Prototypical Control for the Digital Twin of Aircraft Environmental Control System

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Abstract

A digital twin of the overall aircraft Environmental Control System is being developed as part of TheMa4HERA, a large European research initiative. It shall support verification and validation activities by virtually demonstrating the behavior of the complete system in various conditions. To this end, a prototypical control scheme needs to be developed so that a dynamic simulation through complete flight missions is enabled. The prototypical control scheme is tuned using a simplified version of the Digital Twin which focuses on robustness and fast computation time, while making it robust enough to be stable when used with the high-fidelity Digital Twin. An already stable and working controller for simulating the detailed Digital Twin, provides a significant gain of time, allowing for immediate preliminary results on both steady-state and transient system behaviors. This paper describes the base model of the Digital Twin and the methodology used to design the prototypical control architecture.

Keywords: Digital Twin, Modelica, Environmental Control System, Prototypical Control

1 Introduction

Inside an aircraft, the Environmental Control System (ECS) controls temperature, pressure, humidity and fresh air supply of the pressurized areas of the fuselage (Sielemann et al. 2007). Conventionally, this system uses bleed air from the engine as a source of fresh air. Therefore, the engines act as compressors for the cabin, and excess energy can be used in an air cycle machine to cool the air before distributing it to the fuselage. Consequently, ECS increases engine fuel consumption and hence, greenhouse gas emissions. To reduce these emissions, a number of research projects are looking at hybrid, hydrogen-powered or sustainable-fuel aircraft. These new aircraft concepts thus require innovative ECS architectures to replace the traditional bleed air-driven systems.

As part of the European Clean Aviation project TheMa4HERA, the German Aerospace Center (DLR) is developing a Modelica-based Digital Twin of the ECS for a hybrid electrical regional aircraft. Modelica is an object-oriented modeling language (P. Fritzson 2014) and has already been successfully used in the creation of digital twins (Delussu et al. 2022) (Peter Fritzson 2021) (Magargle et al. 2017). The aim of this model is to serve as a virtual test bench for evaluating different ECS architectures throughout a complete gate-to-gate mission and under different environmental conditions (standard, hot or cold day, high or low ambient humidity) and to support the verification and validation process by demonstrating the behavior of the complete ECS architecture in a representative virtual environment. To guarantee the validity of the results, high-fidelity models from each component of the Digital Twin are built by the different partners inside the project and validated with dedicated hardware tests. Then, they are integrated as Functional Mock-up Unit (FMU) in the simulation framework built by DLR using the Thermofluid Stream Library (TFS) (Zimmer 2020), to form the complete Digital Twin. Inside this framework, components are defined as replaceable to be able to easily switch between the robust but simple versions and the high-fidelity ones once they are available. The integration of FMU follows a new method based on a control-like approach described in (Gebhart and Lepais 2025). In this method, FMU outputs, such as a mass flow rate, are treated as setpoint signals used to control the actuator models, such as a compressor, from the TFS library. With this approach, one can integrate FMUs inside a Modelica library framework without decreasing the robustness of the overall model, especially at initialisation. Finally, the Digital Twin is simulated for complete gate-to-gate mission under different environmental conditions. This combination of hardware tests and virtual simulations allows to test and compare different ECS architectures and to evaluate their performance at aircraft level.

In order to carry out these simulations in a realistic way, a prototypical control must be designed to guarantee the respect of various mission setpoints, such as temperature and pressure inside the cabin. This prototypical control must be as robust as possible in order to accommodate various simulation conditions and ECS models of varying fidelity levels. The robustness is particularly crucial since the controller design is carried out without high-fidelity models, relying solely on a simplified version of the Digital Twin that prioritizes computational robustness and fast simulation times. Both robust and high-fidelity models share the same interface, enabling the design of a common control architecture but exhibit different dynamic behaviors, such as response time or damping. The goal of this prototypical control is not to optimize performances with the detailed models while tuning it with the simpler ones, but to ensure it can be directly applied with the high-fidelity models in order to test their integration inside the overall Digital Twin and get preliminary results on both steady-state and transient behaviors.

The Digital Twin framework with robust models, detailed in section 2, includes all necessary components for running a complete mission, such as an atmospheric environment model for outer temperature, pressure and humidity, a mission profile block to define mission-related inputs, such as aircraft altitude, speed and controller set-points. It also defines the interfaces of the different components and how they exchange information in the Digital Twin. In this regard, the Modelica language proves to be highly valuable because it enables the creation of a common interface for a given class of models which makes the exchange of one model by another version very simple and easy. The prototypical control scheme is designed around this common interface definition to ensure compatibility with both the base and high-fidelity versions of the Digital Twin, as shown in section 3. Finally, section 4 presents the simulation results of the base Digital Twin and provides a comparative analysis of two ECS pack architectures, both simulated using the same prototypical control to demonstrate its robustness.

2 Digital Twin

This section outlines the architecture of the Environmental Control System, providing an overview of the entire system. It describes also the objectives of the control architecture, detailing the associated requirements and the various actuators available inside the system.

2.1 Presentation of the model

The open-source Modelica library DLR Thermofluid Stream (TFS) is used as the main modelling library to develop the Digital Twin. This library enables fast and robust modeling of complex thermofluid architectures (Zimmer 2020; Zimmer, Meißner, and Weber 2022), and therefore aligns with the intended goal for the base version of the Digital Twin. The development is done using Dymola 2022x, since it is focus on Modelica development and supports the import and export of Model Exchange and Co-simulation FMUs 2.0. The overall model describes the Environmental Control System of a future regional hybrid electric aircraft, including two ECS packs, a model of the pressurized areas of the fuselage, one outflow valve (OFV) and the ambient environment. An overview of its architecture is available in this paper (Gebhart and Lepais 2025) and the top-level view in Modelica is shown in Figure 1.

ECS packs are used to supply fresh air to the crew and passengers, to control the temperature of the cabin and cockpit and to cool down the avionic bay. The reference architecture consists of an electric cabin compressor connected to the air cycle machine (ACM) and is shown in Figure 2. It is adapted from (Bender 2018) which describes a 3-wheel bootstrap cycle that uses bleed air from the engines as a source of fresh air for the cabin. Since the goal is to model a bleedless aircraft, the pack has been electrified and the bleed air is replaced by fresh air from the outside compressed using an electric cabin compressor. The other modification concerns the ram air fan which is not connected to the turbine anymore, as it is the case in the 3-wheel bootstrap cycle architecture, but to an electric motor in order to be able to fully control the ram air mass flow inside the ram air channel, especially on ground. After being compressed by the electric compressor, fresh air is cooled down against the ram air flow before entering the conventional ACM itself. At this point, part of the air flow is separated and bypassed through the Temperature Control Valve (TCV). The remaining part is compressed a second time, cooled down against the ram air channel and expanded inside the turbine to a sufficient pressure level. Before being expanded, air passes through a water extractor to remove the excess humidity. This dehumidification process, called high-pressure dehumidification, is very important on ground to prevent an excess of humidity inside the cabin and ice at the outlet of the turbine. Finally, air from the turbine is mixed with the separated air from the TCV to reach the correct temperature before leaving the ECS pack. As in today's commercial aircraft, the model includes two ECS packs for the sake of redundancy, contained in the block *environmentalControlSystem* in Figure 1. Compressors, turbine and heat exchangers models are directly taken from the TFS library. Their sizing parameters (e.g. reference mass flow rate, heat exchange coefficient) have been defined according to the project requirements and by manual testing to ensure sufficient cooling in the all conditions. Therefore, these components do not represent existing ones.

The fuselage is a generic model of air circulation between the different pressurized areas (cabin, cockpit, avionic bay and cargo bay) and through systems strongly related to air circulation (mixer, recirculation fans, outflow valve). Its implementation in Modelica is shown in Figure 3. Thermal loads, such as passengers' heat, lights and electric devices as well as heat exchanges inside each area are also part of the model, but there is no leakage to the outside. Certain thermal loads such as battery, fuel cell, or power electronics (converters, ...) are not taken into account because they have their own cooling system. Fresh air from both ECS packs enters the fuselage on the left, is mixed with recirculated air inside the mixer and afterwards distributed to the cabin and the cockpit. Air from the cabin goes directly to the cargo bay while air from the cockpit passes through the avionic bay before entering in the cargo bay. At this stage, air is warmer and more humid than fresh air. A fraction of this air leaves the fuselage by the right to be expelled through the outflow valve to maintain the correct pressure inside the pressurized areas while the rest is fed back to the mixer by the recirculation fans. Inside the cabin and the cockpit, passengers and crew members are modeled by combination of a sink and a source, representing respectively the inhalation of cabin air and the exhalation of saturated, warmer air. With this

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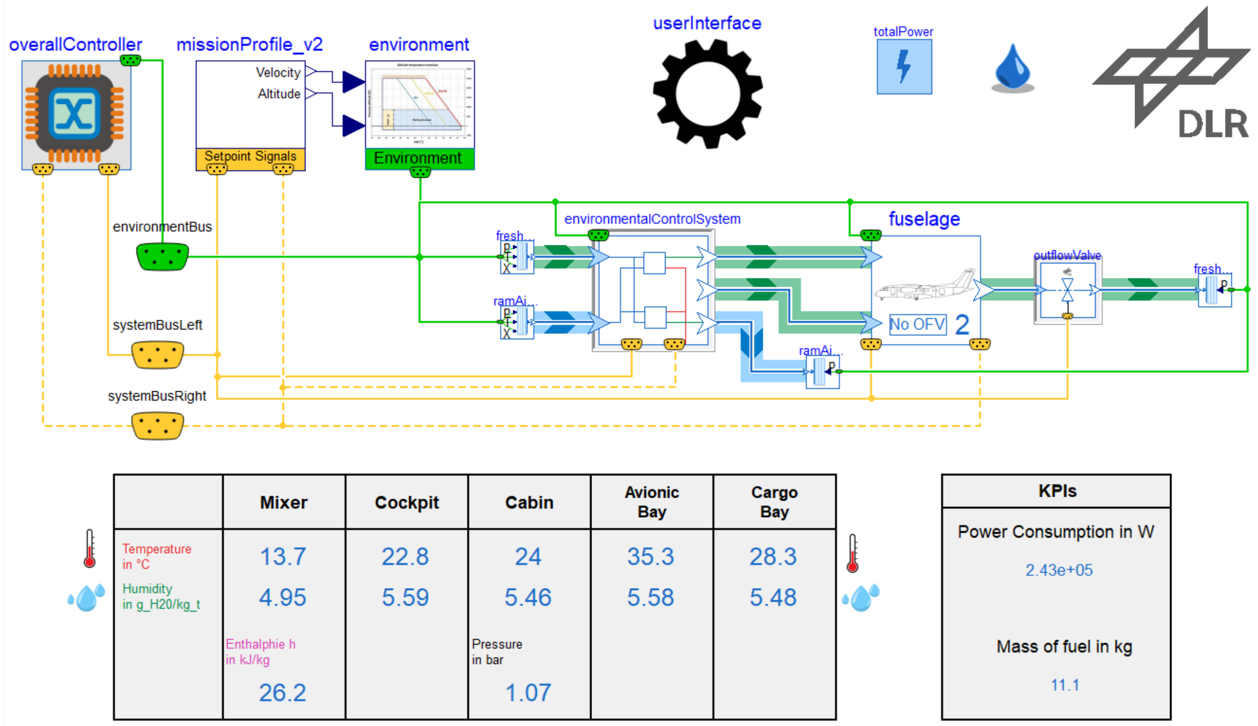

Figure 1. Digital Twin of the Environmental Control System

approach, the additional humidity brought by the passengers when breathing can be taken into account. Additionally, a heat flow source accounts for the body's heat. Each passenger is assumed to breathe at a constant volume flow rate.

The last part of the Digital Twin is the mission and environment model. It computes the temperature, pressure and mass fraction of water outside the aircraft for a given altitude profile and ground conditions, according to the International Standard Atmosphere (ISA). It also models the amount of solar radiations, as a linear function between defined ground and cruise levels. Solar radiations are used to compute the heat transfer through the windows and the fuselage of the aircraft.

This Digital Twin can be simulated for two different mission cases:

- Normal case: gate-to-gate mission with both ECS packs working
- Failure case: gate-to-gate mission with only one ECS pack working.

As described in (Gebhart and Lepais 2025), 3 typical ground conditions can be simulated:

- Standard day (STD): temperature of 15°C (288K) – 100% relative humidity
- Hot day (HD): temperature of 40°C (313K) – 50% relative humidity
- Cold day (CD): temperature of -25°C (248K) – 100% relative humidity

The "Hot day" case is the most challenging case for the design of the ECS pack and the control architecture because the highest amount of cooling power is needed.

This model is an ideal model in many different aspects. All variables can be measured and all sensors are ideal. Hence, there is neither noise nor any transport delay from the sensors or in the actuators command signals.

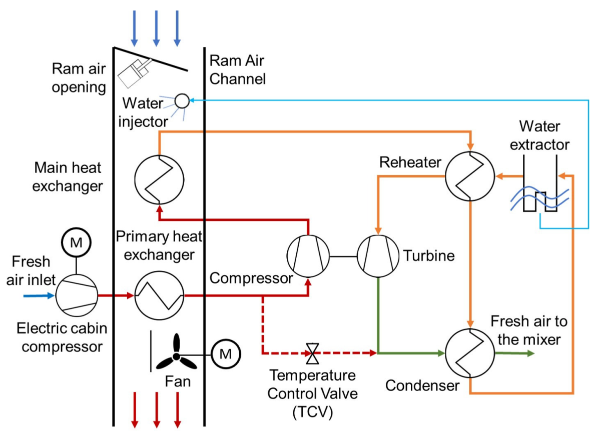

Figure 2. ECS pack architecture

2.2 Control requirements

The control requirements are various. Concerning the environmental conditions inside the cabin, the following requirements are defined:

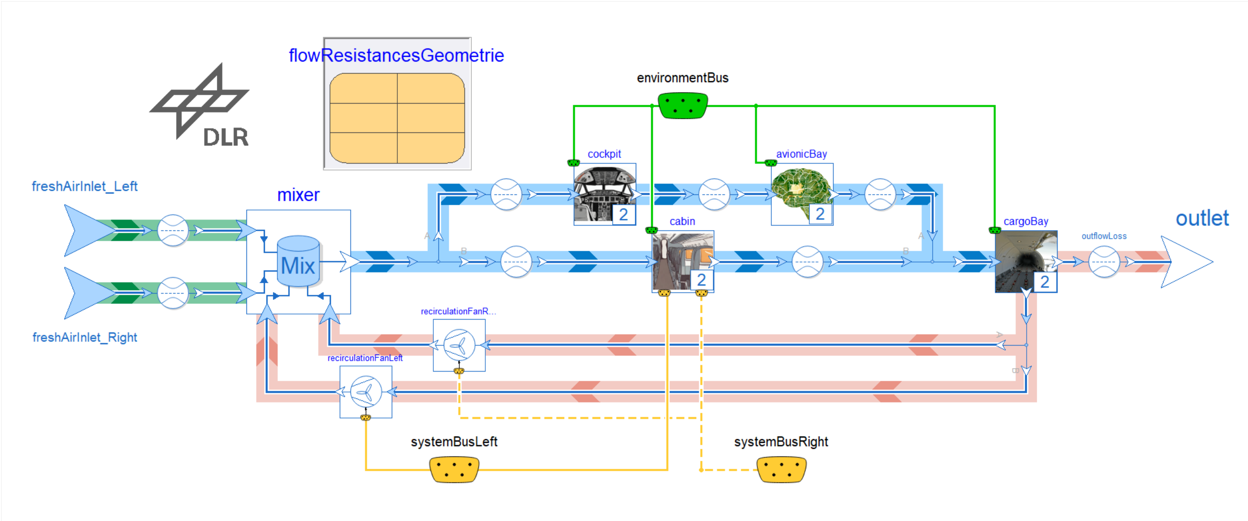

Figure 3. Fuselage architecture

- Temperature inside the cabin: in the certification specification and acceptable means of compliance 25 (CS-25), EASA defines all the constraints concerning cabin heating and ventilation for a cabin temperature equals to 24°C (297K) (European Union Aviation Safety Agency 2022).

- Pressure inside the cabin: a pressurization curve defines the cabin altitude depending on the aircraft altitude. The cabin altitude is converted into cabin pressure using the ISA model. The resulting cabin pressure curve is shown in Section 4.

- Cabin volume flow: the volume flow of air entering the cabin must be kept constant at a certain level to ensure a correct ventilation of the cabin. In today's aircraft, the mixing ratio between fresh air and recirculated is around 50% (Bagshaw and Illig 2019), which gives a volume flow of $0.75 m^3/s$

In the current state of the model, only the cabin environment is controlled that is why there are no requirements concerning the other pressurized areas.

There are two more constraints for the ECS packs:

- Fresh air mass flow: EASA CS-25 defines a minimum amount of fresh air per person to be provided by both ECS packs in normal operation: 0.25 kg/min/person (0.55 lb/min/person)(European Union Aviation Safety Agency 2022). The aircraft transports 80 passengers, 2 crew members and 2 pilots. An additional 20% mass flow of fresh air is also considered to meet additional cooling requirements. It leads to a total fresh air mass flow in normal operation of 0.42kg/s, i.e. 0.21kg/s per ECS pack. In case of failure of one ECS pack, the minimum fresh air flow is decreased to 0.182 kg/min/person (0.40 lb/min/person). In this case, no additional fresh air is considered, leading to a total fresh air mass flow in case of failure of 0.255 kg/s.

- Compressor temperature: this requirement is only used to control the ECS packs. It defines the maximum possible temperature at the outlet of the compressor mechanically connected to the turbine. This temperature will also influence the cabin temperature. Thus, the setpoint value could be the output of a controller that takes as input the cabin temperature error and the flight profile. But this would make the prototypical control scheme more complex, which is not the aim of this first implementation. Therefore, a constant value is considered for the compressor temperature setpoint. The chosen value is 180°C (453K), as done in (Bender 2018), to prevent using too heavy and expensive compressors.

A last constraint is the humidity level inside the cabin. ECS packs are also used to dehumidify the air and avoid too high humidity levels inside the cabin. Usually, the goal is to keep the relative humidity inside the cabin around 20% (Bagshaw and Illig 2019). On cruise it is not a problem since the absolute humidity outside is very low due to the low temperature, but it can be very different on ground for a hot day, for example. The current architecture of the ECS pack contains a water extractor before the turbine, which removes the excess of water inside the air above saturation. Therefore, the inlet temperature of the water extractor is very important since it will directly influence the amount of water extracted by this component. Unfortunately, the humidity level inside the cabin cannot be directly controlled with the current architecture. Thus, the humidity level is verified afterwards to make sure it stays around this value. If it is not the case, the size of the heat exchangers has to be modified.

A summary of all the values for each requirement is given in Table 1.

Table 1. Target setpoints for the control architecture

Requirements	*Normal Case*	*Failure Case*
Cabin temperature	24°C	24°C
Cabin pressure	See Figure 6	See Figure 6
Cabin volume flow	0.75m³/s	0.75m³/s
Fresh air mass flow	0.42kg/s	0.25kg/s
Maximum Compressor outlet temperatures (x2)	180°C	180°C

2.3 Actuators and controlled variables

All target variables (temperatures, mass flow, volume flow, pressure) can be measured so they will be directly used in the control scheme. There are 11 actuators available in the model. Each ECS pack has 4 actuators inside, as shown in Figure 2: cabin air compressor, Temperature Control Valve (TCV), ram air channel (ram air opening and electrical fan). The ram air channel is considered as one big actuator, even if the flow inside is controlled by both the inlet valve and the electrical fan. The fan comes in addition to the valve to increase the ram air flow if needed once the ram air channel is fully open. It is often the case on ground when the aircraft speed is not sufficient enough to generate a ram air flow. Additionally, there are 2 recirculation fans in the fuselage model, as shown in Figure 3, and one outflow valve. In total, there are 11 actuators and each of these actuators will be connected to a Single Input Single Output (SISO) controller.

Input signals have been normalized between 0 and 1. For valve actuators (TCV, outflow valve and ram air channel opening), the opening command is limited by default between 0, valve fully closed, and 1, valve fully opened. The generic TFS valve model integrates leakage when the valve is fully closed, meaning that there is still a small air flow across the valve. For turbo-actuators (compressor, fan), the rotational speed is taken as input. The reference speed ω_{ref} used in the computation of the pressure ratio is set to 1, therefore normalizing the input speed command between 0 and 1.

3 Control Architecture

This section describes the prototypical control architecture and gives some details about the methodology used to tune the different controllers.

3.1 Control Allocation

To design the control loop, all variables are considered independently. For each variable, a limited PI-Controller with anti-windup is designed. Anti-windup is used in order to guarantee a robust controller when dealing with saturation (Bohn and Atherton 1995). These controllers take the error signal between the setpoint and the current value of the controlled variable and compute the input signal for the actuator. Since only SISO controllers are considered, the control loop for each controlled variables defined in Table 1 can be represented by the generic control loop in Figure 4. The control allocation, i.e. which actuator is used to control which variable, is described in Table 2. The use of the TCV to control the cabin temperature and of the ram air opening to control the compressor outlet temperature are derived from (Bender 2018).

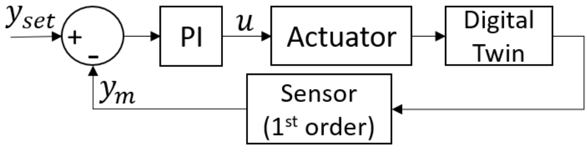

Figure 4. Generic control loop for one variable

For the cabin temperature, there are 2 control loops, one for each TCV. It only happens that both loops are identical since there is only one cabin and therefore one setpoint and one sensor signal. It is the same for the cabin volume flow with the recirculation fans.

3.2 Tuning of the different controllers

3.2.1 Limited PI-Controller with anti-windup for the fresh air mass flow

This controller computes a speed command between 0 and 1 for the electric cabin compressor inside the ECS pack, which is used to regulate the mass flow of fresh air. It has been tuned using a simple test model. In this test model, the fresh air mass flow setpoint follows a step between 0.1kg/s (first value to initialise and start the simulation) and 0.21 kg/s (setpoint of the complete model in normal operation). All other actuators inside the ECS pack (TCV, ram air fan, ram air opening) have constant inputs. To tune the controller, only a P-Controller was considered at the beginning. The gain was changed until the response approached the setpoint. But a steady-state error was still present and the controller output reached the limits. Then, the integrator was added and tuned in order to reach the setpoint value with only a small overshoot and without oscillations afterwards. Finally, the proportional gain was decreased to keep the controller output between the boundaries and avoid saturation, but without decreasing too much the response time. Anti-windup uses the default values of the Modelica limPID model.

3.2.2 Limited PI-Controller with anti-windup for the cabin volume flow

This controller computes a speed command for the recirculation fan between 0 and 1. The tuning of this controller follows the same process as described above. A simple test model including the recirculation fan and the controller, connected to a volume inside a loop, has been used for the tuning. The controller is used to control the speed of the recirculation fan in order to set a given volume flow in the loop. The setpoint for the volume flow is a step between 0.25m³/s and 0.75m³/s. The method de-

Table 2. Target setpoints for the control architecture

Variable	y_{set}	y_m	*Actuator*	u
Cabin temperature	T_{cabin}^{set}	T_{cabin}	TCV (x2)	Valves opening
Cabin pressure	p_{cabin}^{set}	p_{cabin}	Outflow valve	Valve opening
Cabin volume flow	$\dot{V}_{cabin}^{set}$	$\dot{V}_{cabin}$	Recirculation fans (x2)	Fan speed
ECS pack left fresh air mass flow	$\dot{m}_{left}^{set}$	$\dot{m}_{left}$	Cabin compressor left	Compressor speed
ECS pack right fresh air mass flow	$\dot{m}_{right}^{set}$	$\dot{m}_{right}$	Cabin compressor right	Compressor Speed
Maximum compressor outlet temperature left	T_{comp}^{set}	$T_{comp,left}$	Ram air channel left	Valve opening, Fan speed
Maximum compressor outlet temperature right	T_{comp}^{set}	$T_{comp,right}$	Ram air channel right	Valve opening, Fan speed

scribed above is also applied to tune the controller, with the goal to have a response time as small as possible without oscillations or significant overshoot.

3.2.3 Limited PI-Controller with anti-windup for the cabin pressure

Concerning the cabin pressure, the controller to be tuned computes the input signal of the outflow valve (0 valve fully closed - 1 valve fully opened). The test model used for the tuning is very simple and consists of a volume with a constant inlet mass flow. The outflow valve is placed at the outlet of the volume before the sink and is used to regulate the pressure inside the volume. The setpoint for the pressure is not a step but a trapezoid profile reproducing approximately the cabin pressure profile during a mission. The method used to tune the controller stays the same. The controller was tuned to be as fast as possible without creating too much overshoot in order to limit as much as possible drastic pressure changes in a short amount of time.

3.2.4 Limited PI-Controllers with anti-windup for the cabin temperature & compressor temperature

The control loop for the maximum compressor outlet temperature is distinct from the other loops. In this case, the ram air channel is treated as a single actuator, controlled by a SISO PI-Controller. However, two command signals are required: one for the valve opening and another for the fan. The fan operates in tandem with the valve to increase the mass flow when necessary. Since the control signals for both actuators are normalized between 0 and 1, the PI-Controller computes the sum of these two command signals, resulting in a combined signal ranging from 0 to 2. If this sum exceeds 1, the valve opening is set to 1, and the fan speed is adjusted to the remaining value. If the sum is less than or equal to 1, only the valve is opened, and the fan speed remains at 0. This command allocation strategy is made possible by the normalized actuator command signals, enabling the use of a SISO controller to manage two actuators simultaneously.

The method used to tune the two controllers differs from the one mentioned before. For the previous controllers, it was possible to use simple test models to tune them because the cabin pressure, the cabin volume flow and the mass flow of fresh air provided by one ECS pack behaves independently. To control the pressure, the outflow valve controller regulates only the amount of air expelled to the outside and does not need to know the exact mass flow of fresh air supplied by the ECS packs or the exact volume flow inside the cabin. In the test model used for the tuning, it was therefore enough to define a constant mass flow at the inlet of the volume. However, it doesn't work for the cabin and compressor temperatures. The cabin temperature is regulated by changing the pack outlet temperature, but this outlet temperature is strongly linked to the outlet mass flow of the pack, to the recirculation flow and also to the mass flow inside the ram air channel. The choice of a constant temperature setpoint for the compressor outlet temperature was also a way to split these two controlled variables.

Therefore, the complete Digital Twin model has been used for the tuning and, more precisely, a linear version of the model. Linearization has been carried out using the linear analysis tool from Modelica. The TCVs and the ram air openings were set to constant input values and the simulation was run on hot day on ground, since it is the most challenging case, until reaching steady-state (correct pressure and volume flow inside the cabin, correct outlet mass flow from both ECS packs and all other variables constant or at least stabilized). Then, the model was linearized around this steady-state point. Inputs were the TCV command signal and the ram air opening and outputs were the cabin and compressors outlet temperatures. This linear model was then imported in Simulink and both controllers were tuned using Simulink PID Tuner App. During this tuning, robustness was an important aspect so the gain and phase margins have been maximised. The response time of the cabin temperature was chosen to be as fast as possible. To finish, the coefficients of the Simulink PID were translated into the Modelica limPID to finally obtain the

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last two controllers.

4 Results

This section starts by showing some simulation results obtained when simulating the base version of the Digital Twin throughout a complete gate-to-gate mission using the prototypical control architecture. In a second time, the ECS pack model is replaced by a new version to mimic the exchange of the simple model by the high-fidelity one. The new model is again simulated on a complete mission, demonstrating the stability of the controllers with a different model and showing the kind of comparison that can be performed with the Digital Twin.

4.1 Simulation of the base version of the Digital Twin

The Digital Twin is simulated by considering a unique gate-to-gate mission and the 3 environmental conditions defined in section 2 (standard, hot and cold day). The mission is defined by an altitude profile and a speed profile, shown in (Gebhart and Lepais 2025). Initially, the aircraft is stationary on ground, at sea level (0m), to simulate the passenger boarding phase. After the taxi phase and takeoff, the aircraft climbs at 7620m and progressively reaches its cruise speed (154 m/s). The cruise phase has a duration of 24 minutes. After the descent, the aircraft lands at sea level (0m) and taxis to the boarding gate. Once at the boarding gate, the mission is finished that is why there is no stationary phase at the end.

The results display all the controlled variables outlined in Table 1, with the exception of the compressor outlet temperature for the right ECS pack. Since both packs and their associated controllers are identical, their results are identical as well. Therefore, only the compressor outlet temperature for the left ECS pack is presented in Figure 9. The prototypical control architecture is successful on standard and hot days. Indeed, Figure 5 to Figure 9 show that all controlled variables reach their target setpoint. Concerning the compressor outlet temperature shown in Figure 9, the goal of the control loop is mainly to prevent reaching a too high temperature, so a lower steady-state temperature is not really a problem.

On the other hand, on cold day the temperature inside the cabin is too low, as shown in Figure 5. The problem doesn't come from the controllers but from the ECS pack architecture itself. Indeed, in Figure 9, the compressor temperature on cold day is also very low compared to standard and hot days. However, this temperature is one of the hottest one inside the ECS pack. Therefore, it can be inferred that the ECS pack simply cannot heat the air sufficiently to achieve a correct temperature inside the cabin and another device is needed in this case, for example an electric heater. This behavior is directly linked to the decision of designing a bleedless ECS pack. In conventional bleed packs, the bleed air comes directly from the engine at high temperature and therefore always needs to be cooled, even on cold days.

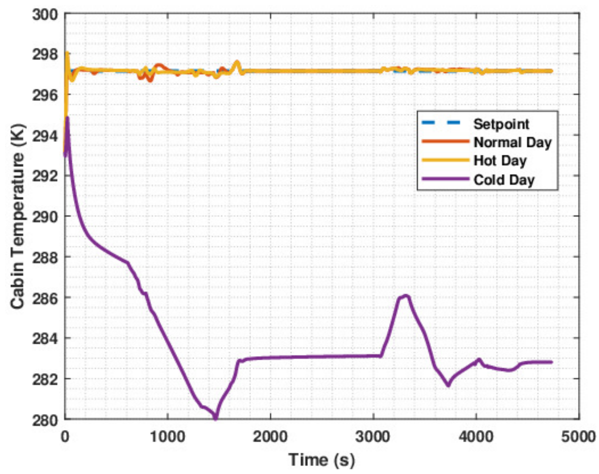

Figure 5. Cabin temperature for a gate-to-gate mission with 3 different environmental conditions

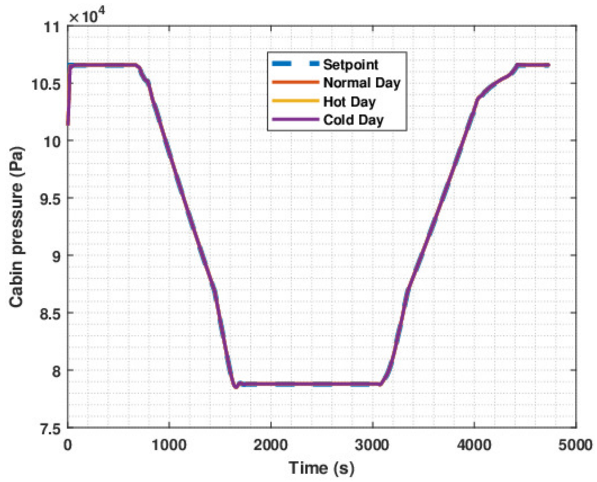

Figure 6. Cabin pressure for a gate-to-gate mission with 3 different environmental conditions

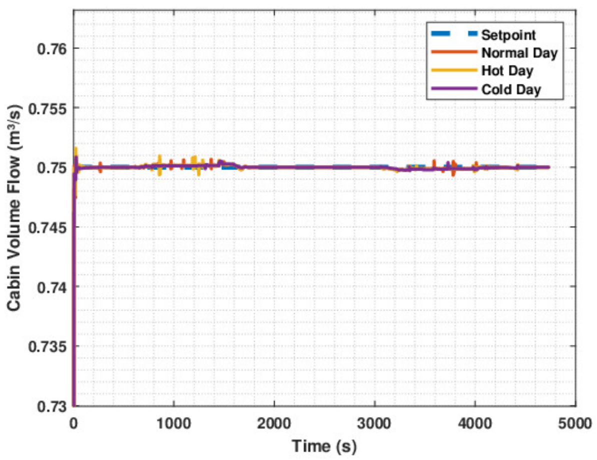

Figure 7. Cabin volume flow for a gate-to-gate mission with 3 different environmental conditions

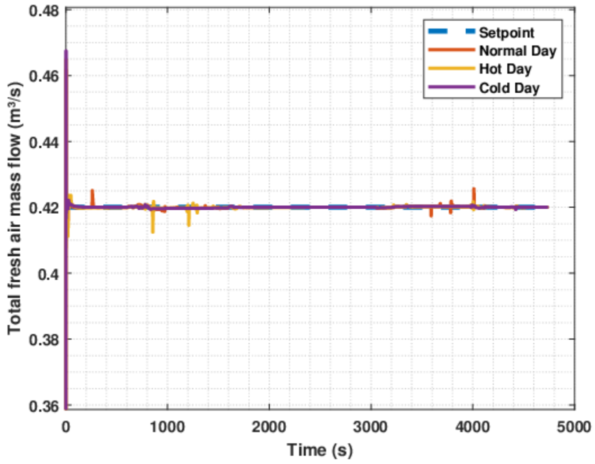

Figure 8. Total mass flow of fresh air provided by the ECS for a gate-to-gate mission with 3 different environmental conditions

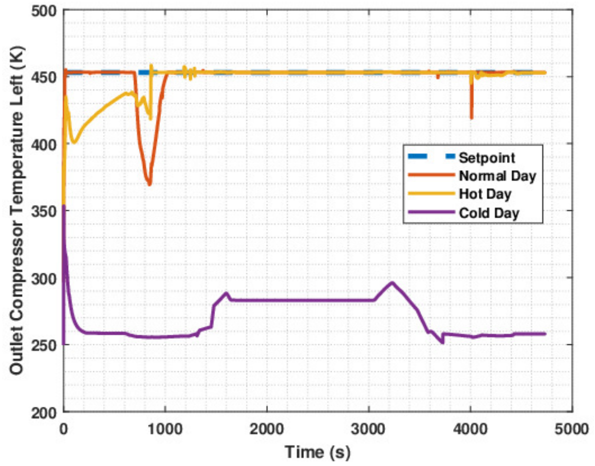

Figure 9. Left compressor outlet temperature for a gate-to-gate mission with 3 different environmental conditions

4.2 Comparison with a second ECS pack architecture

Now that the prototypical controller has been validated, the current ECS pack architecture is replaced by a modified version of a 4-wheel bootstrap cycle, described in (Sielemann et al. 2007) and (Bender 2018), to mimic what would happen when replacing the base ECS pack by a high-fidelity FMU. The conventional 4-wheel bootstrap cycle is based on the 3-wheel bootstrap cycle and adds a second turbine at the outlet of the pack, after the condenser. One of the goals of this architecture is to avoid the problem of icing at the outlet of the first turbine. The ram air fan is still driven by an electric motor. Bypassed air from the TCV is now injected at the outlet of the second turbine.

The results of the simulation with this new architecture are shown in Figure 10, Figure 11 and Figure 12. Since only the ECS packs have been changed, the focus is given on the new cabin temperature and compressor temperature. Results are only shown for standard and hot days since the new pack does not include neither any heating component.

Figure 10 shows the temperature difference inside the cabin between the new and the reference architectures ($\Delta T_{cab} = T_{cab}^{new} - T_{cab}^{ref}$). The difference is small on hot day (maximum 0.2K), but is bigger on standard day (maximum 0.8K) with oscillations during the climbing phase (at time = 1000s). When comparing with Figure 5, there are also oscillations at time = 1000s on standard day. So the controller generates stronger oscillations with the new architecture, but it is still able to ensure the correct temperature inside the cabin. Table 3 also shows a larger overshoot interval for the cabin temperature with the second ECS pack architecture but the difference is relatively small, around 0.5%. For both ECS packs architecture, the cabin temperature is maintained inside a bandwidth of 3% around the setpoint for the whole mission. Since the robustness is the main criteria, the cabin temperature controller still fulfills its goal.

Table 3. Comparison of the performances of the cabin temperature controller for initial and second ECS pack architectures

	Overshoot (%) $[min; max]$	*Mean Square Error Cabin Temperature*
Initial ECS pack	$[-2.06; 2.84]$	0.0777
Second ECS pack	$[-2.43; 3.06]$	0.1218

Figure 11 shows the temperature difference of the compressor outlet between the new and the reference architectures ($\Delta T_{comp} = T_{comp}^{new} - T_{comp}^{ref}$). On standard day, the biggest temperature difference also happens at time = 1000s and is negative. It means that the compressor outlet temperature of the new architecture is smaller than the compressor outlet temperature of the reference architecture. Since the setpoint for the compressor temperature defines a maximum value and not a target value, this smaller temperature is not an issue. However, at time = 4000s, the compressor outlet temperature of the new architecture is higher (around 20K) than the one of the reference architecture. But in Figure 9, the compressor temperature is lower than the temperature setpoint at time = 4000s on standard day. So, this positive difference does not mean that the compressor temperature is 20K above the temperature setpoint. On hot day, the compressor outlet temperature of the new architecture is always lower or equal to the reference architecture.

As for the other controlled variables (cabin pressure, cabin inlet volume flow, fresh air mass flow) they all reach their target setpoint. Performances may vary (more oscillation for example) but the steady-state behavior is the desired one.

Since the prototypical control is working successfully for both ECS architectures, the Digital Twin can now be

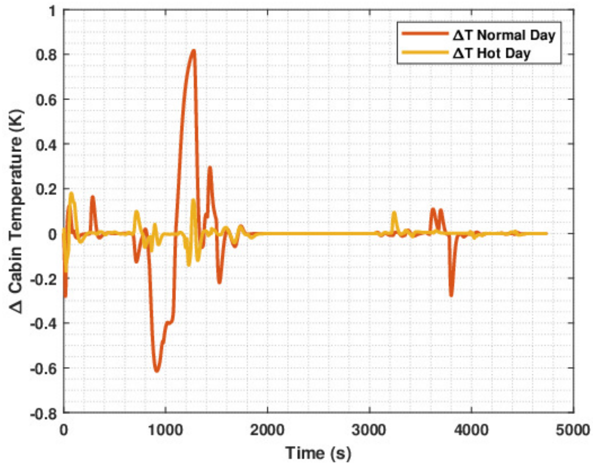

Figure 10. Cabin temperature difference between the new architecture and the reference one

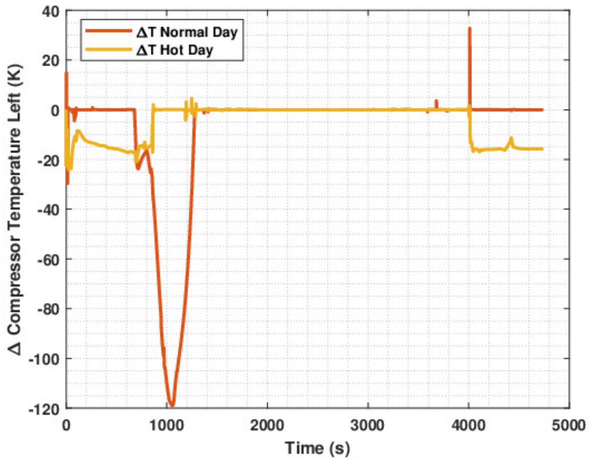

Figure 11. Left compressor outlet temperature difference between the new architecture and the reference one

used to compare them at aircraft level. For example, it can be interesting to compare the total power consumption of both architectures during the flight. Figure 12 shows the difference between the power consumption of the new architecture and the reference one ($\Delta P = P^{new} - P^{ref}$), on standard and hot days. In both cases, the difference is negative. So the new architecture has a lower power consumption for the same prototypical control. By looking more closely at the results, this difference mainly comes from the electric cabin compressors which consume less power, meaning a lower flow resistance to overcome to reach the fresh air mass flow setpoint. Besides, the TCVs are less used in the second architecture. Since, the expansion is done in two steps and air is heated up between the two steps, the temperature at the outlet of the second turbine is higher than the temperature at the outlet of the turbine in the reference architecture. A higher temperature means less hot air needed from the TCV to reach the required pack outlet temperature. A lower mass flow across the TCVs could be the reason of the lower flow resistance and so the lower power consumption from the electric cabin

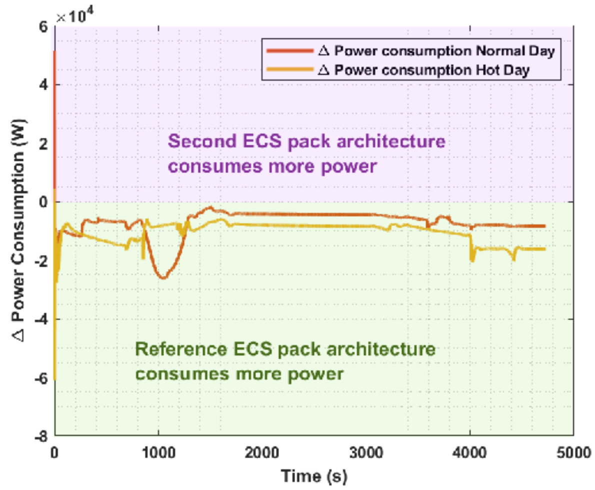

Figure 12. Power consumption difference between the new architecture and the reference one for both standard and hot day

compressors. From a power consumption point of view, the new ECS architecture seems more efficient but power consumption is not the only relevant parameter to design an aircraft. For example, this new ECS will certainly be heavier due to the second turbine. Therefore, the impact of this increased mass on the aircraft should also be taken into account. This short comparison gives an overview of how different architecture can be evaluated at aircraft level using the Digital Twin.

5 CONCLUSIONS

This paper presented the development of a prototypical control for the Digital Twin model of an aircraft environmental control system.

The approach is based on SISO limited PI-Controllers with anti-windup to robustly deal with the saturation of the different actuators, and normalized actuator command signals to ease the transfer of the control authority from one actuator to the other. The normalization is also a good solution to avoid including inside the control architecture the saturation characteristics of specific actuators, which then would require to change the tuning of the controllers each time a characteristic changes. It shows that is possible to obtain a global prototypical control that works for a complete gate-to-gate mission, for different environmental conditions and different ECS pack architectures. Improvements are still needed, especially on cold day, but the problem originates from the ECS pack architecture itself and not from the control architecture.

A comparison with an alternative ECS pack architecture was also conducted. All setpoints were reached without altering the prototypical control, although the transient behavior differed, with more and bigger oscillations observed in the cabin temperature. Nevertheless, the robustness of the controller was successfully tested, although further tests will be needed to confirm the results, especially with FMU models. The new architecture had a lower power consumption compared to the reference one while applying the same prototypical control, highlighting the type of study that can be carried out with the Digital Twin. This demonstrates the possibility to develop a prototypical control using simple models while ensuring it is robust enough for models with different dynamic behaviors, and therefore saving time on tuning again the controllers when changing the models. The next step would be to test the prototypical control with an actual FMU of a high-fidelity ECS pack model to assess the impact of a more detailed dynamic behavior and of sampling time, particularly if a co-simulation FMU is being used. Furthermore, it would also be interesting to observe the effect of sensor and actuator signal delays, sampling times and noise on the stability of the controller. These factors often reduce the robustness, making it potentially unstable when used on the high-fidelity models.

Once the robustness is confirmed, it could also be interesting to test different controller architectures in order to optimize given parameters such as the energy consumption at aircraft level. It would be interesting to see if it is possible to design a control architecture which would minimize a top-level aircraft indicator, independently of the model used for tuning. For future hybrid electrical aircraft, a lowest possible energy consumption of the Environmental Control System would be very interesting because it could lead to smaller batteries and so significantly reduce the weight of the aircraft. This type of study would also require to validate the Digital Twin results with field data to assess the accuracy of the simulations.

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