34th Congress of the International Council of the Aeronautical Sciences
ICAS Florence CONGRESS September 9-13 2024 ITALY

Distributed Thrust Takeoff for the NASA X-57 Mod IV Flight Demonstrator

Nicholas K. Borer[1], Ryan D. Wallace[2], James R. Reynolds[2], David E. Cox[1], Claudia Sales[2], Timothy L. Williams[2], and Wayne M. Ringelberg[2]

[1]NASA Langley Research Center, Hampton, Virginia, 23681, USA
[2]NASA Armstrong Flight Research Center, Edwards, California, 93523, USA

Abstract

The Mod IV configuration of the X-57 flight demonstrator concept featured two forms of distributed electric propulsion—one cruise propulsor at each wingtip for primary propulsion that enabled favorable interaction with the wingtip vortex and six high-lift propulsors distributed along the leading edge of each wing to enhance low-speed flight characteristics. The power system that fed these propulsors was arranged in two independent power buses. This unique arrangement did not lend itself to traditional "one engine inoperative" methods for determining performance after a critical failure in the propulsion system. Several failure scenarios were identified as potential "critical loss of thrust" events, and experiments that included pilot-in-the-loop simulation with the project test pilots were conducted to determine if these events would result in inadequate handling qualities or performance. Prior research showed that a total failure of one of the cruise motors during takeoff or initial climb could result in unacceptable performance for a traditional full-power takeoff. A new technique dubbed Distributed Thrust Takeoff (DiTTo) was developed to reduce the impact of the thrust asymmetry and loss of thrust that could occur in any of the critical loss of thrust scenarios. The results showed that adequate performance and handling qualities could be achieved in each of the critical failure scenarios when using the DiTTo technique.

Keywords: Distributed Propulsion, Electric Propulsion, Critical Loss of Thrust, Airworthiness

1. Introduction

The X-57 "Maxwell" was a NASA flight demonstrator concept for Distributed Electric Propulsion (DEP) technology. This technology resulted from the confluence of distributed propulsion (the integration of propulsive devices strategically placed about the airframe to yield aero-propulsive benefits) and electric propulsion (the use of electric machines to drive propulsive devices). The X-57 project planned to demonstrate this technology through successive retrofits, called Mods (for modifications). The sequence of these Mods is given in Figure 1, which shows the planned evolution of the aircraft from a general aviation baseline in Mod I to a fully distributed electric propulsion flight demonstrator in Mod IV. The Mod IV configuration of the X-57 included two electrically driven cruise propellers located on the wingtips and twelve electrically driven high-lift propellers distributed along the leading edge of a highly loaded, high-aspect ratio wing [1], as shown in Figure 2. All Mods of the X-57 shared (at least) the same fuselage, empennage, and landing gear as a Tecnam P2006T [2], which is a conventionally fueled, combustion-powered aircraft that served as the X-57 configuration and performance baseline. Changes to the wing and the addition of a DEP system were expected to yield a significant savings in energy consumption in cruise as compared to the baseline aircraft while maintaining or enhancing the baseline aircraft's low-speed flight characteristics.

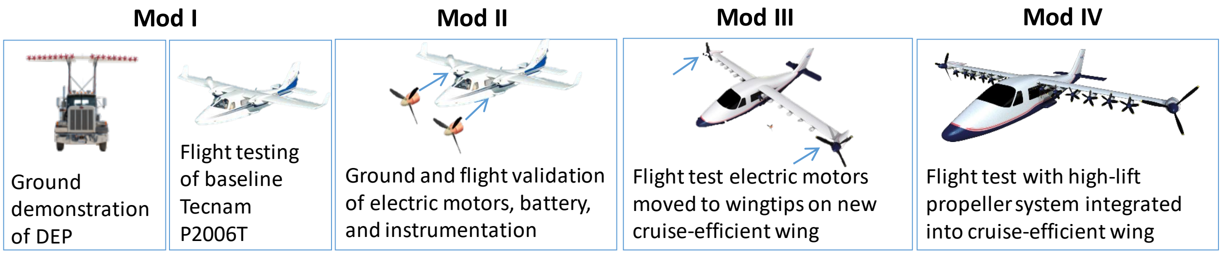

Figure 1 – X-57 development through multiple modifications ("Mods").

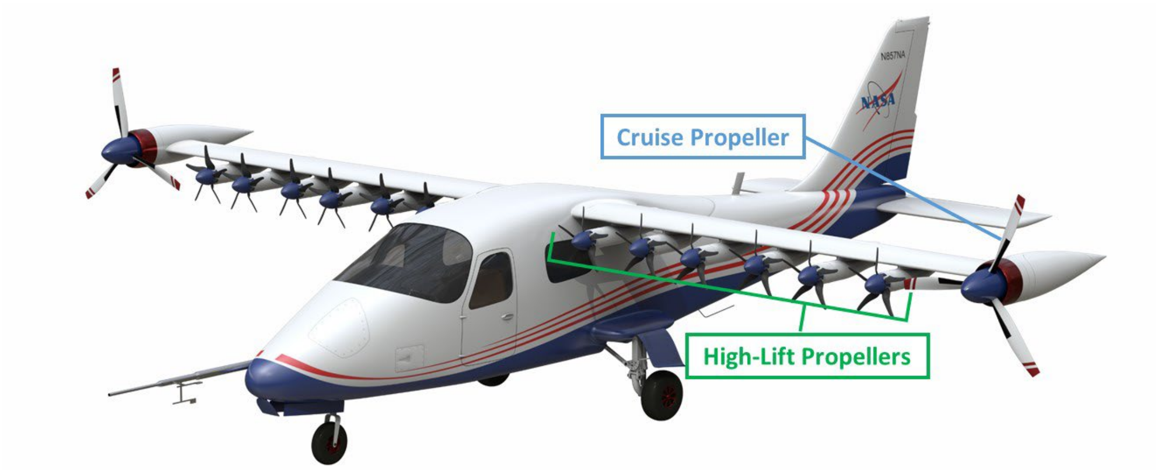

Figure 2 – Rendering of the X-57 in its final configuration with wingtip-mounted cruise propellers and with high-lift propellers distributed along the leading edge of the highly loaded, high-aspect ratio wing.

The unique arrangement of propulsors challenged traditional approaches for determination of adequate performance and aircraft handling qualities in the event of a failure within the propulsion systems. The X-57 cruise propellers were designed to provide primary propulsive thrust within the flight envelope. Typical aircraft, including the baseline twin-engine Tecnam P2006T, are designed to maintain minimum performance and handling quality standards in the event of a failure of one of the propulsors. The cruise propulsors on X-57 Mod III and Mod IV were approximately three times the distance from the centerline of the aircraft as compared to the P2006T, which introduced a significantly larger yawing moment than the baseline aircraft in the event of a total failure of one of the cruise propulsors [3]. Individual failures of the high-lift propulsors may not have resulted in as extreme yawing moments due to their lower thrust levels during typical operation, but failures of multiple high-lift propulsors were possible from a single failure in the X-57 power distribution system. These combined effects may have led to sudden rolling moments due to loss of lift (in addition to yawing moments due to differential thrust), given that the high-lift propellers were designed to increase the lift of the wing at low speeds.

The propulsor arrangement of X-57 Mod IV also provided some unique opportunities to mitigate critical propulsion system failures. A twin-engine aircraft has two propulsion systems that are designed with independence and failure isolation in mind; the X-57 in the Mod IV configuration had 14 propulsors and layered isolation and reconfiguration mechanisms. The electric cruise motors could provide their rated output torque at lower shaft speed than typical combustion engines and were fed from independent and isolated power systems and motor controllers [4]. The high-lift propulsors were also fed by one of two independent and isolated power systems and had two different control modes, including automatic and manual control mode selection [5]. These features enabled several possibilities for amelioration of failure effects or reconfiguration in the event of a critical failure.

This paper discusses identification and evaluation of the failure scenarios related to critical loss of thrust for the X-57 Mod IV configuration, as well as the operational approach that was developed to mitigate the critical failure effects. The analyses centered on results from a piloted simulation model with the capability to model the critical failures identified by the team. This paper provides both the metrics associated with key performance parameters after critical loss of thrust as well as evaluation of post-failure handling qualities using the project's experienced test pilots.

2. Background

Multiengine aircraft can enable higher performance and increased resilience to propulsion system failures. They also introduce different hazards associated with system failures that lead to a partial loss of thrust, both in terms of the potential for asymmetric thrust as well as reduced climb and cruise performance. Legacy aircraft propulsion systems are generally designed such that any failure is isolated to, at most, loss of thrust to a single propulsor. This simplifies aircraft performance analysis for failures in the propulsion system and is often known as one-engine inoperative. Since some propulsors may have more performance impact than others (e.g., failure of the outboard-most engine on airplanes with two engines on each wing will lead to a larger asymmetric yawing moment), some means is necessary for determination of which partial loss of thrust condition leads to a credible worst-case scenario that should be used when designing an aircraft.

2.1 Civil Airworthiness Requirements

The rules governing the operation and certification of civil aircraft in the United States are published by the U.S. Department of Transportation Federal Aviation Administration (FAA) in Title 14 of the Code of Federal Regulations (14 CFR). In 14 CFR §1.1 a critical engine is defined as "the engine whose failure would most adversely affect the performance or handling qualities of an aircraft" [6]. Legacy airworthiness certification requirements for multiengine aircraft combine the concepts of critical engine and one-engine inoperative such that many performance requirements that would be adversely affected by a failure in the propulsion system refer to performance "with the critical engine inoperative."

Some examples of these legacy requirements can be seen in the current airworthiness certification rules for Transport Category airplanes under 14 CFR §25 [7]. The idea of an isolated engine is embodied in §25.903(b), which states, "The powerplants must be arranged and isolated from each other to allow operation, in at least one configuration, so that the failure or malfunction of any engine, or of any system that can affect the engine, will not (1) prevent the continued safe operation of the remaining engines; or (2) require immediate action by any crewmember for continued safe operation." Legacy engine control requirements further enforce this engine isolation requirement; for example, §25.1143 requires a separate power or thrust control "for each engine."

This isolation of engines simplifies performance requirements associated with loss of thrust due to a failure in the propulsion system. The rules in 14 CFR §25.107 and §25.111 define speeds and takeoff path assumptions and §25.121 defines climb performance requirements, including with the critical engine inoperative. Requirements for performance enroute are given in §25.123 with different inoperative engine configurations, and §25.125 defines landing performance requirements with an inoperative engine. In addition to these performance requirements, §25.143 defines general controllability and maneuverability requirements with the critical engine inoperative, §25.147 defines directional and lateral control requirements with the critical engine inoperative, §25.149 defines the minimum control speed with the critical engine inoperative, and §25.161 defines trim conditions with critical and other inoperative engine conditions.

These specific requirements point to more general concerns for multiengine aircraft following a partial loss of thrust: impact on takeoff (and possibly landing) performance, climb performance, and controllability. The advent of electrified aircraft propulsion has led to a rethinking of the requirements for engine isolation and the associated impact of a propulsion system failure on loss of thrust. The fundamental principles that define how engine systems scale in terms of power-to-weight ratio or efficiency are vastly different for electric machines than they are for the legacy combustion-based turbine and reciprocating engines. This introduces new possibilities for more numerous propulsors arranged as distributed propulsion systems that were not previously practical with individual combustion engines [1]. As the number of propulsors increases, fully isolating an individual propulsor or any system that can affect the engine to ensure loss of a single engine in the event of a single failure will penalize distributed propulsion systems. In the case of the X-57 Mod IV, if each of the electric propulsors were to be considered an engine, the X-57 flight crew would be required to have 14 power levers in the cockpit, and each propulsor would need to be able to be isolated to one of 14 electrical buses.

Other airworthiness regulations have been modernized and may offer more flexibility when it comes to engine failure and control isolation. In late 2016, the FAA issued an amendment that was a significant overhaul of the airworthiness rules for Normal Category airplanes [8] under 14 CFR §23 [9]. Overall, this moved the formerly prescriptive airworthiness rules in Part 23 (which previously were similar in content and organization to the Part 25 airworthiness rules noted above) to performance-based rules that enable applicants to use consensus standards as a means of compliance to the rules. Although the former prescriptive rules can still serve as a means of compliance to the new performance-based rules, this new flexibility may allow for approaches in which more than one engine fails due to a single independent failure, or in which multiple propulsors are affected from a single cockpit control. In a nod to this possibility, the performance-based rules in 14 CFR §23 now refer to “critical loss of thrust” rather than “critical engine” in the new rules for takeoff, climb, controllability, and trim (§23.2115, §23.2120, §23.2125, §23.2135, and §23.2140). However, no generally accepted definition for critical loss of thrust has been provided other than ASTM F3179, which states that loss of thrust means one engine inoperative for conventional reciprocating or turbine engine-powered airplanes [10]. This standard does not provide guidance for non-conventional airplanes regarding loss of thrust (including those with electrified or distributed propulsion) other than “the amount of thrust loss shall be proposed by the applicant and accepted by the [Civil Airworthiness Authority].”

2.2 NASA Airworthiness and Research Goals

The X-57 was conceived as a flight demonstrator owned and operated by NASA, and as such was not subject to FAA airworthiness requirements. The X-57 flight test program required approximately 10–15 flights in the Mod IV configuration, and only a single aircraft was to be built. The aircraft was to be operated by highly qualified NASA test pilots. The X-57 was to be operated at the Dryden Aeronautical Test Range, co-located with Edwards Air Force Base in California’s Mojave Desert. This afforded the X-57 the use of runways that are over ten thousand feet in length. In addition, this test range features a large, generally dry lakebed that stretches for many miles and could be configured into additional runways or used as an emergency landing area. The airspace itself is restricted, tightly controlled, and does not generally host commercial traffic. These circumstances indicate that the likelihood and consequence of a loss of thrust for the X-57 are vastly different from similar aircraft that are designed for use in civil aviation, in which hundreds or thousands of aircraft may be operating multiple times per day, flown by a pilot population that includes individuals that meet the very minimum experience requirements, using airfields that may have limited runway length, in busy airspace, over populated areas, with little in the way of suitable emergency landing options.

Due to these differences, the X-57 project carried few performance requirements for critical loss of thrust as compared to civil production aircraft but instead viewed critical loss of thrust as a research area to help inform civil airworthiness standards for aircraft with distributed electric propulsion. NASA’s airworthiness process required the team to track hazards, which included hazards associated with critical loss of thrust, including asymmetric and multiple propulsors lost due to X-57 Mod IV’s unique configuration. Often, hazards with undesirable consequences (e.g., inability to continue takeoff after a critical loss of thrust) included mitigations such as the use of very long runways, something that may not be acceptable for a production civil aircraft. The X-57 team used highly detailed real-time flight simulations [11], with the project test pilots at the controls, to determine if technical or operational mitigations would result in acceptable handling qualities. In addition, these simulations provided a safe, effective means to estimate the performance impact of failure scenarios, such as climb rate, sink rate, and bank angle at touchdown.

The original flight test philosophy for X-57 was to clear new systems at higher altitudes and airspeeds prior to operation at low speeds and lower altitudes close to the ground. This enabled the X-57 to revert, if necessary, to a power-off landing in the event of an unexplained failure in the experimental power and command system. However, since propulsion is a mandatory element for takeoff, it was necessary to operate the cruise propulsion system at low airspeed and low power, increasing the possible exposure of the aircraft and flight crew to system failures during takeoff. Initially, the plan was to prove the airworthiness of the cruise motors and traction power system in the Mod II configuration because it would likely have more benign behavior in the event of the failure of a single propulsor. Flights in the Mod III configuration were to use partial power and the very long runway at the test site to help mitigate propulsion system failures. Initial in-flight operation of the high-lift propeller system of the Mod IV configuration was originally planned to occur at higher altitude and airspeed, using the Mod III configuration for initial takeoff and landing operations.

Piloted simulations of cruise motor failure scenarios for the Mod III configuration indicated poor handling qualities and unacceptable performance metrics [3]. The performance and handling qualities were also found to be marginal to unacceptable for cruise motor failure in the Mod III configuration with the planned mitigations in place, which included partial-power takeoffs, higher-speed takeoffs, and automatic power reduction on the operating engine. These evaluations led the X-57 team to investigate methods of merging the Mod III and IV test programs to include the high-lift propeller system for test flights previously only considered for Mod III as a mitigation to failures in the wingtip-mounted cruise propeller configuration for any flights with the highly loaded Mod III/IV wing. The results of that investigation are discussed later in this paper.

2.3 X-57 Mod IV Propulsion System Interfaces

The X-57 power and command system was designed for simplicity and graceful degradation in the event of component failures, as well as scalability from the Mod II/III configuration to the Mod IV platform. The Mod IV power and command system was the most complex, involving the highest overall power level and most components and system interactions. Still, the Mod IV power and command system used a straightforward approach to nominal and off-nominal operations to reduce the effort required for hazard analysis and system safety quantification.

The power and command system included a high-voltage traction power system to provide electrical power for generation of propulsive thrust; a low-voltage avionics power system to provide electrical power for the command system, instrumentation, and other non-propulsive aircraft components; and a command system that consisted of analog and digital components for data exchange [12]. A brief overview of the Mod IV systems is provided here to identify the failures that could lead to a loss of thrust and the resulting system reconfigurations to respond to said failure.

2.3.1 Power and Command System

The traction power system was fed by two independent high-voltage (HV) traction batteries, noted as Traction Battery A and B. Each traction battery was connected to a Battery Control Module (BCM), which in turn was connected to a Contactor Pallet. The Contactor Pallets further distributed the traction power to the Cruise Motor Controllers (CMCs) and High-Lift Motor Controllers (HLMCs), which in turn powered the Cruise Motors (CMs) and High-Lift Motors (HLMs). A simplified schematic of the X-57 Mod IV traction power system is shown in Figure 3.

The CMs were designed to be driven by two independent CMCs, one on the A traction bus and one on the B traction bus. The CMCs were connected to an independent set of windings within each CM, and each CMC could operate independently of the other in the event of a failure in any component from the traction battery to the CMC on the other bus. The HLMs and HLMCs were each connected to a single traction bus, but the dependence on traction bus was alternated between bus A and B on each wing so that a failure that rendered a single traction bus inoperative would result in a symmetric loss of thrust.

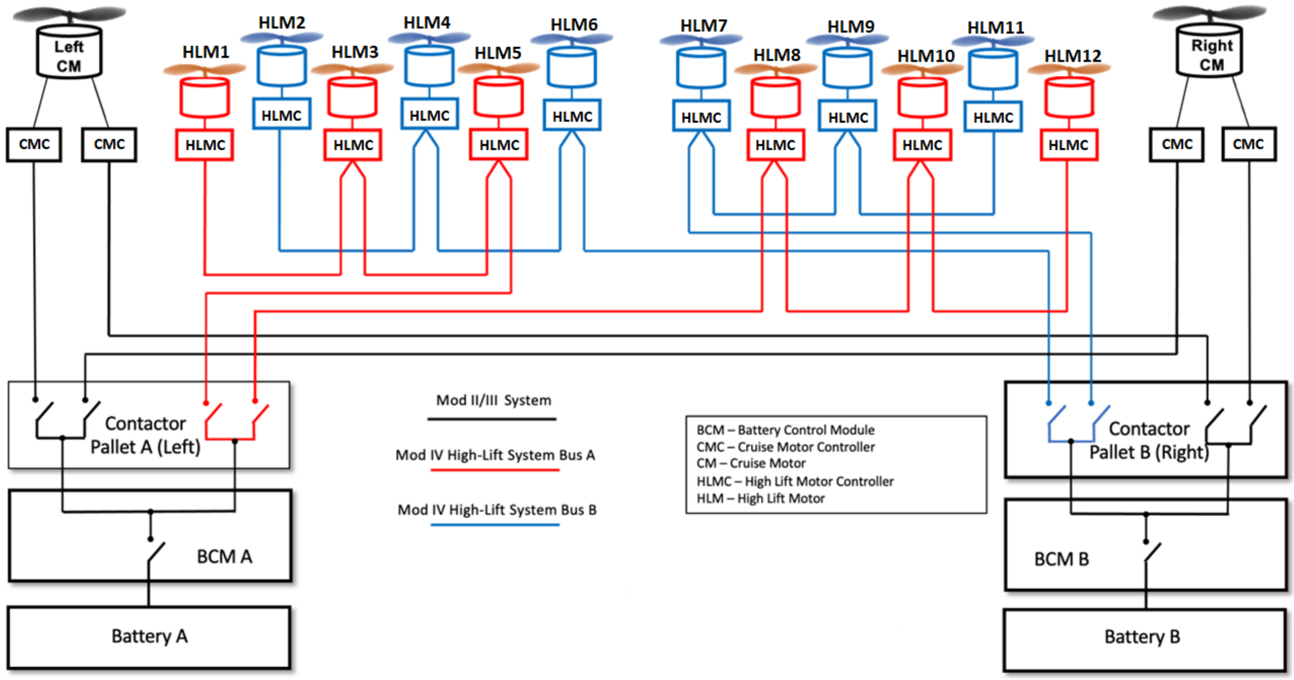

Figure 3 – X-57 Mod IV traction power system.

The avionics power system, which provided low-voltage power to operate the avionics, CMCs and HLMCs, and the command system, which provided command (such as torque command and operating mode) and data interfaces (such as motor speed and health status) with the CMCs and HLMCs, are described more in Ref. [12] and [13]. The connection and data bus philosophy was similar to that of the traction power system in terms of connecting the CMCs and HLMCs to the command system, in that the CMCs for each motor had one CMC on the A-side command bus and one CMC on the B-side command bus, and the HLMCs were symmetrically interleaved between the A-side and B-side command buses as per the traction system A-side and B-side.

2.3.2 Flight Crew Interface

The flight crew interface to the X-57 Mod IV propulsive components consisted of four major elements [14]: (1) the pilot-manipulated torque command levers for each CM; (2) the pilot-manipulated propeller speed levers for each cruise propeller (CP) associated with a CM; (3) the high-lift propeller (HLP) control panel, which included switches associated with arming the HLP system and selection of the HLP control mode; and (4) a yoke-mounted quick disarm switch for the HLP system. The first three propulsion system interfaces are shown in Figure 4 below. Figure 4 does not show the yoke-mounted disconnect switch; it was located on the left side of the pilot yoke and activated with the pilot's left thumb as needed.

The cruise motor torque levers were used by the pilot to set the torque command to the CMCs. There was a single torque lever per CM, and the torque command from a single torque lever was independently processed and executed by CMC A and CMC B for the CM. The torque command was largely linear with torque lever angle, though the torque commands were divided into four regions: Normal, Regen, Idle, and Overdrive. In the Normal region, the throttle map set the torque command to each CMC from the low or "idle" position of 8.0 Nm to a high position of 127.5 Nm. This region was nominally intended for a CM with both CMCs operational, so the actual torque of the CM would be double the individual CMC command as the current supplied from each CMC would contribute to the total motor output torque. The Regen portion of the throttle map was used to command a negative torque to the CMCs to enable glideslope control of Mod IV during approach-to-landing if needed, which could occur due to excess thrust from the HLPs during the descent to landing. This region was also nominally intended to be used with both CMCs operational. The throttle map in the X-57 Cockpit Interface Control Document [14] showed a torque command of 0.0 Nm to each CMC throughout the

Regen region, though updated values were planned for use in Mod IV flights that were never implemented due to the program ending prior to Mod IV flights. The Idle region was a small deadband in the throttle position between the Normal region and the Regen region, and this provided a constant torque command of 8.0 Nm per CMC. The Overdrive region was only allowed for single CMC per CM operations and was a contingency option available to the pilot in the event a single CMC was inoperative. The Overdrive region could only be reached if the pilot manually released a stop that otherwise stopped the torque lever at the top of the Normal range. The Overdrive region enabled a torque command of up to 175 Nm, enabling the pilot to regain some additional capability for contingency maneuvers if needed in the event of a single bus or CMC failure (albeit at a lower overall efficiency and higher thermal load on the active motor windings).

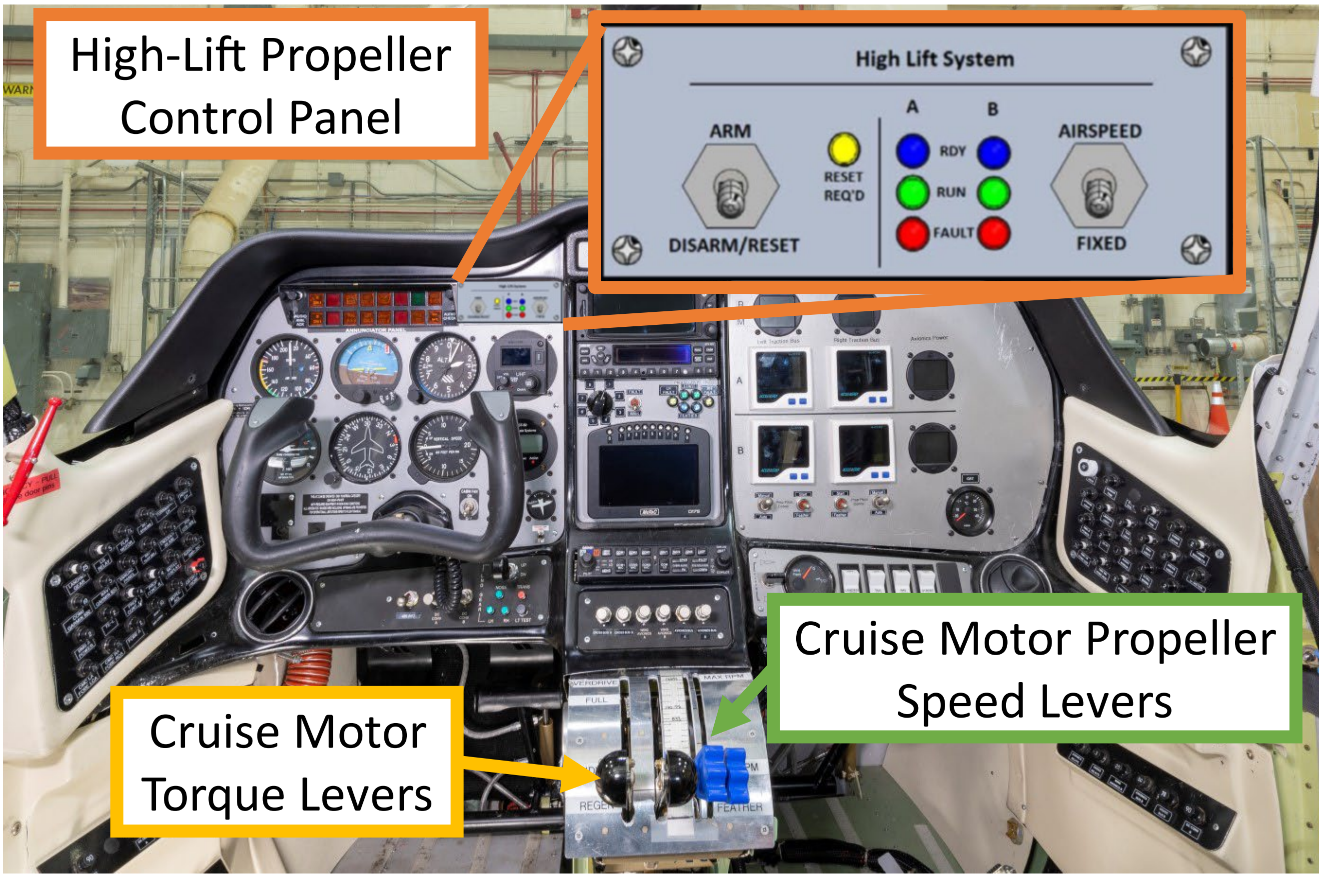

Figure 4 – X-57 Mod IV cruise and high-lift propulsion system cockpit controls.

The cruise motor propeller control levers were used to generate a propeller speed command that was sent to the propeller blade angle controller. The propellers could vary blade angle in a "manual" mode as well as an "automatic" mode that moved propeller blade angle to meet a set propeller speed. The propeller blades could be actuated from a "fine" position of 14 degrees to a "feather" position of 82 degrees. In automatic mode, the propeller blade would adjust the blade angle within these limits to automatically govern the speed to a selected value from 1700 to 2700 RPM. A detent was placed at the lower end of the propeller lever movement that would actuate the "full feather" mode of the blade angle actuator, moving the blade angle towards the full feather position. The feather command was used to reduce the propeller windmilling drag in the event of a complete failure of one of the CMs to produce power in flight.

The HLP control panel was the primary in-flight crew interface to the HLP system. It would arm or disarm the system with one switch, and the other switch was used to set the control mode. The HLPs operated in either a "fixed" control mode, in which the HLMCs were commanded to a motor speed of 4800 RPM, or an “airspeed” control mode, in which the HLMCs were commanded to a motor speed between 1500 and 4800 RPM, depending on the airspeed and altitude of the X-57. The airspeed mode was used for nominal approach and landing operations. The fixed mode was originally developed as a contingency mode in the event of the loss or corruption of the airspeed or altitude data to the command system or within the HLMCs. The fixed mode was also to be used in nominal operations for ground diagnostics and was discovered to be critical for nominal takeoff operations, as discussed later in this paper. More detail on the HLP control system is in Ref. [5], and an update on the HLP idle speed setting is given in Ref. [15].

3. X-57 Mod IV Flight Conditions Scrutinized for Critical Loss of Thrust

The propulsor and systems arrangement of the X-57 Mod IV configuration illustrate the challenges associated with the one engine inoperative and critical engine approach used by legacy airworthiness standards to determine flight performance in critical conditions associated with a single failure in the propulsion system. There are several single component failures in the X-57 Mod IV configuration that may impact the thrust production from multiple propulsors, which may or may not be considered engines in current and future airworthiness rules. As such, the use of partial loss of thrust is a better description of the result of individual failures associated with thrust production, with critical loss of thrust used to describe the off-nominal system configuration that results in the worst performance value associated with a flight maneuver. In this case, the same configuration may not be critical for all maneuvers or even all the performance values scrutinized for a particular maneuver.

3.1 Cruise Propeller Control Failure

As noted in Section 2.3.2, the CPs used a blade pitch actuator and nominally acted in an automatic mode that is similar to a constant speed propeller [16]. A failure of the control, actuator, power, or command signal would have resulted in a loss of propeller actuation control as depicted in Figure 5.

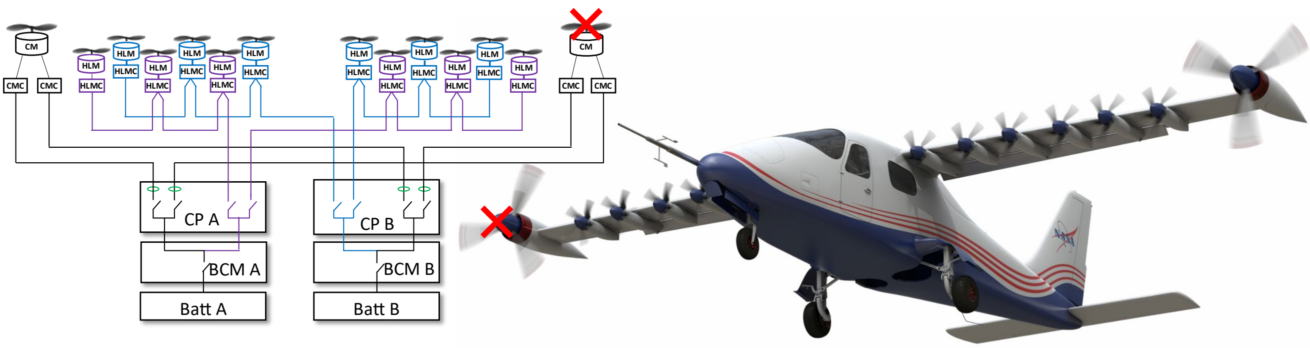

Figure 5 – Cruise propeller control failure.

In typical aviation applications, constant speed propellers use a hydraulic piston fed by engine oil to drive blade angle and maintain the target propeller speed set by the propeller control (governor). This arrangement typically results in fast blade actuation (many degrees per second). However, loss of oil allows the inertial and aerodynamic forces to drive typical hydraulic constant speed propellers to either the full fine blade pitch position or the full feathered position, depending on the engine torque, engine speed, and if the propeller pitch change mechanism has counterweights. In typical multiengine applications, counterweights are attached to the blade angle control such that loss of oil to the propeller governor for a spinning propeller will drive the blades to a “feathered” position. This prevents propeller overspeed and positions the propeller in the lowest-drag configuration, which tends to be advantageous for multiengine aircraft since the other engine(s) should not be affected by the failure that led to the failure of the hydraulic blade control mechanism. The feathered propeller-engine combination is shut down and the aircraft continues safe flight and landing on the remaining engine(s). Alternatively, typical single-engine aircraft do not have counterweights, so the propeller blade angle is moved to the full “fine” position. At higher throttle settings and airspeeds, this can lead to propeller overspeed, but it does allow the flight crew of single-engine airplanes some thrust control at reduced airspeeds and throttle settings.

The CPs for X-57 were commercially available units from MT-Propeller. Given that the X-57 used electric motors that lacked an oil system, the blade pitch actuator was an electrically controlled mechanism that drove the blade angle with a worm-gear type arrangement [17]. In the absence of power, it was not possible for aerodynamic or inertial forces to passively drive the blade angle, unlike the typical hydraulically controlled units. Additionally, the blade angle changed very slowly compared to the hydraulic units (about one degree per second). This meant that the failure of any of the components in the blade angle control system—namely, a failure of the control unit, the power to the control unit, the motor speed sensor or wiring, the electric actuator, the command signal to the actuator, or the avionics power to the actuator—would result in a far less dynamic change of the CP blade angle than a typical failure of a hydraulic unit.

In an omission-type failure of the X-57 CP (loss of power or absence of a command signal), the blade angle would be fixed at its last value, and the propeller would act as a fixed-pitch propeller, increasing rotational speed with increased airspeed and/or increased motor torque. In steady-state conditions, the omission-type failure would not be noticeable until a new flight condition was reached (such as a change in torque command or airspeed). In the event of a corrupted command signal (“propeller runaway”), the blade angle change would be gradual and not cause a sudden propeller overspeed or underspeed event. The associated change in thrust would also be gradual in such an event.

The power and command system was arranged such that loss of control of both CPs from a single failure was not credible. Each unit used independent controllers that were separately connected (including independent circuit breakers) to the essential avionics power bus, which included redundant electrical power sources [13]. The power to the blade angle actuators was on independent buses for each wing. Independent command channels were used to provide the commands to the actuators. The controllers also used a propeller speed sensor that was independent of the speed sensor used to drive the pilot propeller speed displays, and each motor controller (of which each cruise motor had two) generated their own independent speed estimates.

3.2 Cruise Motor Controller Failure

Two independent CMCs were used to control each CM, as discussed in Section 2.3.1. A failure in a single traction power contactor, traction distribution bus, avionics bus, or CMC would result in a partial loss of power to the CM, as depicted in Figure 6. The dual CMC arrangement for each cruise motor afforded one of the graceful degradation responses to failure built into the X-57 power and command system.

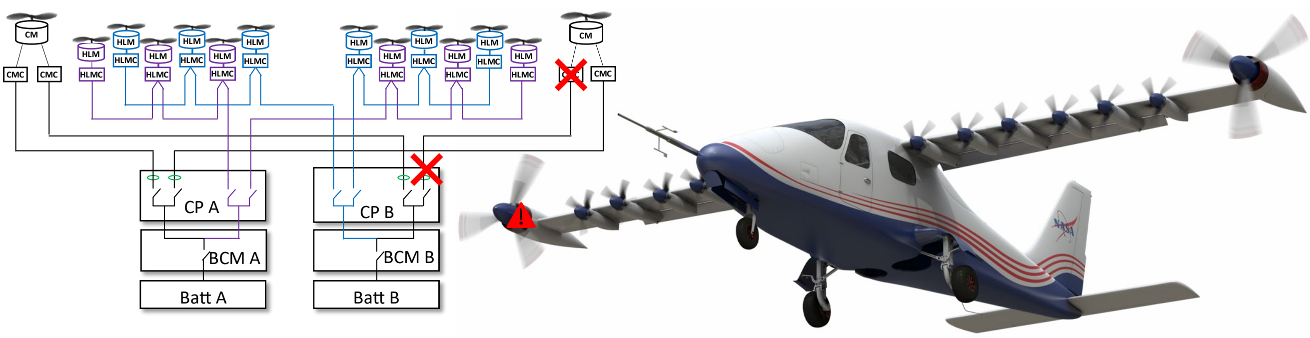

Figure 6 – Cruise motor controller failure.

The CMCs were designed to operate independently of each other for a single cruise motor—neither had any power or data exchange with the other via “sensorless” operation (e.g., sensing motor speed through electromotive force) and each CMC was electrically connected to independent motor windings sets within the CM. Essentially, each CM was really two CMs with interleaved stators and a single rotor. Each CMC received traction power from independent traction buses, avionics power from independent avionics power buses, and data exchange through independent command buses. The CMCs used NASA software development and assurance methods for safety-critical systems, so common mode failure of the CMC software was not deemed to be credible.

A failure of a CMC (including removal of traction power from a failed open traction power contactor to a CMC) would result in an immediate reduction in the total torque output of the CM, which would otherwise be the sum of the torque commands of each CMC (which were normally identical copies of the torque command from the appropriate cockpit throttle encoder). Effectively, the torque output of the CM would quickly drop to 50% of the pre-failure condition. This drop would only occur on a single CM, so some thrust asymmetry would result. Continued operation would still be possible on a single CMC, and the throttle for the CM with the failed CMC could be adjusted to increase torque to match or partially offset the torque asymmetry between the CM with the failed CMC and the CM with two operational CMCs. As noted in Section 2.3.2, an “overspeed” region of the throttle was available to enable higher torque commands from a single CMC in the event of single CMC operation of a CM. Single CMC operation would result in lower overall motor efficiency (i.e., higher electrical energy use for a given mechanical torque setting) and increased temperature of the active portions of the stator but could provide some thrust control for return to base and safe landing operations.

3.3 Cruise Motor Failure

The failure of a CM was expected to be one of the most challenging failures to resolve for the X-57 Mod III and IV configurations due to the large lateral offset of the cruise motors as compared to the conventional arrangement of the Mod II configuration. A failure of the cruise motor would only be associated with the cruise motor itself, as depicted in Figure 7, or its associated throttle encoder. Other total failures of a single CM were not credible due to the dual-bus, independent arrangement of the power and command system and dual CMC operation for each CM.

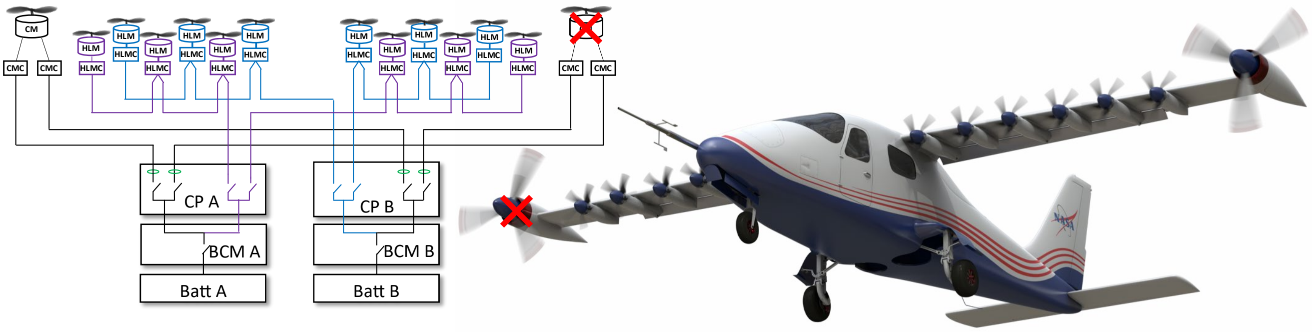

Figure 7 – Cruise motor failure.

A failure of a single CM could occur due to a mechanical failure in the CM itself, such as an issue with one of the motor bearings, which would result in an immediate reduction in torque down to a worst-case of zero torque. A CM mechanical failure would cause, in a worst case, a total loss of thrust to the affected CM, leading to what could be a significant thrust asymmetry if the other CM was commanded to a high torque setting. Mechanical or sensor failure of the throttle could lead to the throttle being stuck at the last position. In this case, the reconfiguration strategy would be to modulate the other throttle as appropriate for the flight condition and then eventually disarm the affected CMCs and/or remove power from the CM by switching off traction power to the CMCs via the contactors.

3.4 High-Lift Motor Failure

A failure of an HLM or HLMC would result in the loss limited to that single HLM. The HLMs and HLMCs were arranged such that no single HLM or HLMC failure could influence others. The failure of the outboard-most HLM is depicted in Figure 8.

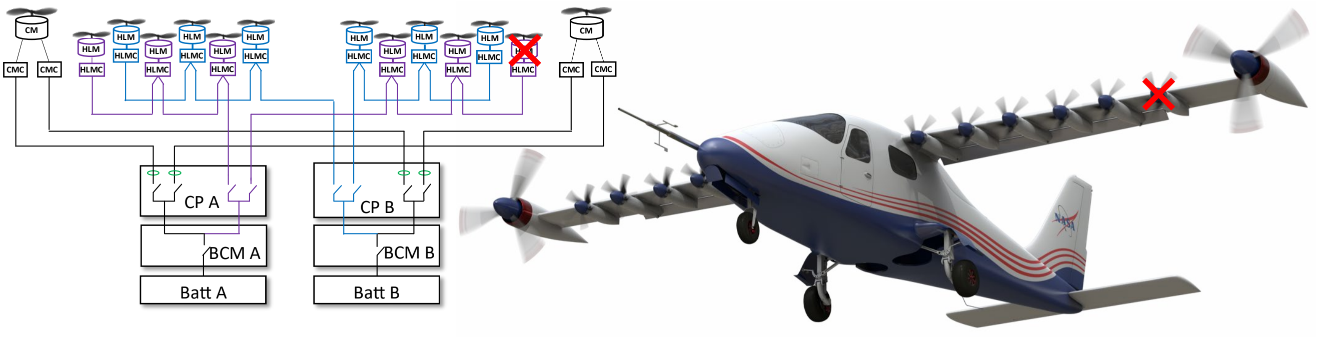

Figure 8 – High-lift motor failure.

The impact of an HLM or HLMC mechanical failure would be up to a 100% sudden loss in commanded motor torque, which in turn would reduce the thrust output and lift augmentation of the affected HLM. Given the number of HLMs, the impact of the loss of thrust and lift from a single HLM, and any resulting thrust and lift asymmetry, was expected to be small. The HLMs produced far less thrust than the CMs, and the most notable impact would occur during approach to landing, when the CMs would be at a lower power state but the HLMs would be at a high-power state. The outboard-most HLMs would have the most adverse effect on thrust asymmetry, but the inboard-most HLMs would have the most adverse impact on lift generation due to the washout of the wing, the length of the inboard wing chord, and the presence of the flap. The HLMC software used NASA safety-critical software development and assurance processes, so HLMC software failure for a single HLMC or common mode failure across all HLMCs was not deemed to be credible.

3.5 Traction Bus Failure

A failure in the traction power system that impacted one of the two traction power buses could occur due an issue with one of the traction batteries or the battery control modules. A depiction of this failure is shown in Figure 9.

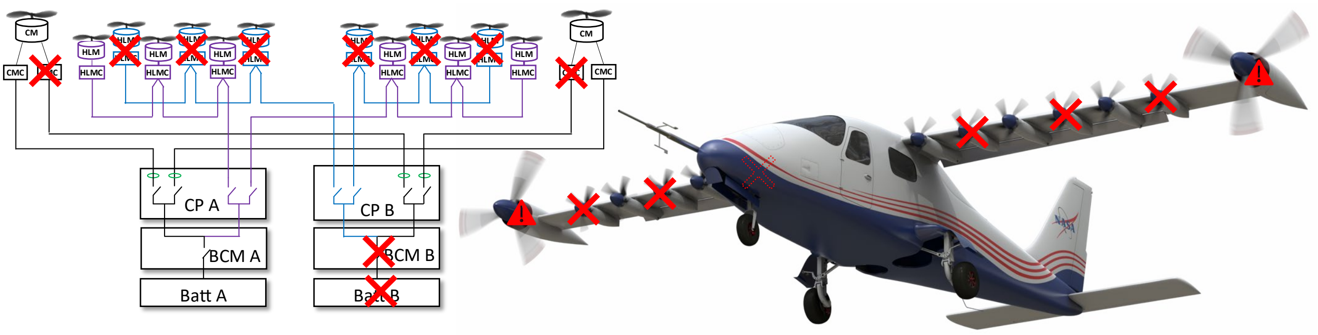

Figure 9 – Traction bus failure.

As noted in Section 2.3.1, the dual traction buses of the X-57 traction power system were arranged such that the CMs and HLMs would be symmetrically impacted. Both CMs would lose a single CMC and experience the effects noted for each CM in Section 3.2, resulting in a sudden 50% loss of torque for each CM. Similarly, six of the twelve HLMs would act as discussed in Section 3.4, leading to a 100% loss of torque on the affected HLMs. The symmetric arrangement would be such that the thrust of the aircraft would be reduced to approximately half of the pre-failure condition, but no appreciable thrust asymmetry would exist. This symmetric loss of thrust would be more benign than experienced by a typical twin-engine airplane. A typical airplane would need to account for thrust asymmetry in addition to a 50% reduction in thrust. Furthermore, as part of the reconfiguration, the CMCs on the remaining bus could be operated in an “overdrive” torque condition to provide even more thrust capability for return to base and landing.

3.6 High-Lift Motor Traction Contactor Failure

One unique asymmetric failure that could occur for X-57 Mod IV was the failure of a single traction power contactor connected to one of the high-lift traction buses in a single wing. A depiction of this failure condition is given in Figure 10.

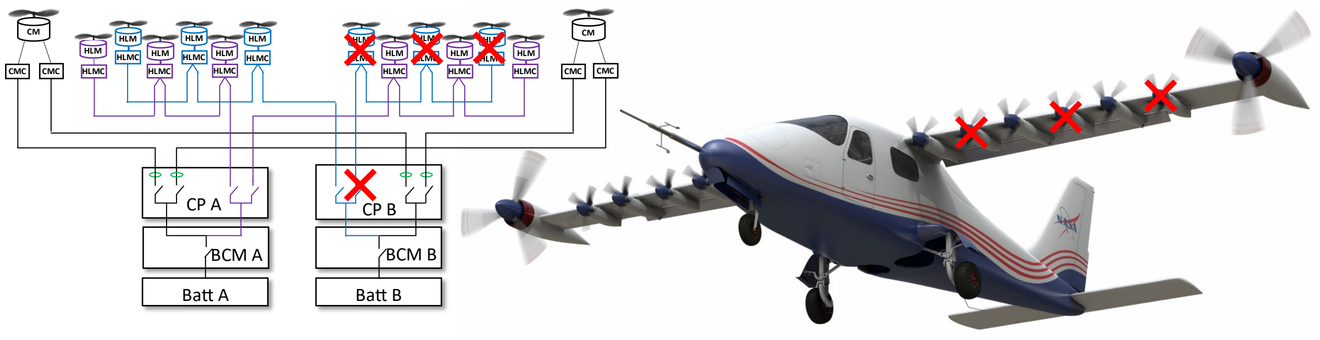

Figure 10 – High-lift motor traction contactor failure.

The loss of a single HLM traction contactor would result in the sudden loss of power and associated torque of three of the six HLMs on one wing. The HLM traction bus was arranged such that this failure would affect every other HLM, rather than three adjacent HLMs. Losing thrust on every other HLM on one wing would result in a loss of thrust and lift that could be challenging, particularly in approach-to-landing conditions where the aircraft would be operating at low speeds and in high-lift conditions with lower power on the CMs. The loss of every other HLM on a wing would also introduce a proverse yaw-roll couple due to the sudden loss of thrust and lift on a single wing, potentially putting the aircraft in a favorable position to enter a spin if the couple was too severe.

3.7 Failures Not Considered for Critical Loss of Thrust

There were several other potential component and system failures that could reduce or otherwise impact thrust production for X-57, but they were not considered for this paper and were generally more benign than the failures listed above or handled via other means. Other failures were not in scope for the X-57 project but could still be considerations for commercial products that use a similar approach as planned by the X-57 team. Some of these failures are listed here for consideration.

3.7.1 Avionics Power System Failures

The low-voltage power system (avionics power) largely repurposed the power distribution bus architecture of the original gasoline-fueled Tecnam P2006T, with changes as appropriate for DC voltage conversion and redundancy management as discussed in Ref. [13]. Since many of the low-voltage components were not a “clean-sheet” design but rather focused on repurposing existing components and pathways, the lessons learned from the avionics power distribution may not be as transferable to new DEP designs. Still, the P2006T avionics architecture provided a redundant and reconfigurable avionics power architecture for all X-57 configurations. In all cases, examination of the impact of single failures of the low-voltage power system resulted in loss of thrust conditions that were no more impactful than the failure conditions listed in Sections 3.1 through 3.6, and in many cases offered additional redundancy and performance.

3.7.2 Total Loss of Traction Power

Given the experimental nature of the X-57 traction power system, the X-57 project carried a hazard associated with total loss of traction power due to an unspecified common mode, design error, or exhaustion of energy storage during the flight tests. Per all estimates, this would take more than a single independent failure, though the flight test team drilled for total loss of power in simulation runs. A discussion of the simulation of total loss of power is given in Ref. [18].

3.7.3 Air Data System

The HLP system included an "airspeed" control mode as discussed in Section 2.3.2 and Ref. [5]. This control mode required access to estimates from the air data system, including equivalent airspeed and altitude, to select the target motor speed in each HLMC. The X-57 was not equipped with a high-reliability, fault-tolerant air data system as may be seen with "fly-by-wire" systems, but rather with a simplex system that could be rendered inoperative with a single fault. Furthermore, each HLMC only had a single data connection to the air data system. The X-57 team instead implemented a "fixed" control mode that would activate in the presence of corrupted, out-of-range, or omitted air data due to a failure in the air data system, the connection to the HLMCs, or in the HLMC communication interface. This "fixed" mode set the target motor speed to a fixed value that was known to produce enough lift to not cause an issue at low speeds in areas of the flight envelope where the X-57 may be using the HLP system for lift augmentation within a few thousand feet of ground level. The "fixed" control mode enabled a much more simple and cost-effective system than a high-reliability, fault-tolerant air data management approach to the HLMCs. The downside was that moving to "fixed" mode may have generated too much thrust from the HLPs to allow for an appropriate descent angle for landing. Rather than attempting to land in this condition, the aircraft would discontinue the landing or would approach at higher airspeeds and land without the HLP system active, much as would be done if an aircraft had a failure in the flap system during approach to landing. Since a failure in the air data system would not result in a "critical" loss of thrust condition it is not considered in this paper.

3.7.4 Other Propeller Failures

The X-57 Mod IV configuration featured a total of 14 propellers – 2 CPs and 12 HLPs. As noted in Section 3.1, the CPs were commercially available, type-certificated propellers. These propellers undergo rigorous testing during type certification and have tight quality controls associated with manufacturing to minimize the probability of catastrophic propeller failures, so these were not considered for the CPs (other than the aforementioned propeller pitch control failures). However, the 12 HLPs were experimental, bespoke designs with five blades each and a single axis folding hinge for each blade. Although several full-scale prototype units were subjected to tens of hours of testing in static and flight-like conditions in a wind tunnel [15], this was not sufficient to determine the reliability of the HLPs. The HLPs were axially separated to reduce the risk of a cascading failure where a shed HLP blade induced a failure in an adjacent HLP assembly [1]. The HLPs were also much lower energy than traditional propeller blades during a separation event—each blade weighed only a few ounces, and at a maximum rotational speed of 5400 RPM and at a diameter of 57.6 cm, the total energy of a shed HLP blade would be miniscule compared to a typical propeller blade separation. As such, failures within the HLP assembly were assumed to have the same effect on performance as an HLM or HLMC failure as described in Section 3.4.

4. Evaluation Approach

The original X-57 flight test approach was to demonstrate flight in the Mod III configuration first without the HLPs, or with the HLPs inactive if they were installed but not yet verified for Mod IV operations. The first activation of the HLP system would occur during Mod IV tests at higher test altitudes to enable recovery from any unexpected adverse events. Only after successful operation was demonstrated at higher test altitudes would the HLP system be evaluated closer to the ground for takeoff and landing handling quality and performance analysis. This cautious approach was taken due to the reliance of the HLP system on the single-string air data system during operation in "airspeed" mode. However, simulation of cruise motor failure scenarios for takeoff in the Mod III configuration resulted in unacceptable performance metrics and poor handling qualities [3]. This led the team to considering combining the Mod III and IV test flights into the Mod IV configuration only, and leveraging the HLPs as a mitigation for critical loss of thrust during takeoff for any flight originally planned for Mod III or IV. This approach would essentially eliminate Mod III as a standalone configuration.

4.1 Distributed Thrust Takeoff

The introduction of a pilot-selectable “fixed” mode for the HLP system, as described in Section 2.3.2 and shown in Figure 4, introduced the potential for a new type of takeoff that used the thrust from the HLPs but did not necessarily rely on the full lift augmentation benefits and thrust deconfliction that necessitated the “airspeed” mode for the landing approach. During development of the HLP control modes, the X-57 flight test team conducted piloted simulations including touch-and-go landings that consisted of repeated takeoffs and landings transitioning right back into takeoffs in the simulated traffic pattern around a runway. The flight test team evaluated these takeoffs using both the “airspeed” and “fixed” modes of the HLP control system. The results indicated that “fixed” mode provided a substantially higher rate of climb than was available in the “airspeed” mode or with the HLP system inactive [5]. Additionally, the “fixed” mode was designed to be very simple in terms of control and data exchange, and reliable operation and thrust production could be verified with ground and wind tunnel tests, greatly lowering the risk of initial HLP operation for takeoff in the “fixed” mode prior to verifying the performance of the “airspeed” mode (generally used for landing) at altitude.

The availability of additional thrust from the HLPs in “fixed” mode for takeoff did not in itself mitigate the dramatic thrust asymmetry that could occur from failure of a single CM at full power and low airspeed, as is typical for takeoff. However, the additional thrust posed an opportunity for reduced power settings from the CMs during takeoff operations without suffering from the very poor rates of climb seen from the Mod III simulations at reduced takeoff power settings. Initial calculations showed that more than sufficient climb rates and greatly reduced thrust asymmetry due to CM failure could occur if the CMs were operated at less than 70% power.

During takeoff operations, the workload of the single pilot of the X-57 included tasks associated with maintaining situational awareness outside the cockpit as well as tasks associated with monitoring critical flight instruments. To manage this workload and mitigate hazards associated with loss of thrust, the team developed a partial thrust takeoff technique called Distributed Thrust Takeoff (DiTTo) that resulted in repeatable power settings without the need for the pilot to look down at the throttle quadrant to adjust the torque or propeller control levers during the takeoff roll. This technique set the propeller controls during the initial ground runup at elevated torque settings to 1800 RPM and then froze the propeller control levers in this position for takeoff. The pilot would then position the aircraft for takeoff, arm the “fixed” mode for the HLPs (which would quickly spin all 12 HLPs up to 4800 RPM), and advance the torque levers to the full forward detent by feel without looking down (127.5 Nm per CMC, 255 Nm per CM). This setting would develop 48 kW of shaft power per CM—about 67% of the full rated power of the CMs. The pilot would then rotate and climb at designated speeds that provided the appropriate margin for stall speed, controllability, and rate of climb in the event of a critical loss of thrust. Upon reaching a safe altitude, the pilot would increase airspeed to the best rate of climb speed in the cruise configuration, configure the airplane for cruise climb (raise landing gear, raise flaps), disarm the HLP system, and climb at cruise climb power (2250 RPM and 255 Nm—approximately 60 kW—for the CMs). At the higher speeds used for cruise climb, the X-57 had sufficient control authority to acceptably counter the transient conditions due to a full loss of a CM prior to reconfiguration and return to base.

4.2 Evaluation of Distributed Thrust Takeoff Technique

The team used the X-57 fixed-base simulation to evaluate the performance and handling qualities of DiTTo [11]. As with other X-57 simulator evaluations, the team used the two X-57 project pilots, both of whom were highly qualified NASA test pilots, to evaluate and compare the control actions and mitigation scenarios. The failure comparisons were conducted at the Mod III takeoff speeds (no lift credit given for operation of the HLPs, even if they were operating) and the Mod IV takeoff speeds (lift credit given for the HLPs operating in fixed mode). These speeds are shown in Table 1.

Table 1 – Speeds used for evaluation of DiTTo technique.

Speed	Mod III Takeoff Configuration (No HLP Lift Credit if HLPs Operational)	Mod IV Takeoff Configuration (Lift Credit from HLPs in Fixed Mode)
Rotation (V_R)	88 KIAS	77 KIAS
Initial Climb ($V_{Y,to}$)	97 KIAS	84 KIAS

Not all the failure scenarios captured in Section 3 were formally captured due to the project ending prior to the flight readiness reviews for the X-57 Mod III and IV configurations. During preliminary investigations, the CP control failure (Section 3.1), CMC failure (Section 3.2), and HLM failure (Section 3.4) did not prove to be remotely critical during initial trials and were instead dominated by the CM failure (Section 3.3), traction bus failure (Section 3.5), and HLM traction contactor failure (Section 3.6). As with the previous Mod III study [3], the team studied multiple failure injection heights, ranging from 10, 50, 100, and 500 ft above ground level (AGL). The pilots were generally aware that they were being evaluated for response to failures during takeoff but were not typically briefed to the exact altitude of the failure trigger, and not all simulated flights involved a failure trigger. Table 2 summarizes the failure conditions that were evaluated, though as noted in Section 5, not all combinations of these failure conditions were able to be evaluated.

Table 2 – Failure conditions applied during evaluation of DiTTo technique.

Failure Condition	Section	Notes
Cruise Propeller Control	3.1	Low impact during takeoff operations, not evaluated in paper
Cruse Motor Controller	3.2	Low impact during takeoff operations, not evaluated in paper
Cruise Motor	3.3	Significant impact during takeoff operations, **evaluated in paper**
High-Lift Motor	3.4	Low impact during takeoff operations, not evaluated in paper
Traction Bus	3.5	Impact on climb but not controllability, **evaluated in paper**
HLM Traction Contactor	3.6	Moderate impact during takeoff operations, **evaluated in paper**
Failure Height	4.2	10, 50, 100, and 500 ft above ground level

Given that the simulated failures occurred on runways with at least 12,000 ft of hard surface available, the pilots were instructed to recover and land straight ahead if possible. Cooper-Harper ratings for handling qualities [19] were established by the pilots during the recovery maneuvers and subsequent landing. The handling qualities tasks involved three different performance targets: bank angle at touchdown, lateral distance from runway centerline at touchdown, and sink rate at touchdown. The adequate and desired values for each performance target are given in Table 3.

Table 3 – Performance targets for piloted simulation handling qualities evaluation.

Performance at Touchdown	Desired	Adequate	Notes
Bank Angle	7.0 deg	9.0 deg	Set by tip prop strike to runway
Distance from Runway Centerline	75 ft	150 ft	Set by extent of hard surface
Sink Rate	Undefined	7.0 ft/s	Set by limit load

5. Results

The end of the X-57 project prior to the Mod III or Mod IV flight readiness reviews meant that the team did not complete a formal test matrix for all of the speeds from Table 1 or all of the failure conditions or failure trigger heights from Table 2. Instead, initial DiTTo evaluations (conducted in 2020 and 2021) focused on the use of HLPs in Mod IV at Mod III takeoff configuration speeds, which implied that HLP operation did not decrease stall speeds in this configuration. The use of Mod III stall speeds had a cascading effect of pushing the rotation speed and climb speeds to higher values since rotation was fixed to a minimum of 10% above the stall speed for the configuration and initial climb speed was constrained to the higher of 20% above the stall speed or the speed for maximum rate of climb for that configuration. At these higher speeds, the fixed-pitch HLPs operating at a fixed RPM produced less thrust and had less impact on the climb rate and lateral/directional control of the aircraft. In later DiTTo trials, the extensive controls database for the X-57 had been completed, and the team felt more confident in providing lift credit for the HLPs in fixed mode for takeoff operations. Hence, later trials (conducted in 2022 and beyond) used Mod IV takeoff configuration speeds when comparing DiTTo to the Mod III configuration at takeoff. Still, a more comprehensive set of trials, using the X-57 simulator configured to the final weights and motor performance maps established during verification, was to be conducted prior to the Mod III and Mod IV flight readiness reviews. The results that follow were extracted from simulator experiments conducted from 2020 through the end of the project in slightly varying configurations and not at all combinations of speeds, heights, and failure conditions.

The use of two project test pilots during the handling qualities evaluation provided an opportunity to evaluate the response of pilots having different familiarity with the aircraft. One of the two pilots worked extensively with the X-57 project team to develop procedures and techniques for nominal and off-nominal operations. The other pilot was intended as a primary crew member for several X-57 flights; however, the assignments of this pilot were such that this individual necessarily spent less time developing techniques and procedures. Though both project pilots would have flown the simulator extensively prior to actual aircraft flights using nominal and off-nominal procedures established prior to the Mod IV flight readiness review, the earlier exploratory flights used to develop the procedures relied heavily on one of the two project pilots. The responses of both pilots are provided in the subsections below, with a note to the reader that procedures for responses to off-nominal conditions had yet to be formalized, so both pilots were relying on their prior experience when responding to failures. One pilot had more direct exposure to simulated X-57 failures and was in the process of developing recovery techniques that were never formalized nor (generally) briefed to the other pilot, resulting in different recovery techniques. Had the X-57 continued into flight operations of the Mod III/IV aircraft, the team would have formalized the failure recovery techniques, and both pilots would likely have approached the same performance.

5.1 Pilot Response to Failures at Mod III Takeoff Speeds

The initial DiTTo comparisons to Mod III takeoff were conducted using the Mod III takeoff speeds from Table 1. The time histories of the left aileron position, rudder position, airspeed, bank angle (φ), roll rate (p), and height above ground were tracked for both project pilots. Figure 11 shows the time histories of the response of pilot 1 for a CM failure in the Mod III configuration, a CM failure in the Mod IV configuration using DiTTo, and an HLP contactor failure in the Mod IV configuration using DiTTo. For these and subsequent figures, the results are shown for failures at 50 ft AGL, which tended to create the most hazardous situations as compared to the other failure heights. This was because the aircraft had enough altitude for the pilots to attempt to respond prior to ground contact but was close enough to the ground that plot response time and technique was critical to a safe outcome.

These time histories show that pilot 1 used large initial aileron and rudder surface position inputs to arrest the roll rates caused by the failure. For the CM failure cases, pilot 1 did not saturate the aileron and rudder controls to arrest the failure with DiTTo (“DiTTo, CM” in the figure) in contrast to the response for the Mod III cruise motor failure (“Mod III” in the figure). The CM failure with DiTTo generated smaller initial roll rate and bank angle upset as compared to the Mod III case. The DiTTo HLP traction contactor failure (“DiTTo, HL” in the figure) resulted in a less pronounced upset that required minor pilot compensation as compared to the DiTTo or Mod III CM failure.

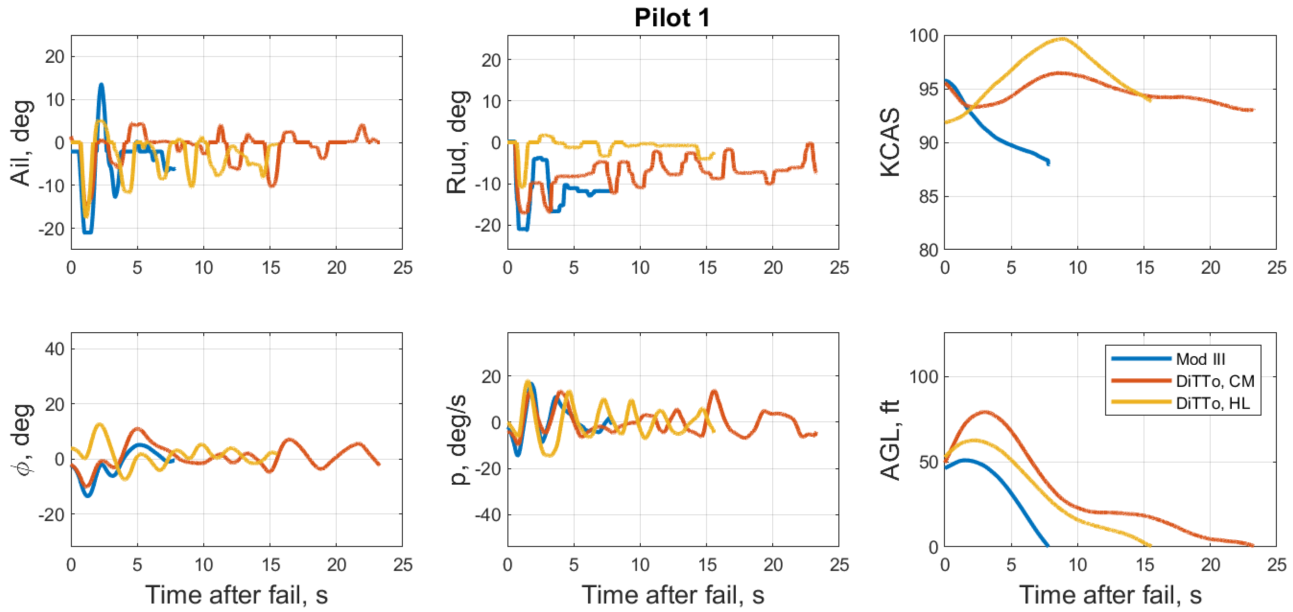

Figure 11 – Time histories from failure at 50 ft AGL to touchdown for pilot 1 at Mod III airspeeds.

The airspeed time history shows that the pilot was not able to maintain airspeed for the Mod III CM failure case and needed to land immediately. As will be shown later, this also led to excessive sink rates that could lead to aircraft damage. Using DiTTo, the pilot was able to maintain an airspeed over 90 KCAS for both the CM and HLP contactor failures, which gave the pilot more time to correct the upset, reacquire the runway centerline, and perform a normal flare to landing.

The response of pilot 2 to the same failure conditions (Mod III CM, DiTTo CM, DiTTo HLP contactor) is shown in Figure 12. Comparison to Figure 11 indicates that pilot 2 used different recovery techniques associated with the failure. As noted previously, the pilots had not yet formalized a technique for failure response at the time of these experiments, so each relied on their own experience and knowledge of the X-57 and its systems, which led to these different responses.

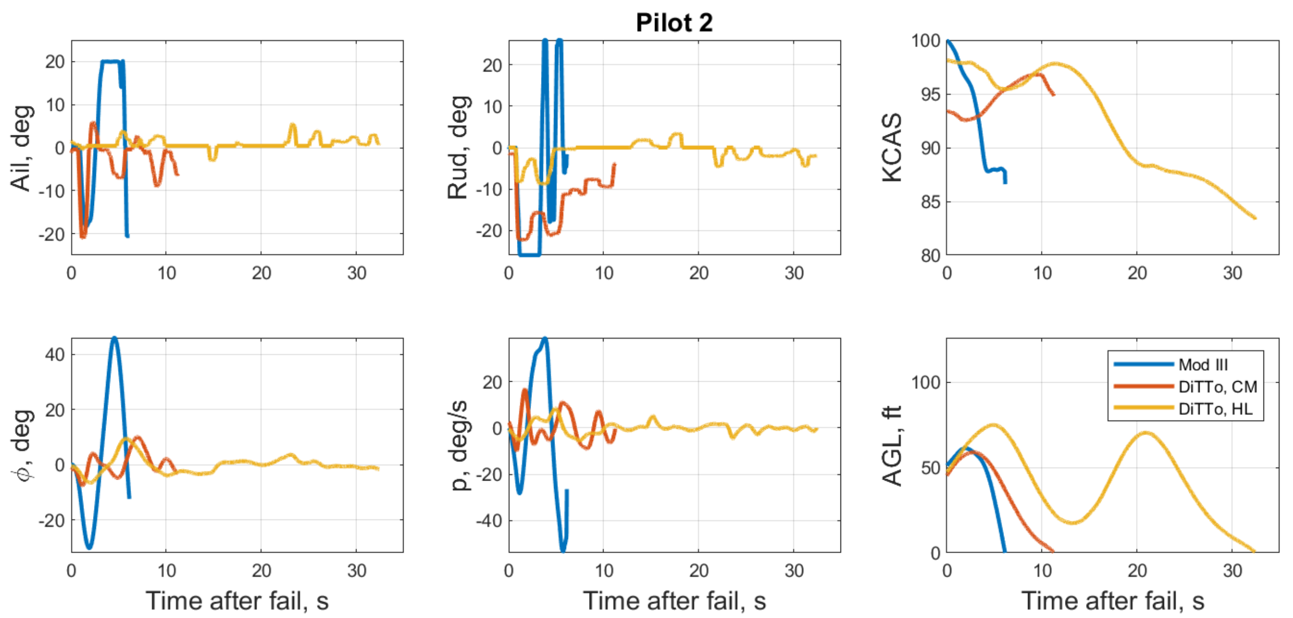

Figure 12 – Time histories from failure at 50 ft AGL to touchdown for pilot 2 at Mod III airspeeds.

In the Mod III cruise motor failure case, pilot 2 quickly saturated the rudder input and nearly saturated the aileron to arrest the initial lateral upset. Pilot 2 then reduced the correction roll rate by initiating control actions in the opposite direction, which again saturated the rudder and aileron. For the DiTTo CM failure case, pilot 2 initiated large rudder and aileron inputs to arrest the initial roll rate but did not saturate the control surfaces. With the DiTTo HLP contactor failure the pilot only used minor control inputs to correct for the failure. Like pilot 1, pilot 2 was able to maintain higher airspeeds after the DiTTo failure cases as compared to the Mod III failure case.

In addition to reducing the lateral and directional excursions due to a CM and HLP contactor failure, DiTTo also provided excess thrust after a CM failure due to the thrust from the HLPs, as well as reduced but trimmable asymmetric thrust from the CM at 67% power. This gave the pilot time and potentially climb capability to redesignate a landing location. With DiTTo, the estimated steady-state, controllable climb capability of the aircraft was 720 ft/min prior to CM failure and 360 ft/min after CM failure at the Mod III climb speed of 97 KIAS. These speeds are compared to the Mod III rate of climb of 430 ft/min with the CMs at 100% power prior to failure and -450 ft/min after a CM failure. The HLP contactor failure resulted in a steady-state rate of climb of 480 ft/min. The post-failure climb capability enabled by DiTTo was important to give the pilot time to manage the failure, work the aircraft back to the runway centerline (or, if necessary, re-enter the traffic pattern for the same runway or redesignate to a new runway), and conduct a normal flare to landing.

5.2 Handling Qualities Evaluation after Failures at Mod III Takeoff Speeds

The performance targets shown earlier in Table 3 were evaluated for the three failures noted in section 5.1 – Mod III CM failure with a full power takeoff, CM failure for a DiTTo takeoff, and HLP contactor failure for a DiTTo takeoff. Figure 13 shows the bank angle at touchdown for both pilots after each of these three failure scenarios overlaid with the adequate and desired performance from Table 3. Similarly, Figure 14 shows the lateral distance from the runway centerline at touchdown, and Figure 15 shows the sink rate at touchdown.

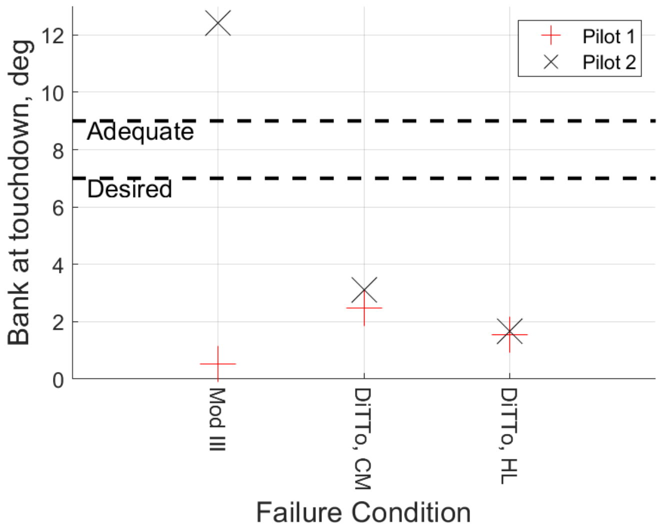

Figure 13 – Touchdown bank angle performance for both project pilots after asymmetric propulsion failures at 50 ft AGL at Mod III airspeeds.

The bank angle performance for the Mod III CM failure indicates that pilot 1 was able to touchdown within the desired performance criteria, but pilot 2 was not able to obtain adequate performance. This extreme bank angle could result in a propeller strike and further hazardous situations. For the DiTTo CM and HLP contactor failures, the bank angles at touchdown were well within the desired criteria for both pilots.

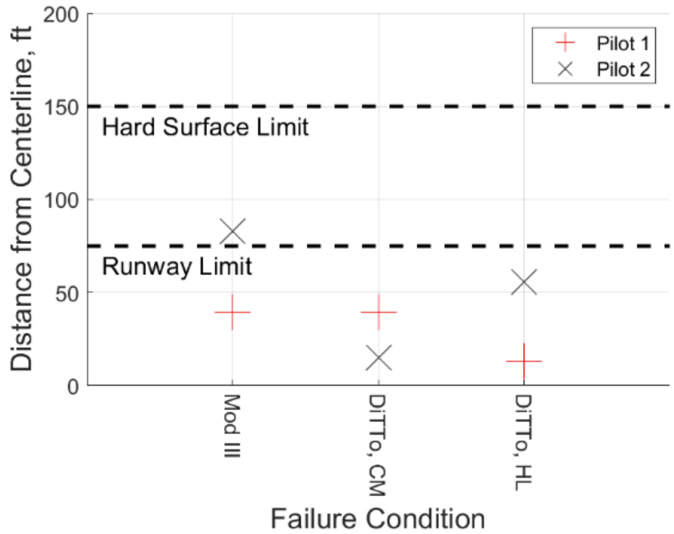

Figure 14 – Lateral distance from runway centerline at touchdown for both project pilots after asymmetric propulsion failures at 50 ft AGL at Mod III airspeeds.

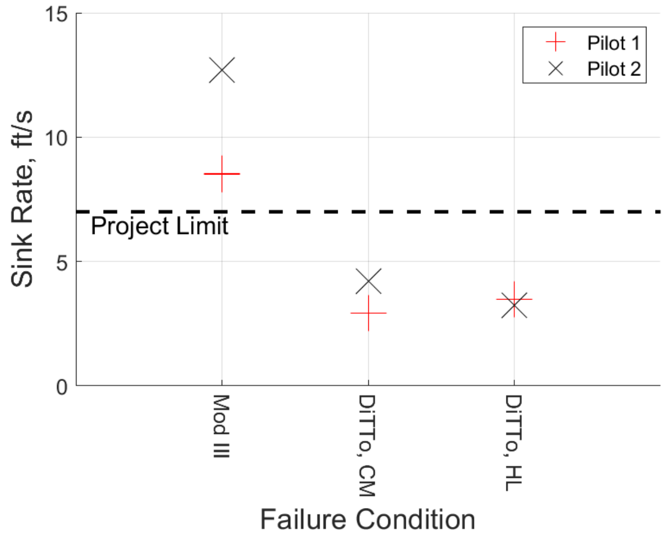

Figure 15 – Sink rate at touchdown for both project pilots after asymmetric propulsion failures at 50 ft AGL at Mod III airspeeds.

The lateral distances from the runway centerline at touchdown and sink rates further indicate the benefits of the time (and excess thrust) DiTTo provides for the pilots to perform a satisfactory landing without introducing other hazards such as off-runway landing or landing at a high sink rate that could damage the aircraft. In the Mod III CM failure case, pilot 2 landed outside of the runway limit but within the hard surface limit, while pilot 1 was able to land within the runway limit. However, both pilots had excessive sink rates beyond the project limit at touchdown, indicating the possibility of damage to the aircraft upon touchdown. For the DiTTo CM failure and HLP failures, both pilots were able to land on the runway and at sink rates below the project limits. This indicates more controllability, time, and excess thrust were available to enable the pilots to avoid introducing additional hazards upon touchdown after these failures.

Cooper-Harper ratings were assigned by the pilots based on the performance objectives from Table 3. A Level 1 rating indicates that no improvement is needed; Level 2 indicates that deficiencies warranted improvement, and Level 3 indicates that deficiencies required improvement. The ratings that the pilots provided for each of the three failure scenarios are seen in Figure 16.

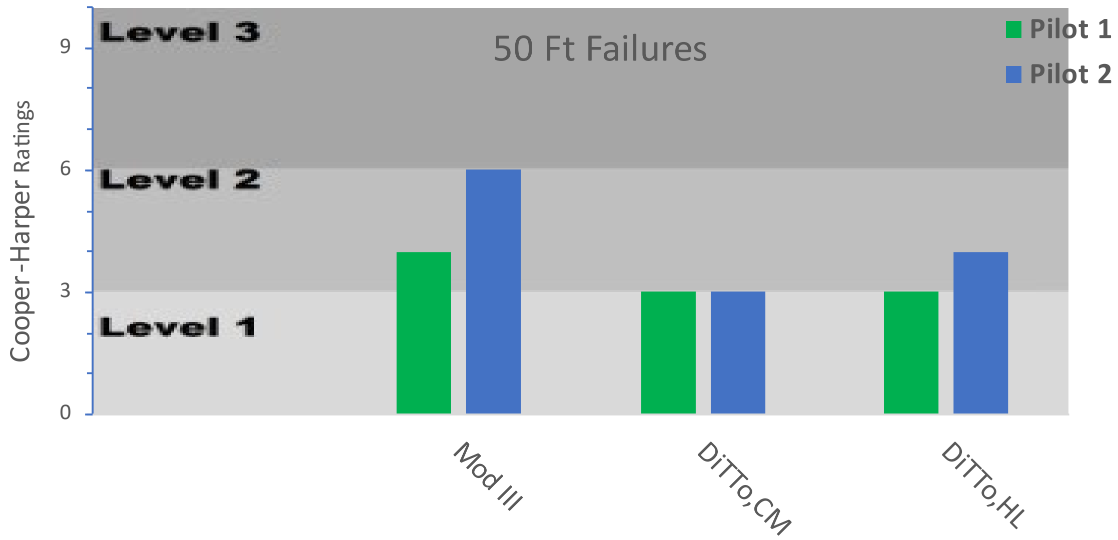

Figure 16 – Cooper-Harper Ratings assigned by project pilots for failure scenarios at 50 ft AGL.

Both pilots assigned a rating to the Mod III CM failure case within the Level 2 region, which corresponded to a large workload to reduce the roll rate and bank from the failure upset. Both gave ratings within Level 1 for the DiTTo CM failure, which indicated that the project pilots felt using DiTTo improved the flying qualities following an abrupt cruise motor failure close to the ground. The HLP contactor failure had mixed ratings, where pilot 1 gave a Level 1 rating while pilot 2 gave a Level 2 rating. Pilot 2 found that the flying qualities were acceptable, but the failure itself was harder to diagnose, leading to the higher rating.

5.3 DiTTo at Mod IV Takeoff Speeds

Evaluations later in the program focused on DiTTo at reduced takeoff speeds that could take credit for the lift augmentation of the HLPs in fixed mode given the higher-resolution, higher-fidelity aero database available to the team. These later DiTTo evaluations used the lower rotation and initial climb speeds seen in Table 1. The time histories of aileron deflection, rudder deflection, bank angle, roll rate, airspeed, and altitude above ground level from the time of a DiTTo CM failure to touchdown at Mod III and Mod IV airspeeds are given in Figure 17 for pilot 1 and Figure 18 for pilot 2.

Figure 17 shows that pilot 1 employed similar control techniques in both takeoffs which resulted in similar bank angle and roll rate performance. Pilot 2 experienced a larger initial bank angle upset for the Mod IV takeoff speeds case. Inspection of the time history for altitude and airspeed shows that pilot 2 continued to climb with decaying airspeed rather than to trade climb rate for increased speed, which led to lower lateral controllability characteristics. Once they recovered from the upset, both pilots used the extra thrust from the high-lift system to gain speed in the Mod IV takeoff speed cases.

The slower Mod IV climb speeds resulted in a better rate of climb as compared to a DiTTo takeoff with Mod III speeds. Nominally (with no failures), climbing at the reduced Mod IV climb speed resulted in a climb rate of 1000 ft/min. In the failure condition, the Mod IV climb speed resulted in a climb rate of 530 ft/min after a CM failure and of 740 ft/min after an HLP contactor failure. The ultimate choice of climb speeds for DiTTo would be a tradeoff between the potentially more marginal handling qualities at the slower Mod IV climb speed versus the increased rate of climb after the failure.

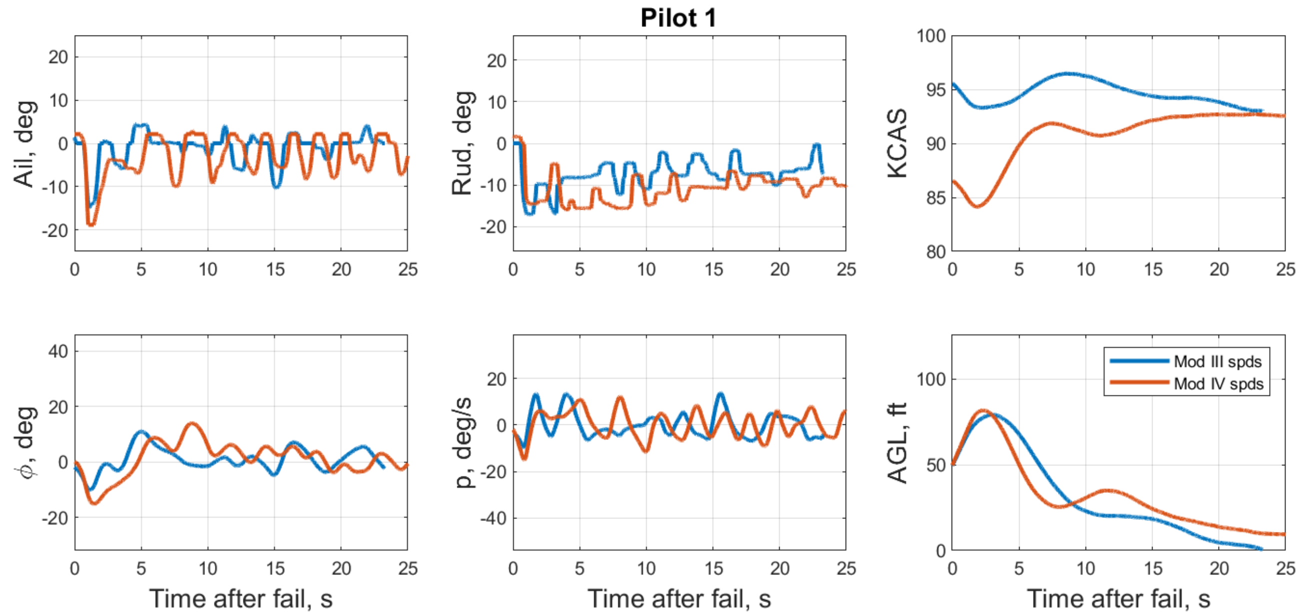

Figure 17 – Time histories from CM failure at 50 ft AGL to touchdown for pilot 1 using DiTTo at Mod III and Mod IV airspeeds.

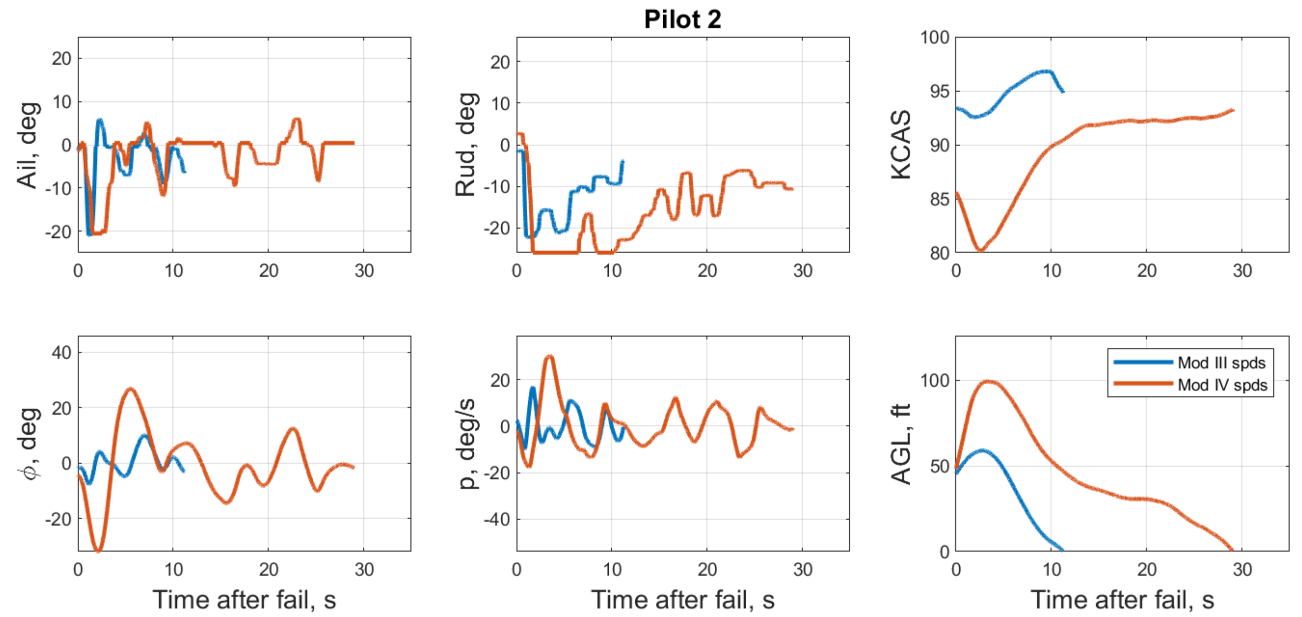

Figure 18 – Time histories from CM failure at 50 ft AGL to touchdown for pilot 2 using DiTTo at Mod III and Mod IV airspeeds.

5.4 Traction Bus Failure

A traction bus failure would result in a completely symmetric loss of thrust. Each of the CMs would immediately go to 50% power, and six of the 12 HLMs (three on each wing) would go to 0% power. In the Mod III configuration, the traction bus failure reduced the rate of climb to -300 ft/min. For DiTTo, the rates of climb after a traction bus failure were -100 ft/min at the Mod III speeds and 100 ft/min at the Mod IV speeds. In the Mod III case, the rate of climb could be increased by moving to the Overdrive region of the torque lever as discussed in Section 2.3.2. In the case of DiTTo, the propeller RPM control could be increased from 1800 RPM to generate more power, or the torque levers could be placed in the Overdrive region. The rates of climb were not established in either of these post-failure reconfiguration options. The handling qualities and pilot workload after this failure were benign.

6. Summary and Conclusions

Distributed electric propulsion technology can enable new aircraft configurations with many more propulsors than traditional aircraft, including propulsors only used for certain phases of flight. The arrangements of these distributed propulsion systems may be such that layered redundancy and degradation features are possible that are not typical of traditional aircraft. Though increased redundancy and connectivity between propulsion systems represents new opportunities for aircraft designers and operators, it also represents new challenges for certification of these distributed propulsion configurations since traditional airworthiness rules may not accommodate failures that cross past the boundary of one engine inoperative analysis. The 2017 update of the airworthiness rules for Normal Category airplanes [8] changed the nomenclature for performance requirements associated with one engine inoperative to loss of thrust. Similarly, the critical situation for a particular performance-based requirement under the new airworthiness rules considers critical loss of thrust in the place of critical engine inoperative [9]. Although this is an important change that allows for the possibility of new and novel propulsion arrangements, no generally accepted definition for critical loss of thrust has been provided other than ASTM F3179, which states that loss of thrust means one engine inoperative for conventional reciprocating or turbine engine-powered airplanes [10]. This standard does not provide guidance for non-conventional airplanes regarding loss of thrust.

NASA's X-57 Mod IV distributed electric propulsion flight demonstrator concept utilized 14 different electric propulsors with an intertwined power and command distribution system designed to gracefully degrade in the event of a failure of any single component. This degradation may still have reduced or eliminated output of more than one propulsor after a single failure, leading to a loss of thrust situation greater than a traditional one engine inoperative assumption. This paper investigated several failure scenarios and identified those that may be considered critical for takeoff performance. Of the six failure scenarios discussed in detail, three were evaluated in the X-57 fixed-base piloted simulator using the two project test pilots. These three failure scenarios were (1) the total failure of one of the wingtip-mounted cruise propulsors, (2) loss of three of the six high-lift propulsors on a single wing from an electrical contactor failure, and (3) symmetric loss of half the power to each of the cruise propulsors and total loss of power to six of the twelve high-lift propulsors due to a failure of one of the traction power buses. Failure scenarios (1) and (3) were evaluated in the Mod III configuration with full power applied to the cruise motors, and scenarios (1), (2), and (3) were evaluated in the Mod IV configuration in the DiTTo technique. With DiTTo, the high-lift propulsors were operated in the "fixed" control mode, and the cruise propulsors were operated at maximum nominal torque but reduced propeller RPM for approximately 67% of rated power to reduce the otherwise large asymmetric moments that could occur with a sudden wingtip cruise propulsor failure. The DiTTo failures were evaluated using takeoff speeds defined by two stall speeds—one set for which HLP operation was not assumed to reduce stall speed (Mod III) and one for which HLP operation was assumed to reduce stall speed (Mod IV). Table 4 provides a summary of climb rates and associated gradients from the simulator flight experiments for these different configurations, airspeeds, and failure cases at the flight conditions expected on a typical day at the NASA Armstrong Flight Research Center test range.

The investigation of these failure scenarios showed that the best climb performance could be obtained using the DiTTo technique with takeoff speeds based on the reduced stall speeds associated with HLP operation (Mod IV climb speeds). For the Mod III configuration, the most critical performance condition was the cruise motor failure. The extreme thrust asymmetry with cruise motor failure in the Mod III configuration resulted in higher drag and generally unacceptable steady-state conditions. For DiTTo, the most critical climb performance case was the traction bus failure, which still resulted in a mild sink rate at the Mod III speeds but a mild climb gradient at the Mod IV speeds. However, given that the cruise propulsors were at a lower propeller speed for DiTTo, and that the propulsors had an Overdrive region capable of providing more torque from a single cruise motor controller in the single-traction-bus configuration, the climb capability of the Mod IV aircraft using DiTTo could improve after reconfiguration to higher propeller speed or cruise motor torque.

Table 4 – Summary of climb rates and gradients of climb for various X-57 configurations and failure scenarios at a density altitude of approximately 2500 ft.

Configuration / Failure	**Mod III Climb Speed (97 KCAS)**		**Mod IV Climb Speed (84 KCAS)**	
	Rate of Climb	Gradient	Rate of Climb	Gradient
Mod III | None	430 ft/min	4.2%	N/A	N/A
Mod III | CM	-450 ft/min	-4.4%	N/A	N/A
Mod III | Traction Bus	-300 ft/min	-2.9%	N/A	N/A
DiTTo | None	720 ft/min	7.0%	1000 ft/min	11.2%
DiTTo | CM	360 ft/min	3.5%	530 ft/min	6.0%
DiTTo | HLP Contactor	480 ft/min	4.7%	740 ft/min	8.3%
DiTTo | Traction Bus	-100 ft/min	-1.0%	100 ft/min	1.1%

The critical loss of thrust investigation of the X-57 included evaluation of handling qualities using targets for bank angle, lateral distance from runway centerline, and sink rate at touchdown. Several failure heights were investigated, but the failures at 50 ft AGL were found to result in the highest workload and most adverse conditions for the project test pilots. The results showed that the Mod III aircraft had poor to marginal handling qualities in the event of a cruise propulsor failure—not a surprise given the extreme asymmetric moments that could develop with such a failure of a wingtip propulsor. The handling qualities were found to be, at best, Level 2, with significant potential to damage the aircraft during landing after the failure. The pilots found the failure to be quite dynamic with little time to recover and land. Furthermore, landing generally resulted in high sink rates and possibly unacceptable bank angles and lateral distances from the runway centerline.

Investigation of the handling qualities for cruise propulsor failure or HLP contactor failure when using DiTTo indicated good to marginal handling qualities for both failures. The pilots noted the lack of extreme dynamics after the failures and the increased excess thrust after failure would enable reconfiguration and landing redesignation. Both pilots were able to land well within the adequate ranges of bank angle, lateral distance from runway centerline, and sink rate.

Though the X-57 project concluded without flight, the lessons learned from the design of the distributed electric propulsion architecture and system failure assessment can be used to help future aircraft designers develop systems and demonstrate compliance with critical loss of thrust requirements. The development of a high-lift propulsor control architecture with two straightforward but effective control modes enabled better tailoring of HLP system use for takeoff and landing, and ultimately enabled X-57 to use reduced cruise propulsor power settings to mitigate hazards associated with asymmetric moments due to cruise propulsor failure. Use of techniques such as DiTTo may enable safer, higher-performing designs in the complex failure scenarios that can occur with highly integrated and distributed propulsion system architectures.

7. Contact Author Email Address

nicholas.k.borer@nasa.gov

8. Copyright Statement and Acknowledgements

This work was funded by the NASA Aeronautics Research Mission Directorate. Initial funding came from the Convergent Aeronautics Solutions Project within the Transformational Aeronautics Concepts Program, and funding for later efforts was provided by the Flight Demonstrations and Capabilities Project within the Integrated Aviation Systems Program.

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