DISTRIBUTED ELECTRIC PROPULSION TESTED ON SCALE IN FLIGHT

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Abstract

A scaled aircraft with distributed electric propulsion was built and tested in flight. The approach for the tests, the test campaign and the results are presented. Demonstrating the benefits of distributed propulsion and identifying the risks of the development with scaled flight testing are the objectives of the tests.

The scaled aircraft was first installed in a large wind tunnel to acquire aerodynamic data and to test the aircraft and the aircraft systems. The electric propulsion system with propellers was also operated in the wind tunnel to acquire thrust effects.

After the wind tunnel campaign, the batteries were installed and the aircraft was tested on the ground. Regretfully, a thermal runaway of the batteries caused an incident destroying the aircraft. The aircraft was built again with modified batteries and modifications in the power distribution system. Iron bird tests preceded the ground testing of the aircraft with batteries. Lessons learned from the incident and improvements in the design of the aircraft are addressed.

After stationary ground tests, the aircraft was subjected to taxi tests on Deelen Air Base in the Netherlands and eventual flight tests were on the airport in Grottaglie, Italy. The aircraft was operated from a ground control station in which pilots and test engineers controlled the aircraft Beyond Visual Line Of Sight (BVLOS). The test flights were initially attributed to qualify the aircraft for the flight envelope foreseen for the test objectives and in a second phase dynamic manoeuvres were executed by a dedicated autopilot.

Accurate instrumentation was installed in the aircraft that measures, amongst others, air data, inertial data, angular position of surfaces and engine parameters. Furthermore, the electrical power system is closely monitored to reveal the condition of batteries and systems.

Manoeuvres were performed with symmetric thrust on left and right propellers and with asymmetric thrust. Controllers were developed by partners ONERA and CIRA to control and steer the aircraft with differential thrust, also with the remote human pilot in the loop. The control during one-engine-inoperative conditions was also subject of the campaign. Results demonstrate the DEP technology with respect to flight dynamics and control.

Abbreviations

BVLOS	Beyond Visual Line Of Sight	LiIon	Lithium Ion
DEP	Distributed Electric Propulsion	LPA	Large Passenger Aircraft
ESC	Electronic Speed Controller	OEI	One Engine Inoperative
FTI	Flight Test Instrumentation	RPM	Revolutions Per Minute
GNC	Guidance, Navigation and Control	SFD	Scaled Flight Demonstrator
JU	Joint Undertaking	VDC	Voltage Direct Current
LiPo	Lithium Polymer		

1 INTRODUCTION

Novel aircraft technologies in new aircraft configurations are developed to reduce the climate impact of aviation. The integration of the novel technologies in aircraft configurations introduces risks in the development process. Downscaled testing in a wind tunnel is an established method for reducing the risk. However, several aspects of the design, such as the dynamic responses on control actuation and damping of motion around the various axis, cannot be measured in a wind tunnel, for which scaled flight testing is a method to reduce risks [1], [2], [3], [4]. The scaled flight testing approach was validated for assessing the dynamics and control of a typical large passenger aircraft (LPA) powered with two combustion jet engines. A downscaled version of this aircraft was built, the Jet-Scaled Flight Demonstrator (Jet-SFD), for this purpose. The validation was described in several papers, see [5], [6], [7]. In this paper, it is described how scaled flight testing is applied to investigate Distributed Electric Propulsion (DEP). This technology promises to improve the energy efficiency of the propulsion [8], also through enhanced control possibilities applying differential thrust [9], [10]. Risks related to the dynamics and control of the aircraft are reduced by implementing and testing control algorithms and measuring the characteristics on scale.

The activities described are performed in a collaborate effort by Airbus, ONERA, CIRA, TU Delft, Orange Aerospace and NLR.

2 OBJECTIVES FOR SCALED FLIGHT TESTING DISTRIBUTED ELECTRIC PROPULSION

Many aircraft configurations benefit from implementing distributed propulsion, see ref. [8], and the electric propulsion allows for having multiple propulsors on the aircraft without the efficiency reductions associated with multiple combustion engines on the aircraft. In the Clean Sky 2 programme, it was decided to investigate and demonstrate the distributed electric propulsion in flight on a reduced scale. One of the key benefits of electric propulsion is that differential thrust can be generated with a higher bandwidth than for combustion engines, so that the propeller can be used for roll and yaw control. This leads to the following goals for the flight test campaign:

- demonstrate DEP technology in flight;
- reduce the risk of developing aircraft with distributed propulsion;
- determine stability and control derivatives under dynamic conditions;
- determine control and stability in engine-out conditions;
- assess yaw and roll control capabilities of differential thrust;
- develop and demonstrate a pilot interface for controlling aircraft with distributed propulsion.

3 DESIGN AND MANUFACTURING

The airframe for investigating and demonstrating DEP is chosen to have the same external shape as the Jet-SFD, the scaled aircraft designed, manufactured and flown to validate the scaled flight test methodology [1], [6]. This allowed to apply the same moulds for manufacturing most parts of the aircraft, enables to compare and apply some of the results of the Jet-SFD and reduced the design effort for the aircraft. The electric propulsion system has been designed and manufactured and comprises:

- 14 LiPo (lithium polymer) pouch battery units are integrated into the fuselage, placed in the centre between the wings, as a power source for the electric propulsion system. The three battery units with LiIon (lithium ion) cylindrical cells powering the avionics system, flight control and flight data system are located here as well.
- The electric power distribution connecting the LiPo propulsion batteries to a busbar, from which the power is supplied to the distributed electric propulsion system. Cables, sensors and connectors are part of this power distribution setup.
- Electronic Speed Controllers (ESC) regulating the RPM of the electric motors and thereby the propellers.
- An avionics system, the Hexa Engine Controller, that receives power control signals from the autopilots and sends the control signals to the speed controllers.
- Electric motors converting the electrical power to mechanical power to drive the propellers.
- Six fixed pitch propellers designed by NLR and manufactured by the company Mejzlik. The design and specifications of the propellers are based on analyses performed by TU Delft and NLR resulting

in propellers with adequate performance and suited for integration on the aircraft. The propeller diameters are 0.406 m for the inboard and middle propellers and 0.319 m for the wing tip propeller. The nacelle inclination angle is 3 degree pitch down. Applying a higher rotation on the smaller propeller enables the generation of about equal thrust on all propellers. The smaller tip propeller is selected for aerodynamic, structural integration and tip ground clearance benefits. Integration of the propellers on the aircraft was designed by TU Delft, see ref. [13].

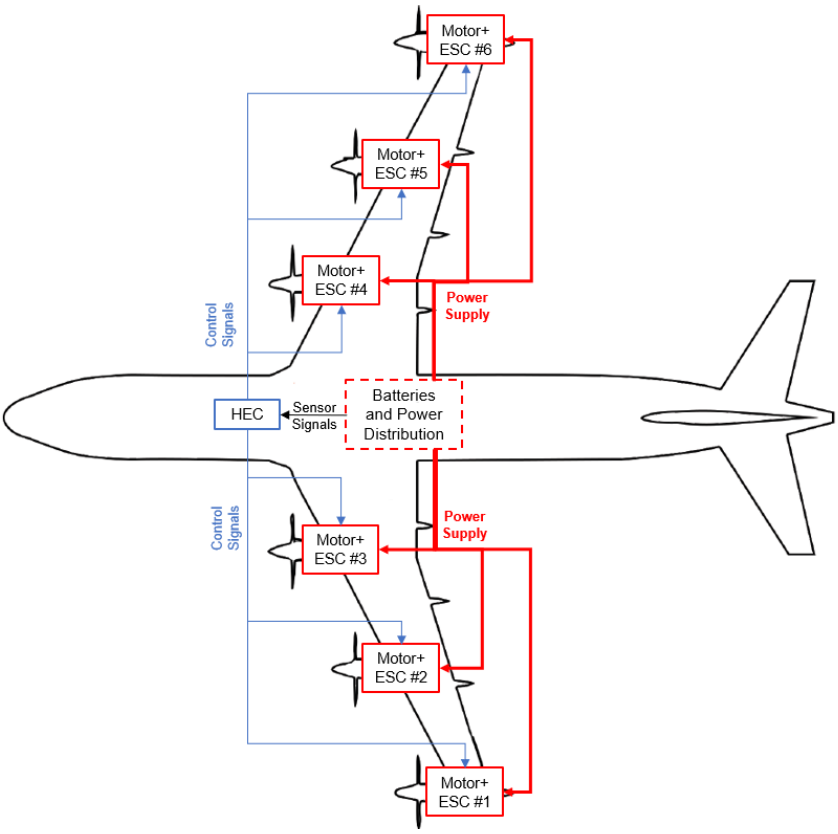

Figure 1 Electric propulsion system in the DEP-SFD

Many systems not related to propulsion were re-used from the Jet-SFD or were built with identical or similar components and were described in ref. [1]. The DEP-SFD systems comprise:

- Most of the Jet-SFD avionics, the FTI and the landing gears;
- A new airframe manufactured from carbon fibre-reinforced polymers applying the same moulds as used for the Jet-SFD;
- The ground station for remote Beyond Visual Line-of-Sight (BVLOS) control of the aircraft that was used for the Jet-SFD;
- 2 autopilots, one for supporting the pilot and one for executing the measurement manoeuvres automatically, ref. [11];
- FTI to monitor systems and measure responses accurately. The FTI comprises amongst others an air data boom with sensors integrated in the boom for fast responses, an inertial and position measurement unit supported by satellite navigation and control surface position sensors. The FTI is described in ref. [1] with combustion engine parameters replaced by parameters characterising the electric propulsion.

4 GROUND TESTING

4.1 Wind tunnel testing

After integrating and testing the aircraft stationary in the lab, the aircraft was installed in the DNW Large Low-speed Facility wind tunnel, see Figure 2. Before the flight test, the data generation for the reduction of risk for the first DEP flight and the evaluation of the DEP technology appeared valuable, ref. [1], [12]. Aerodynamic data was also used for developing a simulator to train the pilots and to develop control laws. A test program with 178 measurement conditions was run. The DEP-SFD systems could be controlled remotely, which allowed for fast operations, and in two days the measurements were performed.

Figure 2 DEP-SFD in the DNW wind tunnel

4.2 Stationary testing, taxi testing and a fire incident

Taxi tests were successfully performed at Breda International Airport at low speed and in March 2023 on Deelen Air Base at high speed. Acceleration tests were performed to ensure safe take-off with the DEP-SFD up to 80 % of the stall speed, i.e. 60 knots in clean configuration, 55 kts for half flaps and 50 kts for full flaps. The aircraft was operated BVLOS from the ground station. The taxi characteristics were good and the control from the ground station including the data links worked well.

Also, stationary tests were executed with the DEP-SFD on chocks and brakes to test the propulsion system. During the taxi and stationary tests, a temperature rise was observed in the batteries for the propulsion that was larger than expected. As the flight operations were planned for the summer in the south of Italy where the ambient temperatures were expected to be higher than the temperatures in the Netherlands in March, the temperature rise was expected to approach the upper batteries operational temperature limit. After an analysis and tests of several battery types in the laboratory, it was decided to select a new similar battery type of the same manufacturer for the flight tests. The batteries were installed in the aircraft and new stationary tests were performed. Regretfully, during the second ground test on11th May 2023 an abnormality developed, leading to an internal battery fire. No personal injuries occurred, but the DEP-SFD was damaged beyond repair.

The DEP-SFD was equipped with FTI and the data measured during the incident was analysed, together with the damage to the aircraft, to reveal the possible cause of the incident. Three sub-systems in the aircraft experienced severe damage during the incident and a failure in one of these was identified as the most likely root cause of the incident. The three sub-systems are the propulsion batteries, the electrical propulsion power distribution system and the avionics batteries. Neither the measurement data nor the damage status of the aircraft after the incident provide definite clarity on the root cause.

4.3 Redesigning and rebuilding the DEP-SFD

The DEP-SFD has been rebuilt after the incident, where only the landing gears were not damaged and re-used in the new version. The structure, the avionics, the FTI and the GNC were rebuilt according to the old design. The design of the suspected failed subsystems, i.e. the propulsion batteries, the power distribution and the avionics batteries were improved. The improvements comprise:

- Application of alternative, custom-made propulsion batteries with
    - A higher voltage configuration

      The battery configuration was changed from 12 cells in series to 14 cells in series (12S to 14S), leading to a nominal voltage increase from 44.4 VDC to 51.8 VDC, see Table 1. The custom-made batteries have the 14 cells in one unit, whereas the initial configuration had 6-cell units, two units in series. The higher voltage is beneficial for the performance of the electric motors and at the same time reduces the currents in the power distribution when the same power is supplied. The currents govern heat generation for fixed resistance components.

    - Additional monitoring for propulsion battery packs

      Currents for each battery pack, voltages of each battery cell, and temperatures per battery pack are monitored during battery tests, system tests, taxi tests and during the flights. The in-flight monitoring is a sub-set of the ground monitoring and comprises:

        - voltage of each cell (6 batteries x 14 cells = 84 voltages)
        - current & sum of cell voltages of each battery (6 currents and 6 voltages)
        - busbar voltage
        - current, voltage & rpm in each controller and motor (6 currents, 6 voltages and 6 rotation speeds)
        - temperature on top and at side of each batteries (6 batteries x 2 sensor = 12 temperatures)
    - Extensive testing of batteries before installation

      A concern that emerged during the incident analysis is that the propulsion batteries did not have sufficient operating hours before installation in the DEP-SFD to exclude the possibility of a manufacturing fault. Extensively testing of each battery through several charge and discharge cycles at relevant power settings before any application of a battery is introduced after the incident.

- Higher quality components in the power distribution system

  Components in the power distribution are mostly not aerospace quality as these are too heavy and large. Higher quality connectors and many more fuses have been applied in the new design to conduct the large currents.

- Redesign of the fuselage interior

  The interior of the fuselage is reorganized, such that the batteries can be installed with more space between them and that the routing of the cables in the fuselage is better defined. The hatch of the fuselage over the battery compartment is larger, providing easier access to the battery compartment.

- Improved avionics battery setup

  Improvements of the avionics batteries housing and on the monitoring of voltages, currents and temperatures are implemented.

Table 1 Propulsion battery assembly configurations for the initial Tattu and eventual Grepow setup

LiPo Battery Units	Number of Battery Units	Configuration of Assembly (S: in Series, P: Parallel)	Total Voltage (nominal)	Total Charge Capacity	Total Energy Capacity (nominal)
Tattu 6S1P 30C 22Ah 22.2V	14	12S7P	44.4 V	154 Ah	6838 Wh
Grepow 14S1P 22Ah 51.8 V	6	14S6P	51.8 V	132 Ah	6838 Wh

4.4 Iron bird, stationary and taxi testing

The new design of the propulsion system was much more thoroughly tested than the initial design. An “iron bird” ground test facility was built with the components and the environment of propulsion system represented. In the iron bird it was easy to measure many parameters like temperatures and electrical performance of components, much easier than in the aircraft because weight is no constraint and installation is easy, see Figure 3.

Figure 3 Iron bird test facility and the DEP-SFD on chocks during a stationary test

Special interest was the temperature of batteries and other components during a flight. The power uptake expected during the flight was demanded from the electrical system, first in the iron bird and later from the system installed in the DEP-SFD with the DEP-SFD on brakes and on chocks. The power during a simulated flight with three go-arounds and the temperatures measured on the hottest points on the batteries are plotted in Figure 4.

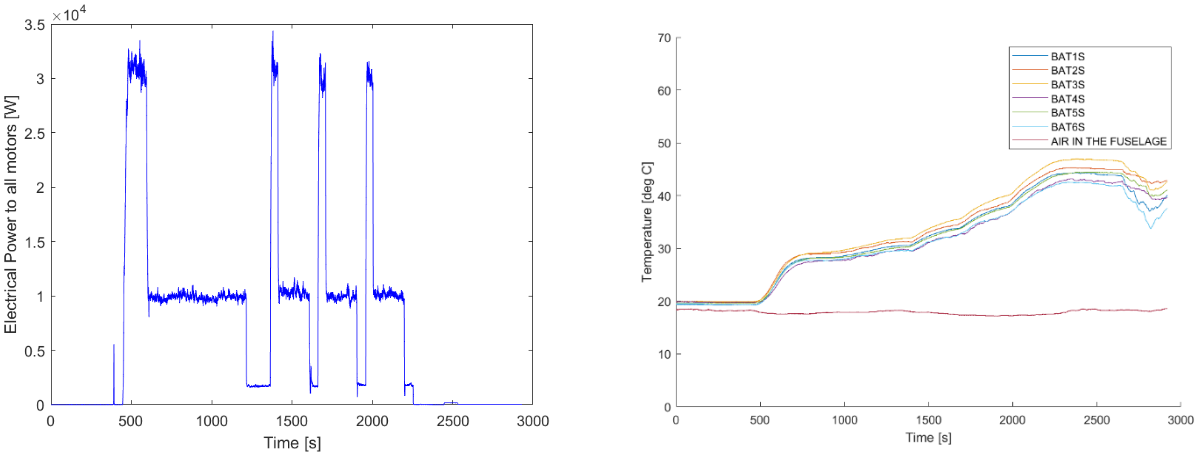

Figure 4 Power consumed in the stationary DEP-SFD test set-up, being in good approximation equal to the power consumed during a flight (left) and the temperature on batteries and in the air around the batteries (right) during a simulated flight

After the successful completing of the stationary tests the taxi tests were repeated on Deelen Air Base to verify the proper ground handling, including the power supply.

5 FLIGHT TESTING

The flight testing started like any new aircraft’s first flight, with opening the flight envelope. The first flight was devoted to a first evaluation of the handling of the aircraft. The pilot had been trained with a simulator based on the wind tunnel measurements, calculations and Jet-SFD derived data. The simulator model appeared very valuable and accurate such that the pilot was not confronted with surprises. The different flight modes, manual or assisted, the operations of systems and the approach and landing performance were also verified.

The next 4 flights were dedicated to open the flight envelope further, to the envelope necessary for the mission flights, performance evaluation of the aircraft in level flight, gliding flight, climbs and one engine off. The flight altitudes were up to 2000 feet. The autopilot for flying the mission manoeuvres was also tested.

In 22 mission flights the dynamics of the aircraft were measured. The manoeuvres in which the actual measurements were made were flown with the autopilot, specifically developed for flying the manoeuvres accurately at a fixed indicated airspeed of 95 kts. The manoeuvres comprise:

- Normal, symmetric thrust flight: Inboard, middle and tip motors on left and right wing have the same thrust. Flight control only by classical control surfaces: rudder, elevator and ailerons:
    - Demonstrate flight characteristics and handling qualities;
    - Standard doublets, step input for stability and control derivatives determination;
- Asymmetric thrust flight: Flight control with combinations of control surfaces and differential engines thrusts also for drag reduction:
    - Normal aircraft mission manoeuvres;
    - Demonstrate flight characteristics and handing qualities using asymmetric thrust;
    - Standard doublets, step input for derivatives determination;
    - Demonstrate flight control by differential thrust;
    - Demonstrate flight control could also have been achieved with a reduced vertical tail plane size;
- Failure conditions; One Engine Inoperative (OEI):
    - Demonstrate flight with an inboard, middle or wing tip propeller inoperative.

Some manoeuvres were successfully flown by the remote human pilot in the ground station controlling the aircraft with control surfaces in combination with different levels of differential thrust. The algorithm for controlling the aircraft on the pilot inputs was also implemented in the GNC, the autopilot for the measurements.

The aircraft operation was from a ground control station in which pilot and test engineers controlled the aircraft Beyond Visual Line Of Sight (BVLOS) and verified the proper operation of systems. This set-up worked well for this aircraft flying at airspeeds in the range of 65 to 115 kts, a wing span of 4 m and a weight of 167 kg. Figure 5 shows some impressions of the operations at Aeroporti di Puglia in Taranto-Grottaglie, Italy.

Figure 5 The DEP-SFD and the ground control station operating at the airport in Grottaglie, Italy

6 RESULTS

Results of the flight test campaign are provided in this chapter. Section 6.1 gives a general overview of the results. In total 27 flights, more than 100 test runs with 46 different manoeuvres were flown to assess the dynamics and control of the aircraft. Section 6.2 focusses on specifically selected manoeuvres demonstrating the possibilities of differential thrust and the adequate control of the aircraft with the most critical engine inoperative. The selected manoeuvres are listed in the table below.

Manoeuvres
1.9 Tip engine doublet
3.7 Roll angle flown with control surfaces
3.8 Roll angle flown with aileron and DEP
3.9 Roll angle flown with rudder and DEP
3.10 Roll angle flown with DEP
3.12 Roll angle with tip engine failure

Table 2 Manoeuvres selected to show DEP characteristics

6.1 Dynamics and control

A large number of singlets, doublets, turns, climbing turns, altitude changes and other manoeuvres were flown in different conditions of the aircraft. Manoeuvres were flown with the traditional control surfaces and with various levels of differential thrust, for instance, with differential thrust and without rudder or without aileron, or without rudder and aileron. The aircraft shows good flight characteristics, in line with the characteristics measured on the Jet-SFD. Differential thrust gives new and interesting options for controlling the aircraft and these were demonstrated successfully in flight. Applying the extra control options for either assigning the most sustainable option as described in ref. [9] and [10] or as an alternative to reduce the size of control surfaces is confirmed with these flight tests and can be further developed for full scale aircraft.

6.2 Control with differential thrust

6.2.1 Tip propeller doublet

Manoeuvre 1.9 is a demonstration of the impact of differential thrust of the tip engines. In Figure 6, it can be seen that the flight control surfaces aileron and rudder are kept fixed during the manoeuvre. Additionally, the throttle of the 6 engines is shown, divided in the corresponding engines: tip engines, middle engines and inboard engines. No differential thrust is applied for the middle engines and the inboard engines. The tip engines perform a doublet. The impact of this tip engine doublet is seen mainly in the roll angle and also in the angle of sideslip while the ailerons and rudder are fixed. The tip propeller doublet validates that with differential thrust both roll and yaw control can be achieved for the DEP-SFD. In the next section, this effect is used for roll and yaw control of the aircraft.

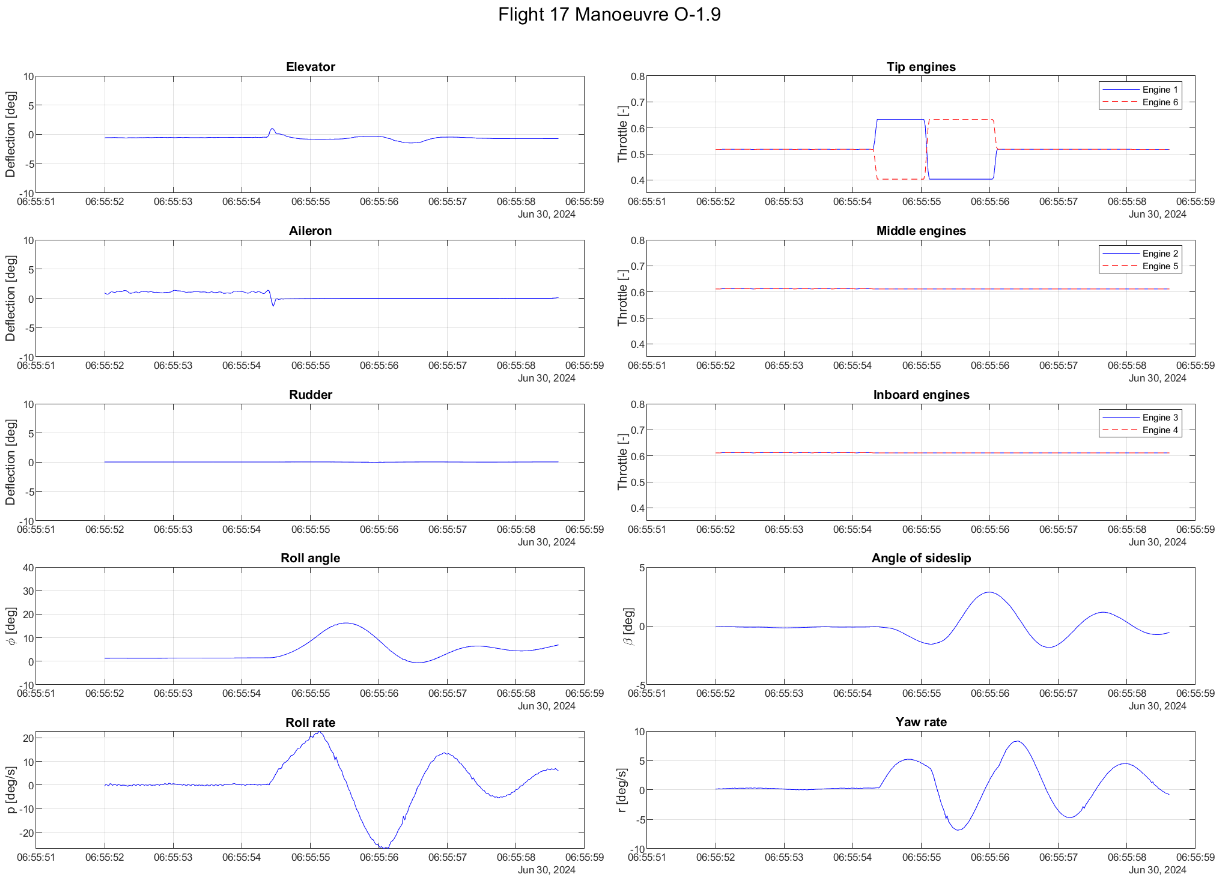

Figure 6: Tip engine doublet

6.2.2 Rolling and yawing the aircraft with differential thrust

The goal of the following shown manoeuvres is to reach the target roll angle of 30° for a coordinated turn with zero degrees sideslip and keeping cruise velocity and altitude. This target roll angle is reached with various input combinations of control surfaces and differential thrust.

First, in manoeuvre 3.7 the target roll angle is attained via the use of the classic control surfaces as it can be seen in Figure 7. Differential thrust is not applied; the corresponding engines on the two sides have the same value of the throttle as shown in the figure. The roll angle of 30° is flown with the use of aileron and rudder. This also includes a measured maximum angle of sideslip of 3.5°, which the controller gets back to approximately 0° for a coordinated turn.

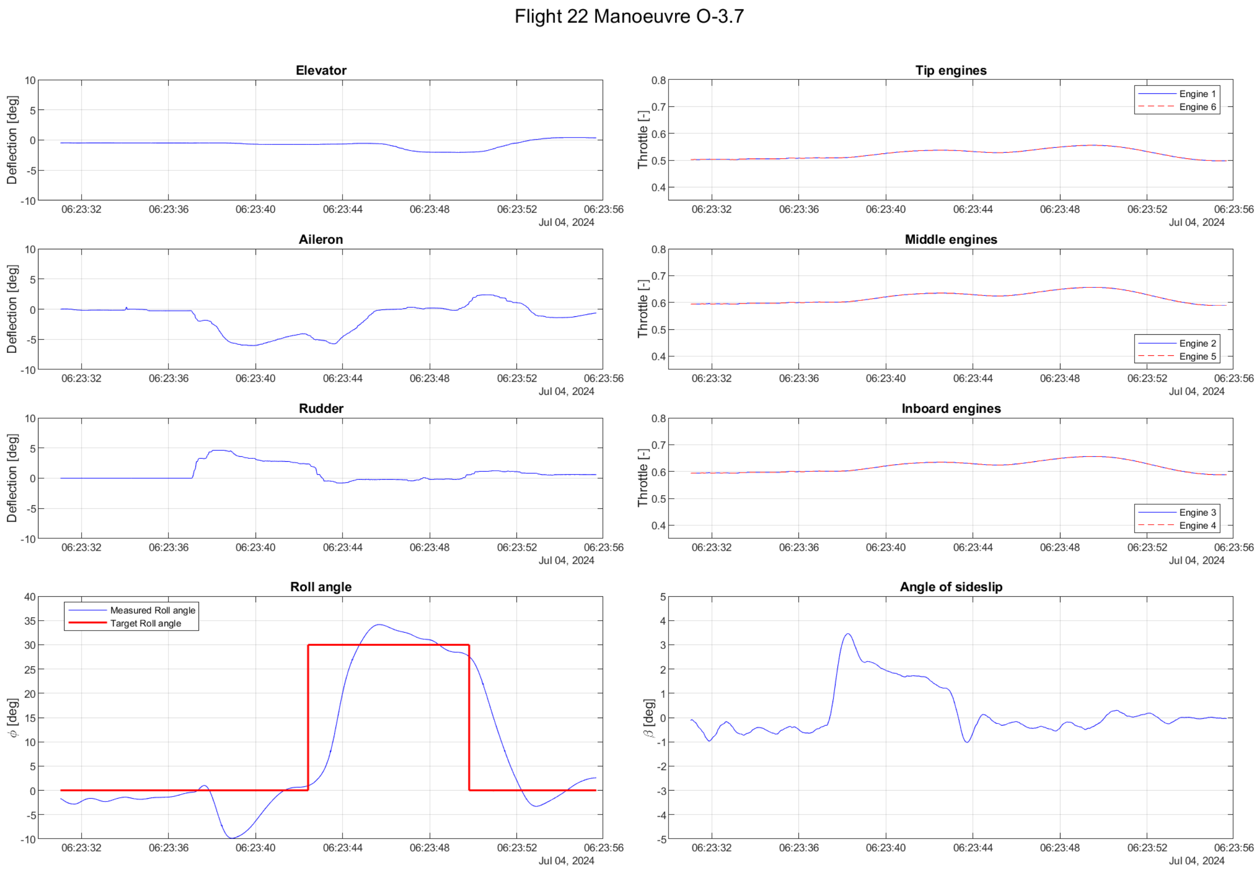

Figure 7: Roll angle flown with control surfaces

The second manoeuvre 3.8 with a similar target roll angle of 30° for coordinated turn and cruise velocity and altitude is shown in Figure 8. In that manoeuvre, the rudder is kept fixed, while the roll angle is controlled with the aileron. Differential thrust is then used for the necessary yaw control. It is shown that the roll angle and sideslip angle can be controlled by using differential thrust instead of the rudder.

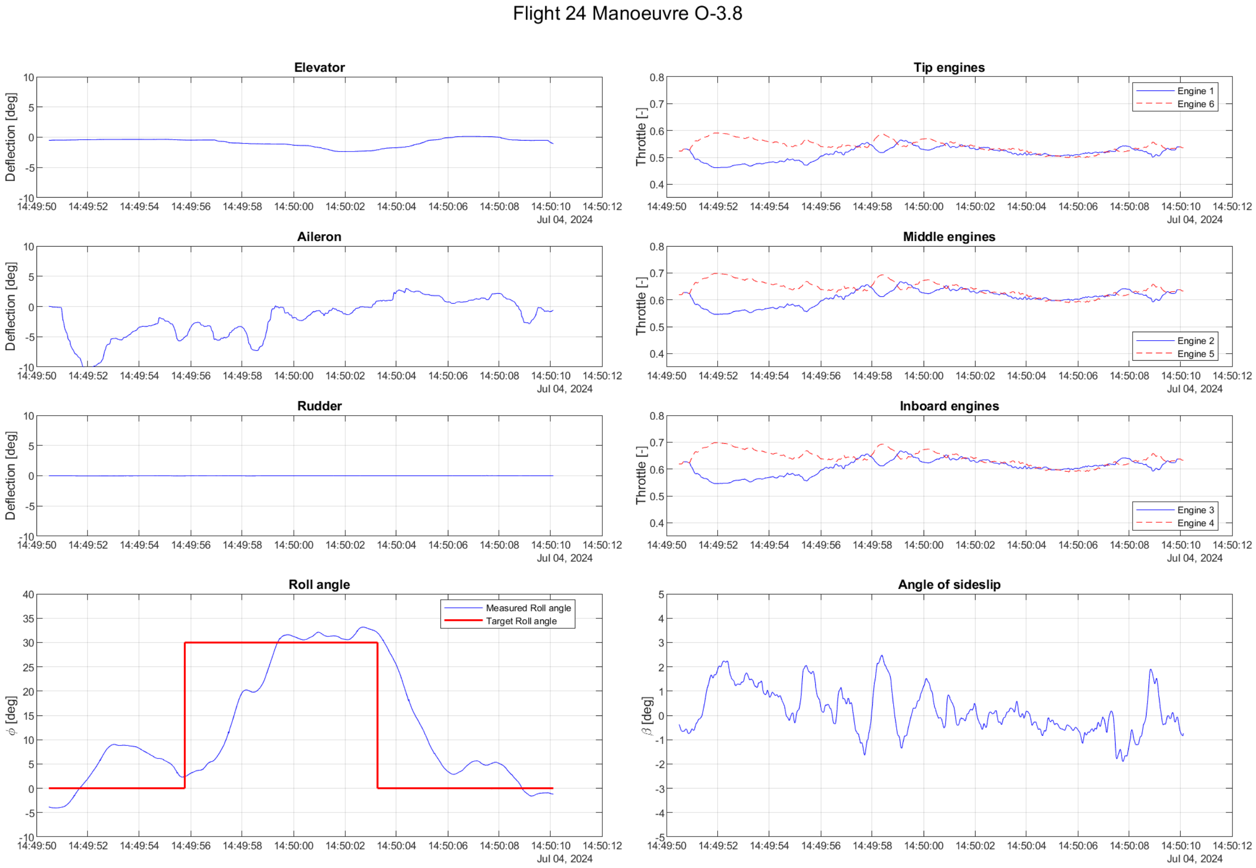

Figure 8: Roll angle flown with aileron and DEP

In manoeuvre 3.9, shown in Figure 9, the same result of a target coordinated roll angle of 30° is reached with differential thrust and rudder. The aileron is kept fixed and not used to control the roll angle. Inboard engines, middle engines and tip engines are used to control the roll angle with differential thrust. It is shown that it is possible to fly the coordinated roll angle without the control with the aileron but using the differential thrust effect.

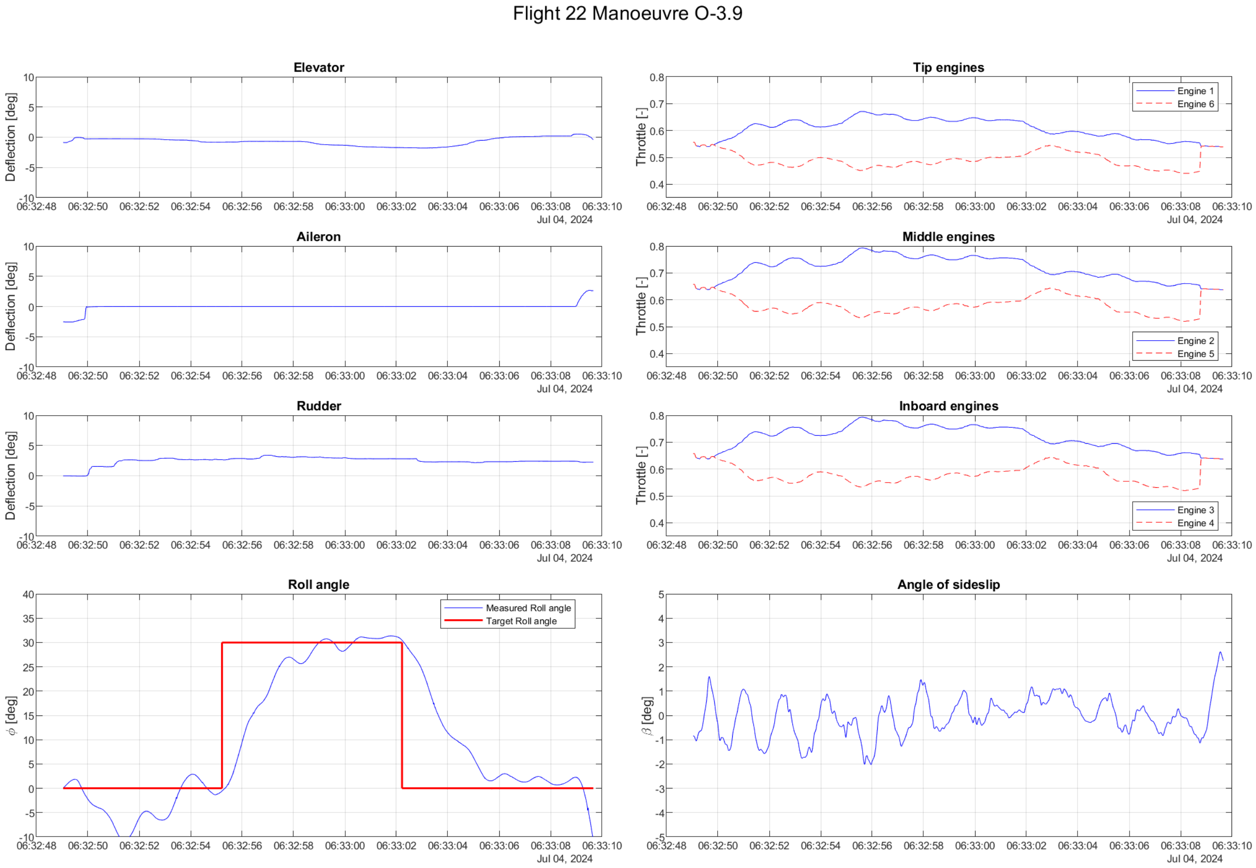

Figure 9: Roll angle flown with rudder and DEP

Manoeuvre 3.10 is a demonstration to control the roll angle only via differential thrust. As it can be seen in Figure 10, the aileron and rudder are kept fixed and are not used to control the roll angle. The manoeuvre is flown entirely with differential thrust. All engines are used for that as shown with the throttle value of the engines. Also with a full control with differential thrust, it is possible to fly a coordinated roll angle of 30° while maintaining cruise velocity and altitude. This shows the potential of using DEP for aircraft control as the control surfaces are not needed and can thus possibly be reduced in size which results in less drag.

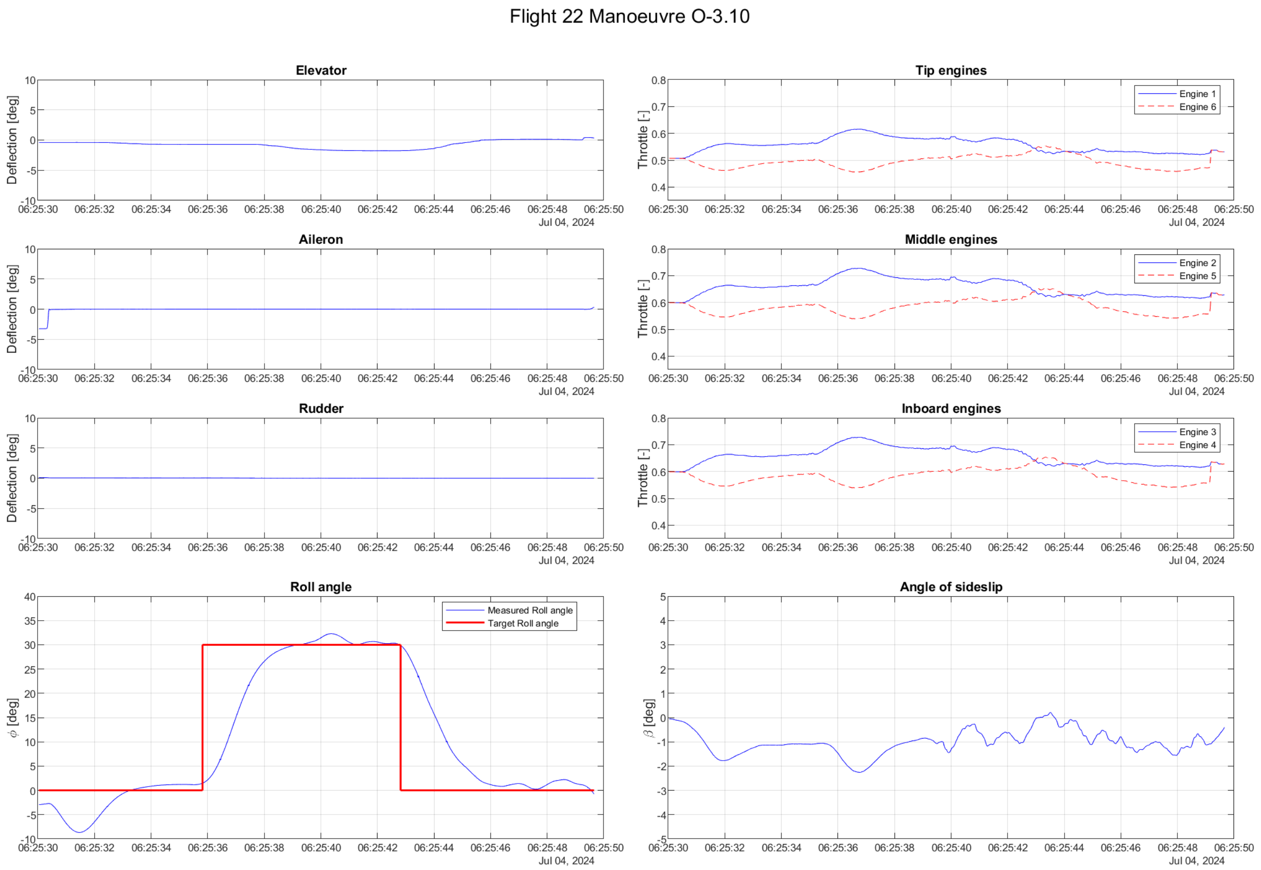

Figure 10: Roll angle flown with DEP

6.2.3 Engine Failure

In manoeuvre 3.12, an engine failure case is demonstrated. As shown in Figure 11, one tip engine is off, while the other engines are used to fly the manoeuvre. As in the previous shown manoeuvres, a coordinated roll angle of 30° is demonstrated. For this case, the rudder is kept fixed and the aileron and differential thrust are used, while one tip engine is off. It can be seen that even with one of the propeller failing, the aircraft can be controlled with the ailerons, elevator and remaining five propellers. Still, there is an effect of the propeller failure as the oscillations in the sideslip angle are higher. This can be explained by the fact that the rudder cannot be used for controlling the sideslip and the remaining five propellers have to compensate for the tip propeller failure. The main conclusion for this test is thus that propeller failure can be resolved by the remaining propellers without using the rudder.

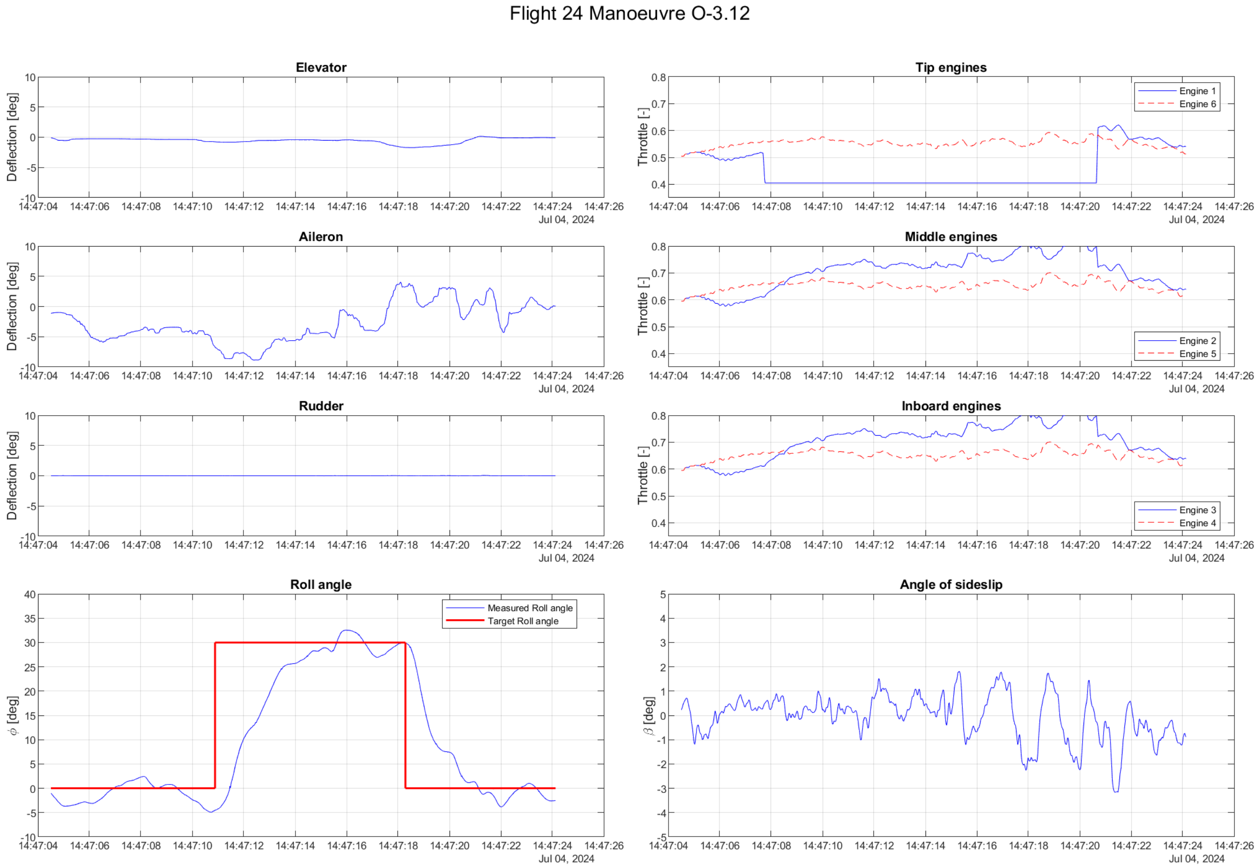

Figure 11: Roll angle with tip engine failure

7 CONCLUSION

A new technology, Distributed Electric Propulsion (DEP), was successfully demonstrated in flight on scale, providing a wealth of data. For the identified risks associated to the DEP technology during the development process and flight testing, corresponding mitigations were developed. This knowledge is very valuable for future DEP aircraft designs, going to full-scale development. The approach of scaled flight testing, starting with the design of the scaled aircraft, followed by building it, testing it on the ground, testing it in the wind tunnel and then flight testing it BVLOS is thorough and leads to good results for the dynamics and control.

Valuable lessons have been learned with respect to the electric propulsion of the aircraft. Building an iron bird test facility for the electric propulsion system and batteries and careful monitoring all electric parameters in flight have been introduced after the fire incident to reduce the risk in operating the electric aircraft.

Scaled flight testing was applied to demonstrate the distributed electric propulsion technology and its potential towards developing more sustainable aircraft configurations. The dynamics and control of the scaled aircraft including the potential of differential thrust has been shown. Assigning the control in aircraft with distributed electric propulsion such that the control surfaces cause a minimum of drag can be further developed. Reducing the sizes of control surfaces and the vertical tailplane can be part of the improvement. Both these developments will result in more efficient flight and, therefore, contribute to the development of more sustainable aircraft. Finally, robustness for engine failures has been demonstrated showing how DEP can still be safely used for control even in this failure case.

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