Materials Research Proceedings 69 (2026) 650-655 https://doi.org/10.21741/9781644904251-115

Automated Flight Testing of a Distributed Electric Propulsion Flying Model

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Keywords: Distributed Electric Propulsion, Aero-Propulsive Interaction, Automated Flight Testing, Model Identification

Abstract. This work presents the development and implementation of a fully automated flight testing methodology for the SwitchMaster, a Distributed Electric Propulsion (DEP) demonstrator designed to investigate aero-propulsive coupling effects. Previous manual flight campaigns were limited by variability in trim conditions and inconsistent excitation inputs, constraining both data quality and the range of blowing conditions achievable in flight. The proposed framework integrates mission design, nonlinear Simulink simulation, Software-in-the-Loop validation and autonomous flight through the onboard PX4 autopilot, forming a coherent and reusable flight test suite. A total of 38 autonomous missions and 141 maneuvers were conducted across an expanded envelope of airspeeds and climb angles, enabling exploration of blowing regimes previously inaccessible. Automated trim acquisition and maneuver execution significantly improved repeatability and reduced variability in key stability and control derivatives, yielding clearer trends with the propeller advance ratio J and enhancing subsequent model-identification fidelity. The methodology provides a robust foundation for future DEP research, control-law development and aero-propulsive modelling.

Introduction

Distributed Electric Propulsion (DEP) represents one of the most promising technological pathways for future sustainable aviation. By distributing multiple propellers along the wing, DEP enables aero-propulsive coupling effects that can enhance lift, modify stability characteristics and introduce new opportunities for vehicle control. The SwitchMaster demonstrator (Fig. 1), a scaled aircraft equipped with six wing-mounted electric motors, was developed within this broader research effort to experimentally investigate these phenomena. Previous work focused on establishing the AeroSwitch [1] concept and on developing modeling strategies capable of capturing the influence of the propeller advance ratio J on aerodynamic derivatives [2]. These studies demonstrated the potential of DEP architectures but also highlighted the need for more refined flight data to support accurate model identification.

In this context, the present contribution describes the transition from manual to automated flight testing, providing the methodological foundations required to acquire consistent, repeatable and high-quality flight data, widening the spectrum of the conditions to be tested with respect to previous campaigns. The development of an autopilot, based on a Total Energy Control System [3], and the associated control logic is addressed in a complementary article [4], while another contribution focuses on advanced modeling and identification techniques [5]. Here, attention is devoted to the experimental framework that supports those efforts, with particular emphasis on trim stabilization, maneuver execution and the resulting improvements in data fidelity.

Figure 1: The SwitchMaster before a test flight.

Limitations of manual Flight Testing

Initial test campaigns relied on a remote pilot to perform trim and excitation maneuvers [6]. Although adequate for preliminary qualitative analyses, manual piloting introduced intrinsic variability that limited the reliability of the collected data. Achieving a stable trim condition requires finely balancing airspeed, climb angle and control surface deflections, a task that proved difficult to perform consistently across multiple repetitions. Even small deviations in the steady-state flight condition resulted in significantly different levels of propeller blowing and, consequently, different values of the aerodynamic coefficients at the start of each maneuver.

Similarly, manual execution of elevator, aileron or rudder doublets and 3-2-1-1 inputs leads to variations in amplitude, timing and input shape, reducing the effectiveness of the excitation and making it challenging to isolate specific dynamic modes such as the short-period and Dutch-roll.

Moreover, high-blowing conditions typically require trimming the aircraft in steep climbs, a regime that was difficult to maintain manually with sufficient precision. These limitations motivated the development of a fully automated testing system, capable of reproducible trim settings and consistent maneuver execution across the entire test matrix.

Automated Flight Test Framework

To address these challenges, a complete automated testing framework was developed, integrating mission planning, autonomous flight control and maneuver execution into a unified methodology. A nonlinear simulator built in MATLAB/Simulink, incorporating flight dynamics, aerodynamics and autopilot logic, served as the foundational tool for mission design. This simulator allowed the prediction of trim points across a wide range of airspeeds and climb angles, ensuring that each combination corresponded to a feasible steady-state flight condition.

Onboard, the aircraft relied on a customized autopilot system capable of reaching and maintaining precise trim values of airspeed and climb angle. Once stabilized, the controller executed predefined excitation maneuvers while following programmed flight paths. Only the essential aspects of this control architecture are recalled here, as the detailed implementation is discussed separately; the focus of this article remains on its role within the experimental process. Importantly, automation allowed not only superior data quality but also access to flight regimes previously unreachable.

Flight Test Planning and Mission Design

Mission profiles were designed to span the entire range of propeller advance ratio J relevant for the aero-propulsive characterization of the SwitchMaster. For each airspeed setpoint, several climb and descent angles were selected to vary blowing intensity while remaining within the limits of the aircraft performance and battery endurance. The simulator was used to calculate the expected mission duration, the time required to reach trim conditions and the geometry of the flight path, including straight segments and turns. Fig. 2 illustrates a representative mission profile generated during simulation.

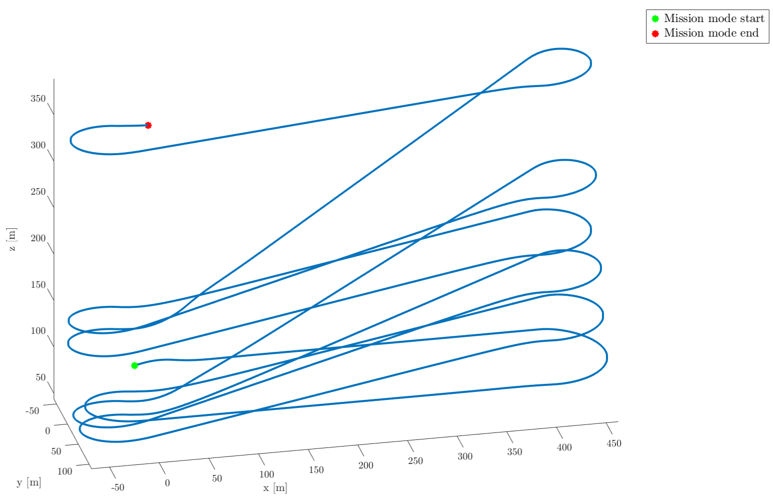

Figure 2: Example of a simulated mission.

This approach ensured that each mission could be completed safely, with sufficient energy margins for contingencies. The resulting mission plans were translated into MAVLink-compatible files and uploaded directly to the aircraft, enabling fully autonomous execution without the need for manual intervention (except for takeoff and landing).

Automated maneuver execution and environment

Once the aircraft reached the prescribed trim state, the system evaluated the tolerances on airspeed and climb angle before triggering the selected maneuver. The maneuvers included elevator doublets, ailerons and rudder doublets, 3-2-1-1 sequences and combined inputs. Each excitation was parameterized to deliver consistent spectral content close to the natural frequencies of the relevant dynamic modes.

The execution took place at the Mach Aurora airfield, east of Milan, where the flight path was designed to account for nearby obstacles and geometric constraints. During each maneuver, the autopilot temporarily suspended TECS and other modules regulation, applied the commanded input and then allowed the aircraft to settle, ensuring clear observation of both forced and free responses. Fig. 3 shows a typical elevator doublet executed during a stabilized descent.

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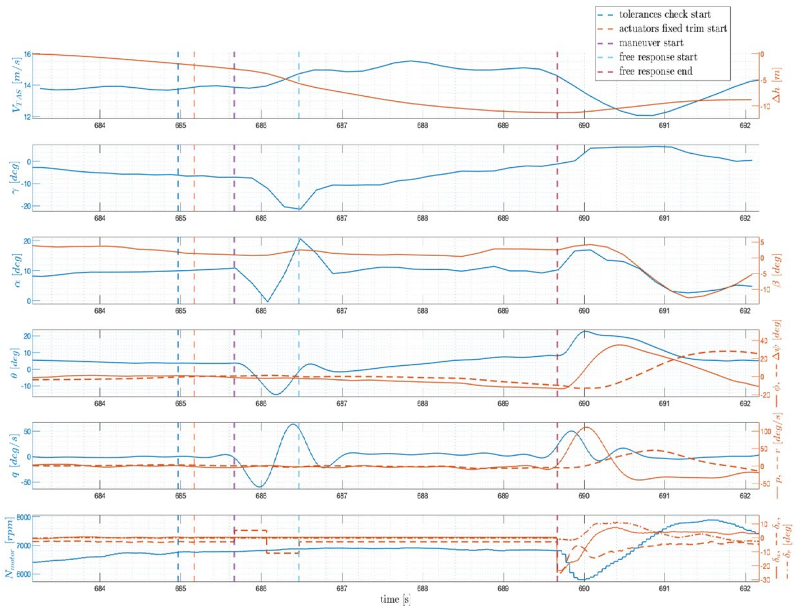

Figure 3: Elevator doublet time histories during stabilized descent.

The improvement in input precision achieved through automation is evident when comparing automated and manual doublets. Fig. 4 illustrates this contrast, highlighting the superior repeatability and stability obtained through autonomous maneuver execution.

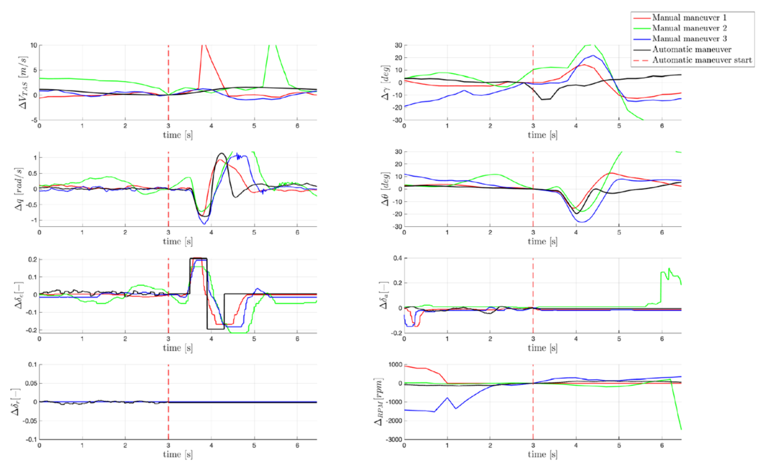

Figure 4: Comparison between manual and automated elevator doublets.

Beyond enabling automated trim acquisition and maneuver execution, the methodology developed in this work effectively constitutes a coherent and reusable flight testing suite specifically tailored for DEP aerodynamic and aero-propulsive investigations. The suite integrates all stages of the experimental workflow into a unified process, ensuring continuity between mission design, simulation and real-flight execution. Mission profiles are first generated and analyzed within a nonlinear MATLAB/Simulink environment, where the complete aeromechanical model of the SwitchMaster and the high-level autopilot logic are used to predict trim feasibility, expected values of the advance ratio J, maneuver windows and total mission duration. The same missions are then replicated in a Software-in-the-Loop environment based on Gazebo, enabling verification of the flight path, software testing and safety protections within a physics-based simulation prior to deployment.

Once validated, the mission and software build is transferred unchanged to the real aircraft and executed by the onboard PX4 autopilot, ensuring full traceability between predicted and observed

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aircraft behavior. This integrated workflow provides a robust methodological backbone for conducting systematic DEP flight test campaigns and ensures that variations observed in aerodynamic coefficients derive from physical effects rather than inconsistencies in piloting or test execution.

Safety Checks

Following an accident during a test flight [7], the safety architecture of the system was substantially reinforced. Prior to each maneuver, the autopilot verified that the computed control surface offsets required to maintain trim remained within acceptable bounds. If the aileron or rudder offsets exceeded these thresholds, the maneuver was not initiated, even if all other conditions were satisfied.

During maneuvers, additional protections monitored attitude limits, aborting the excitation if excessive roll or pitch angles were reached. In addition, there were checks on altitude, airspeed, vertical speed and horizontal limits, plus a manual switch for the pilot to interrupt a maneuver and possibly regain manual control. These safeguards contributed to the integrity of the test campaign, ensuring both the safety of the vehicle and the consistency of the logged dataset.

Flight test campaign and data acquisition strategy

The final campaign included the setpoints listed in Table 1, covering airspeeds between approximately 12 m/s and 20 m/s and climb angles from about −15° to +40°. This structure enabled the acquisition of data in conditions of descent, level flight, moderate climb and steep climb, the latter being particularly valuable for exploring strong blowing conditions.

Table 1: Tested flight conditions.

Airspeed setpoint [m/s]	Angle of Climb setpoint [deg]
20, 18	40, 30, 20
16, 14	10, 0, -5
13, 12	-10, -15, glide

Between February and June 2025, a total of 38 autonomous missions were executed, yielding 141 valid maneuvers. These included elevator doublets, 3-2-1-1 sequences and combined ailerons and rudder doublets, each initiated from a stable trim condition. The avionics suite, comprising PX4 inertial sensors, GPS, Pitot probe, telemetry and RC link, provided comprehensive logging of all variables required for model identification.

All logs were stored in *.ulg* files for offline processing. The consistency of the trim states and the precision of the maneuver execution rapidly became evident when comparing automated data with that obtained during earlier manual tests.

Results and impact on model identification

The transition to automated testing produced a clear and quantifiable improvement in the quality of the recorded data. Time histories of doublets and 3-2-1-1 inputs exhibited sharply defined input profiles with uniform amplitude and timing. The stabilization preceding each maneuver was markedly more precise, resulting in consistent initial conditions even across different days and environmental conditions.

These enhancements translated directly into improvements in system identification. The reduced variability in the experimental data led to tighter clustering of aerodynamic derivatives, clearer trends with the propeller advance ratio J and more reliable application of both Equation-Error and Output-Error methods. Particularly, coefficients such as C_{m0} and selected lateral-directional derivatives displayed smoother and more physically interpretable behaviors, reinforcing the validity of the underlying modelling assumptions. The automated framework thus

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proved essential for obtaining the fidelity required to advance the aero-propulsive modelling of DEP configurations.

Conclusions

The automated flight testing methodology presented in this work represents a significant advancement in the experimental analysis of DEP aircrafts. By eliminating the variability inherent in manual piloting and enabling consistent execution of trim and excitation maneuvers, the framework provides a robust foundation for accurate model identification.

Together with ongoing developments in modelling and control, the results obtained from this campaign contribute to a broader effort aimed at understanding and exploiting the unique characteristics of Distributed Electric Propulsion. Future work will extend this methodology to expanded flight envelopes, advanced control strategies and more refined modelling approaches, further strengthening the experimental basis for DEP technologies.

References

[1] D. Pasquali, A. Santeramo, L. Alberti, M. Tombolini, L. Trainelli, C.E.D. Riboldi, Distributed Electric Propulsion Aircraft Simulating a Single Propeller Aircraft, European Patent EP21725107.3 (published December 11, 2024; priority date May 8, 2020).

[2] S. Cacciola, G. Filippoli, B.M. Perri, C.E.D. Riboldi, N. Terzaroli, L. Trainelli, Autonomous Flight Tests of a Distributed Electric Propulsion Demonstrator Based on a Total Energy Control System, 11th European Conference for Aeronautics and Aerospace Sciences (EUCASS), Rome, Italy, 2025.

[3] L.F. Faleiro, A.A. Lambregts, Analysis and Tuning of a 'Total Energy Control System' Control Law Using Eigenstructure Assignment, Aerospace Science and Technology 3 (3) (1999) 127–140. https://doi.org/10.1016/S1270-9638(99)80037-6

[4] G. Filippoli, B.M. Perri, N. Terzaroli, L. Trainelli, S. Cacciola, C.E.D. Riboldi, Development of an Autonomous Flight Control System for a Distributed Electric Propulsion Flying Model, 10th CEAS Aerospace Europe Conference / 28th AIDAA International Congress, Turin, Italy, December 1–4, 2025.

[5] G. Filippoli, N. Terzaroli, B.M. Perri, S. Cacciola, C.E.D. Riboldi, L. Trainelli, Aero-Propulsive Modeling and System Identification of a Distributed Electric Propulsion Flying Model, 10th CEAS Aerospace Europe Conference / 28th AIDAA International Congress, Turin, Italy, December 1–4, 2025.

[6] S. Cacciola, L. Bottà, C.E.D. Riboldi, L. Trainelli, Identification of the Impact of Blowing on the Aerodynamic Model of an Airplane with Distributed Electric Propulsion, 34th ICAS Congress, Florence, Italy, September 9–13, 2024.

[7] G. Filippoli, L. Trainelli, N. Terzaroli, B.M. Perri, Accident Investigation and Lessons Learnt during an Automated Flight Test Campaign of a Distributed Electric Propulsion Demonstrator, Flight Test Safety Committee Workshop, Trieste, 2025.