, °C	Red temperature limit, °C
MOSFET temperature	123	134
FPGA temperature	89	100
Driver board temperature	89	100
Vicor temperature	89	100
CPU board temperature	74	85
Winding temperatures	124	135
Bearing temperatures	88	99

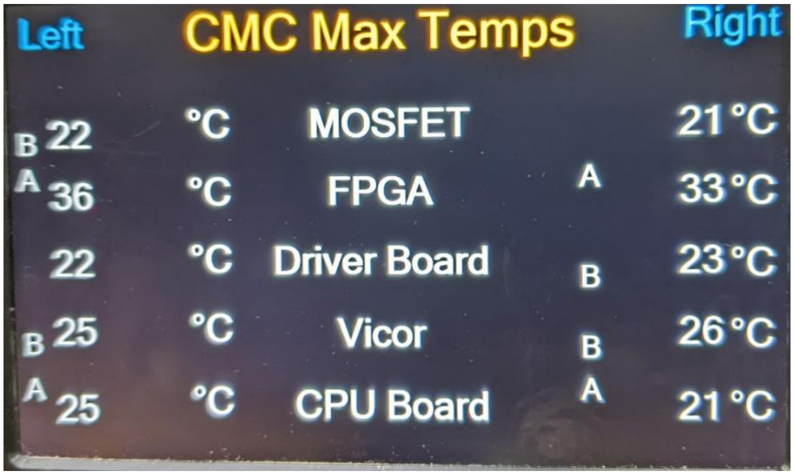

Fig. 9 Display page 2 (a photograph of a portion of the cockpit display in the X-57 airplane).

Figure 10 shows display page 3, which displays the maximum motor winding and motor bearing temperatures. Maximum temperatures are calculated by the ACL. There are six winding temperatures and six bearing temperatures per motor, the bearing temperatures having two sensors for the forward (“Fwd”), middle (“Mid”), and aft bearings, which are sampled by the SVIMs. These temperatures will also be highlighted if any of them exceed their yellow or red limits and alerts will be generated on the main page. The left motor winding temperature that is 125 °C generates a yellow temperature alert for the left-hand side, and the Mid bearing temperature at 100 °C generates a red temperature alert for the right-hand side.

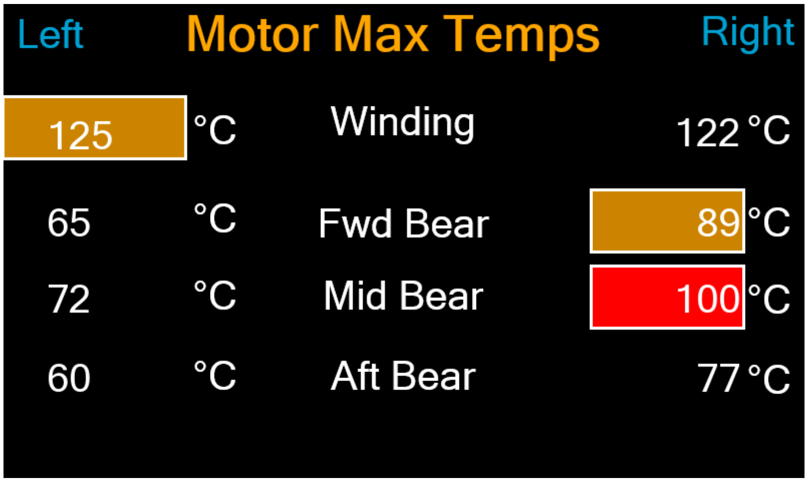

Fig. 10 Display page 3, showing temperature alerts.

Figure 11 shows display page 4, which displays the multifunction display (MFD) software version number, the ACL software version number, and the propeller pitch. During EMI troubleshooting and mitigation, the wires transmitting propeller pitch data were a significant source of noise and at the time of this publication a solution has not been identified. As such, the propeller pitches were placed on the fourth page so that the requirement to display pitch was met but would not display erroneous data to the pilot during flight.

Fig. 11 Display page 4.

Figure 12 shows display page 5, which displays each motor winding (MW) temperature. Unlike the previous display pages, temperatures on this page are not highlighted even if a limit is exceeded.

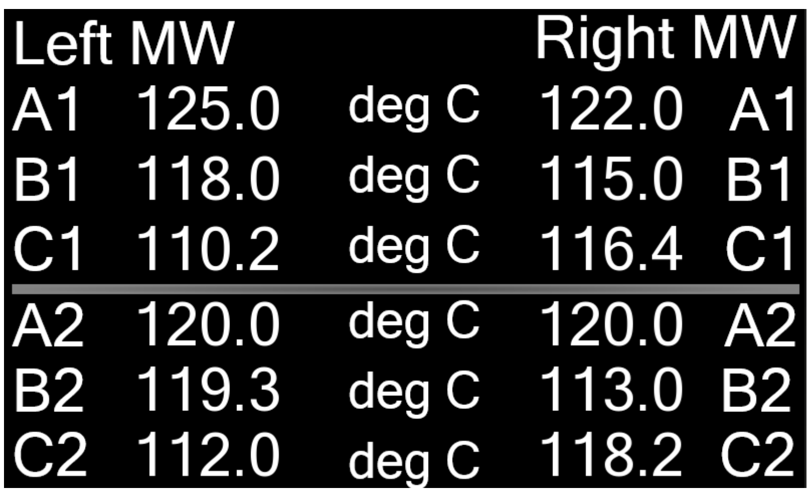

Fig. 12 Display page 5.

Figs. 13 and 14 show display pages 6 and 7, which display all 11 of the temperatures monitored in the left and in the right nacelle, respectively. The initial design had four sensors per nacelle to monitor air temperatures, but during the troubleshooting phase of the project it was decided to utilize the rest of the existing channels in the SVIMs and not leave any pins unpopulated. The thermistors for the Duct In1 and In2 are placed at the forward end of the CMC heat sinks (HSs); Duct Out1 is placed at the aft end of the CMCs; CM Out1 and Out2 are placed between the cruise motors and the forward end of the CMCs; Aft HS1 and HS2 are placed at the aft end of the CMC heat sinks; the miniature data acquisition unit (MDAU) is placed in the left miniature data acquisition unit compartment; and the right-hand fiber-optic bus extender (FOBE) is placed next to the left-hand FOBE.

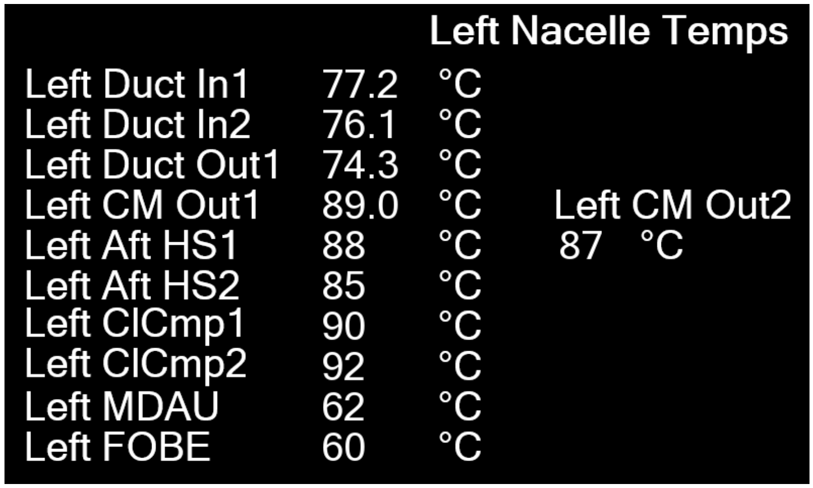

Fig. 13 Display page 6.

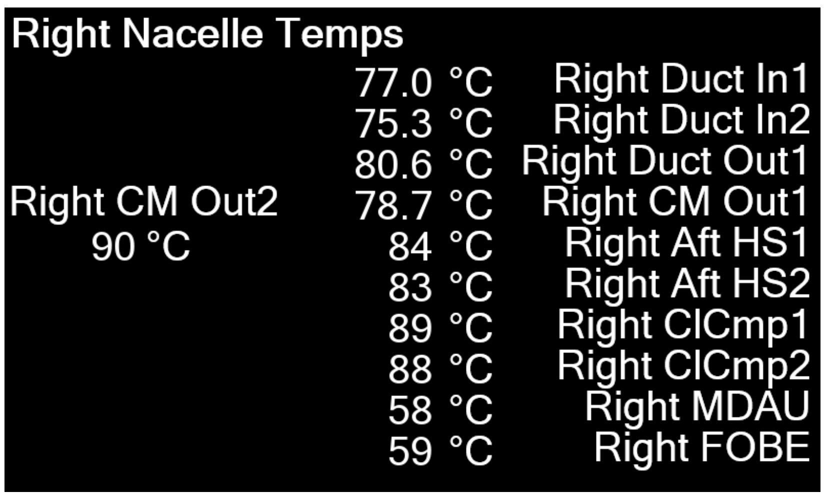

Fig. 14 Display page 7.

B. Light-emitting Diode Indicators

The 10 LEDs shown along the top of the display in Fig. 15 are used as status indicators of 10 different devices on the CAN bus. The LEDs are numbered 0 through 9; each corresponds to the device listed beside it in Table 2.

Table 2. Light-emitting-diode-to-signal map.

LED	Signal
0	Left Cruise Nacelle SVIM
1	Left Cruise Motor Controller A
2	Left Cruise Motor Controller B
3	BCM A
4	Left Torque Encoder
5	Right Torque Encoder
6	BCM B
7	Right Cruise Motor Controller A
8	Right Cruise Motor Controller B
9	Right Cruise Nacelle SVIM

If a device is transmitting data on the bus, then the LED illuminates. If a device is not transmitting, then the LED remains off. In Fig. 15, all of the devices are transmitting except for the Right CMC A and the Right Cruise Nacelle SVIM.

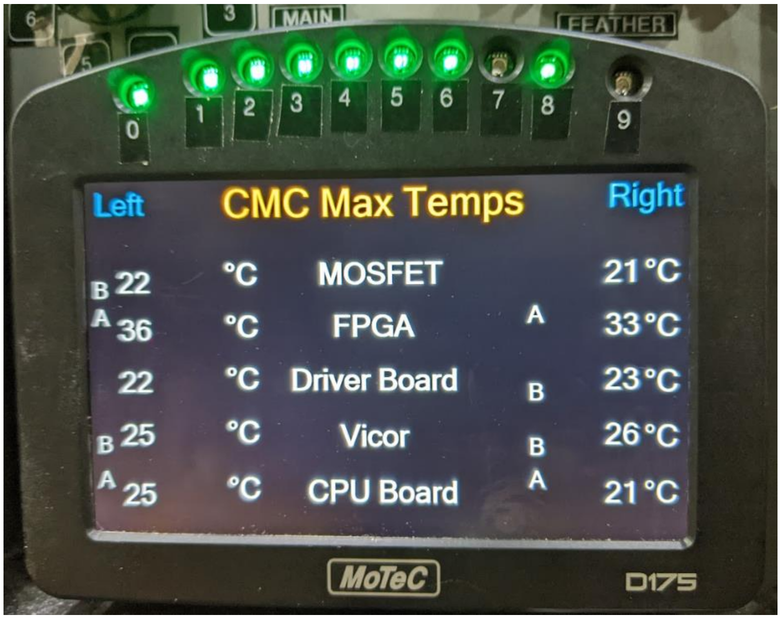

Fig. 15 Light-emitting diode indicators 0-9.

C. Verification and Validation Testing

In order to thoroughly test the CDS software, a test point matrix was written to ensure that each requirement was met. The first phase was performed on laboratory hardware by testing each parameter from its originating device to its final display. The measurements displayed on pages 1, 2, and 4 were tested by a set of Python scripts that transmitted messages simulating each of the parameters. Pages 3 and 5-7 were tested by injecting voltages to each SVIM input pin and checking the corresponding value displayed. Pass/fail criteria were set to be within one percent of the expected values.

V. Challenges

A. Electromagnetic Interference

Electromagnetic interference (EMI) has affected nearly every part of the X-57 airplane, including the cockpit display system. The analog inputs to the SVIM modules have been a significant path for noise to propagate on and prevented them from clearly transmitting their data to the ACL. When noise is high, the LED indicators for SVIM communication turn on and off quickly and the corresponding temperature data drops out, rapidly switching between the last transmitted value, 0 °C, and an open-circuit value. In previous tests, the effects of EMI were closely related to the switching frequency of the MOSFETs inside the CMCs and the speed of the cruise motors. During ground testing, as the motor speeds increased the data dropouts also increased. This problem was mitigated by the addition of toroidal chokes to filter high frequency noise and software techniques in the CMCs.

B. Software Development Version Tracking

The software development concurrently took place on laboratory hardware and on the X-57 airplane. The final portions of development were done on the X-57 airplane itself because the electrical characteristics could not be replicated in the laboratory. Three different engineering software versions were installed on the X-57 airplane to aid in understanding how the CDS hardware was being affected by EMI. These software versions were not intended for flight or for verification and validation testing. Transitioning between established versions and engineering versions created configuration management difficulties that took extra time and collaboration to resolve.

C. Lessons Learned

The cockpit display system focuses on thermal measurements because this is a good way to understand the operational health of the propulsion system. It was useful to validate the thermal models of the motor controller components, the motor itself, and the heat flow paths through the nacelles and the cabin. By monitoring these sensors and the internal health and status parameters reported by the CMCs and BCMs, the pilot and the ground monitoring team can verify that the experimental propulsion system is operating as intended and can track changes in performance over time. The CDS data are a valuable supplement to the safety-critical data on the right-hand instrumentation panel and what is available in the MFD.

The adverse effects of EMI were present throughout the entire X-57 airplane, including sections of the CDS. Electrical design, including shielding, grounding, and filtering is more rigorous than the design employed for a nonelectric airplane. Laboratory testing of individual systems is not sufficient to produce a full system that is ready for flight. Development of an iron bird ground-based test device is recommended to fully understand the use of new technologies and the new applications of existing technologies to electric aviation.

VI. Conclusion

A cockpit display system is an important instrument for the X-57 Maxwell airplane because it provides the pilot with additional situational awareness and mission-critical data and gives the ground crew and test team easy access to data without requiring the use of specialized equipment. Provision of nacelle temperatures, quick-look checks of torque, battery state-of-charge, and battery voltage substantially increases the pilot's situational awareness. The cockpit display system was not immune to the effects of electromagnetic interference, with the Synchronous Versatile Input Modules being especially impacted, which required the application of toroidal chokes to achieve reliable data. Testing, development, and troubleshooting must be performed on the flight asset if an iron bird ground-based test device is not developed, which could make configuration management of the hardware and software challenging.

Acknowledgments

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