



APPLICATION OF A MORE INTEGRATED TOTAL ENERGY CONTROL SYSTEM FOR IMPROVING AIRCRAFT AND ENGINE CONTROL EFFICIENCY

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Abstract

This article presents improvements obtained by the integration of flight and engine control systems in terms of control efficiency with the development of the More Integrated Total Energy Control System (MI-TECS). In this proposal, the standard Total Energy Control System (TECS) is modified to account for engine control capabilities, such that flight and engine control laws are computed in a single controller and unified design framework. Both approaches are compared through an application example, in which it is shown that for controllers with very similar responses in terms of speed and flight path angle tracking, the MI-TECS approach can improve fuel consumption and metrics related to engine degradation. Furthermore, additional advantages associated with the MI-TECS architecture are briefly discussed. This work highlights how an integrated controller and design framework can offer advantages to explore balanced designs and improved control efficiency, especially when compared to conventional control approaches.

Keywords: Flight control law design, Engine Control System, Total Energy Control System (TECS), Robust Control

Notation

$D(s)$	=	Reference model transfer matrix	g	=	Gravitational constant
$d_{c/r}$	=	Turbine blade creep or rupture damage rate	J	=	Cost functional
E_T	=	Aircraft total energy	h	=	Altitude
$E_{T/W}$	=	Aircraft total energy normalized by the aircraft weight	q	=	Aircraft pitch rate
$\dot{E}$	=	Specific total energy rate	T	=	Engine thrust
$F(s)$	=	Feed-forward controller transfer matrix	V	=	Aircraft airspeed
$G(s)$	=	Plant model transfer matrix	W	=	Aircraft weight
K	=	Controller gain element	W_f	=	Engine fuel flow rate
L_{rl}	=	Remaining life in turbine blades damage model	α	=	Aircraft angle-of-attack
$\dot{L}$	=	Specific total energy distribution rate	γ	=	Aircraft flight path angle
N_1	=	Low-pressure assembly engine shaft speed	θ	=	Aircraft pitch angle
N_2	=	High-pressure assembly engine shaft speed	δ_{elev}	=	Elevator deflection
P_{s3}	=	Static pressure at the exit of the engine high-pressure compressor			
T_{45}	=	Temperature at the exit of the engine high-pressure turbine			
Q	=	Linear quadratic output weight matrix			
R	=	Linear quadratic input weight matrix			

1. Introduction

This article discusses the enhancements obtained by the integration of flight and engine control capabilities using energy and linear robust control principles with the development of the More Integrated TECS (MI-TECS) architecture [1, 2, 3], in which features from the original TECS [4, 5, 6] control law are modified to support indirect thrust control, in addition to coordinated and decoupled longitudinal motion as in the original concept. The MI-TECS controller changes the original controller interface to use the fuel flow rate instead of thrust commands, adding feedback loops typical from the setpoint controller of the Engine Control System (ECS) into the core TECS control law, and modifying the standard TECS architecture to use a two degree of freedom approach with independent feedback and feed-forward controllers, following the principles from Kreisselmeier's work [7], considered herein in the multivariable context, as suggested by [8].

A comparison of MI-TECS against the standard TECS approach is presented. By considering the engine dynamics as a part of the design framework, the MI-TECS offers the possibility of determining controller configurations oriented to combine aircraft and engine performance simultaneously. A design example is detailed in which the MI-TECS approach is used to demonstrate how the integrated design framework can be used to balance the engine and aircraft responses concerning a fixed target for the flight path and speed tracking. In this example, the MI-TECS controller improves the relative fuel consumption and engine components metrics associated with degradation locally for linear step responses associated with speed tracking.

2. Total Energy Control System

As presented in [4, 5], the main feature of the TECS approach is the use of energy-related quantities to provide decoupling of the flight path trajectory and speed in such a way that thrust commands are used to regulate the total aircraft energy and the elevators are used to change its distribution, following given flight path and speed references. From the aircraft total energy E_T , assuming slow weight variations, the total energy derivative normalized by the aircraft weight $\dot{E}_{T/W}$ is written as a function of the speed, flight path angle, and acceleration, as in Eq. 1, where $\dot{h} = \gamma V$, assuming that $\sin \gamma \approx \gamma$, and $g = 9.81 \text{ m/s}^2$.

$$E_T = Wh + \frac{W}{g} \frac{V^2}{2} \xrightarrow{d/dt} \dot{E}_{T/W} = \frac{1}{W} \dot{E}_T \approx V \left(\gamma + \frac{\dot{V}}{g} \right) \quad (1)$$

The two main controlled variables are defined recalling the aircraft energy states: one term proportional to the specific total energy rate ($\dot{E}$) and another one related to the specific total energy distribution rate ($\dot{L}$), defined according to Eqs. 2 and 3.

$$\dot{E} \triangleq \gamma + \frac{\dot{V}}{g} \quad (2)$$

$$\dot{L} \triangleq \gamma - \frac{\dot{V}}{g} \quad (3)$$

In order to decouple the longitudinal aircraft response in terms of airspeed and trajectory, the controller must be capable of simultaneously zeroing the error associated to both variables, as stated in [4, 5]. The thrust and elevator control commands are depicted in Eqs. 4 and 5, where ε denotes the error with respect to the corresponding variable. Also, as remarked in [4], the errors associated with energy variables are only fed to integral terms to improve transient response and reduce overshoots.

$$T_{cmd} = \int \left(\gamma_\varepsilon + \frac{\dot{V}_\varepsilon}{g} \right) dt K_{TI} + \left(\gamma + \frac{\dot{V}}{g} \right) K_{TP} \quad (4)$$

$$\delta_{elev}^{cmd} = \int \left(\gamma_\varepsilon - \frac{\dot{V}_\varepsilon}{g} \right) dt K_{EI} + \left(\gamma - \frac{\dot{V}}{g} \right) K_{EP} + qK_q + \theta K_\theta \quad (5)$$

The original TECS formulation proposes proportional and integral closed loops for both energy variables, and the elevator control path is also coupled with a closed-loop longitudinal dynamics augmentation system for short-period mode improvement, formed by proportional feedback of the aircraft

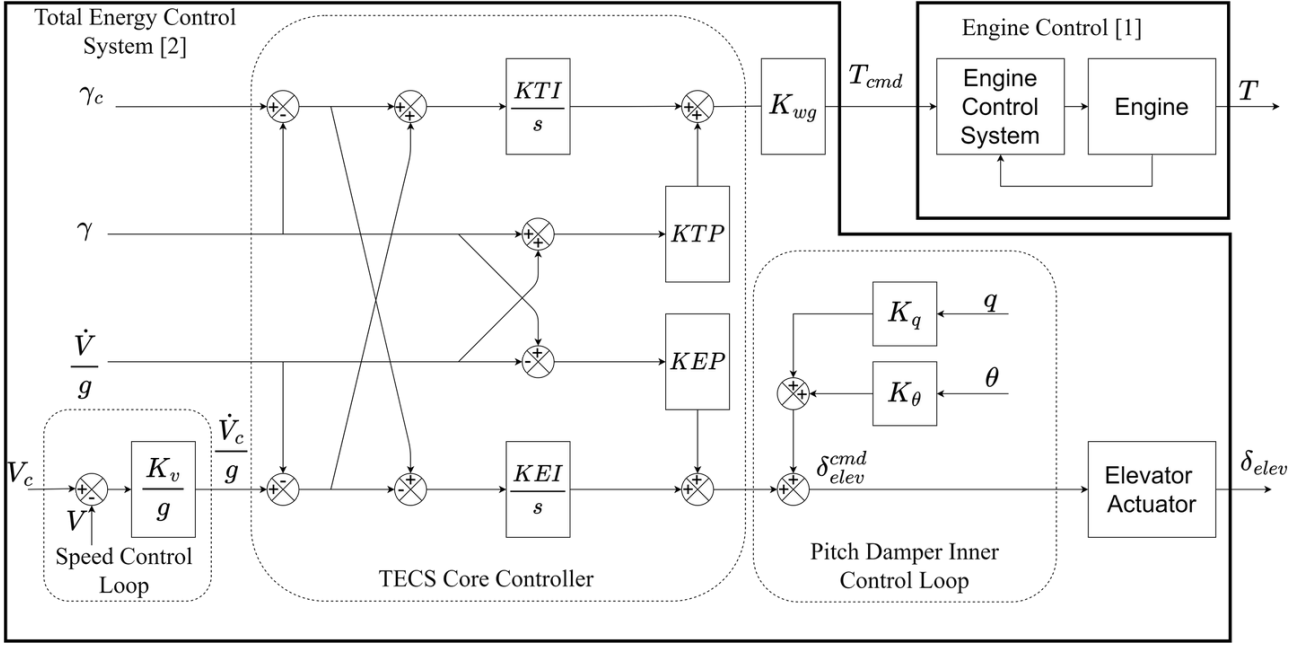


Figure 1 – TECS control architecture with functional elements

pitch rate (q) and pitch angle (θ). The thrust control path is coupled with the engine control system to produce normalized thrust demands, scaled by the aircraft weight as a function of K_{wg} , which are transmitted to the digital engine controller.

The architecture of the TECS controller is presented in Fig. 1, where a functional division is added considering the control systems at the component level (aircraft and engine).

Each element from the standard architecture is associated with its functional goals, enumerated as follows in a non-exhaustive list:

1. Engine Control System:

- (a) To provide homogeneous thrust response within its operational envelope
- (b) To protect the engine integrity

2. Total Energy Control System:

- (a) To provide homogeneous aircraft response in terms of the controlled variables
- (b) To protect the aircraft against inadvertent operation outside its limit envelope

The premise adopted in the standard architecture is that engine and aircraft control systems can be designed independently, with reasonable segregation. There are two possible ways for this assumption to hold: (1) the engine dynamics is sufficiently segregated from the aircraft dynamics so that the engine dynamic modes are not dominant, or (2) the aircraft control accommodates the engine behavior so that it acts as a design restriction.

3. Engine Control System

ECS architecture and design are extensively discussed in [9, 10, 11, 12, 13]. The behavior of a two-spool turbofan engine can be fairly approximated by a linear parameter varying second-order system in terms of N_1 and N_2 . Much of the complexity of the controller architecture comes from the need to add a protection layer to preserve the engine integrity in a vast range of operational conditions.

The architecture of the engine controller is discussed in detail by [10] and [11]. The basic scheme is presented in Fig. 2. Considering practical applications from the aeronautical industry, the turbofan engine controller of a commercial aircraft has two main components: a setpoint or power management controller and a transient and limit protection controller. The setpoint controller is responsible for converting a throttle lever demand into a suitable thrust response, and the limit protection controller

is a safeguard against inadvertent operation outside the engine envelope to avoid phenomena such as blowout, surge, and stall, among others, maintaining the engine within safe limits of operation. In the setpoint controller, the variables used to control the engine thrust are either the Engine Pressure Ratio (EPR) or N_1 , as thrust is not a measurable quantity. Rather than estimating the actual thrust, using an indirect measure as the controlled variable is preferable. The demanded thrust can be easily transformed into an EPR or N_1 demand, given a static table that maps the relation between the demanded thrust T and the controlled variable as a function of the corrected pressure δ_p and Mach number. This results in a two-dimensional lookup table. Then, the engine controller receives the demand and computes the final command accounting for all restrictions associated with the engine limits (surge, blowout, etc). It is remarked that some references, such as [14] and [15], indicate that these types of fixed schedules are generally affected by engine degradation and may deteriorate the system performance. This characteristic is to be accounted for in the MI-TECS controller architecture.

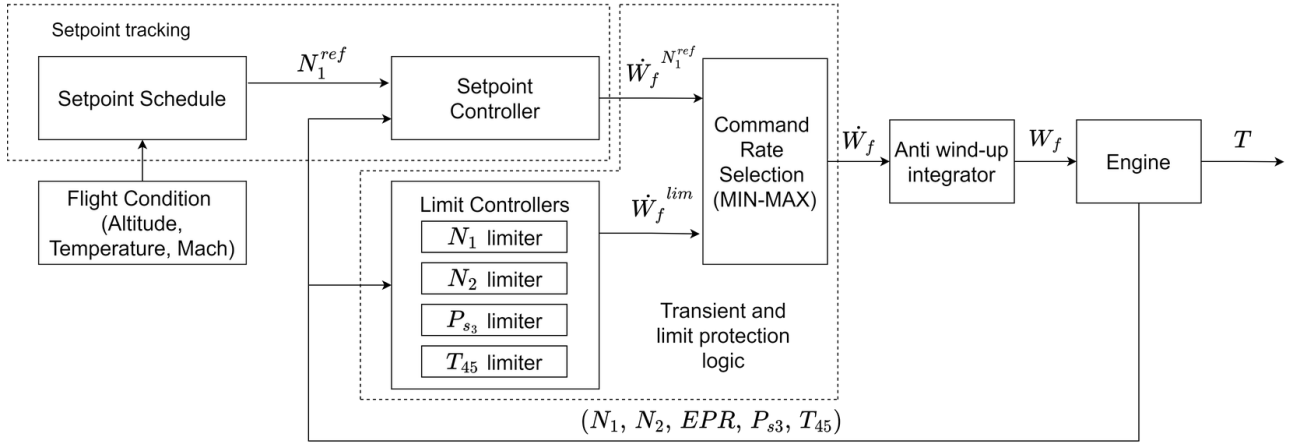


Figure 2 – Engine control system schematics

Following [12] and using $\dot{W}_f$ as the command variable, a generic engine limit controller structure is depicted in Fig. 3, showing the schematic of a state feedback controller. This generic controller structure can be applied for each engine variable for which control is sought, such as the engine limit variables or thrust, as examples. It is recalled that the integrator is placed downstream, after the min-max selection, as presented in Fig. 2. The control action $\dot{W}_{fi}$ is determined according to Eq. 6,

$$\dot{W}_{fi} = -K_{FB_i}x_{eng} + K_{R_i}R_i, \quad i \in [2, 6] \quad (6)$$

where R_i is the engine limit reference associated to a given variable, K_{FB_i} is the feedback gain matrix and K_{R_i} is the reference gain.

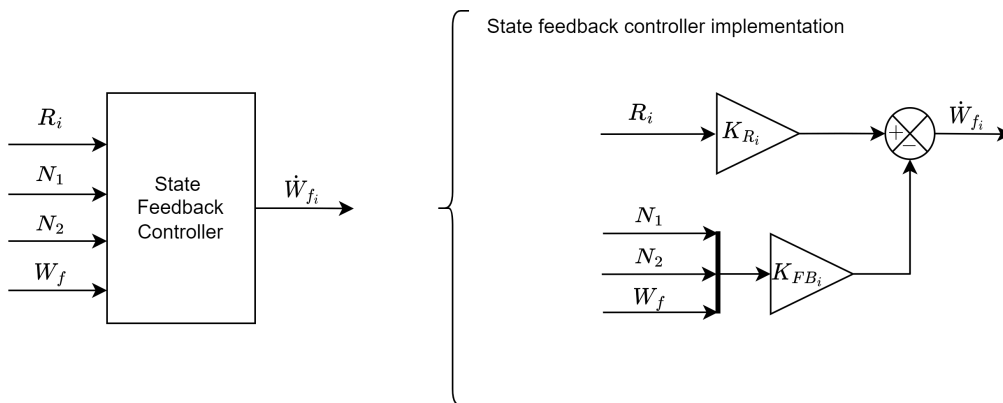


Figure 3 – Basic state feedback controller unit for the ECS

4. More Integrated Total Energy Control System

The MI-TECS controller architecture is presented in Fig. 4. The main aspect of the MI-TECS architecture is to replace the demand based on the fuel flow rate $\dot{W}_f$ from the setpoint controller of the ECS by a demand computed in the TECS controller, which results from the energy balancing characteristics inherent from the TECS control law. In practice, the feedback loops from the setpoint controller N_1 , N_2 and W_f are integrated with the existent feedback loops in the TECS algorithm $\dot{E}$, $\dot{L}$, q and θ , providing indirect thrust control, in the same fashion as in the set point controller, and eliminating the need to convert normalized thrust commands to N_1 or EPR references.

The original TECS is modified to account also for setpoint controller characteristics. The MI-TECS controller becomes responsible for determining the fuel flow rate demand required to balance the aircraft in terms of thrust and to provide decoupled and coordinated longitudinal motion. This extension follows the same principles from the original TECS proposal, with the advantage that the fuel flow rate demand can be readily combined with the transient and limit protection logic, and there is no need for using a built-in static schedule for command conversion or to scale the commands as a function of weight. Removing the static schedule contributes to mitigating the loss of performance associated with engine degradation. Additionally, since the weight typically needs to be estimated, the controller performance becomes subject to the accuracy of this estimator, and favoring the direct usage of sensors with higher availability and accuracy can contribute to the system's reliability.

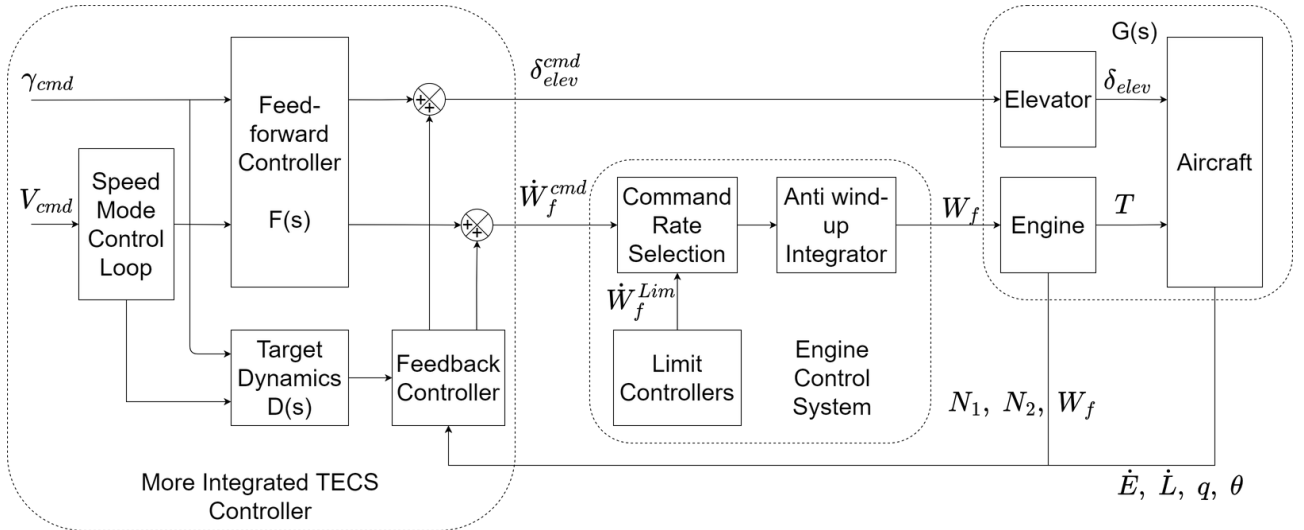


Figure 4 – More Integrated TECS architecture

The MI-TECS feedforward controller is computed using a model follower approach, based on [7, 8]. The MI-TECS feedback controller is computed using a full-state feedback methodology, adapted from [16] and [17]. The MI-TECS controller design is detailed in [2, 3]. Especially for the case of multivariable systems, this methodology allows for frequency domain shaping. It simplifies the design regarding choices related to stability margins, input control activity, and disturbance rejection without the need for high-order feedback controllers. The general procedure for determining the controller involves defining a linear design model, which consists of an open loop model of the plant, augmented with actuators and integrators, with output weighting in the frequency domain. This model is used for solving a linear quadratic optimization problem, and the matrices Q and R in the cost functional are used as additional tuning parameters for balancing control activity and shaping the closed-loop frequency response. The controller is computed minimizing the cost functional detailed in Eq. 7, where u is the input vector of the design model and z is the weighted output vector.

$$J = \int_0^\infty (z^T Q z + u^T R u) dt \quad (7)$$

In the case of the MI-TECS design, the inputs are the control variables δ_{elev} and $\dot{W}_f$. The outputs correspond to weighted signals associated with the specific energy variables $\dot{E}$ and $\dot{L}$, whose weights

are shaping transfer functions, and aircraft and engine variables, whose weights are scalars. Figure 5 provides the linear design model schematics.

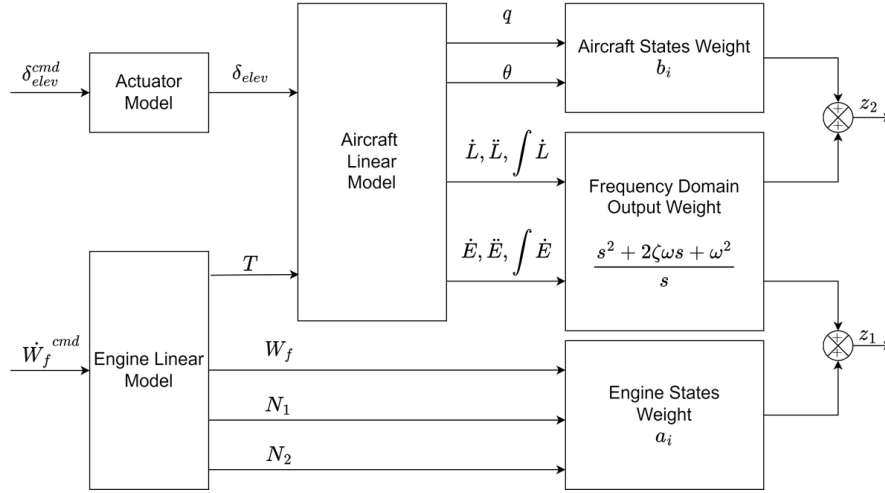


Figure 5 – Linear design model

5. Comparison of TECS and MI-TECS Controllers

The examples presented herein are based on an six-degree of freedom, nonlinear model and non-proprietary Boeing 747 Simulink[®] simulation package, described in [18, 19, 20, 21, 22]. The engine model corresponds to a non-proprietary model of a Pratt & Whitney JT9D two-spool turbofan engine available in the Simulink[®] package provided by the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) [23, 24]. Figure 6 presents the operational envelope for retracted flaps conditions. For the examples presented in this article, the nonlinear aircraft and engine models are linearized at Mach 0.6, varying the altitude according to Fig. 6.

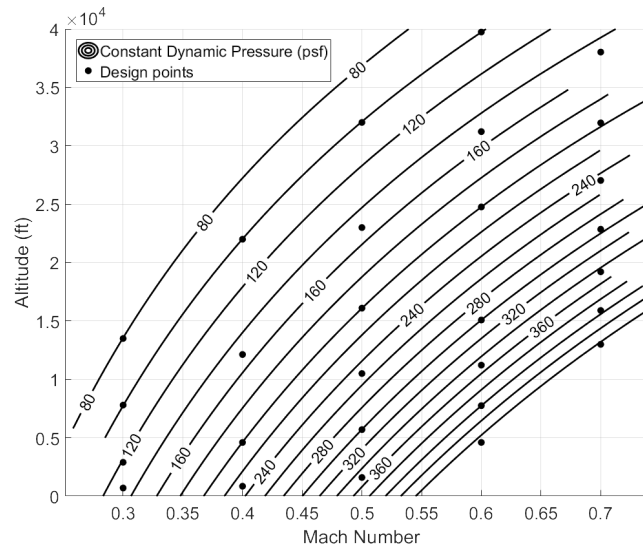


Figure 6 – Design envelope as a function of Mach number and pressure altitude

Figures 7a and 7b presents the aircraft and engine open loop poles for several conditions within the operational envelope. It is noticed that the dominant modes of the engine are comparable to the fastest modes of the aircraft, and it is expected that the engine behavior influences the design of the aircraft control system to some extent.

In the standard TECS design, it should be remarked that the control objectives associated with the ECS are restricted to engine-level behavior, and the control objectives associated with the TECS are

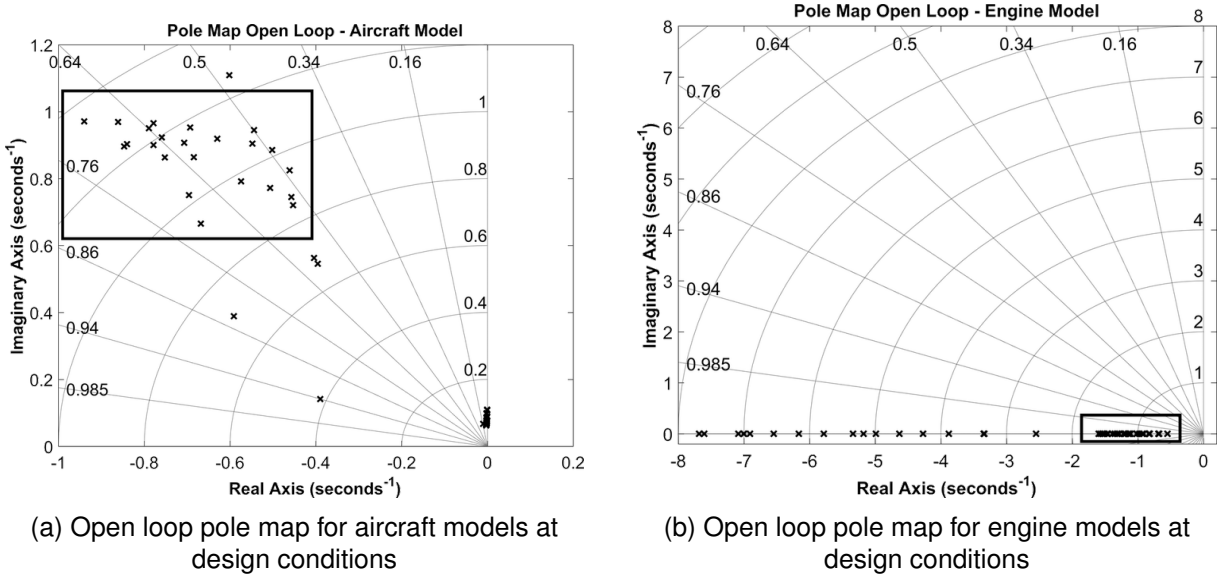


Figure 7 – Open loop pole map for aircraft and engine linear models in design envelope

associated with aircraft-level behavior. Then, according to the premises from the standard architecture, the following layout is arranged:

1. Aircraft level control design is subject to restrictions associated with component-level design since the ECS does not account for requirements at aircraft level behavior;
2. Aircraft level control design must adapt to the ECS imposed dynamics since engine dynamic modes are comparable to the aircraft dynamic modes;
3. Independence from TECS and ECS needs to be continuously verified throughout the design to ensure consistency;
4. From a control system design perspective, controller solutions that directly explore the mutual influence of aircraft and engine dynamic modes are disregarded, somewhat restricting the solution space.

These facts are illustrated with practical examples for design conditions at Mach 0.6. The standard TECS controller configuration is computed using a fixed structure optimization algorithm described in [25], which is available as the routine *systune* in the MATLAB® framework. The comparison between two different controller structures might not be straightforward since the tuning process might influence the results. Therefore, the general goal was to obtain a standard TECS controller compliant with the requirements established for the MI-TECS controller, focusing on optimizing the linear step response behavior against requirement targets for speed and flight path tracking. In that sense, both strategies result in controllers with an approximately equivalent behavior. The design is performed considering a baseline linear engine dynamic model and two modified versions in which faster and slower responses regarding a thrust step input were introduced. This is achieved by augmenting the linear engine model using inner feedback loops at the engine level. The baseline rise time is 1.98s. It is set respectively to 0.5s and 5.13s in the alternative configurations. This setup is presented in Figs. 8a and 8b, in which the thrust unit step response and the frequency domain responses are plotted for each configuration.

Suppose the same input-output behavior is intended to be preserved at the aircraft level, herein treated as a function of airspeed and flight path angle step responses. In that case, the outcome of changing the engine characteristics can be inferred from the changes introduced in the controller feedback gains configuration since the standard TECS controller does not augment the engine dynamics. The TECS feedback controller gains are computed for each modified version of the engine, for design conditions at Mach 0.6, and the results are presented in Fig. 9.

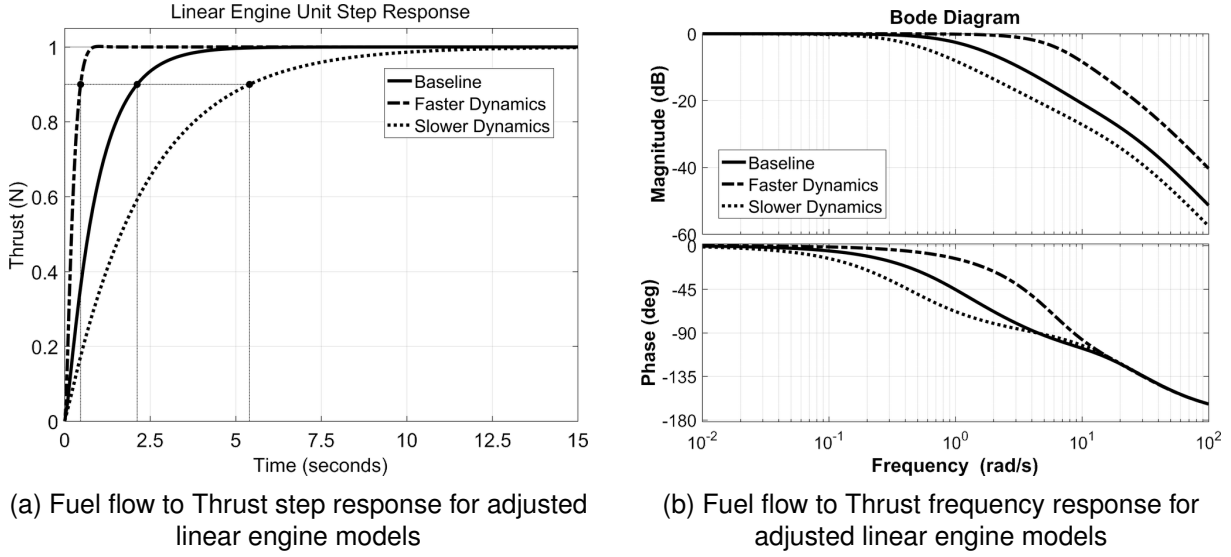


Figure 8 – Characterization of adjusted linear engine models in time and frequency domain

It is remarked that from the point of view of the optimization algorithm that computes the feedback gains, the values associated with both control channels were affected, although in less extension for the elevator control augmentation. The energy variables' feedback gains changed consistently: the gain magnitudes were reduced for faster engine dynamics and vice-versa. Therefore, even if the engine response is assumed to be homogeneous within the aircraft's operational envelope, a minimum performance requirement associated with the engine response is helpful so that the aircraft level controller is designed in acceptable terms. Slower engine dynamics leading to higher feedback gains could result in a reduction of stability margins or the need to compromise controller performance at the aircraft level. This is a practical demonstration of the influence of engine behavior from the aircraft control system design perspective.

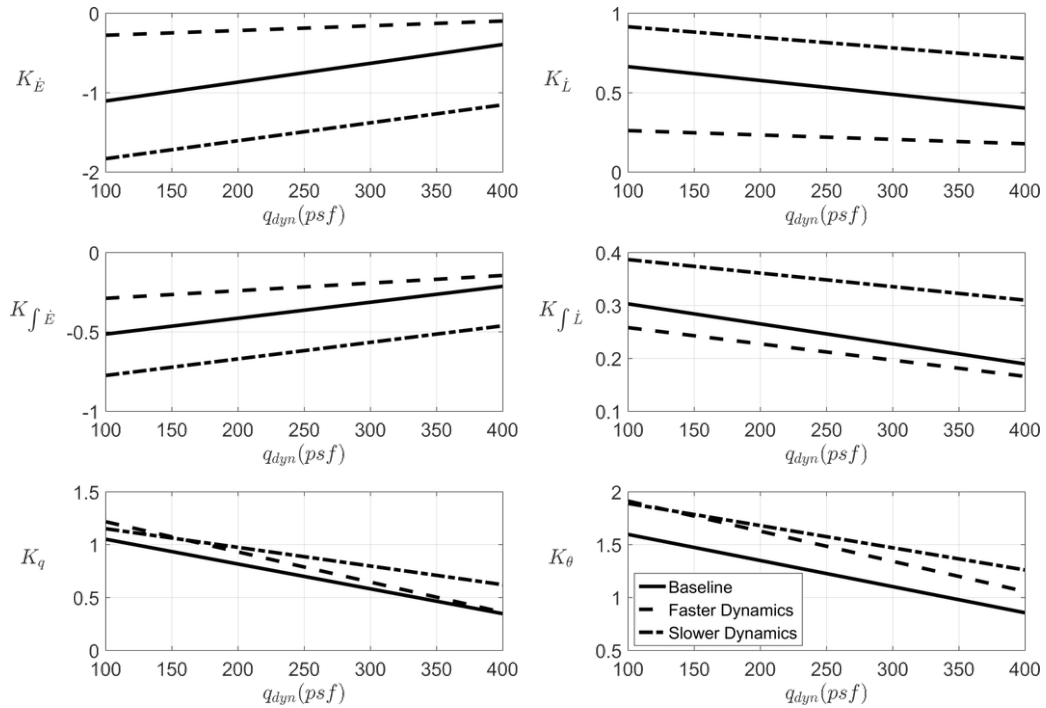


Figure 9 – TECS controller gains computed for adjusted linear engine models

In contrast to the standard TECS architecture, the MI-TECS addresses the unification of functional objectives [1a] and [2a] as listed at the beginning of this article, within a common design framework. In this context, it is possible to establish a target for [1a], in conjunction with requirements for [2a]. The

engine closed-loop behavior becomes a byproduct of the integrated design, and the engine dynamics is used as an additional degree of freedom for the design rather than a restriction.

Figure 10 shows an equivalent closed-loop linear engine model used to assess the augmented engine behavior, using the same formulation of the engine limit controllers in Eq. 6, where the input for the equivalent controller is thrust. This formulation allows a comparative analysis of open and closed-loop dynamics, considering only the gains associated with the engine feedback variables in the engine control channel, designated by W_f , N_1 and N_2 .

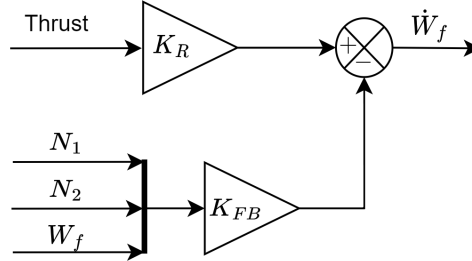


Figure 10 – Model for equivalent engine closed-loop response with MI-TECS

In the next examples, the linear quadratic feedback cost functional is changed concerning scalar weights associated with the engine feedback variables. This is used to modify the target for the equivalent closed-loop engine dynamics. The first example (Figs. 11a and 11b) has as design target to obtain a homogeneous engine response. In the second example, shown in 12a and 12b, the engine target dynamics is set to be both homogeneous and more aggressive than the open loop engine.

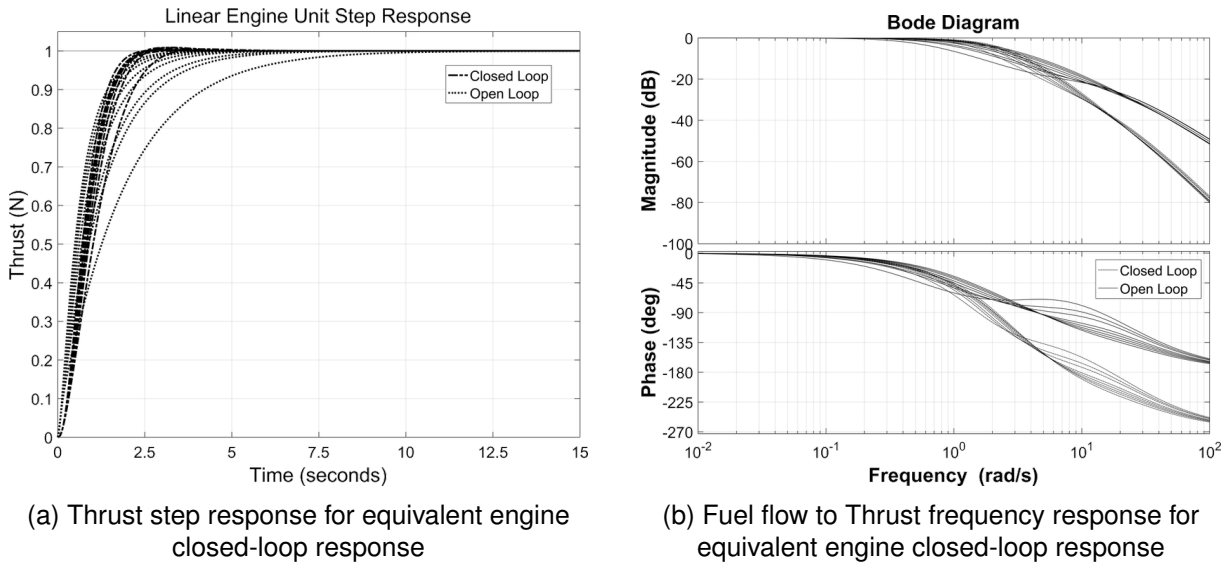


Figure 11 – First example of equivalent engine closed-loop response with MI-TECS

These examples show how the MI-TECS approach offers flexibility for balancing the gain design among the several components of the architecture. Additionally, it allows specifying requirements at the engine level while it ensures proper behavior at the aircraft level and anticipates integration aspects at early design stages.

A simulation using the linearized aircraft dynamics coupled with the nonlinear engine model compares the conventional TECS and the MI-TECS controllers. The TECS controller was designed considering the baseline engine behavior, and the MI-TECS was designed to provide faster engine dynamics, as in the example of Fig. 12. The aircraft response and fuel flow inputs are presented in Fig. 13b, considering a speed step input. Comparing both responses, smaller transients are noticed for the MI-TECS controller, combined with faster engine demands.

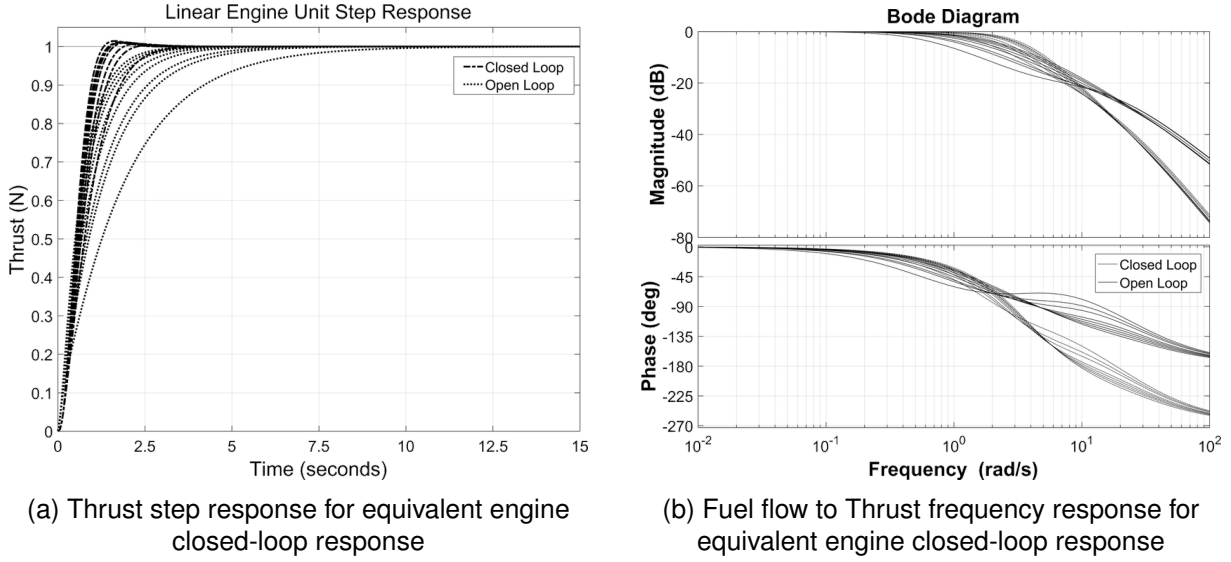


Figure 12 – Second example of equivalent engine closed-loop response with MI-TECS

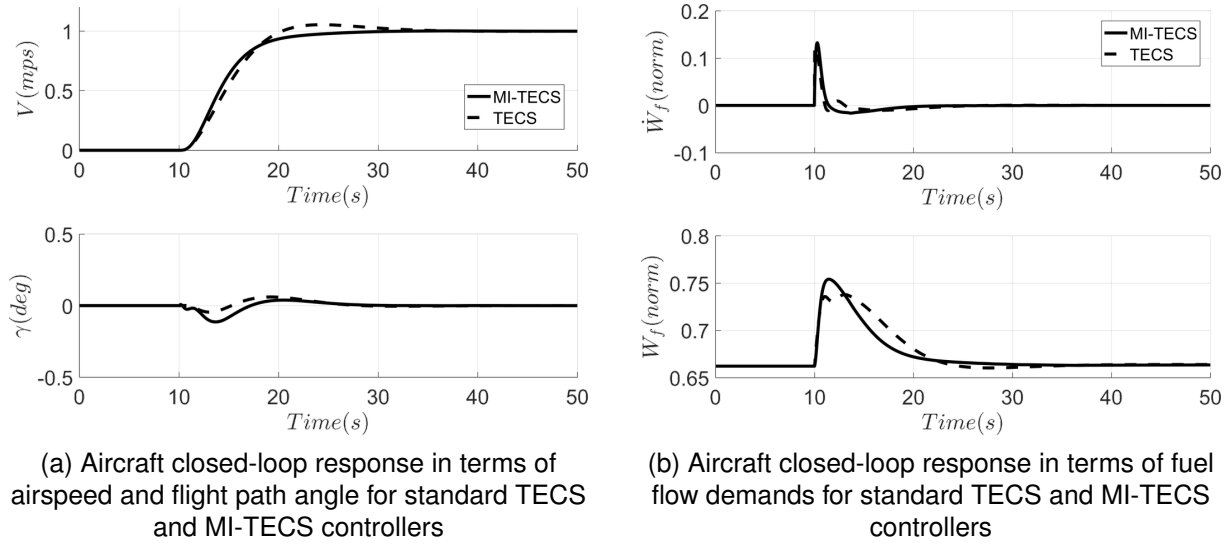


Figure 13 – Aircraft closed-loop response for standard TECS and MI-TECS controllers

In the context of an integrated design, the differences observed in the engine behavior can also be regarded in terms of engine health and maintenance aspects. Herein, the fact that the engine dynamics becomes an additional degree of freedom in the controller design allows the assessment of how much aircraft level maneuvers could adversely affect the engine in terms of degradation of its internal components. Using [10] as a basis, empirical models can be used for estimating the impact of engine component degradation and its lifespan in terms of its internal variables, such as the high-pressure turbine speed N_2 and temperature T_{45} . Equation 8 provides a damage assessment criterion for turbine creep or rupture damage rate, and Eq. 9 provides a forecasting model for the remaining life of turbine blades,

$$d_{c/r} = \left[c_1^{T_{45}} \right] \left[c_2 + c_3 N_2^2 \right] \quad (8)$$

$$L_{rl}(T_{fe}) = T_{f0} - \sum_{i=1}^{T_{fe}} \left[c_1^{T_{45}} \right]_i \left[c_2 + c_3 N_2^2 \right]_i \quad (9)$$

where $c_{1,2,3}$ are empirical constants, i represents a cycle or time interval, L_{rl} is the remaining life, T_{fe} is the time or cycle of failure and T_{f0} is the predicted lifespan. In qualitative terms, the damage rate increases as a square function of N_2 and a power function of T_{45} .

These algorithms are used to compare qualitatively the two design approaches to the influence of N_2 in the turbine blades' lifespan. When variables associated with engine health are compared, a reduction of 14.23% in the accumulated squared ΔN_2 component is obtained with the MI-TECS design for the condition evaluated, as presented in Fig. 14a. This indicates that for the same maneuver, less impact in the turbine blades lifespan is expected for the MI-TECS approach than the standard one. Furthermore, it is possible to establish comparisons in terms of relative fuel consumption, as exemplified in Fig. 14b. Considering the relative accumulated ΔW_f in each case, a reduction of approximately 8.75% is obtained for the MI-TECS design regarding accumulated fuel consumption for the speed step input maneuver. Table 1 summarizes this analysis for additional design conditions at Mach 0.6. The quantities ΔN_2 and ΔW_f account for variations around the initial equilibrium condition, so only the effects due to the maneuver are considered in the analysis. Also, any condition in which the limit controllers had become active were disregarded, such that only contributions from the main controllers are considered in the comparison.

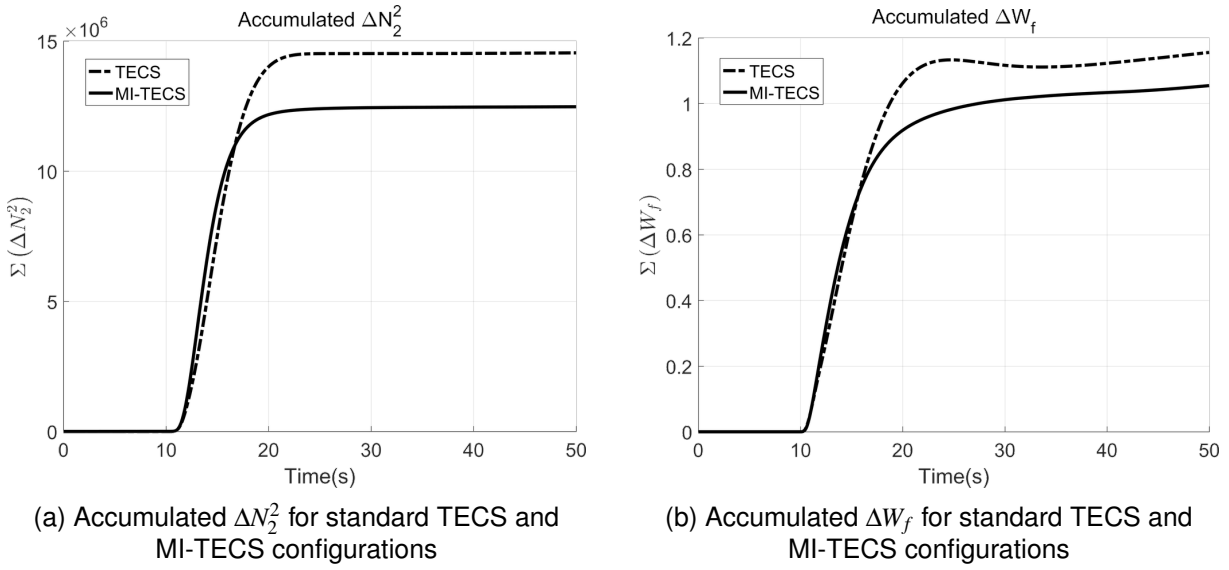


Figure 14 – Accumulated ΔN_2^2 and ΔW_f for standard TECS and MI-TECS controllers

Table 1 – Relative improvements of the MI-TECS compared with the TECS controller in accumulated fuel flow variation and accumulated squared N_2 for conditions at Mach 0.6

Alt. (kft)	$\Sigma(\Delta W_f)$ (%)	$\Sigma(\Delta N_2^2)$ (%)
4.60	7.86	6.02
7.80	7.63	8.5
11.20	9.5	10.45
15.00	8.75	14.23
24.80	11.19	19.83

Finally, the MI-TECS offers at least three structural advantages compared to the conventional TECS:

1. All variables used in the closed-loop control are measurable directly from aircraft sensors: quantities such as weight and thrust are not used within the controller. Although estimators could be used to infer weight and thrust, the controller performance would be subject to the accuracy of these estimates throughout the envelope. This modification favors the use of sensors with higher reliability, such as air data probes and inertial sensors. This enhances the overall reliability of the system.
2. The two degrees of freedom structure allows for better allocation of design requirements associated with controller robustness and performance, leading to reduced transient behavior [2, 3].

3. Since the control interface between the controller and the engine is specified in terms of the derivative of the fuel flow rate, it is not required to use conversion lookup tables from thrust to N_1 or EPR as in the standard ECS design; this is a welcome mitigation for system performance deterioration due to engine degradation.

6. Conclusion

This article presented a comparison of the standard TECS and the MI-TECS. In conclusion, the integrated design can be explored to enhance the performance and lifespan at the engine level while preserving performance at the aircraft behavior level. Furthermore, this approach yields more efficient controllers and ultimately to improvements associated with costs related to engine maintenance.

By considering the engine dynamics as a part of the design framework, the MI-TECS offers the possibility of determining controllers oriented to combine aircraft and engine performance at different levels. Firstly, given a modular design in which the ECS setpoint controller is treated separately from the Flight Control System (FCS), the integrated framework could be used to determine explicit targets regarding engine response for the ECS design. This additional layer of requirements allows for improving the harmonization between the ECS and the FCS. Secondly, since aviation moves towards increased demands for more efficient and sustainable systems, integrating FCS and ECS offers solutions to enhance the efficiency of existing airframes. In the integrated framework, aircraft performance can be associated with metrics such as fuel consumption and accumulated damage of engine components.

In that sense, future works can address optimal design criteria for specific aircraft maneuvers, aiming to explicitly reduce fuel consumption or engine damage with minimal influence on system performance. Another aspect to be detailed would be the robustness under degraded operation conditions when compared to conventional designs that apply fixed conversion schedules from thrust to N_1 or EPR and are subject to variability throughout the engine lifespan.

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