X-57 Flight Controls Lessons Learned

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Committee Meeting #133, 20-22 November 2024

Overview

- X-57 Program Background
- Project Lessons Learned
- Flight Controls Role on X-57
  - Mod III/IV Cruise Motor Failure Evaluations
- Flight Controls Lessons Learned

X-57 Program Background

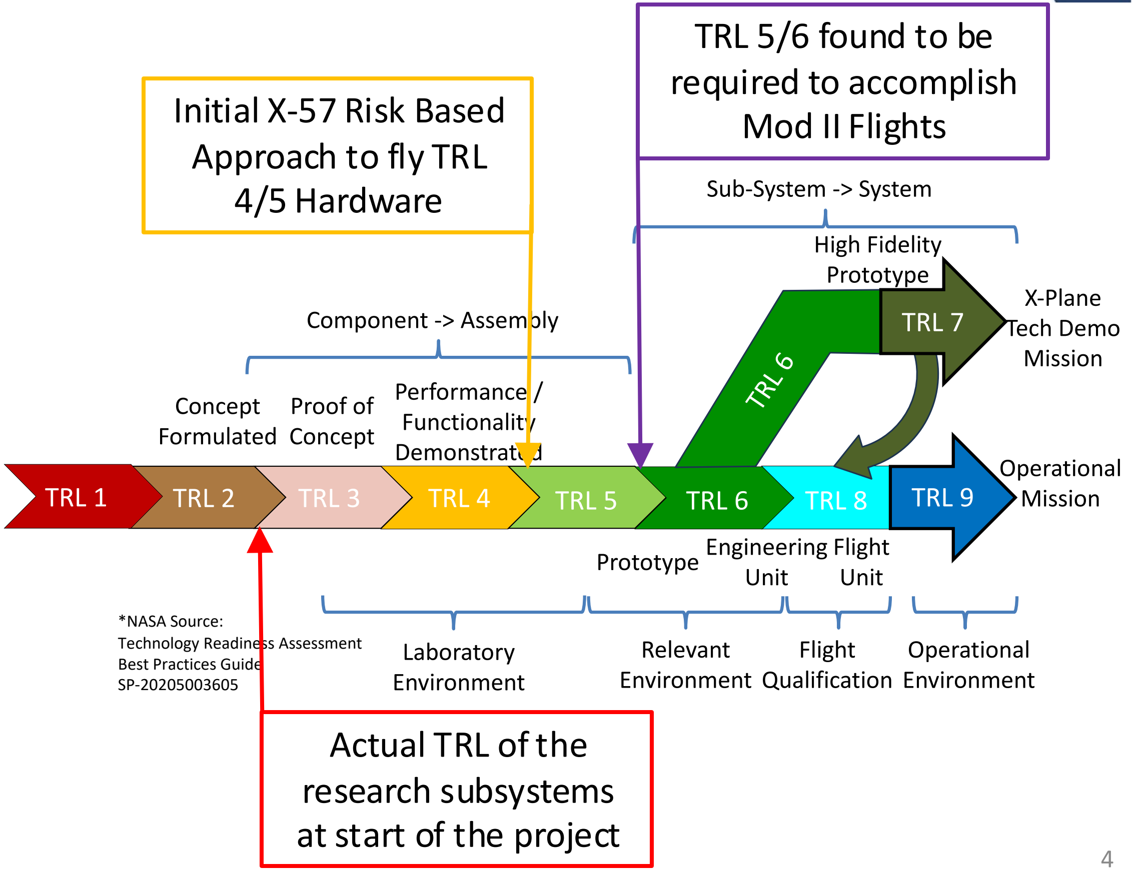
X-57 is NASA's Flight Demonstrator for *Distributed Electric Propulsion Technology (DEP)*

- **Project Goals**: generate data and procedures and share these with academia, industry, standards organizations, and regulators to enable design and certification of DEP concepts
- **Project Approach**: spiral development through multiple design "Mods"

Mod I: Flight Testing of the baseline Tecnam P2006T	**Mod II:** Retrofit a baseline General Aviation aircraft with an electric propulsion system.	**Mod III:** Modify the configuration with a cruise-optimized wing and distributed electric propulsion system.	**Mod IV:** Design for adequate low speed takeoff and landing characteristics with an integrated DEP system.
Mod I provides baseline data 	Mod II reduces risk for Mods III and IV: 	Mod III provides cruise speed data for DEP designs, technologies and systems: 	Mod IV provides low speed data for DEP designs, technologies and systems: 

X-57 Technology Challenges

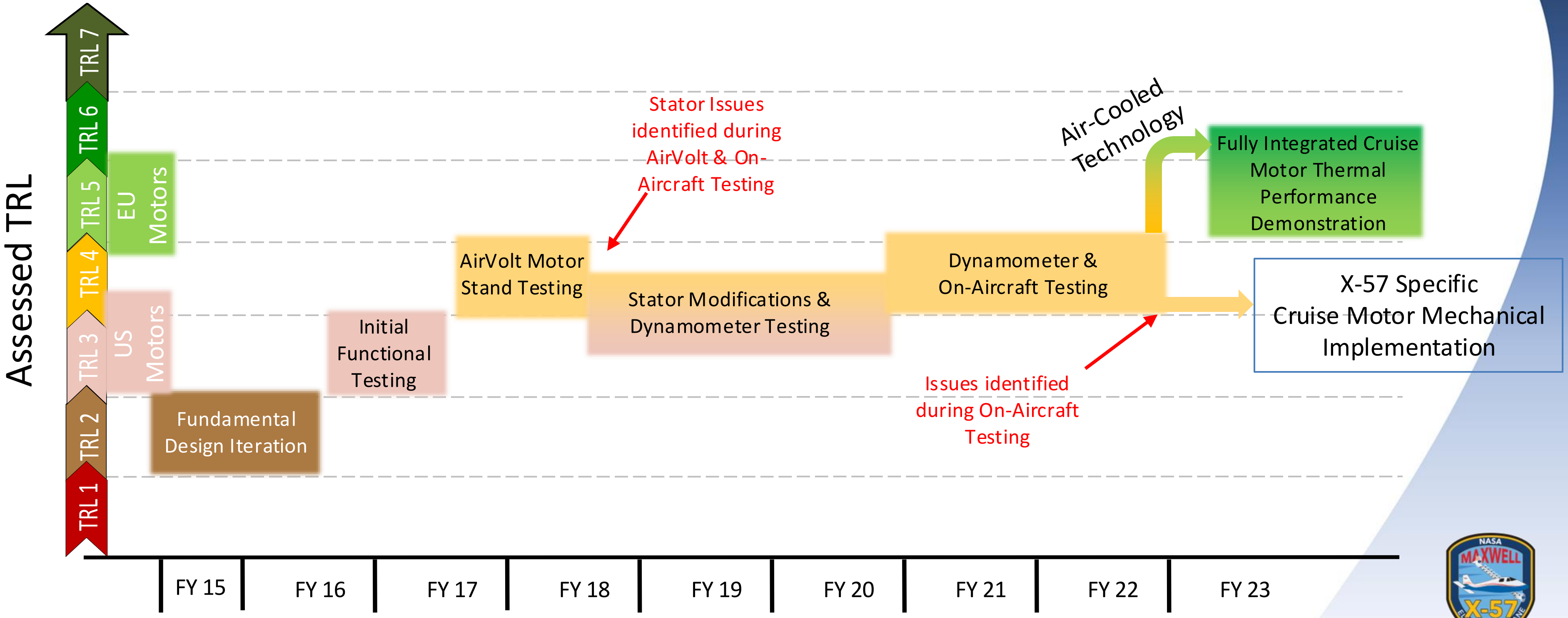
- For X-57, nearly all aircraft subsystems were at a lower TRL or impacted by the new subsystems
  - Initial approach was to purchase motors, controllers, and batteries from European companies that had the highest TRL at the time
    - Directed to procure hardware at lower TRL from American companies to stimulate nascent electric aircraft industry
  - Met significant challenges while developing and integrating lower TRL hardware for a flight project.
- X-57 embarked on subsystem development efforts to advance the key technologies to the TRL 5/6 range when the challenge of flying lower TRL hardware became apparent



X-57 Cruise Motor Approach Background

- The Original X-57 Subproject Goal was to develop and flight-test a Distributed Electric Propulsion (DEP) wing
  - Project assumed flight-proven hardware available for the required subsystems
- X-57's implementation strategy based in part on the assumption that the required electric aircraft subsystems were at a higher TRL
  - Given this assumption, no subsystem design reviews were needed
  - Project team was structured based on the higher TRL assumption, so no significant rotating machinery expertise was present on the team
- The Project team's specifications and design decisions were focused on reducing weight and ensuring ease of assembly/disassembly

X-57 Air-Cooled Cruise Motors TRL Advancement



Project Lessons Learned

- Subsystem design reviews with independent subject matter experts are a necessary component of the systems engineering process, even when assuming the product is at a higher technical maturity
  - Important to actively reassess TRL and the system wide impacts if the TRL of a subsystem drops, rather than triaging one thing at a time
- Because of unplanned development and technical challenges, X-57 was consistently working towards a flight milestone that was a year away
  - Could not stop to redesign, test, and allow for development of technology that was on critical path to flight

Flight Controls Role on X-57

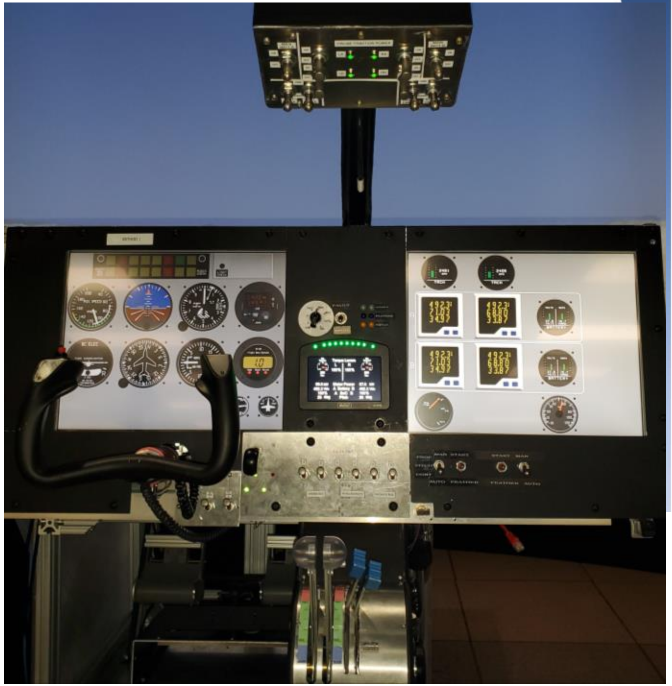
- Assess aircraft airworthiness
  - Sim based pilot evaluations examine off nominal conditions in each Mod
    - Single motor failures, propeller failures, electric failures, etc.
      - Developed and evaluated key mitigations to cruise motor failures via failure scenarios
  - Linear and batch sim analysis done to examine aircraft stability across airspeed and altitude envelopes
  - Trim studies done across airspeed and CG envelope to ensure adequate control authority
    - Verified that the Mod IV high-lift system allows the vehicle to trim at Mod II airspeeds
- Mission planning and emergency procedures developed with simulation inputs
  - Determined takeoff procedures for altitude above ground to retract gear and maximum altitude for straight-ahead landing
- HSI training and pilot feedback
  - Developmental displays were evaluated by project pilots in simulator before being integrated on the aircraft

AFRC Piloted Simulator Cockpit

- Simulator cockpit uses a combination of aircraft switches and simulated instrument panel
  - Simulates start up and shutdown procedures based on aircraft cockpit video
  - Provides aural alerts and visual emergency alerts during failure scenarios
    - Synched with motor, propellor and power failures
- Capability to switch between Mod II and Mod III/IV cockpit

Mod II Aircraft

Mod II Piloted Simulator



Mod III/IV Takeoff Evaluations

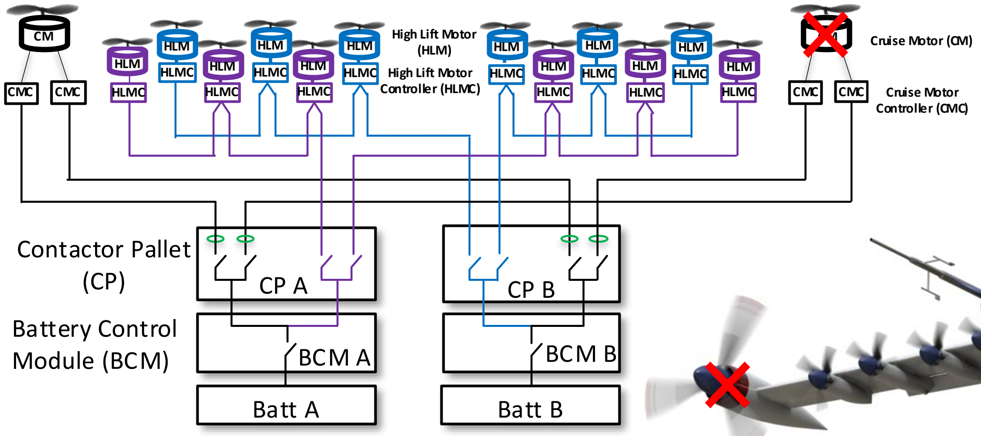
- Mod III takeoffs near minimum control speed while at full power leads to potentially hazardous situation
  - Requires changes to takeoff operations or automatic supervisory system to mitigate
    - E.g., Increased takeoff speeds, lower power takeoffs, automatic thrust inhibitor
      - R. Wallace, "Mitigation of High Lateral Asymmetry Rates Due to Loss of Cruise Motor on Mod III X-57", AIAA 2024-4210, July 2024.
- Mod IV Distributed Thrust Takeoff (DiTTo) used to augment initial climb rate and increase safety
  - Wingtip motors at reduced power (1800 RPM & full torque = ~2/3 peak power)
  - Operate with high-lift motors in fixed RPM mode
    - Provides consistent thrust along wingspan during takeoff

	Mod II	Mod III	Mod IV DiTTO
Vs1 (kts)	60	80	70
Vy (kts)	72	96	84
Vmca (kts)	60	86	73

Cruise Motor Failure Test Conditions:

- Unmitigated cruise motor failure (Mod III takeoff)
  - Vr = 88kts, Vy = 97kts, RPM = 2700 (max)
- DiTTo High-lift system contactor failure
  - 3 motors on one side fail
  - Vr = 77kts, Vy = 84kts, RPM = 1800
- DiTTo Cruise motor failure
  - Vr = 77kts, Vy = 84kts, RPM = 1800
- Failure at 50 ft AGL during takeoff climb
- Cooper-Harper Ratings
  - Desired: < +/- 7 degrees bank at touchdown
  - Adequate: < +/- 9 degrees bank at touchdown

Simulated Failure: Cruise Motor

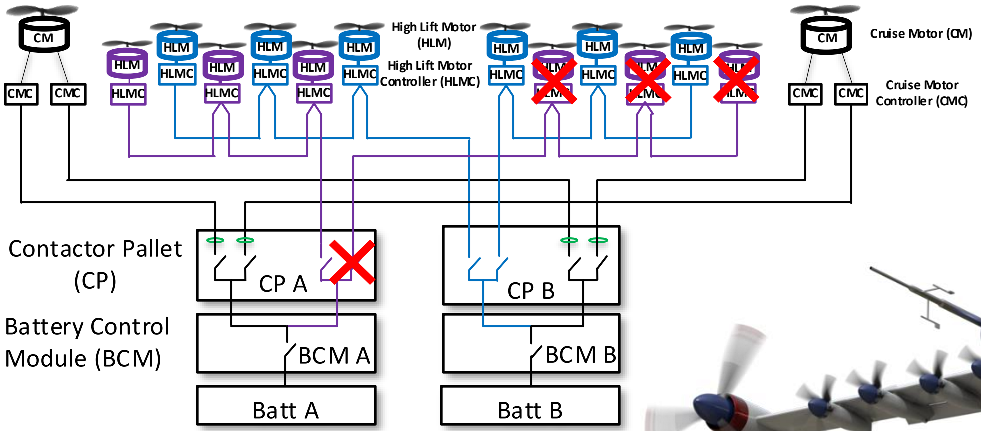


- Simulates complete loss of thrust to one or both cruise motors
- In Mod III and IV, unable to maintain altitude and airspeed
- High workload during takeoffs due to large asymmetric transient combined with lack of control authority
  - 3x increase in roll and yaw moment compared to Mod II

Mod III Takeoff Cruise Motor Failure

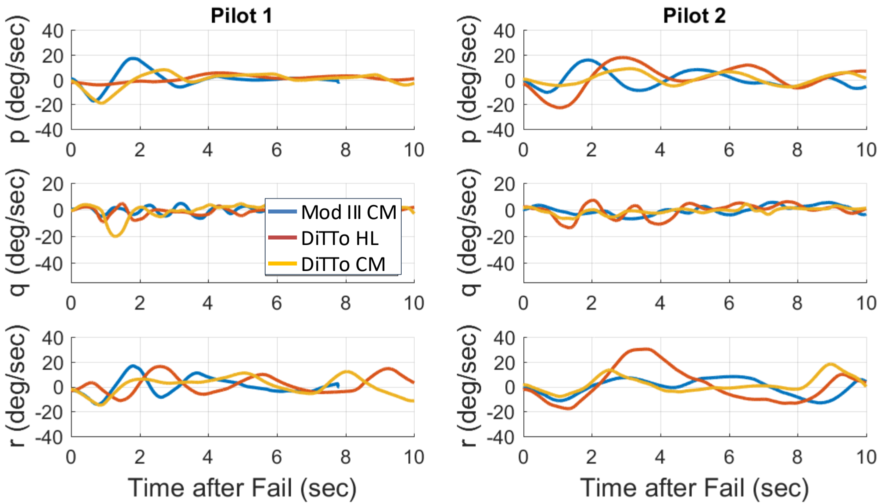
Mod IV DiTTo Cruise Motor Failure

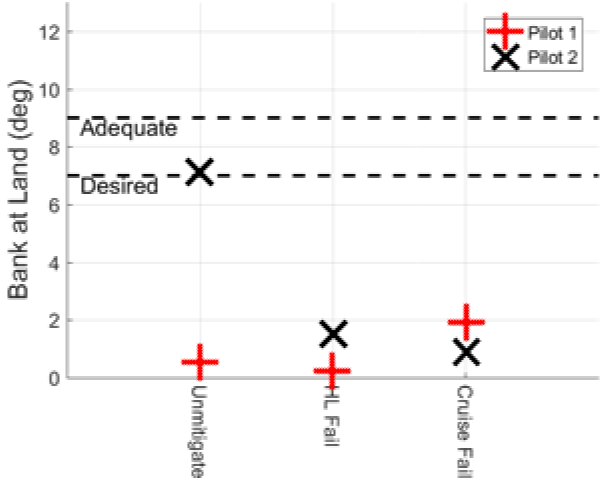
Simulated Failure: High-Lift Contactor



- Results in loss of three HL motors on one side
- Transient is manageable with training

Motor Failure with DiTTo Results

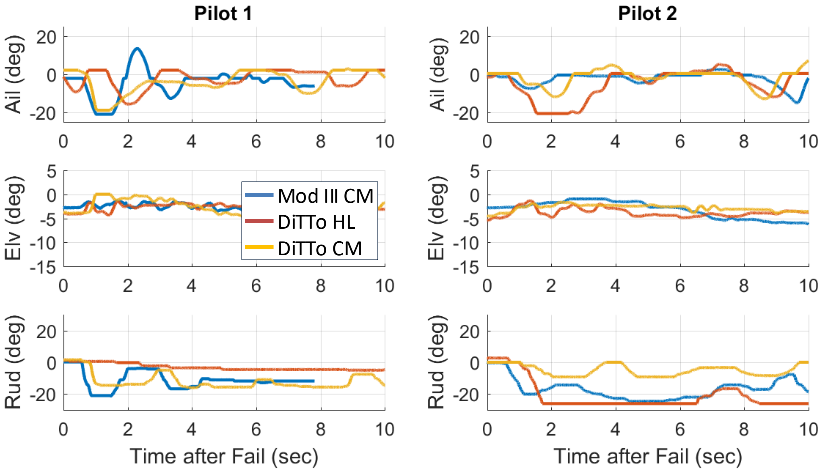


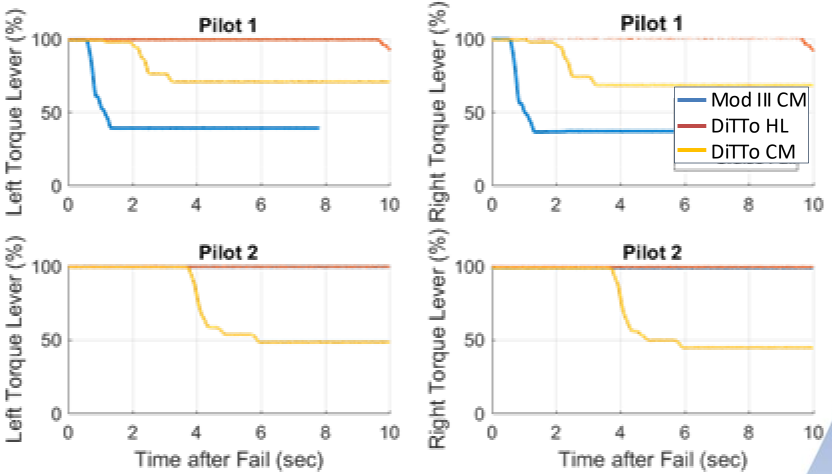


- Roll rates incurred during DiTTo cruise motor failure were quickly reduced by both pilots compared to unmitigated case
- During DiTTo cases, the pilots were able to laterally work their way back to centerline after recovering from initial upset
  - Unmitigated case required immediate landing due to lack of energy

- Pilot 1 and Pilot 2 achieved desired for the DiTTo cases
- Pilot 2 achieved adequate for the unmitigated case

Pilot Control Inputs



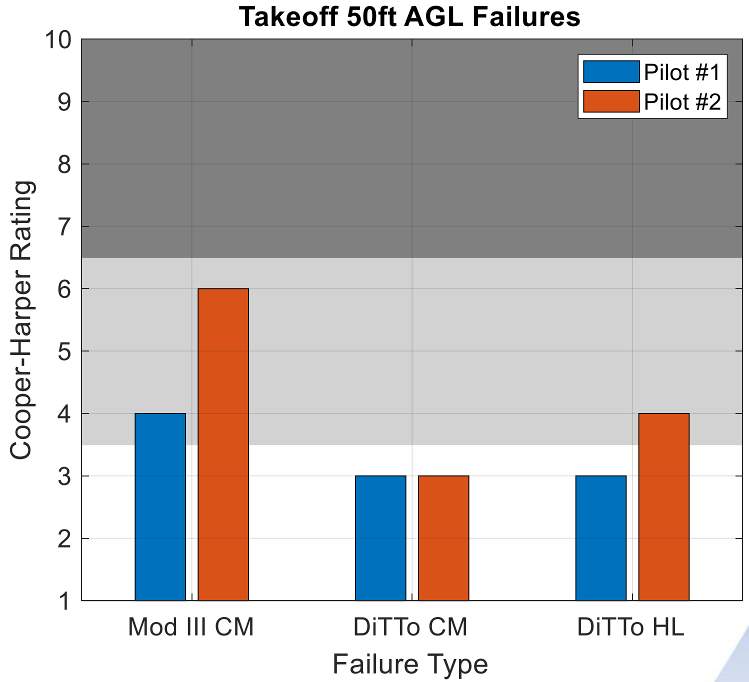


- Both pilots had quick, aggressive control surface within the first second after failure
- Pilot 1 performs a “bunt” to pitch down the aircraft and maintain airspeed after recognizing failure
- DiTTo cruise motor failure require less control input to recover by both pilots

- Pilot 1 pulled throttles back to around 50% in unmitigated case to reduce asymmetry
- Both pilots did not adjust torque lever for HL fail
- Pilot 2 uses throttle position in DiTTO cruise motor failure after initial recovery with ailerons and rudder

Motor Failure with DiTTo Flying Qualities

Failure Case	Pilot Comments
Mod III Cruise Motor Failure	• No time for inputs other than open loop commands into power levers and control surfaces • Airspeed critical to recovery, very technique dependent • Training will be key to survival
DiTTo Cruise Motor Failure	• Lateral upset felt as dynamic as unmitigated case • Thought the upset was dynamic but controllable • Excess thrust help provide enough energy to recover and setup for touchdown
DiTTo HL Contactor Failure	• Had plenty of energy to recover and correct back to centerline after upset • Used HL disarm button on yoke quickly after failure to remove asymmetry • HDD warning lights helped diagnose failure



Pilot assigned rating using CH flow chart
Level 1 = No improvement needed
Level 2 = Deficiencies warrant improvement
Level 3 = Deficiencies require improvement

Motor Failure with DiTTo Conclusions

- DiTTo significantly reduces the pilot workload in the event of a cruise motor failure
  - After the failure, the high-lift system provides enough thrust for the aircraft to maintain altitude and airspeed while setting up for landing
- DiTTo introduces a new potential asymmetric event with the loss of several high-lift motors simultaneously
  - The asymmetry introduced with this event is overcome by the thrust from the cruise motors

Flight Controls Lessons Learned

- Developing a simulator with high fidelity models allows pilots to become familiar with operating the research system early in the life of the project
  - Key models for the X-57 simulator include the aerodynamic, failure modes, and battery models
  - Pilots were able to train and collaborate on best practices for energy assessment and emergency response procedures well ahead of flight testing
- An accurate simulated cockpit provided an ability for pilots and HSI experts to evaluate and provide feedback on early prototypes of cockpit displays and alerts
- Having pilots fly and evaluate development models of the simulator can help quickly identify modeling errors

Questions?

Sim Model Development

- Propulsion and Battery Model
  - Motor Model: proportional torque command
    - Torque lever position to command mapping duplicated from cruise motor controller software
    - Includes over-speed and under-speed protection logic
  - Prop Model: constant speed system calibrated to the manufacturer provided performance data
    - Blade Element analysis (Xrotor) with detailed propeller geometry
  - Battery Model: estimate state of charge and cell temperatures
    - Thevenin Equivalent Circuit Model
      - Experimental data collected from battery cell testing matched with model computed values to determine Thevenin equivalent circuit variables
  - Includes Motor, Propeller and Power Failures
- Aerodynamic Model
  - Mod II model
    - Utilized Tecnam published data and PID analysis from instrumented Tecnam flights
  - Mod III and Mod IV model
    - Combination of CFD analysis power-off aerodynamic, cruise motor effects, high-lift motor effects and propulsion failures
      - Includes CFD modeling of rate derivatives and uncertainty parameters on aero coefficients