X-57 Flight Systems Integration Path

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The foundation for a safe and successful flight test of the National Aeronautics and Space Administration (NASA) X-57 Maxwell all-electric experimental airplane, or any X-Plane, is comprehensive system testing on the ground. This test campaign includes verification and validation (V&V) that the integrated system operates as designed and expected, as well as understanding how the system reacts and responds to failures that can occur during flight by performing failure modes and effects testing (FMET). The aircraft should be in the final flight configuration for these test activities because any modifications, even those that appear insignificant, could affect test outcomes. Although the plan was to perform V&V and FMET testing once the airplane was in the flight configuration, due to multiple component redesigns, concurrent software development, and other problems with on-aircraft testing, the X-57 Maxwell never made it into a full-flight configuration. As a result, a build-up approach was followed to test software and hardware as they became ready in order to continue making progress wherever possible. Using this approach revealed problems with the hardware and software faster than waiting for a full-flight configuration, allowing solutions to be found more quickly and in parallel with other project tasks. Other than unloaded motor testing in a lab setting, the only other test setup was on the airplane itself. On-aircraft testing was preferrable in order to test things as close to a flight configuration as possible but was time consuming due to the requirements for testing on the airplane. To overcome some of the on-aircraft barriers, off-aircraft test configurations, such as the Systems Integration Laboratory (SIL) and hardware-in-the-loop (HIL) setups, were used, but each of these setups had limitations to be considered. As a result, solutions found in the SIL or HIL configurations did not always work as expected on the airplane, resulting in an iterative process between on- and off-aircraft testing to find the final solution. Having a dedicated test platform such as an iron bird that closely represents the aircraft - without flight hardware - would have been the most effective off-aircraft test setup, which could have allowed the project to save time and money and potentially reach flight. This paper will highlight the V&V and FMET considerations and testing prerequisites, the build-up approaches to both software and system testing, the benefits and drawbacks to different test configurations, as well as battery testing and operations.

I. Introduction

The X-57 Maxwell all-electric experimental airplane is a Tecnam P2006T (Costruzioni Aeronautiche Tecnam srl, Capua, Italy) twin-engine airplane that has been modified for electric propulsion. Three different modification phases were planned for the lifecycle of the project but, for the purpose of this paper, only Modification II (Mod II) will be discussed. It should be stated that the verification and validation (V&V) testing, failure modes and effects testing (FMET), and other activities required prior to flight were never completed. These activities were halted in June 2023

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when the project was directed to begin closeout after technical problems with the motors were identified that required more schedule and budget to resolve than what remained for the project.

In addition to a new data acquisition system and cockpit display systems, one of the most considerable modifications to the stock Tecnam for Mod II was the traction system. The main elements of the traction system are the cruise motors (CMs), cruise motor controllers (CMCs), contactor pallet, battery control modules (BCMs), and the traction batteries. These systems are outlined in Fig. 1. The development of these systems was driven by requirements for redundancy, fault tolerance, and performance. As seen below, there are two independent high-voltage battery packs providing independent power to two traction buses. Each traction bus provided independent traction power to two motor controllers, one on the left cruise motor and one on the right. A more in-depth description of the system design can be found in Ref. [1] as well as Ref. [2].

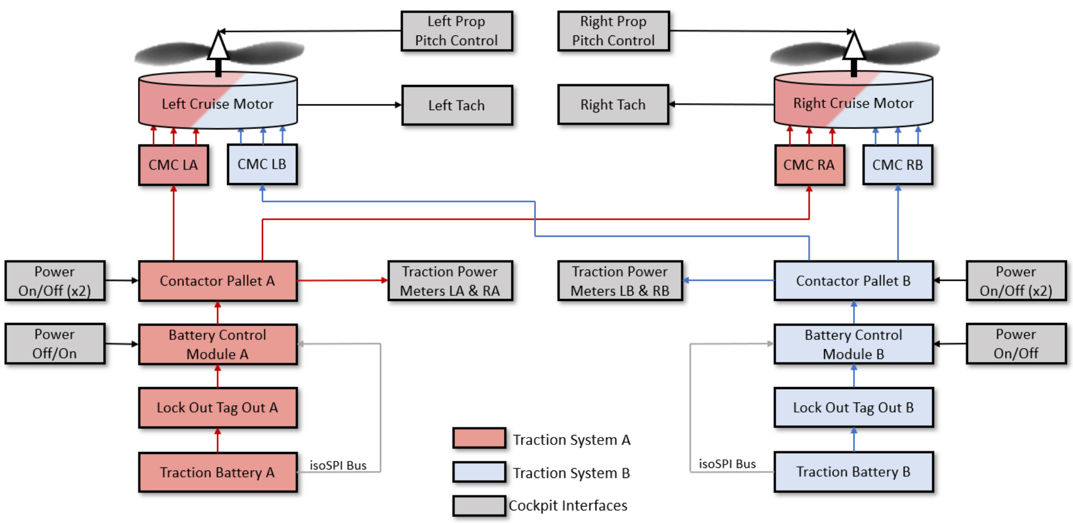

Fig. 1 Traction system and interfaces.

A. Aircraft Subsystems

1. Cruise Motors

The cruise motors (CMs) are dual winding 3-phase, air-cooled, out-runner electric motors custom designed for the X-57 Maxwell by Joby Aviation (Joby Aviation, Inc., Santa Cruz, California). These motors operate with inverters at 461 VDC nominal, providing 72 kW peak power to the propeller at 2,700 RPM and 60 kW continuous power at 2,250 RPM. These motors directly drive the propellers and provide primary thrust for the X-57 Maxwell airplane. Each of the independent 3-phase windings in the CM is driven by a sensorless motor inverter called a cruise motor controller (CMC). In the event that a single CMC becomes inoperable, the remaining operational CMC for that motor can be commanded into overdrive, which is considered greater than 100 percent torque capacity. For Mod II, the electric motors were located within the stock Tecnam P2006T nacelle locations.

2. Cruise Motor Controllers

The cruise motor controllers (CMCs) were redesigned by the National Aeronautics and Space Administration (NASA) with assistance from Empirical Systems Aerospace (ESAero) (Empirical Systems Aerospace, Inc., San Luis Obispo, California), reusing Joby components. The CMCs convert DC power from the traction battery systems to the 3-phase AC power for the X-57 cruise motor. The CMCs use a sensorless control inner loop (feedback uses motor current) to maintain commanded torque control across a range of speeds, traction bus voltages, and operating conditions. The CMC is composed of five custom-printed circuit boards outlined below.

1) Connector board.
2) Central processing unit (CPU) board.
3) Low-voltage power board.
4) Metal-oxide semiconductor field-effect transistor (MOSFET) gate driver board.
5) DC bus filter or high-power DC and AC transmission board.

The normal operating voltage for the X-57 traction bus was between 320-538 VDC. The nominal output power per CMC was 36 kW and up to 45 kW in peak operating conditions. Each CM was to be controlled by two CMCs, for redundancy, for a total of four CMCs operating in flight. Each CMC used three silicon carbide (SiC) half-bridge MOSFET modules to convert between DC bus and motor winding power.

The CMC used a commercial-off-the-shelf (COTS) motor-control field-programmable gate array (FPGA) IP-core, designed by QDESys (Verona, Italy), and a separate outer-loop CPU executive application layer developed at Armstrong Flight Research Center (AFRC). Controller area network (CAN) communication was used for torque command input and telemetry output. Ethernet communication was used for software maintenance. The BM2s, developed by Joby and QDESys, were the original design for the CMCs. This iteration was intended for flight, but environmental testing revealed that a more robust design was needed that resulted in a NASA-led redesign, known as the XM3s, which reused some of the original components from the BM2s.*

3. Traction Busses

To ensure redundancy, there were two traction busses (Traction Bus A and Traction Bus B) that connected the CMCs (two per traction bus) to the battery system via the contactor pallet (one per traction bus), designed by ESAero. There were two traction contactor assemblies (TCAs), internal to each of the contactor pallets, that provided inrush current protection to each of the CMCs and isolation between the traction battery system and the CMCs via switches in the overhead cockpit panel.

4. Traction Battery System

The X-57 traction battery system was the primary energy storage system for the X-57 airplane and provided the electrical power during flight to the electric propulsion system and vehicle avionics. Electric Power Systems (EPS) (Electric Power Systems, Inc., Logan, Utah) developed the traction battery system. The traction battery system has two independent or isolated (A and B), battery packs, each comprised of battery modules, a Lock-Out/Tag-Out (LOTO) unit, and a battery control module.

5. Traction Battery Modules

Each battery pack includes eight battery modules connected in series. Each battery module includes 320 Samsung (Samsung Group, Suwon-si, South Korea) INR18650-30Q lithium-ion cells arranged in a 20P16S architecture as well as a cell monitoring board that collects voltage and temperature measurements from each 20 "brick."

6. Lock-Out/Tag-Out

The Lock-Out/Tag-Out (LOTO) unit was located between the traction battery and the BCM for each battery pack. The LOTO included three high-voltage switches that could be opened to isolate the positive, negative, and center tap terminals of the traction battery. Test points were located on the input and the output of the LOTO to verify voltage. The LOTO also contained 200-amp fuses on the positive and negative legs to protect personnel from arc flash during battery modules maintenance and to protect the traction system from an overcurrent condition.

7. Battery Control Module

The battery control module (BCM) collected cell data from the cell monitoring boards in the battery modules, overall pack current, and internal BCM temperatures. These measurements were reported on the command bus for real time and post-data analysis. The BCM also monitored electrical isolation between the high-voltage system and the airplane chassis.

8. Avionics System

Each BCM also included DC power converters to supply power to the avionics systems, outlined in Fig. 2. The avionics power architecture was designed in such a way that certain buses could be disabled in case of emergency while maintaining aircraft functionality and limiting critical data loss Ref. [3]. Note: Fig 2 acronyms defined: TDR GTC 328 is a transponder, miniature data acquisition unit (MDAU), flight data recorder (FDR); Chassis Mount Isolated Dc-Dc Converter (model VHK200W-Q24-S24) by CUI (CUI Inc. (a Bel Group), Portland, Oregon).

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* Different iterations of the CMCs were used as testing progressed throughout the life of the project. Early testing used the original CMCs, referred to as BM2s, whereas later testing used the redesigned CMCs, referred to as XM3s. In cases that are relevant, the CMCs are referred to as BM2s or XM3s to specify the iteration of the CMC being tested in that instance.

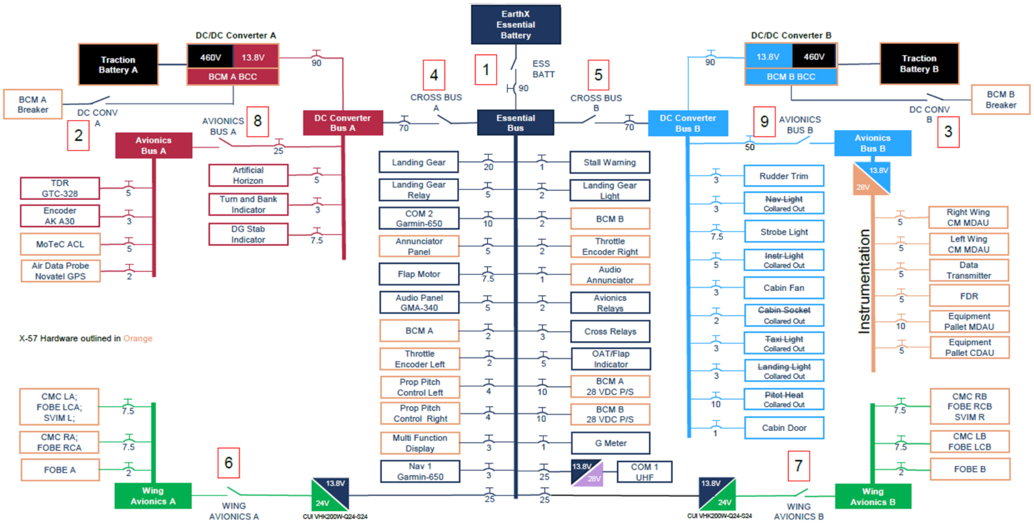

Fig. 2 Modification II avionics power architecture.

9. Command System

The command system on X-57 Maxwell, outlined in Fig. 3, uses a 1-Mbit CAN bus architecture to provide torque commands from torque levers in the cockpit to the CMCs. The command system consists of five CAN bus segments. The fuselage segment and four remote segments, one at each CMC, are connected via fiber-optic modems. These segments can be considered in three CAN bus rings: 1) the fuselage ring, 2) the right nacelle ring, and 3) the left nacelle ring. The fiber-optic links minimize the electromagnetic interference (EMI) effects on the CAN bus signal by avoiding long conductive runs between the fuselage and the nacelles. Each of the X-57 subsystems, such as the CMCs and BCMs, have a CAN bus interface that provides health and status of the subsystem. The CAN bus data is displayed to the pilot on a multi-function display (MFD) located in the center cockpit panel. This data is also recorded by the data acquisition system (DAS) and transmitted to the ground for real-time ground displays during testing. Note: Fig 3 acronyms defined: remote data acquisition unit (RDAU), torque encoder (TE), cockpit display console (CDC).

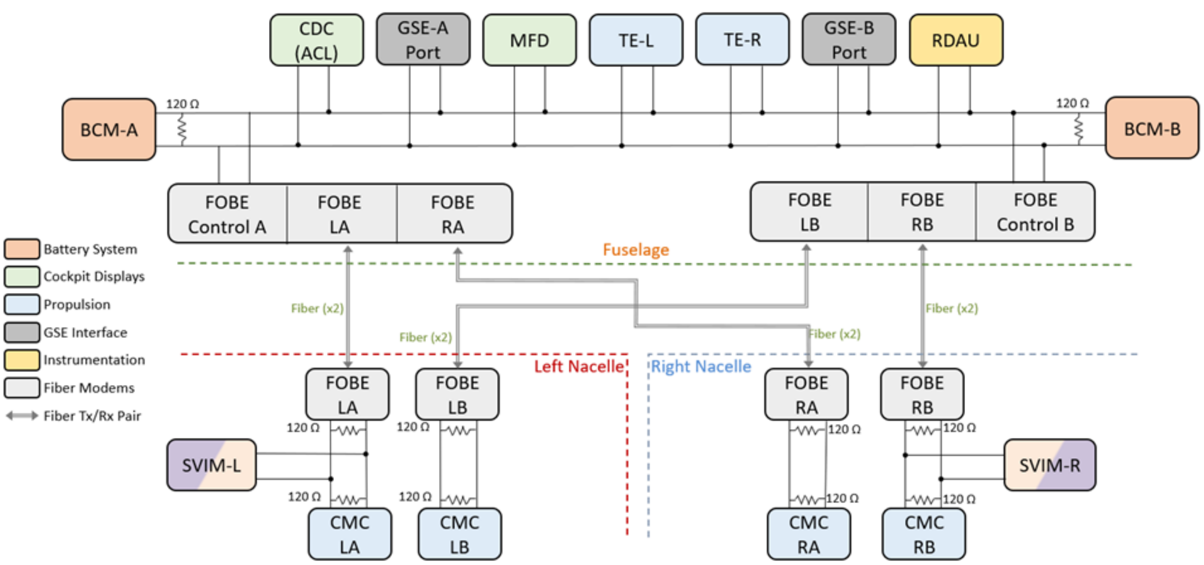

Fig. 3 Command bus interface diagram.

II. Aircraft Test Approach and Test Point Development

Prior to flight, it was critical to perform systems-level testing of the airplane to ensure that all systems operated together as designed, including during off-nominal conditions. Having an iron bird available for this testing, along with subsystem testing, prior to formal aircraft testing is optimal because changes can be made quickly and problems can be unveiled early on without posing any risk to the flight hardware. Unfortunately, the X-57 team did not have an iron bird because the project had made a risk-based decision early on that it was not necessary because most items were considered COTS, and the integration-to-flight efforts were expected to be minimal and quick with any necessary testing taking place on the airplane. This testing was grouped into two different test campaigns for the X-57 Maxwell. The first planned test campaign was V&V testing, which would confirm that that the Mod II airplane would meet both ground- and flight-test requirements. The second planned test campaign was FMET. This test campaign was designed to only focus on the failure modes of the systems that were added to the stock Tecnam P2006T airplane. The prerequisites to performing V&V testing, and therefore FMET, were that all hardware and software components had successfully completed subsystem-level testing and that only modifications resulting from V&V and FMET findings were outstanding. It should be noted that the V&V and FMET campaigns were never performed for score because subsystem-level testing was incomplete. To continue making progress, risk reduction activities, such as CMC software evaluations and V&V dry runs were performed on the airplane. This build-up approach and testing activities will be discussed further throughout the paper.

There were two V&V test campaigns that needed to be conducted on the airplane. The first was CMC software V&V, comprised of six lab procedures and three on-aircraft procedures, which will be discussed further in Section III. The second was the Flight Systems V&V, comprised of ten procedures. It was required to run the CMC software V&V procedures first to uncover and resolve any problems within the subsystem. Although it was still possible that problems with this subsystem would be uncovered in later test campaigns, completing these software tests first provided a configuration that was as close to the flight configuration as possible. Having an aircraft in a flight-like configuration for ground testing allows discrepancies to be found and resolved prior to flight and limits unknowns during flight, all of which reduce risk to the pilot and airframe.

The CMC software V&V test points, created not only by using the requirements but also the findings and processes from the lab, were developed to verify that the software performed the following: met the system requirements, communicated correctly per the system interface control document (ICD), implemented motor control algorithms to meet mission objectives, and included safety features that worked as designed. The test plan for the software contained over 400 test points, including both on- and off-aircraft testing, and provided guidance on generating test procedures, test environments, success criteria, and test artifacts to verify the performance of the X-57 Maxwell CMC software. The build-up approach to ensure that the software was functioning as expected was used to perform incremental steps from testing on the development board to spinning the unloaded motor in the lab and, finally, spinning the loaded motors (with propeller loads) on the airplane.[†]

The flight systems V&V test points that are performed in the ten system-level procedures were created through an iterative process of reviewing requirements, interfaces of components, and through discussions with system subject matter experts (SMEs). After reviewing all the subsystems and components of the Mod II airplane, a list of the interfaces that existed on the airplane was produced. From this list, test points were drafted and sent to SMEs for review and revision. Additionally, an interface matrix was created using the subsystems and components of the airplane, as seen in Fig. 4. This interface matrix was cross-referenced with the draft test points. If there were interfaces that did not have test points linked, new test points were generated. The updated list of test points then went through a review with SMEs and was revised as necessary to ensure that all required test points were captured and any unnecessary duplication was limited. Subsequently, the system-level requirements were reviewed to ensure that test points were mapped to each system level requirement with the correct verification methods. This method led to the final set of V&V test points that were later broken into test procedures at the discretion of the team (Appendix B).

[†] The cruise motor is referred to as an unloaded motor if no propeller is attached and no external loads are applied, and a loaded motor if a propeller is attached or any external loads are applied. For the test activities described in this paper, all off-aircraft testing was performed using an unloaded motor and all on-aircraft testing was performed using a loaded motor.

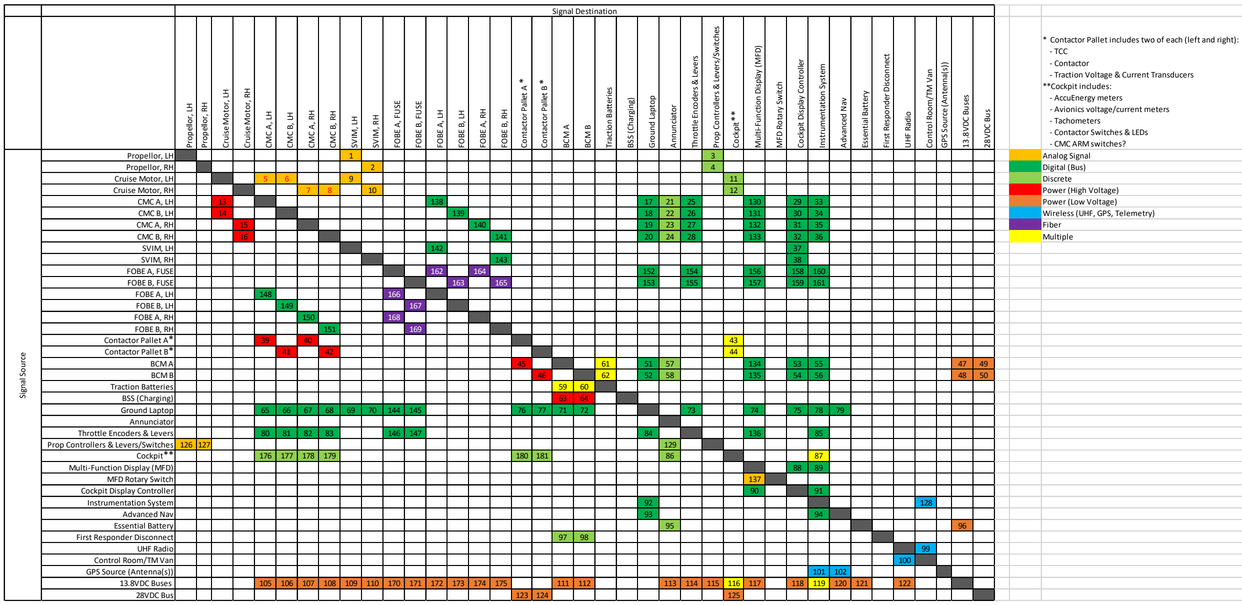

Fig. 4 The V&V Interface Matrix.

The FMET was to be performed as the last test campaign prior to combined systems test (CST), taxi runs, et cetera. This campaign consisted of two procedures that were also developed through an iterative process. After discussing the systems and interfaces with SMEs, the team determined that FMET was only necessary on the modified portion of the airplane: the traction system. The instrumentation systems would not be specifically covered in FMET because they were COTS systems that would not cause critical problems. System-level failure conditions for unplanned and/or unknown failure scenarios were also examined, and test points were created as necessary. This test campaign relied heavily on the fact that the traction system was redundant, and this redundancy was to already be tested thoroughly during V&V. The FMET was intended to show that the integrated system could still operate safely regardless of how many components failed and to test corner cases where the outcome was not well-defined.

The FMET matrix, found in Fig. 5, was developed by first assessing a single component (or primary) failure, then inducing a second (or secondary) failure with the worst possible outcome. This matrix shows different scenarios and the expected outcomes. From this matrix two procedures were created (Appendix C).

Primary Failure	Secondary Failure	Failure ID	Cruise Motor L	Cruise Motor R	CMC LA	CMC LB	CMC RA	CMC RB	Contactor Pallet A	Contactor Pallet B	Traction Bus A	Traction Bus B	Traction Battery A/BCM A	Traction Battery B/BCM B	Avionics Bus A	Avionics Bus B	FOBE A	FOBE B	Torque Encoder L	Torque Encoder R	Prop Pitch Controller L	Prop Pitch Controller R	Wing Avionics Bus A	Wing Avionics Bus B	CDS	Test Points/Hazards	Expected Outcome
Traction Battery A/BCM A	None	1.0	D	D	I		I		I		I		F		D											HR 37	50% loss in thrust, 2 CMCs are non-operational
	CMC (LB)	1.1	I	D	I	F	I		I		I		F		D											HR 21	75% loss in thrust, 3 CMCs are non-operational
	Traction Battery/BCM (B)	1.2	I	I	I	I	I	I	I	I	I	I	F	F	I	I	I	I	I	I	I	I			I	HR 21	100% loss in thrust, Loss of both Traction Batteries, Essential bus only
	FOBE (EQP-B)	1.3	D	D	I	D	I	D	I		I		F		D			F							D	HR 21	50% loss in thrust, 2 CMCs are non-operational and no commands from the other 2 CMCs
	Torque Encoder (R)	1.4	D	D	I		I	D	I		I		F		D					F						HR 21	75% loss in thrust, 2 CMCs are non-operational, no commands from 1 CMC
	Prop Pitch Controller (L)	1.5	D	D	I		I		I		I		F		D						F					HR 37	Loss of Prop/Motor Speed control identifiable from tachometer. Some amount of loss of thrust which may lead to Control Room Query/RTB
	Wing Avionics Converter (B)	1.6	I	I	I	I	I	I	I		I		F		D			I						F	D	HR 21	100% loss in thrust, 4 CMCs are non-operational
	Cruise Motor (R)	1.7	D	F	I		I		I		I		F	I	D											HR 21	75% loss in thrust
	Contactor Pallet (B)	1.8	I	I	I	I	I	I	I	F	I	I	F		D											HR 21	100% loss in thrust, no high voltage from CMCs
Wing Avionics (A)	None	2.0	D	D	I		I										I						F		D	HR 37	50% loss in thrust, 2 CMCs are non-operational
	CMC (LB)	2.1	I	D	I	F	I										I						F		D	HR 21	75% loss in thrust, 3 CMCs are non-operational
	Traction Battery/BCM (B)	2.2	I	I	I	I	I	I		I		I		F		D	I						F		D	HR 21	100% loss in thrust, 2 CMCs are non-opertional, 2 CMCs have no high voltage
	FOBE (EQP-B)	2.3	D	D	I	D	I	D									I	F					F		D	HR 21	50% loss in thrust, 2 CMCs are non-operational and no commands from the other 2 CMCs
	Torque Encoder (R)	2.4	D	D	I		I	D									I			F			F		D	HR 21	75% loss in thrust, 2 CMCs are non-operational, no commands from 1 CMC
	Prop Pitch Controller (L)	2.5	D	D	I		I										I				F		F		D	HR 37	Loss of Prop/Motor Speed control identifiable from tachometer. Some amount of loss of thrust which may lead to Control Room Query/RTB
	Wing Avionics Converter (B)	2.6	I	I	I	I	I	I									I	I					F	F	D	HR 21	100% loss in thrust, 4 CMCs are non-operational
	Cruise Motor (L)	2.7	F	D	I		I										I						F		D	HR 21	75% loss in thrust
	Contactor Pallet (B)	2.8	I	I	I	I	I	I		F		I		I		I	I						F		D	HR 21	100% loss in thrust, 2 CMCs are non-operational and no high voltage from the other 2 CMCs
Cruise Motor (L)	None	3.0	F																							HR 37	50% loss in thrust, Loss of 1 Cruise Motro (L)
	CMC (RA)	3.1	F	D			F																			HR 21	75% loss in thrust, 1 CMC failed which caused 1 cruise motor to have decreased performance.
	Traction Battery/BCM (B)	3.2	F	D		I		I				D		F		I										HR 21	75% loss in thrust, Loss of Traction Battery B will cause CMC Bs to lose hight voltage.
	FOBE (EQP-A)	3.3	F	D	D		D										F								D	HR 21	75% loss in thrust, only 1 CMC functional
	Torque Encoder (R)	3.4	F	D	`	D		D												F						HR 21	75% loss in thrust, only 1 CMC functional
	Prop Pitch Controller (R)	3.5	F	D																		F				HR 21	Loss of Prop/Motor Speed control identifiable from tachometer. Some amount of loss of thrust which may lead to Control Room Query/RTB
	Cruise Motor (R)	3.6	F	F																						HR 21	100% loss in thrust
	Contactor Pallet (B)	3.7	F	D		I		I		F		I				D										HR 21	75% loss in thrust, 2 CMCs are non-operational, only 1 CMC fully operational
Contactor Pallet (A)	None	4.0	D	D	I		I		F		I															HR 37	50% loss in thrust, 2 CMCs are non-operational
	CMC (LB)	4.1	I	D	I	F	I		F		I															HR 21	75% loss in thrust, 3 CMCs are non-operational
	Traction Battery/BCM B	4.2	I	I	I	I	I	I	F		I	I		F	I	I										HR 21	100% loss in thrust, 4 CMCs are non-operational
	FOBE (EQP-B)	4.3	I	D	I	D	I	D	F		I							F							D	HR 21	100% loss in thrust, 2 CMCs are non-operational and no commands from the other 2 CMCs
	Torque Encoder (R)	4.4	D	I	I		I		F		I									F						HR 21	75% loss in thrust, 2 CMCs are non-operational and 1 CMC has no commands
	Prop Pitch Controller (R)	4.5	D	D	I		I		F		I											F				HR 21	Loss of Prop/Motor Speed control identifiable from tachometer. Some amount of loss of thrust which may lead to Control Room Query/RTB
	Contactor Pallet (B)	4.6	I	I	I	I	I	I	F	F	I	I														HR 21	100% loss in thrust, no high voltage from CMCs
CMC	None	5.0	D		F																					HR 37	25% loss in thrust
	CMC (LB)	5.1	I		F	F																				HR 37	50% loss in thrust
	FOBE (EQP-B)	5.2	D	D	F	D		D										F							D	HR 21	75% loss in thrust, 1 CMC is non-operational and no commands from 2 other CMCs
	Torque Encoder (R)	5.3	D	D	F		D	D												F						HR 21	75% loss in thrust, 1 CMC is non-operational and no commands from 2 other CMCs
	Prop Pitch Controller (R)	5.4	D	D	F																	F				HR 21	Loss of Prop/Motor Speed control identifiable from tachometer. Some amount of loss of thrust which may lead to Control Room Query/RTB
FOBE (EQP-A)	None	6.0	D	D	D		D										F								D	HR 37	50% loss in thrust, no commands from 2 CMCs
	Torque Encoder (R)	6.1	D	D	D		D	D									F			F					D	HR 21	75% loss in thrust, no commands from 3 CMCs
	FOBE (EQP-B)	6.2	D	D	D	D	D	D									F	F							D	HR 21	100% loss in thrust, no commands from 4 CMCs
	Prop Pitch Controller (L)	6.3	D	D	D		D										F				F				D	HR 21	Loss of Prop/Motor Speed control identifiable from tachometer. Some amount of loss of thrust which may lead to Control Room Query/RTB
Torque Encoder (R)	None	7.0		D			D	D												F						HR 37	50% loss in thrust, no commands from 2 CMCs
	Torque Encoder (L)	7.1	D	D	D	D	D	D											F	F						HR 21	100% loss in thrust, no commands from 4 CMCs
	Prop Pitch Controller (L)	7.2	D	D			D	D												F	F					HR 21	100% loss in thrust, no prop pitch control on 1 motor
Prop Pitch Controller (L)	None	8.0	D																		F					HR 37	Loss of Prop/Motor Speed control identifiable from tachometer. Some amount of loss of thrust which may lead to Control Room Query/RTB
	Prop Pitch Controller (R)	8.1	D	D																	F	F				HR 21	Loss of Prop/Motor Speed control identifiable from tachometer. Some amount of loss of thrust which may lead to Control Room Query/RTB

Operational: Component operates as expected

D Degraded: Component operates, but with degraded performance

I Inoperable: Component not functioning as expected caused by other component failures

F Failed: Component that is the primary or secondary source of failure for the scenario

Fig. 5 Failure modes and effects testing matrix.

Once V&V and FMET testing were completed, the team would be confident that the airplane would operate as expected. The X-57 Maxwell would have been prepared to enter into combined systems and taxi testing prior to first flight.

III. Cruise Motor Controller Software Testing

The CMC outer-loop software was developed by the NASA CMC software team to interface with the FPGA produced by QDESys controlling the cruise motors on the X-57 Maxwell airplane, This section addresses the build-up approach to the V&V of the CMC software, the development of the ground support equipment (GSE) and software tools used during testing, the formulation and usage of the Systems Integration Laboratory (SIL) for software evaluation, and any obstacles encountered during on-aircraft software testing.

A. Build-Up Approach

In the beginning of the CMC software development efforts, several weeks were spent defining the software requirements with the stakeholders for the BM2 CMC, the predecessor to the redesigned XM3 CMC. There were two requirement documents developed, one to define the project-level functional software requirements and the other to decompose the high-level requirements from the first document. These derived requirements were held at the software development level to augment - not replace - the project-level functional software requirements.

These CMC software requirements, along with the knowledge captured from the early lab checkouts of the software, were used to generate the test points. The test points were divided into multiple test procedures and several dry runs were performed to ensure proper operations of the procedures prior to formal V&V. This approach provided the ability to sort through the logistics required to carry out the procedures, correct or expand test steps, ensure required data was captured, and identify any gaps in testing. After the test procedures were finalized, formal V&V was conducted in the lab to verify that the software, specifically the algorithms and safety features, operated as intended in a low-power unloaded-motor configuration. This V&V gave confidence that the software was ready and could be safely used in the high-power, loaded-motor configuration of the airplane. During on-aircraft software testing, more problems were found that had to be addressed in order to complete formal testing. The software was updated to correct the problems and formal testing was repeated in the lab using the new software. This version of software was then loaded onto the airplane and the remaining on-aircraft software V&V procedures were completed. As part of the formal V&V, an external vendor was also brought in to perform modified condition/decision coverage (MC/DC) testing on the software. The build-up approach that was followed for the BM2 software is detailed in Fig. 6.

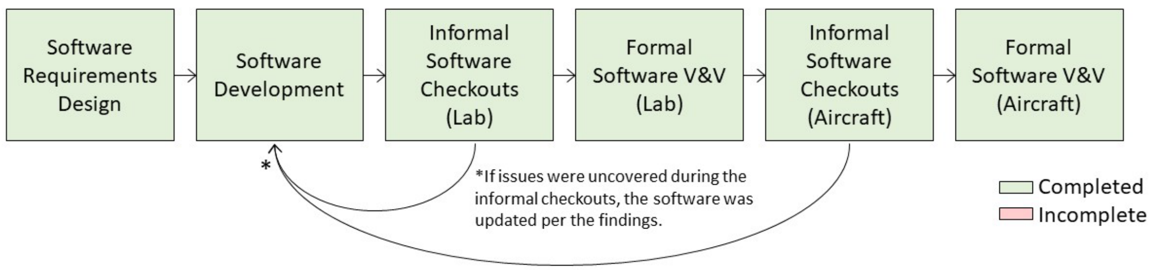

Fig. 6 The BM2 software build-up approach.

During development of the XM3 software, a build-up approach, similar to the process used for the BM2s, was followed. Several hardware and FPGA firmware differences between the BM2s and XM3s drove changes in requirements, designs, and tests. The requirements documents were reworked to incorporate the added XM3 requirements and lessons learned from the BM2s. The test plan was updated to include several additional test points based on the hardware and requirement modifications. The BM2 software was modified to support the XM3 build with an updated interface to support the newer FPGA firmware, several additional functions to support the new algorithms, supplemental safety features, and more robust CMC operations. The XM3 software then underwent several checkouts in the lab to verify the code changes worked correctly; the team returned to software development as needed to address any problems.

Once the informal XM3 software checkouts were completed in the lab, a software evaluation was conducted on the airplane, which resulted in additional changes to the software that required regression testing. Several iterations of this process were performed, specifically evaluating the software on the airplane, implementing the desired software changes, and performing regression testing in the lab prior to returning to the airplane, then repeating the process. Findings from these evaluations were used to update the test plan, which drove procedure modifications and the generation of any new modifications. After a dry run of the procedures and required changes were made, a final candidate baseline release of the CMC software was created and tested using the formal lab V&V procedures. Due to project closeout, this candidate release could not be transitioned to the airplane to compete the final on-aircraft formal V&V testing. The build-up approach that was followed for the XM3 software is detailed in Fig. 7.

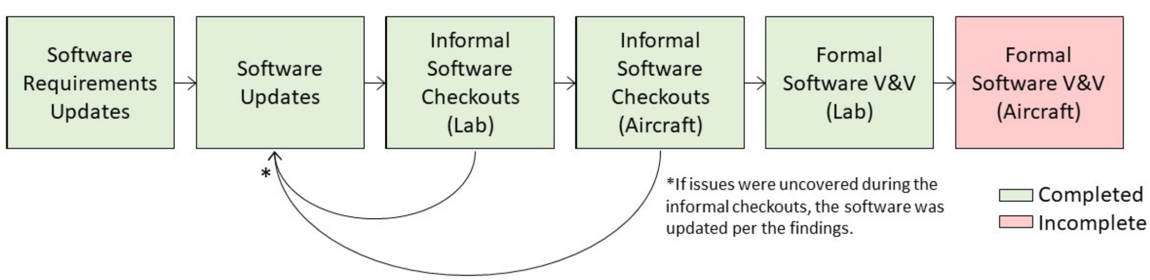

Fig. 7 The XM3 software build-up approach.

B. Electrical Ground Support Equipment and Software Tools

As the NASA CMC software development progressed, the necessity for a diverse set of tools to operate, monitor, and maintain the CMC arose. The cruise motor controller maintenance software (CMCMS), shown in Fig. 8, was developed early on to perform several basic maintenance operations for the software via Ethernet. The supported maintenance functions included loading the CMC software boot file into the flash memory of the CMC, assignment of the CMC node to memory for addressing purposes, downloading CMC logfiles, and calibration (zeroing) of the phase and bus currents and voltages. Additionally, the CMCMS could be used in the lab to monitor the CMC log messages in real time for debugging, with the condition that the CMC software was compiled in debug mode. Over multiple iterations, several additional tools were also developed based on the requirements and usage needs for testing in the lab and on the airplane, leading to the development of PRICKS, THORN, BRIAR, and SPINE, collectively called the Spiky graphical user interfaces (GUIs).

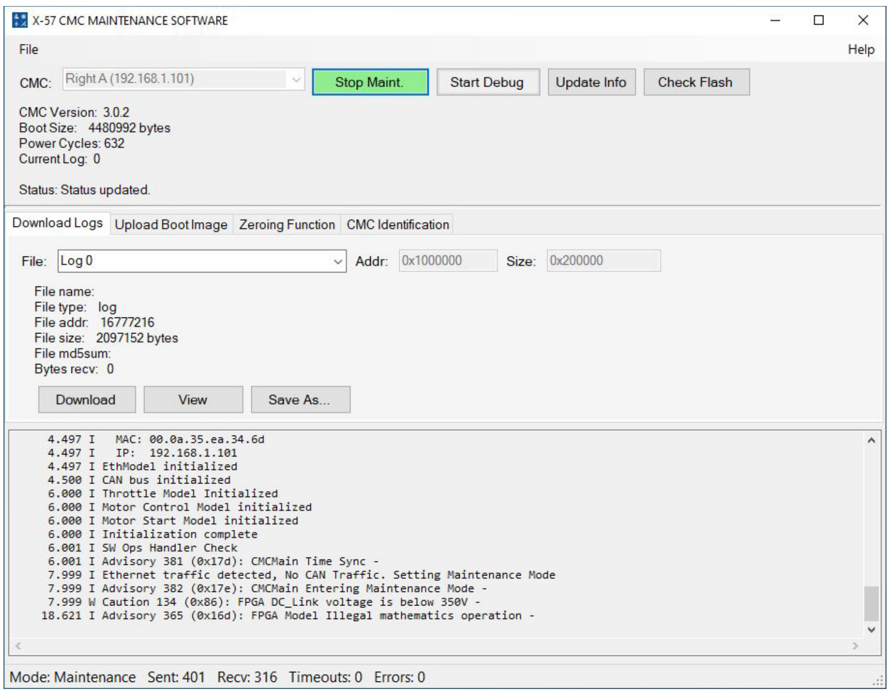

Fig. 8 The CMCMS GUI.

Prototypes of the Spiky GUIs were first built and evaluated with a development board acting as the CMC. In an iterative fashion, feedback and new requirements were gathered from the development board evaluations and implemented accordingly to improve the robustness of the software tools prior to use with the actual hardware. After testing with the actual CMCs, any necessary changes were made to the software tools, and V&V was performed, which certified the tools for use during any formal testing activities.

The PRICKS, the first of the Spiky GUIs, was used for monitoring only and displayed data from all four CMCs, the left and right torque levers, and the left and right CMs. The THORN, the second of the Spiky GUIs, was developed for the sole purpose of sending torque commands. This tool provided the ability to precisely control the encoder count values, which was a necessity for testing of the torque control logic in the CMC software. The THORN could also be used when the torque levers were unavailable, such as in the lab or on the airplane if the torque levers were removed. The THORN, however, could only be used for either the left or right torque lever at one time but not for both. The BRIAR was also developed to monitor data and control torque for two CMCs controlling a single motor, which was particularly useful in the lab environment with a single unloaded motor. This program inherited code from both PRICKS and THORN, as shown in Fig. 9, but narrowed down the data monitoring and torque control to only one wing instead of both wings.

Fig. 9 The BRIAR GUI.

The PRICKS, THORN, and BRIAR were developed for real-time operations, so timing was an important factor. As a result, the decision was made that these three GUIs would not have the ability to archive data to prevent any potential time delays during aircraft operations. Instead, SPINE was developed to reliably archive large datasets over long test runs without crashing. The SPINE reused sections of code from the PRICKS software to receive and read CAN messages and served as a very robust and accessible method of data collection throughout the rest of the project lifecycle.

This entire suite of GSE tools was developed in C++ programming language for better performance and robustness during real-time operations. The Spiky GUIs also took advantage of the Qt cross-platform framework to build GUI components and the Total Phase (Total Phase Inc., Silicon Valley, California) Komodo “Komodo (open-source software, Silicon Valley, California)” software application programming interface (API) for CAN communication. The rapid development of these tools to support a variety of test activities was made possible by the implementation of strong modular programming, good coding practices, up-to-date documentation, and easily maintainable and reusable code.

C. Systems Integration Laboratory Testing

The Systems Integration Laboratory (SIL), depicted in Fig. 10, was first built to include an unloaded motor and a single CMC. At the time, the only available hardware was an older preproduction version of the cruise motor and a dismantled CMC that needed to be reassembled because on-aircraft assembly and testing were taking place in conjunction and took priority of existing resources. Even with these impediments, the SIL served as a useful tool to evaluate and improve the software, as well as work through several bugs, because it provided the ability to run the software on a closely representative target platform without pulling resources from other high-priority tasks. Because the SIL itself is a small laboratory setting, it did have some additional safety restrictions, such as a lower-allowed motor speed limit compared to the airplane. Several constants in the flight software also needed to be modified to operate an unloaded motor. Specifically, several of the motor constants and the torque map had to be adjusted for the low-power lab environment, which resulted in a modified unloaded motor version of the flight software build (henceforth referred to as “SIL software”). Nevertheless, enough of the logic could be executed in the SIL to give confidence that the software was operating as intended.

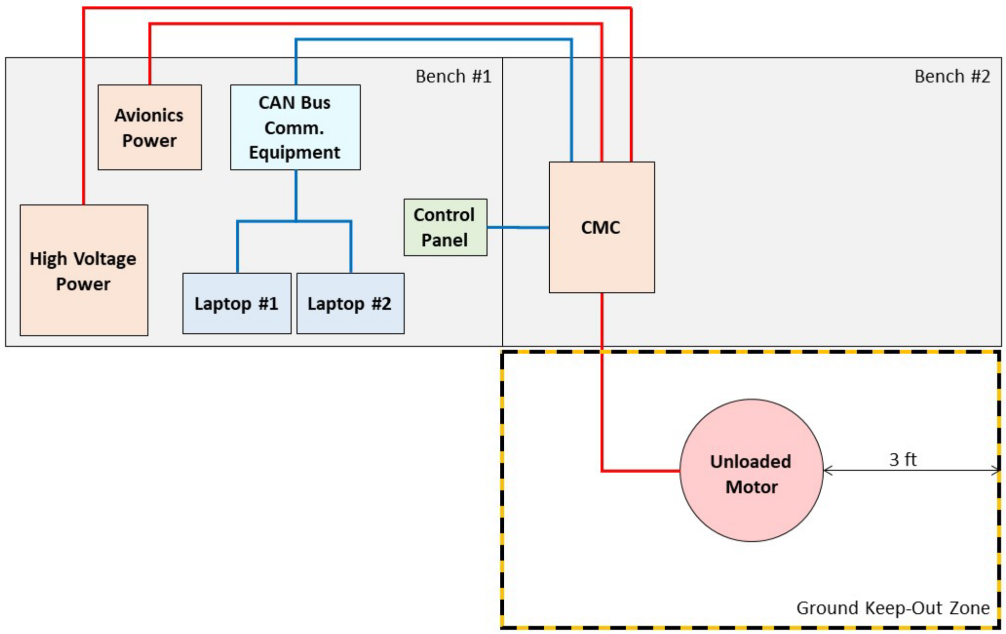

Fig. 10 Systems Integrations Laboratory.

During the early software development stages, prior to any formal testing, the team repeatedly exercised the code in the SIL to both uncover and eliminate any software bugs. In fact, one of the initial informal checkouts in the lab, shortly after the high-voltage board was installed in the CMC and before the motor was connected, revealed a problem with the fault handling implementation. The requirement stated that the CMC shall enter a safe state when a fault is detected. In this case, the CMC should set an overvoltage fault and transition from Operations Mode to Wait Mode when the traction voltage exceeds the limit of 600 V. Once the voltage drops back within the normal range, the fault should clear, and the expectation is that the CMC remains in Wait Mode. When the voltage dropped below the limit, however, and the fault cleared during this specific test, the CMC log messages displayed by the CMCMS in real time showed that the CMC had not remained in Wait Mode and was outputting advisories indicating a transition from Wait Mode to Motor Start Mode. The CMC immediately returning to the motor start sequence once the fault was cleared meant that the intent of the requirement was not met. This gap in the logic was noted and the fix was quickly implemented to ensure that the relevant requirement was met. Fortunately, this problem was caught prior to connecting the actual motor, emphasizing the importance of a build-up approach when testing software.

The installation of the unloaded motor with the BM2 CMC in the SIL greatly expanded the testing capabilities of the lab. This addition provided the team with the ability to evaluate the motor start sequence and the motor operations logic, including the speed protection algorithms and the torque rate limiting. Several minor bugs and improvements were discovered and fixed during these inaugural motor spins, but one of the biggest modifications had to do with the MOSFET switching frequency schedule, which included both pulse-width modulation (PWM) and recursive pulse-frequency modulation (RPFM) mode. The initial design scheduled PWM mode in the lower region of the speed envelope and RPFM mode in the upper region. During early speed envelope expansion tests in the lab, some unexpected motor behavior was noted upon transition to RPFM mode. As the torque command was slowly increased, the motor speed appeared to increase in a consistent gradual fashion, until the transition from PWM to RPFM mode. At this point, the motor began to speed up rapidly and became less responsive to reductions in torque command. The torque command had to be dropped down to idle to prevent motor runaway. Further testing and data analysis confirmed that this unstable behavior was specifically linked to RPFM mode, so the decision was made to only use PWM mode. Once the change was implemented in the software, this runaway condition was no longer observed, and the motor operated in a more controlled manner.

After extensive software development and testing in the lab, the team corrected any discernible bugs in the code and baselined the BM2 CMC flight software and SIL software in preparation for formal testing. The lab software test points were divided into six test procedures (Appendix A), which were all successfully executed with the SIL software. All of the procedures, except for those requiring the unloaded motor to be connected, were then repeated using the flight software. The combination of testing on the SIL software and the flight software gave confidence that the code logic was functioning as designed and that the flight software could be safely operated on the airplane. The flight software was subsequently loaded onto the X-57 Maxwell to perform the remaining procedures and complete formal software testing (Section III, D).

Once on-aircraft software testing of the BM2 CMC flight software concluded, the software team returned to the lab to develop the updated software for the redesigned CMC hardware, known as the XM3 CMC. There were, however, challenges involved with the software modifications for the new hardware, some of which could be managed in the SIL environment. This section will delve into the more pertinent problems that were addressed in the SIL.

One major concern that was not accounted for during the BM2 test cycle but was flagged during the XM3 redesign was the unkeyed connectors. The decision was made to keep the connectors unkeyed, but this decision remained a significant concern because the connectors that were used for CMC addressing determined the side on which the CMC is installed. Should the CMC be physically located on the left wing with connectors mistakenly configured for the right, the software will read the data from the right torque lever instead of the left torque lever. The System Safety Working Group (SSWG) determined that safety interlocks were required to prevent this unexpected operation, and a new interlock implementation requirement was added at the software level. The new logic was implemented in Maintenance Mode, with the CMCMS used to assign a node to the CMC and the CMC then saving the assigned node to memory. During initialization, the software would compare the assigned node from memory against the addressing connectors and set a failure in the event of a mismatch. Keeping with the build-up approach, this new implementation was evaluated in the lab with the CMC using all possible combinations of memory node assignments and physical address pins prior to updating the relevant procedures in preparation for formal testing.

Another problem that was missed during the initial software design was uncovered using the Spiky GUIs. The usage of the Spiky GUIs during lab and aircraft testing offered many benefits, but the ease of data and error monitoring specifically led to the discovery of a bug in the CMC software. In PRICKS or BRIAR, the error manager functions by extracting the relevant data from the corresponding CAN message, building a chronological stack of the error codes detected, then providing their accompanying information. The chronology is based on the time stamp from the error manager in the CMC software with the oldest error at the bottom of the stack and the newest error at the top. Through several tests, the team noticed that the cleared errors always landed at the bottom of the stack instead of the top. This behavior was initially thought to be a PRICKS or BRIAR bug but eventually it was found to be a CMC bug. In the CMC software, whenever errors were cleared, the timestamp was reset to 0 instead of the current timestamp. This problem was swiftly corrected and evaluated successfully in the lab. Although this discrepancy could have been discovered in a different way using the raw CAN data, PRICKS or BRIAR offered real-time monitoring of the data, making it significantly quicker and easier to identify and subsequently fix the bug.

Once the updates for the newer XM3 CMC software were complete, the software was baselined. By this time, the existing procedures had been modified and restructured to include any new requirements, removals of deleted test points, and improvements to test efficiency based on knowledge gained throughout the development cycle (note Appendix A for additional information). The resulting six procedures were successfully executed for the XM3 CMC software, marking the completion of lab testing. At this point, the software was ready to be loaded on the airplane to finish the remaining motor operations procedures. Due to motor safety concerns, these tests were never performed, but the challenges experienced throughout the on-aircraft software test campaign will be detailed in the following section.

D. Aircraft Operations and Testing

Integration of the CMC flight software with the airplane disclosed several new challenges, as was expected due to the identified constraints of the SIL. Many of the obstacles encountered on the airplane were not realized in the low-power SIL configuration and only manifested with a loaded motor and two CMCs, or specifically with the integrated airplane flight-systems The late discovery of these complications during airplane testing significantly slowed down operations and also led to the use of the airplane as not just a test platform, but rather a testbed for troubleshooting.

The first discrepancy was discovered soon after applying power to the airplane. Using the Spiky GUIs, the team determined that the arm switch logic, used to start and stop the motor, was reversed. The software, by design, recognized that the switch was in the armed position upon power on and responded appropriately by entering a faulted state. The fault logic subsequently enabled the fault lights in the cockpit, providing the pilot with a visual cue to a problem. The root cause of the discrepancy was eventually traced to the interface between the physical arm switch and the FPGA firmware being used. The initial determination that an open switch would correspond to a disarmed state and a closed switch would correspond to an armed state was incorrect. The logic was swiftly corrected to continue with high-voltage testing (HVT) on the airplane, but this testing demonstrated the first of several problems that remained hidden until integration with the airplane flight systems.

After resolving the initial integration problems, the loaded motor was able to spin on the airplane for the first time by using the NASA-developed CMC software, marking a huge achievement. Prior to execution of the on-aircraft software test procedures, the propellers on the motors had to be balanced. This process required spinning up the motors to approximately 1,700 RPM. During each attempt to reach this desired motor speed, the flight software triggered an overcurrent fault on the ramp-up. Similar behavior was not witnessed in the SIL, with the caveat that the SIL was a low-power environment with a procedurally enforced speed limit of 1,500 RPM. As a result, troubleshooting of this problem had to be conducted on the only power-representative system available- the airplane. Through data analysis, a correlation was ultimately discovered between the overcurrent faults, the motor speed, and the PWM frequency that was driving the switching of the MOSFETs in the CMC. The software would consistently fault when commanding higher currents and trying to reach higher speeds with lower PWM switching frequencies. As the switching frequencies were increased during troubleshooting, the motor was able to achieve faster speeds before the software would fault. Eventually, a frequency was reached at which the faults no longer occurred; however, as the PWM frequencies were increased, another problem emerged. Since the frequencies corresponded directly to the rate at which the MOSFET gates switched, the higher switching frequencies were found to cause the MOSFETs to overheat rapidly. Overheating of the MOSFETs significantly slowed down ground testing because any motor operations had to be stopped frequently for cooling. As a result, various PWM frequency settings were evaluated, ranging from a constant frequency to a schedule of frequencies dependent on specific test parameters. With a constant PWM frequency, the MOSFETs quickly overheated at high commanded current values, as shown in Fig. 11. A prototype PWM frequency schedule, depicted in Fig. 12, was devised to set higher frequencies at higher speeds and lower frequencies at lower speeds. This frequency schedule resolved both problems, allowing the motors to spin through the entire speed envelope without the CMCs faulting at higher commanded currents and faster speeds or overheating at slower speeds (Fig. 13). The prototype schedule was optimized further throughout the course of the BM2 and XM3 CMC test cycles to improve motor efficiency, prevent the CMCs from overheating, and provide the ability for the motors to spin through the full-speed range without faulting.

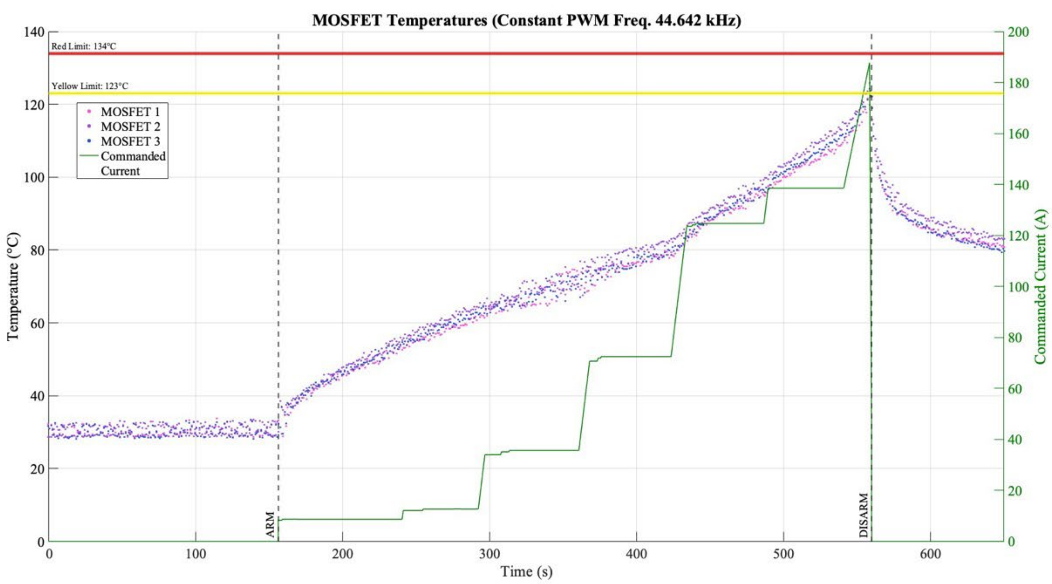

Fig. 11 The MOSFET temperatures with constant PWM frequency.

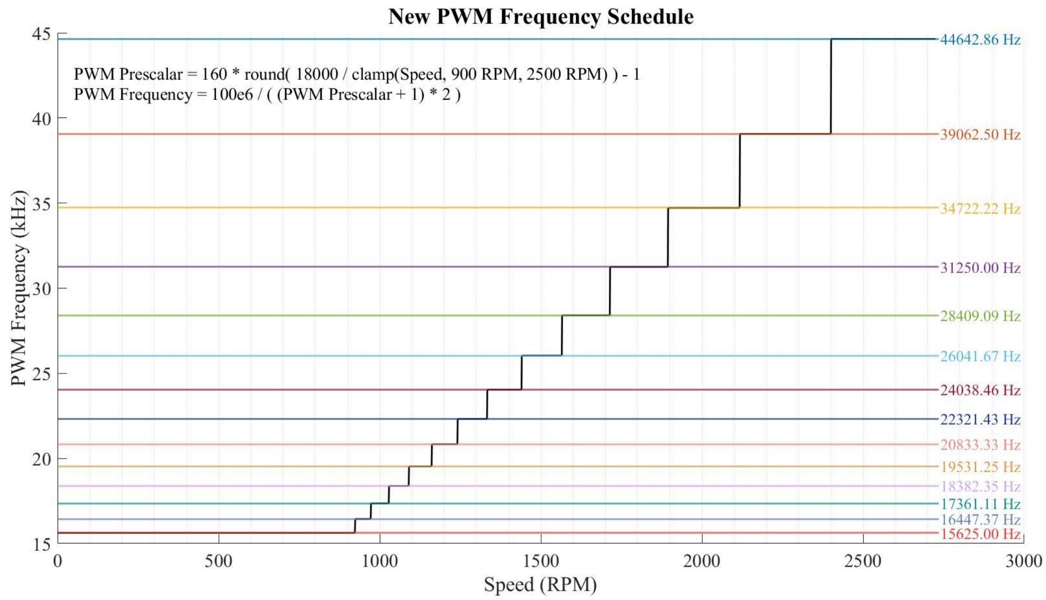

Fig. 12 Prototype PWM frequency schedule.

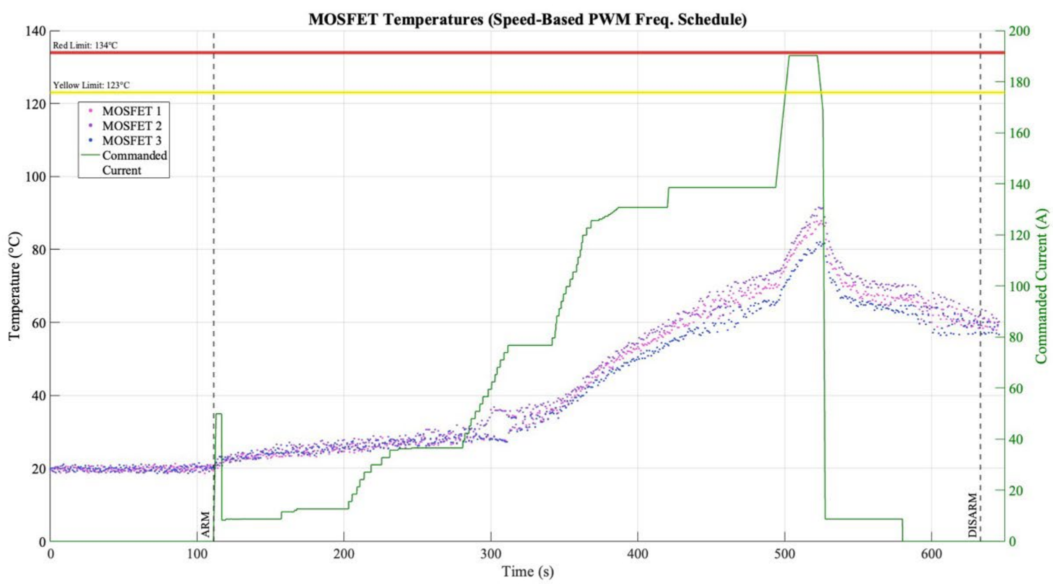

Fig. 13 The MOSFET temperatures with speed based PWM frequency schedule.

During data analysis for the frequency scheduling problem, the team discovered that the software was incorrectly estimating the motor speed when the controller was in a disarmed state. As shown in Fig. 14, the estimated speed produced by the disarmed CMC remained at 0 RPM and did not match the estimated speed produced by the armed CMC. The software uses the motor speed estimate produced by the FPGA when in the armed state, but the FPGA version that was available at the time was unable to estimate motor speed with the controller disarmed. As a result, the team implemented a back electromotive force (BEMF) speed computation algorithm in the software, specifically, for the disarmed state. Demonstration of the functionality of this algorithm prior to airplane testing, however, was not possible due to the lack of dual CMC capabilities in the SIL. With the limited amount of hardware, only one CMC was available for lab use. Additionally, there was no feasible way to systematically spin the unloaded motor in the lab without arming the single CMC, so any evaluation of the algorithm had to take place on the airplane. After much analysis, the problem was ultimately traced to incorrect documentation regarding the BEMF speed estimation equation. Once the single line of code was fixed, the software was able to correctly estimate the speed using the BEMF algorithm, and the estimated speed produced by the disarmed CMC closely matched that of the armed CMC, as shown in Fig. 15. This fix was critical because dual CMC operations would not be possible without the speed estimation equations working properly. Shortly after these problems were resolved, specifically the arm switch logic, aircraft wiring, frequency scheduling, and speed estimation algorithm, the first dual CMC operations were successfully conducted on the airplane, marking another major success for the team.

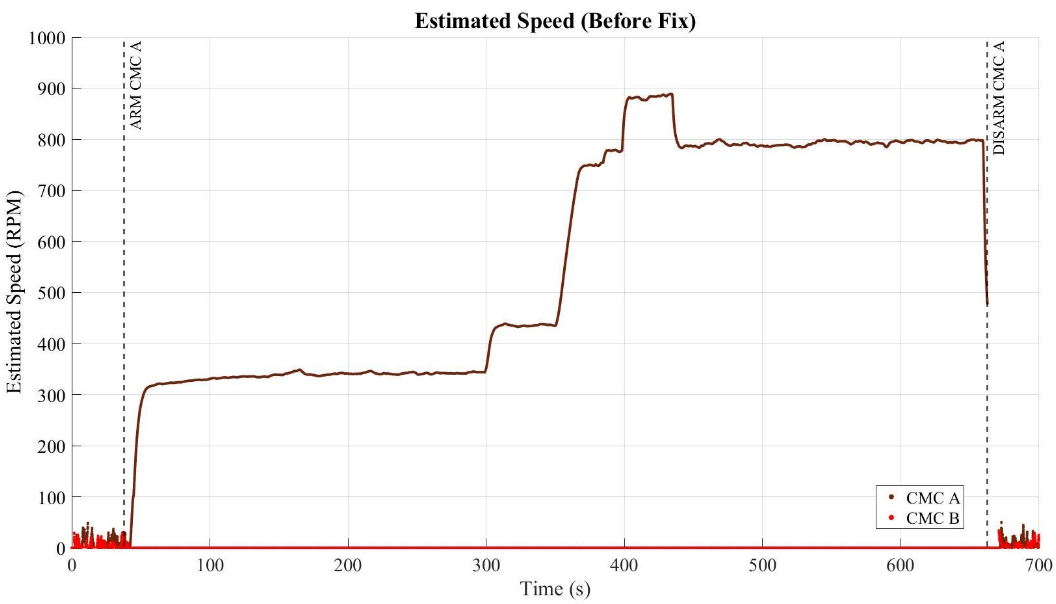

Fig. 14 Estimated speed prior to software fix.

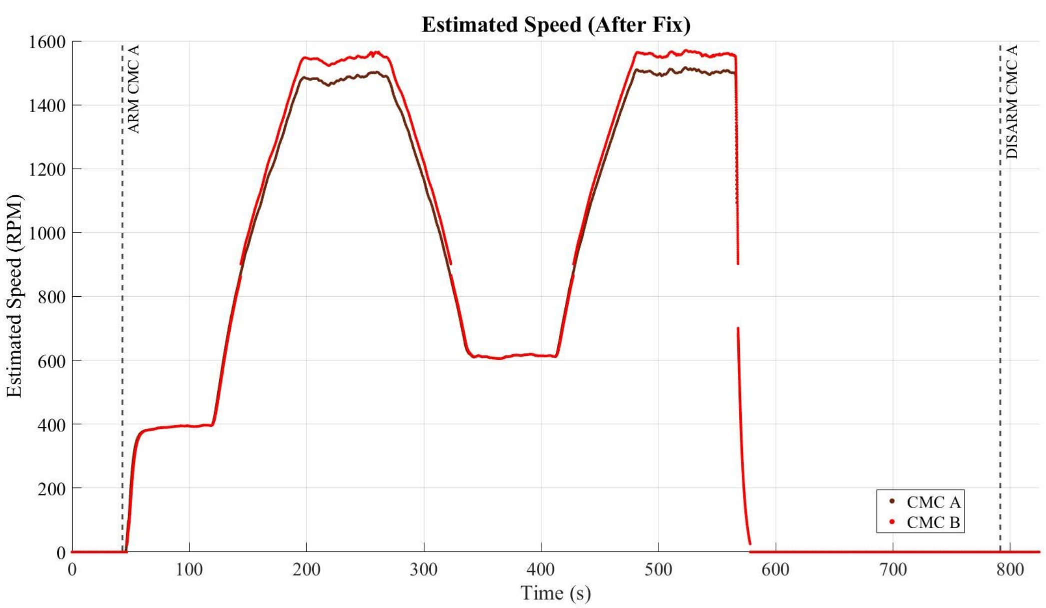

Fig. 15 Estimated speed after software fix.

With these critical problems resolved, formal software testing could finally take place. The on-aircraft software test points were divided between three test procedures covering various motor start and operations scenarios (Appendix A). All three test procedures were successfully executed, signifying the completion of formal software testing for the BM2 CMC software. Subsequently, the software team pivoted focus towards code development for the newly designed XM3 CMCs that had just started production. The XM3 CMC software was intended to be an updated version of the BM2 CMC software and included a newer version of the FPGA, bug fixes to the discrepancy reports generated during formal testing, as well as any necessary performance improvements based on the results of the BM2 CMC test cycle. The modifications required for the newer FPGA and the discrepancy reports could be handled in the SIL, but any necessary changes to achieve the performance improvements required a testbed that accurately represented the on-aircraft power consumption levels. At this stage of the project, a dynamometer capable of acting as a loaded motor SIL had been developed but was located off-site at the contractor facility, making it less accessible. This meant that the airplane was still the most practical structure that fit the necessary criteria, so the airplane continued to serve as one of the primary troubleshooting platforms.

During the BM2 CMC test cycle, the frequency scheduling appeared to solve the faulting issue at higher motor speeds, but the solution was not as effective at lower traction voltages. At lower traction voltages and higher motor speeds, there were test runs where an overcurrent fault on one CMC would instantly cause a second CMC, which was either connected to the same motor or on the same traction bus line, to fault. With each motor being powered by two CMCs, a single CMC provides a portion of the amperage to the motor; therefore, the motor will lose power if one or both CMCs on the corresponding side fault. The primary concern was that one faulted CMC could potentially take out up to two other CMCs and significantly reduce power to the motors. Analysis of aircraft data pointed to a connection between the overcurrent faults and a specific modulation index. Modulation index is defined as a proportional relationship between the instantaneous motor speed and the traction voltage. This occurrence persisted with the XM3s, but the faults took place at a higher modulation index. Since there was no conclusive solution to this phenomenon, a provisional measure called the Modulation Index Rate Limiting (MERLIN) logic was developed to prevent the CMCs from faulting in these conditions. The MERLIN logic was designed as a proportional integral derivative controller that would limit the current commanded by a CMC (and consequently, the motor speed) when the modulation index crossed a set limit. Although this would reduce motor speed in a low-traction voltage scenario, the MERLIN logic would keep the controllers operating and prevent total loss of power from a CMC.

Several other improvements were also implemented to the software, including the adjustment of several tuning constants to improve motor efficiency, updates to the torque map to achieve the desired power output, and other minor modifications. Once on-aircraft software troubleshooting was completed and the XM3 CMC software build was released, formal V&V testing was performed in the SIL, leaving three on-aircraft procedures remaining to conclude all software testing. Although these three procedures were written using the airplane as the test platform, the intent of the test points could be met with a comparable flight-representative platform. Without an iron bird, however, or similarly representative testbed readily available, software testing required the use of the airplane. Once aircraft testing was halted due to cruise motor safety concerns, software testing came to a halt as well, and the final three procedures remained incomplete.

IV. Systems Testing

While the BM2 CMC software was being formally tested in the lab, the team was also conducting various tests such as low-voltage system checkouts and propellor balancing on the airplane to ensure that it would be ready to use for the remainder of the CMC software V&V. Once the CMC software completed formal testing on the airplane, the Post Shipment Functional Test campaign began. Since the plane was delivered from the subcontractor and reassembled at NASA, testing was required to ensure that the systems endured the travel environment with no damage and were integrated correctly, but the batteries were still being developed and tested at EPS. The project procured a Gustav Klein Infeed Test System, referred to as the battery support system (BSS), with a two-channel configuration that could act as a DC power supply, load bank, and battery simulator. These tests, using the BSS provided more information about the operability of the airplane prior to the integration of the battery system. The completion of this test campaign not only provided insight into items that worked as expected but also revealed discrepancies that would need to be addressed. After this test campaign, the team conducted investigations into drawings versus as-builts on the airplane and worked through problems that needed to be resolved to baseline a configuration that could be used moving forward. The high-level approach that was followed is detailed in Fig. 16.

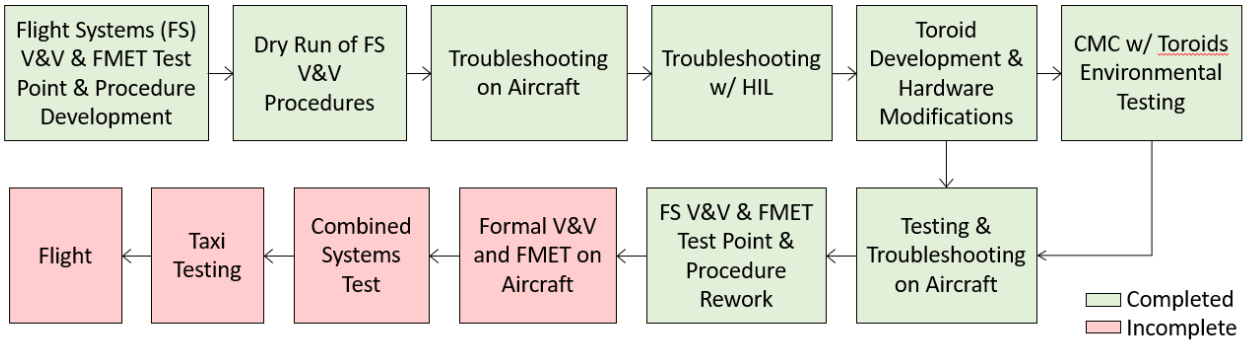

Fig. 16 Flight systems build-up approach.

A. Build-Up Approach

Once a baseline of the airplane operability was known, the next step was to integrate the flight battery system into the airplane. Although the BM2 CMCs on the airplane were not the flight units, it was important to test the closely representative traction system as soon as possible to ensure that systems would operate as expected or allow time to troubleshoot if they did not. Since this would be the first time the batteries were used with the integrated system, a build-up approach was planned to reduce risk by first testing the low- and high-voltage portions, respectively, and ultimately the spinning of the motors.

To perform any hazardous testing, which was defined as testing with any voltage over 67.2 V, a comprehensive procedure review by the SMEs was required. As a result, any testing with the batteries or any on-aircraft testing where motors or high voltage were used was considered hazardous. Luckily, prior to receiving the battery system components, the system-level V&V procedures were written to allow for testing as soon as the airplane was ready. Instead of writing new procedures, the team decided that the V&V procedures would be conducted as dry runs to test components on the airplane when possible. Performing the procedures as dry runs gave insight into how the systems were performing, shed light on any problems with the procedures themselves, and provided the team with a better understanding of the inner workings of the airplane. These dry runs were crucial since many team members had not joined until after the development and integration of systems on the airplane. Furthermore, if a testing method did not meet the intent of a test point or if discrepancies with procedures were found, then conducting these dry runs early would allow time for the procedures to be changed and proved to be necessary for many of the V&V procedures.

B. Aircraft Operations and Testing

Significant challenges were uncovered during operational ground testing of the X-57 Maxwell when dry runs of the V&V test procedures with the battery system were first attempted. These tests were the first time the flight batteries were integrated with the airplane. The team decided that the batteries would not be physically installed on the airplane for these tests because the parallel installation of the batteries in the airplane would make it hard to troubleshoot any battery anomalies should any wiring or single modules came into question. This configuration would also reduce risk to the entire airframe since it was the first time the battery system would be operated outside of the manufacturing facility. Rather than being installed in the airplane, the two battery packs (2 BCMs, 2 LOTOs, and 16 modules) were placed on a tow cart by the side of the airplane to limit the length of wiring as much as possible, as shown in Fig. 17. Placing the battery system on the tow cart would also allow the system to be moved outdoors quickly in case of emergency.

Fig. 17 Aircraft testing setup with batteries on tow cart.

In this configuration, the plan was to spin the motors using battery power for the first time. To do this, the batteries had to be charged for the first time at AFRC. This operation allowed the team to better understand the battery system and the limitations that the design presented during charging. These takeaways will be discussed more in Section V.

After charging the battery packs, a dry run of one of the V&V procedures was performed to ensure the avionics (low-power) portion of the battery system was operating correctly. This dry run went well, so the system was considered fit to attempt the first motor spin off of battery power by dry running another V&V procedure. This V&V procedure tested the isolation detection unit (IDU) component of the BCM (discussed further in Section V, A) and required a test box to be connected at the BM2 CMC. The first time the CMC was armed with batteries, there were a few problems encountered. One main problem was that the health and status information from the batteries, including cell temperatures, pack voltage, pack current, and others, were no longer transmitted or displayed at the monitoring station until the CMC was disarmed. During battery operations, it is critical to have insight into battery data to make sure the batteries are operating correctly and within limits. Without this critical data, an event, such as a thermal runaway, could occur without the team having time to respond. Having this data made it clear that not fully integrating the batteries onto the airplane for initial testing was an excellent decision because troubleshooting this problem and determining the root cause of the loss of data was much easier when performed off of the airplane in a less configuration-controlled and more physically accessible environment.

The test box for the IDU had been connected during these tests, meaning the system was not in a normal flight-like configuration. As a result, the team decided to remove the test box to determine whether it was causing some of the problems that were encountered. By removing the test box, the dry run would be diverging from what the procedure had defined, so red lines were required. Red lines are not uncommon and are required to ensure that any deviations from the procedure are documented, ensuring that all artifacts accurately represent the events that occurred and can be referenced correctly in the future - which is especially useful if anomalies occur. Red lines, however, can be time consuming and create more confusion if not carried out correctly or if the original intent of the procedure is altered. Since a procedure was always needed when testing on the airplane, the team took to red-lining V&V procedures to accomplish the necessary tasks, even if that meant red-lining out the majority of a procedure. When red lines are created in the hazardous portion of a procedure, which in the case of X-57 Maxwell is the majority of the procedures, there are three sign offs needed for every red line. Red-lining procedures for all troubleshooting events caused multiple schedule delays, but it was deemed the most efficient way for the project to continue testing without developing entirely new procedures that still could require red lines based on findings during testing. To reduce the number of step-by-step procedures, an iron bird would have been useful during these troubleshooting activities. Although it would have still been considered high-voltage testing, there would have been less risk, since non-flight hardware would have been in use, meaning less stringent control and more real-time troubleshooting modifications could have been tested.

Once the red lines were made and the procedure was signed off, the test box was removed to determine whether it was the culprit. Although removing the test box did not fix the problem, further attempts to arm the CMC uncovered more complications that would need to be addressed before formal V&V testing and safe flight could occur. One of the major problems was that the high-voltage converter in the BCM was not operating correctly at all times. Usually when the airplane operator flipped on the Main Batt A or Main Batt B switch, a fan turned on in the respective BCM and a display, specifically the Accuenergy (Accuenergy Canada Inc., Toronto Canada) traction meters display, became active with readings of the respective battery pack voltage and current. This phenomenon occurred sporadically with both BCMs at different times, so only the operational BCM and corresponding battery back were used for several of the tests. Uncovering this problem early allowed time for modifications to be made and reduced the risk of having to perform formal V&V testing multiple times. There was also a limited amount of BM2 CMCs available at the airplane, so testing became more and more limited. It was vital to determine the root cause of the battery data drops and testing on the airplane was the only available option at the time. This is another case in which an iron bird and plenty of spare hardware would have been useful in reducing the time to work through troubleshooting activities, as well as reducing stress surrounding testing with flight hardware.

Testing on the airplane was very difficult and time consuming because a strict set of operational processes and safety procedures had to be followed. These protocols are necessary and were designed to keep aircraft pilots and support personnel safe during hazardous test and flight operations. In addition, there is a strict configuration management process to track all hardware and software changes made to airplanes managed by AFRC. These processes help ensure that aircraft are in a known and safe configuration for ground operations and flight. Although these processes are necessary and useful, they were intended to be used for established aircraft. The X-57 Maxwell was baselined upon delivery to AFRC, which meant the same protocol had to be followed, but the airplane was much further from being flight-ready than the project originally thought. It is important to keep track of configuration changes and testing completed so that artifacts can be referenced in the future, but following the rigorous protocol required for operational aircraft made low-risk troubleshooting and testing activities more challenging, slowed down progress, and required more personnel than was necessary to accomplish certain tasks. Taking all of this into account, a lot of time would have been saved if the airplane was baselined prior to conducting formal V&V versus when the airplane was delivered to AFRC. It would still be important to manage the configuration of a non-baselined aircraft to ensure that any differences in testing could be tracked to different configurations, but finding a less-stringent process for experimental aircraft would have made testing and troubleshooting activities faster and less challenging. In addition, having an iron bird could have cut down on required personnel and configuration management processes since non-flight hardware would be at risk and changes could be completed much faster when compared with the flight aircraft.

After many different troubleshooting configurations were tested and other problems were discovered on the airplane, the team determined that the battery data dropouts only occurred once the CMCs were armed, meaning the likely source of the problems was somewhere along the traction line, specifically at the CMCs or CM. Focusing on this segment of the airplane configuration would allow the team to focus specifically on the dropouts and isolate the problem faster. Once wiring problems were ruled out, it was decided that the timeliest way to troubleshoot the traction line alone would be to create a hardware-in-the-loop (HIL) setup with only the high-voltage components. Although the upfront time to get the setup approved and wiring built would be substantial, the setup would save an immeasurable amount of time compared to testing on the airplane and allow the team more freedom with troubleshooting efforts by limiting the amount of personnel and documentation required.

C. Hardware-In-The-Loop and Lab Testing

Although testing subsystems on a fully integrated platform is the most thorough and reliable way to verify and validate the subsystems, this process can be difficult, or even impossible, to achieve when obstacles arise during the on-aircraft testing and troubleshooting efforts. Testing in an off-aircraft HIL configuration provides an alternative and is more flexible environment to help narrow down the cause of any observed discrepancies and ensure correct operation of the subsystems prior to integration with the aircraft. This approach proved to be the best path forward to troubleshoot the loss of battery data during on-aircraft motor operations.

Since the loss of battery data appeared upon arming the CMC, testing was moved to an off-aircraft HIL setup that allowed for troubleshooting of the problem without putting the airplane at risk. This setup was necessary to isolate the problems in some of the subsystems, such as the BCMs and CMCs. This setup consisted of an unloaded motor, one CMC, a contactor pallet, a BCM, a battery pack, and the required wiring, switches, et cetera to operate the hardware in this configuration, as shown in Fig. 18. Safety meetings were held to determine that proper precautions were taken to operate in this way.

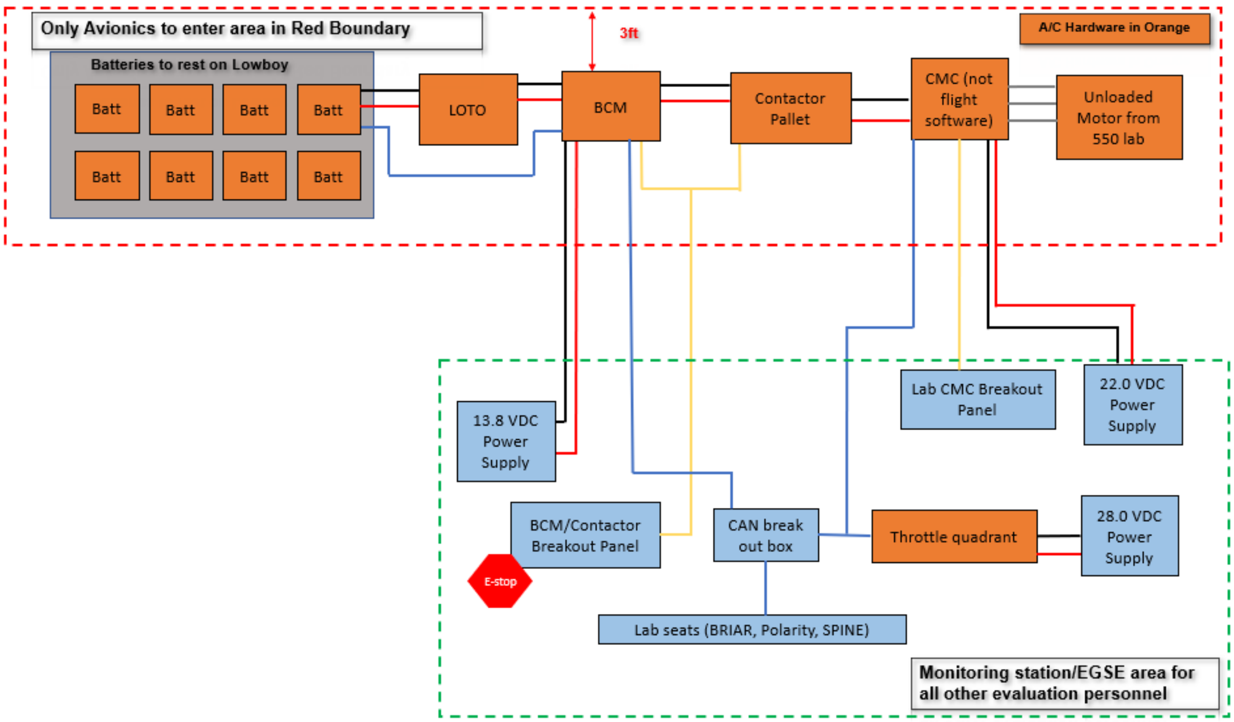

Fig. 18 The hardware-in-the-loop setup.

When the off-aircraft troubleshooting began, the XM3 CMCs were still in production, so there were only a limited number of operational units. Using an XM3 in this setup, compared to the BM2s that were used in the earlier aircraft troubleshooting, would provide a more flight-like configuration and demonstrate how the new XM3s operated with the batteries and a motor. During one of the troubleshooting efforts, an event occurred where the capacitors failed internal to the CMC; the cause was traced to a breakdown of the nonconductive thermal pad inside the CMC that occurred above approximately 100 VDC. This breakdown in the thermal pad caused the XM3s to fail a *hipot* test because some or all of the phase output and DC input surlok connections were no longer electrically isolated but were tied to the CMC chassis instead. As a result, the thermal pads in all XM3s had to be replaced. This discrepancy limited the amount of parallel work, such as environmental testing and software evaluations, that could be completed, because the team was down a CMC and all others had to be reworked. To limit schedule delays, the team allocated CMCs to different testing events as they were available, but it became difficult to track the testing that each CMC had completed. Although this discrepancy caused rework of all XM3s, uncovering this problem in the off-aircraft HIL configuration meant that problems were able to be resolved before flight; therefore, avoiding risk to the flight crew. It also helped expedite analysis of the XM3 CMC and other relevant components, limited the amount of hardware affected, and facilitated data analysis.

From this testing, the root cause of the loss of critical battery and systems data was found to be electromagnetic interference (EMI). To mitigate the effects of EMI in the HIL setup, Pi filters (discussed in detail in Subsection D) were ultimately introduced to the high-voltage traction lines between the contactor pallet and the CMC. Through testing different Pi filter configurations, the proper solution was found for the power profile of the HIL setup. More information about EMI and the solution that was developed can be found in Ref. [4].

In addition, other problems were discovered with the BCMs, CMCs, and battery modules through this HIL testing. With so many of the subsystems having problems, the decision was made to convert one of our spare BCMs and

CMCs from flight units to engineering units. This decision meant that the units were no longer being configuration-managed and allowed the team to conduct lab testing more freely on the units to isolate problems, implement redesigns, and retest to verify the effectiveness of the solutions. This approach provided the ability to evaluate and verify multiple solutions before they were implemented on airplane assets. Without this process, the team would not have been able to isolate or correct many of the problems that occurred with both the BCMs and CMCs.

Converting the spare BCM into an engineering unit helped uncover the reason for the fans not turning on when the Main Batt switches were activated. There was insufficient output current from the 28-VDC Vicor (Vicor Corporation, Andover, Massachusetts) power supply within the BCM because the original design did not consider the fan that was added into the BCM to keep components cool. To mitigate this problem, an additional DC/DC converter was added to the BCM to supply the necessary current to the fan. This design update was implemented on all of the BCMs to ensure they operated as optimally as possible. Finding a solution to this problem was only possible in off-aircraft operations but was only discovered through testing the integrated system. Understanding differences between what was possible on- and off-aircraft became essential to making progress toward flight.

D. Challenges Between On- and Off-Aircraft Testing

An off-aircraft configuration can be used to verify and validate the functionality of components without risking the entire aircraft, making it a valuable asset for systems integration. Unlike on-aircraft testing, however, off-aircraft testing simply cannot take everything into consideration because not all the hardware and components are in place. For example, during the early stages of EMI troubleshooting in the SIL with the unloaded motor, the team found that shielding on the cruise motor phase cables resulted in significantly reduced EMI coming from the cruise motor. The team took this finding and implemented the shielding onto the airplane cruise motors, only to find out later in the testing process that the shielding created a short path to the airplane chassis, resulting in increased EMI as opposed to the decreased EMI found in the SIL testing. The shielding was then removed from the airplane and the amount of EMI dropped.

From the HIL testing, the team determined that Pi filters (Fig. 19), consisting of capacitors and soft-core magnetic material inductors, needed to be added to the traction line to reduce the effects of EMI caused by the switching transients between the inverter and battery. Using the HIL setup to create the Pi filters was beneficial for many reasons, but the team had to keep the differences between this type of setup and the airplane in mind throughout the progression of testing. Since the unloaded motor was being used for testing in the HIL, the team knew that the size of the Pi filters, which were used to mitigate noise in this setup, would not be adequate for the airplane. The Pi filters were sized up to accomplish a similar noise mitigation on the airplane to accommodate the higher power environment. In addition to the Pi filters on each traction input to the CMCs, stand-alone soft-core magnetic inductors were used on all other copper interfaces with the motors. Advance knowledge that this difference existed was important to limiting the amount of redesign the Pi filters had to go through and allowed the team to implement the solution as quickly as possible on the airplane.

Fig. 19 Final Pi filter design.

The off-aircraft HIL setup was an incredibly useful tool for troubleshooting problems with the BCM and batteries because many functions of the BCM required all eight modules and the LOTO to be connected. This setup made any troubleshooting efforts hazardous, requiring a large group of people to support, certain safety guards to be in place, and a detailed procedure. This setup, however, could not be functional at the same time as the airplane because of limited hardware and personnel. There were also safety concerns with having two high-voltage test events occurring simultaneously in a relatively small area. As a result, the HIL setup was torn down once the Pi filters were developed to begin testing on the airplane. This meant that any future troubleshooting of the BCM and batteries requiring high voltage would have to take place on the airplane.

Performing lab testing and any necessary redesign with engineering units instead of flight units early in the troubleshooting process would have significantly saved schedule and allowed for the implementation of more efficient and effective redesigns. This type of testing should be completed before finalizing the aircraft design. After the completion of lab testing with individual systems, HIL testing should be performed before integrating anything onto the aircraft. This HIL testing will lead to the early discovery of systems integration problems and allow for faster corrections prior to integration on an aircraft.

V. Battery Testing and Operations

A. Charging and Discharging System Design Isolation Detection Unit

The traction battery system, developed at EPS, consisted of two battery packs (A and B) each with a nominal operating voltage range of 320-538 V. This range was achieved by using eight 67.2-V battery modules that were connected electrically before charging and discharging operations. Each battery pack was designed to be capable of powering the entire airplane independently of the other. The power was routed from each of the battery packs through their respective LOTO boxes that would prevent any inadvertent power flow when the batteries were not in use. From the LOTOs, the power was then routed to BCMs (A and B, respectively). Each BCM contained a DC/DC converter that converted the power from the traction bus into 13.8 V in order to power the DC converter bus and the avionics bus and a series of contactors that controlled power to the rest of the high-voltage bus, including the CMCs (Fig. 20). The BCMs also housed the Battery Management System (BMS) software that was used to monitor the health and status of the battery packs, which included traction current, state of charge (SOC), charging conditions, cell voltages and temperatures, and more. The BCMs contained the IDU as well, which was used to detect potential shorts from anywhere on the high-voltage bus to the chassis of any subsystem on the airplane.

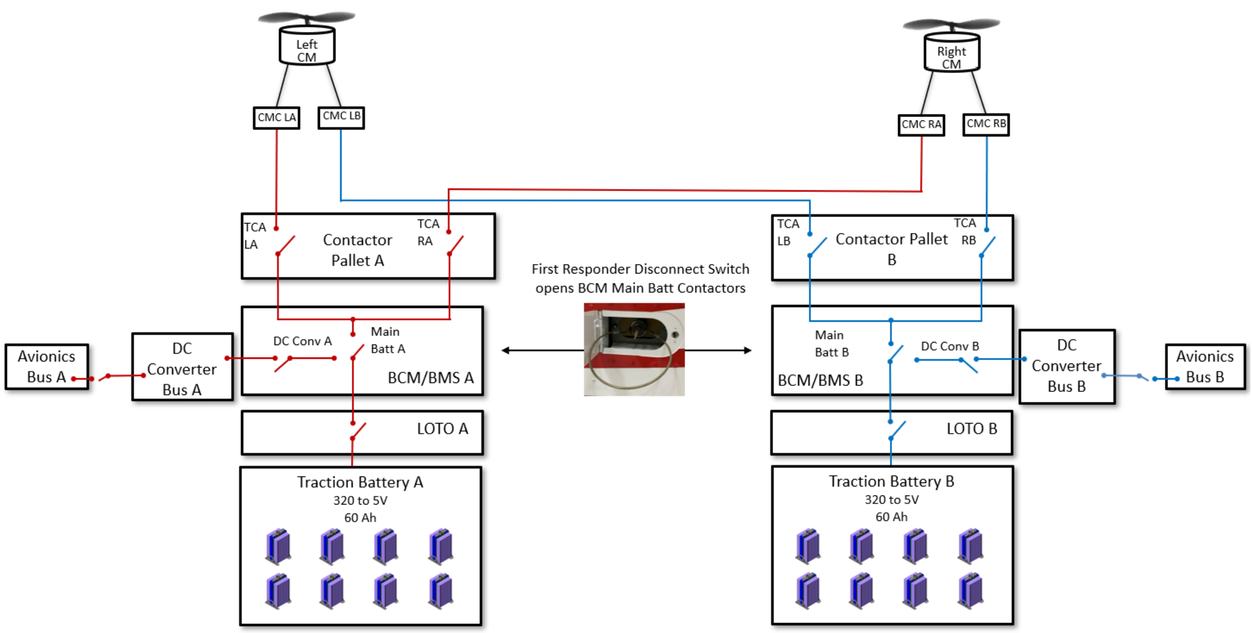

Fig. 20 Modification II traction power system.

While the IDU is an important safety feature and the redundancy of having two isolated battery packs is necessary to ensure that there are no potential single-point failures, this configuration led to complications with charge and discharge operations using the BSS. The BSS is equipped with two channels, but they share a common ground, which meant that Pack A and Pack B were no longer isolated and that each IDU would trigger the other. Since both battery packs could not be charged or discharged concurrently using the BSS, the amount of time necessary to complete these operations doubled. Physically, both packs could be charged simultaneously by connecting one pack to each channel of the BSS. Both battery packs, however, shared a common ground in this configuration, which caused the IDU check in one BCM to trigger an isolation fault in the other BCM if they attempted to check for an isolation fault simultaneously. Upon detecting an isolation fault, the BCM triggered the charge contactors to open, electrically disconnecting that battery pack from the rest of the traction bus. The BSS itself also had an IDU check that was disabled during charging operations. This check allowed for a software work-around to be implemented that turned off the BCM IDU check while in charge mode. With this version of the software, the BSS IDU check would always need to be enabled during charging. This solution could not be implemented for discharging operations, since it is necessary for flight. An alternate solution to this problem could have been the use of two separate power supplies that were capable of charging each battery pack and did not share a common ground. This solution would allow for not only charging but also discharging to be completed simultaneously.

B. Balancing

Balancing the batteries is necessary to maintain a consistent SOC and voltage across all the cells in each battery pack. If the cells are out of balance with each other, the full battery capacity cannot be achieved. For the X-57 Maxwell, passive battery balancing was utilized. Through this process, the BMS would attempt to achieve a cell-to-cell balance within 20 mV. Specifically, the BMS enabled the balancer for any cell with a voltage difference greater than 20 mV above the lowest cell voltage. When the balancers were active, extra voltage was slowly bled off the cell through a resistor. This process was lengthy, especially since it had to be conducted slowly due to the heat produced by the resistors while active. During this process, the BMS monitored the cells, turning off each balancer as the cells reached their 20-mV target.

The temperature and voltage of each cell was also monitored by the system to ensure that no minimum or maximum temperature or voltage limits were reached. If any of these conditions were reached during charging, the BMS opened the charge contactors to stop the charging process. This was only witnessed in practice during an attempt to achieve a SOC of close to 100 percent. Because the cells were not balanced enough to achieve this high of a charge, a cell reached the 4.2-V maximum voltage limit, triggering an automatic cutoff. As a result, additional balancing had to be done to individual modules to allow the cells to become more uniform before charging the batteries to a higher SOC. Since changes in capacity for lithium-ion batteries occur as they age and the charge of each cell is affected by parasitic losses from cell monitoring, keeping the batteries in balance can be a challenging and lengthy process. More information regarding this process and some of the limitations of passive battery balancing can be found in Ref. [5].

C. The LOTO

The Lock-out/Tag-out (LOTO) is used to electrically isolate the batteries entirely from the rest of the aircraft for maintenance purposes and to make the battery module connection process safer; however, the closing of the LOTO also caused a potential problem with the DC/DC converters in the BCMs. When the LOTO was closed, there was an inrush current to the BCM that was greater than the maximum allowed inrush current for the converters. This finding should have been captured in an original requirement for the LOTO because it would have led to the failure of the converters if the problem remained unaddressed. Inrush current limiters were added between the LOTO and the converters to mitigate the risk of this failure. Although the LOTOs were only intended to be used for maintenance and battery module connection purposes, the project team decided early on to use the LOTOs between operations to try to maintain a secure airplane. This decision became problematic, because the inrush current limiters were found to be ineffective above a certain temperature, which was further exacerbated by their rise in temperature during each use. To ensure the inrush current limiters were working properly, the team had to add delays between manually operating the switches. This required time between closures caused schedule delays in all operations that required the LOTOs to be opened and closed multiple times within a day. Defining specific operational requirements for the LOTOs early in the design phase could have prevented these problems.

D. First Responder Disconnect

While testing with high voltage, it is imperative to ensure that there is a quick way to isolate the battery system in case of emergency. In the original battery design, this function was carried out by two switches in the cockpit that only the pilot could control. This functionality scheme does not consider a scenario where the pilot becomes incapacitated during ground tests, flights, or from a hard landing and presents a shock hazard to any personnel aiming to assist the pilot. To work around this potential hazard, a First Responder Disconnect Switch (FRDS) (Fig. 21) was added to the traction system on the airplane. The FRDS had the same functionality as the two switches in the cockpit but was accessible from outside the airplane at the tail, allowing personnel other than the pilot to quickly remove high voltage from the airplane. The first responder disconnect never had to be utilized for an emergency event during ground operations, but it was tested with the traction system to ensure that it functioned properly. This safety feature was critical because it could save the pilot's life in the event of an emergency. Considerations like this should be taken into account when designing a high-voltage system.

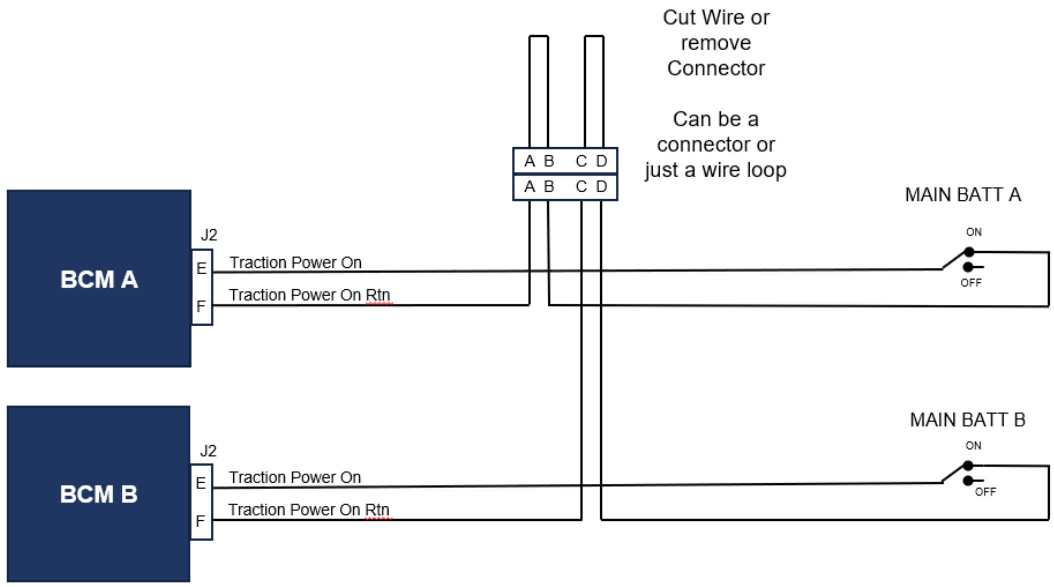

Fig. 21 First responder disconnect.

VI. Conclusion and Recommendations

Even though the National Aeronautics and Space Administration (NASA) X-57 Maxwell all-electric experimental airplane did not achieve first flight, the NASA Armstrong Flight Research Center project team gained significant insight throughout the course of the flight systems integration campaign. The challenges faced during both software and systems testing revealed several aspects of the integration that were done effectively, as well as some that were limited due to project constraints. The AFRC project team successfully developed various tools to support testing activities and improved upon the troubleshooting processes due to the restrictive nature of aircraft testing. What became evident, however, was that the early allocation of resources towards engineering and spare units, as well as an iron bird, or similar test platform, would have greatly improved efficiency and saved schedule during the integration phase of the project.

lthough the various electrical ground support equipment (EGSE) tools, specifically the cruise motor controller maintenance software (CMCMS) and Spiky graphical user interfaces (GUIs), were initially developed to support software testing, these tools became quite effective in supporting the testing and troubleshooting efforts both on and off the airplane. Since these tools were developed in-house, the test team had the ability to customize the displays to monitor the distinct parameters relevant to different environments and remotely control the motor torque as necessary for different test scenarios. The Spiky GUIs proved to be useful across various test platforms as well, from the Systems Integration Laboratory (SIL) to the Hardware-in-the-Loop (HIL) setup to the aircraft. Although the aircraft was equipped with the Multi-Function Display (MFD), along with other data displays, the MFD proved to be insufficient for some of the troubleshooting activities. Use of the MFD during troubleshooting put increased workload on the aircraft operator that could be distributed more effectively amongst the test team using the Spiky GUIs. The external software tools also provided the ability to monitor extra parameters that were not available on the MFD, which provided additional situational awareness. Allocation of project resources to develop these tools early in the project lifecycle was determined to be essential, especially given the incredible value of the tools throughout the different test campaigns.

One major impediment that the team faced was limited assets or hardware. The restricted quantity of hardware strained the amount of parallel work that could take place, so the team did its best managing a multitude of testing events. This hardware quantity restriction was especially true for the XM3 cruise motor controllers (CMCs), which had to go through a plethora of testing, such as software, environmental, qualification, HIL, and aircraft testing. In addition, having limited hardware meant that assets used for developmental testing were actually flight units. As a result, additional pressure was put on the team to treat these units with caution and required that most work on the units, such as wiring, be performed only by specific shops at the Armstrong Flight Research Center (AFRC). This further hindered the schedule since many of the shops are limited in staff and support all of the projects taking place at AFRC. The decision of the team to designate some of the assets as engineering units was beneficial because it allowed the team to work through troubleshooting faster. Advanced planning for engineering and spare units is something projects should invest in because it may save a lot of time and money in the long term.

Another challenge during the integration troubleshooting efforts was the strict operational requirements that accompanied hazardous aircraft testing. Although these requirements were in place to ensure the safety of personnel and assets, they sometimes slowed down troubleshooting progress. Since signed procedures were needed, with several additional signatures for any red lines, the team became creative during the latter portion of the integration campaign. Operational procedures and checklists were developed to start up and bring down the aircraft systems so that the core of the troubleshooting activities could be written into test cards. These procedures and methods provided the team with more flexibility on the testing that was performed. The test cards were developed prior to the day-of-test and reviewed at the pretest briefing with the entire test team, eliminating the use of procedures outside of their original intent through red lines. The use of designated setup and teardown procedures along with test cards significantly improved efficiency and allowed for more dynamic troubleshooting.

Testing on the aircraft is useful to understand how components work together and to discover problems early, but the drawback is that certain protocol has to be followed since flight assets are at risk. These protocols can limit the potential troubleshooting activities and cause huge delays in schedule. The Systems Integration Laboratory (SIL) and hardware-in-the-loop (HIL) setups are beneficial, but there can still be differences in system behavior between these types of setups and the aircraft. For example, it was found during software testing that several aspects of the software performed differently in the high-power aircraft environment compared to the low-power SIL environment; this difference was true for the HIL setup as well. As a result, many features of the hardware and software components remained untested until integrated on the airplane where the discrepancies were finally found. The team was forced to work through an iterative process to find solutions to these problems. The SIL and HIL setups are also limited to what components are tested together as a system, which can lead to delayed discovery of problems between certain components working together. Having a setup such as an iron bird that is closely representative of the aircraft, but without flight hardware, would be very beneficial. An iron bird would have given the team an early understanding of how components work as an integrated system and would have allowed troubleshooting to occur much faster than on an airplane.

Although an iron bird is a huge upfront cost, the amount of time an asset like this could have saved the X-57 Maxwell project is invaluable. An iron bird would have allowed the team to test hardware and software as an integrated system earlier in the developmental phase, which could have uncovered problems prior to their integration on the airplane. Additionally, advance consideration regarding any tools that would enhance testing, such as the EGSE tools, can improve testing capabilities without rushing the development process. The use of an iron bird would help in developing these tools as well because it would give insight into the parameters pertinent to understanding different systems. The team was able to learn a lot from the challenges presented by an all-electric aircraft, but resources are available that may have allowed for faster solutions and lessons learned. Even though the X-57 Maxwell did not make it to flight, the lessons learned and technologies developed helped advance the path towards sustainable flight solutions.

Appendix A

Cruise Motor Controller Software Verification and Validation Test Procedures

- The CMC Software Operations Handler – assesses the transitions of the CMC software into the correct modes (Maintenance, Wait, or Software Park) based on specific conditions and confirms that the software successfully sends commands on the CAN bus to initialize and operate the torque levers.

- The CMC Throttle (Torque Lever) Operations Handler – tests all logic associated with the torque levers, including processing encoder data, performing data and range validity checks, converting from encoder counts to torque command, generating faults and performing resets, detecting changes in message rate or loss of data, limiting to smoothen out step functions, and providing health or status information on the CAN bus.

- Low-Voltage Maintenance Mode – tests the ability of the CMC software to successfully perform the following: establish communication with the CMCMS, accept the software load from the CMCMS, perform zeroing functions when commanded by the CMCMS, save the CMC node assigned by the CMCMS to memory, rotate the logfiles every power cycle, send logfiles to the CMCMS when commanded, and record the correct information in each logfile.

- High Voltage – evaluates the motor start sequence with faults associated with different traction voltages, monitors the FPGA and motor winding temperatures, verifies the appropriate messages are received and operations are performed when the voltage is ramped up and down, verifies that the status of the arm switch is checked when powered on, and confirms that the software transitions to Wait Mode whenever the voltage exceeds the limit during any given phase of the motor start sequence.

- Unloaded Motor Start – tests the motor start sequence in various initial conditions and verifies that the software transitions to Wait Mode in the event of any faults when the unloaded motor is connected. This procedure was removed for the XM3 CMC test campaign and the test points were consolidated with the corresponding on-aircraft Loaded Motor Start procedure to improve test efficiency.

- Unloaded Motor Operations – tests the motor operations logic, including stability and transitions between various motor speeds, performance of the speed protection algorithms, and fault interruption during motor operations using the unloaded motor. This procedure was removed for the XM3 CMC test campaign and the test points were consolidated with the corresponding Loaded Motor Operations (Single CMC) on-aircraft procedure to improve test efficiency.

- High Voltage with Unloaded Motor – tests that the software transitions to Wait Mode when exceeding the traction voltage at any given motor speed and monitors internal CMC temperatures while MOSFETs are switching during motor operations using the unloaded motor. This procedure was created for the XM3 CMC test campaign to cover any test points from the Unloaded Motor Operations procedure that could not be incorporated into the Loaded Motor Operations (Single CMC) procedure.

- The CMC Development Board – tests the various FPGA fault and failure bits, verifies the FPGA register values, checks that the software sets a caution during frame overruns, and evaluates the watchdog timer. This procedure, performed on the development board (without a CMC or motor) was created after the BM2 CMC test campaign.

- Loaded Motor Start – tests the start-up sequence for the motor at different initial conditions, as well as fault handling during the start-up sequence on the aircraft.

- Loaded Motor Operations (Single CMC) – tests the motor operations logic at various speeds, performance of the speed protection algorithms, and fault handling during motor spin with a single CMC active on the aircraft.

- Loaded Motor Start (Dual CMC) – tests the motor operations logic at various speeds, performance of the speed protection algorithms, and fault handling during motor spin with two CMCs active on the aircraft.

Appendix B

Flight Systems Verification and Validation Test Procedures

- Initial – tests that the overall system is operational, that the annunciator panel in the cockpit operates as expected when faults or audio messages occur, the accuracy of the DC Converter and Avionics Bus A and B meters, and the accuracy of the torque encoders.

- Propeller Controller – tests that the propeller controller system operates as expected in both Manual and Auto modes, tests that the MFD tracks changes of the propeller pitch angle, quantifies the tolerance of the tachometers, and determines the minimum governable speed by the propeller pitch controllers.

- Cruise Motor and Controller – tests the cruise motor and cruise motor controllers by verifying behavior of all four CMC annunciator fault lights; tests the arming and disarming behavior of the CM and CMCs, tests both single and dual CMC restart are possible while the motor is spinning, behavior during and after loss of torque lever encoders while motors are spinning and ensures the propeller does not travel out of the start position during a motor run while in Manual mode; tests the torque-rate limiting and overspeed functions of the CMCs; tests that an incomplete start is executable by measuring the time it takes for a motor to stop from idle with the propeller pitch at the Start position; and tests the time it takes for a motor to stop from maximum torque with the propeller pitch lever at full-forward position.

- Avionics and Traction Voltage Range – tests that the traction and avionics buses operate within the specified voltage limits by verifying the propulsion system is functional at 320 and 550 VDC; tests that the power buses can carry maximum current; and verifies operability of the 13.8- and 28-VDC avionics bus components at their respective minimum and maximum voltages.

- Right-Hand Panel – tests that the right-hand panel is operating as expected by verifying the following: overspeed fault and audio annunciator work correctly; traction voltage and the displayed current is within range when compared to measurements at the CMCs and BCMs; RPM displayed is within range compared to that measured by the CMC; and torque matches the CMC torque lever encoder counts and location of the torque lever.

- Avionics – tests the avionics power circuits by verifying the following: essential battery can be charged by the DC converters and is capable of powering the essential bus, each DC converter and the essential battery can power the 13.8-VDC Avionics Bus when the other DC converter is disabled, both DC converters can power the 13.8-VDC bus and measure how much current they supply, both BCMs can power the contactor pallets and right-hand (RH) panel and measure the current supplied, a single BCM can power the contactor pallets and RH Panel, and all avionics can be successfully powered on.

- Traction – tests that the traction system operates as expected with the batteries and BCM installed by verifying the following: voltage readings in different scenarios at different monitors are within range of each other, good communication between BCM, batteries, and other aircraft components, no voltage is seen on the cockpit monitors when the first responder disconnect is pulled, and the contactor pallet functions correctly in different scenarios.

- Propulsion System Matrix – tests the redundancies in the propulsion system including the batteries, motor controllers, and motors, and checks that specific aircraft systems, such as the CMC arm switches, torque levers, and propeller controllers, are configurable by the pilot to be operated in all prescribed configurations.

- Command Bus – tests all CAN bus and data timing on the aircraft to ensure each component operates as intended.

- Fully Integrated System – tests the fully integrated aircraft system during power up, motor idle, motor at maximum power, and at low voltage to ensure that all systems operate as intended and expected.

Appendix C

FMET Procedures

- Command System – tests the command bus response to a cockpit fiber-optic bus extender (FOBE) failure; tests unexpected command bus loading; tests an increased command bus message rate; and different commands being received by CMC A and CMC B.

- Cruise Motor Controller – tests how the CMC will respond to the following: when overspeed protection is activated at different torque ramp rates and voltages, the torque levers are swept at different frequencies, a CMC is armed while the torque levers are not in the idle position, a propeller controller is commanded to feather at an idle setting, an inadvertent feather command or loss of propeller controller occurs while spinning motors, when there is a loss of the propeller pitch RPM sensor, and the torque levers are rapidly transitioned from high torque command to idle.

Appendix D

Spiky Graphical User Interfaces

This appendix provides additional detailed information about the Spiky GUIs, specifically PRICKS, SPINE, THORN, and BRIAR, including the individual parameters that were monitored in each tool, as well as some of the intricate elements of the functionality of the tools.

1. PRICKS

Below are the various parameters displayed on PRICKS. Parameters from both the left and the right wing can be displayed at the same time, so data is available for all four CMCs, both torque levers, and both cruise motors.

CMC	Torque Lever	CM
3 MOSFET temperatures (°C)	Encoder 1 (counts)	2 Duct inlet temperatures (°C)
FPGA temperature (°C)	Encoder 2 (counts)	2 Duct outlet temperatures (°C)
3 Low Voltage Board (LVB) temperatures (°C)	Encoder average (counts)	6 Motor winding temperatures (°C)
Estimated motor speed (RPM)	CAN traffic status	6 Bearing temperatures (°C)
Actual torque command (Nm)	Encoder average region	Blade pitch angle (°)
Filtered traction voltage (V)	Absolute zone	Advanced Central Logger (ACL) status
CMC state		Synchronous Vehicle Input Module (SVIM) status
Arm switch position		
Fault light		
CAN traffic status		
Error manager		

2. SPINE

The SPINE displays the directory location where the data files are saved, the file index number, the total number of CAN data packets recorded, and the percentage of error packets. Also included is a visual representation of the recording status, as well as a basic start or stop button.

3. THORN

The THORN displays the parameters listed below for either the left or right toque lever.

- Encoder 1 (counts).
- Encoder 2 (count).
- Encoder average (counts).
- CAN traffic status.
- Encoder average region.
- Absolute zone.

The THORN also provides the ability to control the torque lever functionality. The options available include setting the message rate, increasing or decreasing the counts in set increments for one or both encoder(s), ramping up or down or oscillating the counts at a user-defined rate for one or both encoder(s), setting both encoders to different torque region setpoints, and bringing the torque levers immediately to idle in case of anomalous behavior.

4. BRIAR

Below are the various parameters displayed on BRIAR. Only the parameters from either the left or the right wing can be displayed at one time, so data is available for two CMCs, one torque lever, and one cruise motor.

BRIAR also provides the ability to control the torque lever functionality. The options available include setting the message rate, increasing or decreasing the counts in set increments for one of both encoder(s), ramping up or down or oscillating the counts at a user-defined rate for one or both encoder(s), setting both encoders to different torque region setpoints, and bringing the torque levers immediately to idle in case of anomalous behavior.

CMC	Torque Lever	CM
3 MOSFET temperatures (°C)	Encoder 1 (counts)	6 Motor winding temperatures (°C)
FPGA temperature (°C)	Encoder 2 (counts)	6 bearing temperatures (°C)
3 LVB temperatures (°C)	Encoder Average (counts)	ACL status
Estimated motor speed (RPM)	CAN traffic status	SVIM status
Actual torque command (Nm)	Encoder average region	
Raw traction voltage (V)	Absolute zone	
Filtered traction voltage (V)		
CMC State		
Arm switch position		
Fault light		
CAN traffic status		
Error manager		

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