

Architecting ATA 28 with Model-Based Systems Engineering (MBSE): Center of Gravity (CoG) Balance and System Performance

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Abstract

The fuel management system for a fixed-wing aircraft has been developed and explored with the Model-Based Systems Engineering (MBSE) methodology for maintaining the Center of Gravity (CoG) and analyzing flight safety. The system incorporates high level modeling abstractions exploiting a mix of behaviors and physical detail resembling real world components. This approach enables analysis for a multitude of system requirements, verification and failure scenarios at high simulation speed which is necessary during system definition. Initially, the CoG is maintained by directly accessing at the flight deck the valves and pumps in both wings and controlling them through the bang-bang control law. In the refinement phase of the fuel system controller, the manual and individual controls of the valves and pumps are replaced with an autonomous fuel transfer scheme. The autonomous scheme achieves no more than 20 kg difference in fuel between the wings during normal conditions. In the event of failures, the controller achieves no more than a 100 kg difference in fuel between the wings. The difference returns to 20 kg within a settling time of 5 sec and a maximum allowable overshoot safety margin of 10% of the 20 kg difference in normal conditions (+/- 2 kg). The specification 20 kg/5 sec band varies with pump and valve parameters. Although this specification is sufficient for a system-level model, it can be refined with pump and valve parameters and nonlinear effects in the network. The system identification method is also trialed to control an individual engine by estimating a Proportional Integrator Derivative (PID) controller of the engine plant. The safety tests are initiated in a user interface enabling error detection and injection. The fuel system model is used for analyzing refueling, defueling and jettison scenarios with appropriate flow rates.

Besides the CoG maintenance, several aspects of configurations of the system's functional and logical architecture considering increasing component redundancy and activities for MBSE framework have been conducted. The logical and temporal verification of system requirements are performed in simulation. To ensure traceability and coverage, the requirements and the associated verification artifacts are digitally linked to the implementing blocks. Test scenarios are implemented for investigating resultant and emergent behaviors at various levels of system hierarchy by isolating either the subsystem, or components have been performed. To further check out the MBSE workflow, fuel system controller code has been directly emitted from the controller model for DO-178C objectives. At the mission level validation, a jettison scenario is developed for a mission and flight plan in the digital mission engineering and systems analysis environment of Systems Tool Kit (STK) Aviator. The aircraft fuel system configuration is set using the fuel system model.

The power of MBSE methodology supported by a modeling and simulation framework provides plenty of opportunities for through-life analysis in the early design lifecycle phase.

Keywords ATA 28, Center of Gravity (CoG), Control, Fuel system, Model-Based Systems Engineering (MBSE) Proportional-Integrator-Derivative (PID), Safety, System Identification, Wings

1. Introduction

The fuel system (ATA Chapter 28), normally embedded in the wings, tails and fuselage in a commercial aircraft, virtually affects all aspects of aircraft design, stability, flight modes and safety. In a large aircraft, the fuel system is a complex network that connects the fuel tanks located at the farthest boundaries of the aircraft to the engines. The major components in the fuel system are tanks, valves, pumps and pipes. Gauging probes facilitate all fuel related on-board operations of transferring the fuel around the network in different flight conditions, gauging the fuel quantities in different tanks and reporting the current distribution of fuel mass for maintaining the aircraft stability. The fuel system thus plays a critical role in maintaining the Center of Gravity (CoG) [1] from take-off to landing. Validating the correct operation of fuel system when integrated with other systems, in part, is performed on a full-scale test rig (iron bird). The iron bird is used in the full fuel system qualification program and covers aspects of fuel system certification [2]. Much of the work in fuel system analysis in the conceptual and preliminary design phases of the aircraft systems engineering concerns meeting the safety requirements.

This paper demonstrates that in-flight fuel management, CoG maintenance, safety checks and several other aspects such as on-ground refueling and defueling and jettison can be sufficiently addressed in a high-level Model-Based Systems Engineering (MBSE) approach. The approach includes requirements Verification and Validation (V&V) and test scenarios and downstream detail design activities, such as fuel computer code generation and safety-critical analysis for initial DO-178C compliance objectives.

2. System Model-Based Systems Engineering (MBSE) Methodology for Fuel System Engineering

Central to the MBSE methodology is the idea of model sharing and exchanging, especially for models captured in multiple languages, multiple domains or tool vendors. Such integration can be accomplished with both MATLAB/Simulink and SysML based MBSE workflow. Central to the MBSE methodology is the idea of model sharing and exchanging, especially for models captured in multiple languages, multiple domains or tool vendors. The MBSE methodology is language independent. The MBSE language may be textual, e.g., SysML v1, MATLAB, or visual e.g., SysML v2 or Simulink. MBSE can be implemented in any expressive language. The language should share the principles of MBSE philosophy and enabling modeling of hierarchical systems. Object Oriented (OO) programming models and OO ontologies such as Object-Oriented Systems Engineering Method (OOSEM) or Systems Modeling (SYSMOD) are popular for implementing MBSE. The popular languages for MBSE are MATLAB, UML, SysML, ANSYS SCADE One, SystemC which is an OOP language based on C++ and SAE standardized Architecture Analysis & Design Language (AADL). For descriptive physics, MATLAB and variants (Octave, SciLab), Simulink, Python, Modelica and Dymola are opted. CATIA Magic Systems of Systems Architect tool by Dassault Systèmes allows integration and cosimulation of models written in BeanShell which is lightweight scripting for OOP language Java, Apache Groovy which is a Java like language, Apache Java Expression Language (JEXL) suited for dynamic and scripting features in applications and frameworks written in Java, open-source Rhino JavaScript and MATLAB/Simulink and Python. Domain-specific languages that are not based strictly on OO principles of classes, encapsulation, inheritance, and polymorphism can be used to implement MBSE for modeling certain systems. ANSYS SCADE One is an example of such a language.

A composable architecture modeling approach is adopted for building the system of interest from modular and reusable components in a library. The approach unifies abstract views in modeling the system behavior as well as the physical effects of components and their connectivity. This enables safety analysis in sufficient depth. Abstract modeling establishes a generalized model without a regard to the physical world. Often, this is the case when the physical detail of the aircraft size, dimensions, systems, avionics and controllers, or hydraulic components are not known, but their behaviors are well-understood. Design traceability can be ensured from the system model at the

downstream activities of detailed design and validation at the full-scale iron bird test rig [3] or at the component level for electromechanical and hydraulic operations according to correct sequence and order, such as model integration in hardware-in-the loop testbed [4].

Abstract modeling captures only the necessary and relevant behavior and ignores the marginal elements and detail. For example, details of the fuel system architecture given as the collector cells and refueling or feed subsystem [2]. A complex mathematical model of the fuel network's dynamics can be replaced with a dataflow model in the Laplace domain. This dataflow model offers faster simulation speeds while retaining the model's detailed dynamics. Physical modeling supplements behavioral style with concrete information. Such modeling style allows interaction between components through ports that mimic mechanical interface. The flow of energy-related quantities such as fluid or throttle may be finely controlled with the physics of each component, such as the friction in the fuel line or the fact that fuel cannot get through a valve.

The library of components scheme [4] is a powerful way to develop multiple system architectures for scaling the system model to a particular aircraft, system configuration or trade space analysis. For example, the two-engine system model can be quickly upgraded to a four-engine system by dropping the engine components and routing the fuel lines to the tanks. Feeding the engines from the collector cells can involve several alternatives depending on weight, efficiency and reliability compromise such as feeding via a single emergency valve and a feed pump or a single emergency valve but redundant pumps. Instead of a single crossfeed valve from either side transfer, four crossfeed valves can be routed so that each engine can be fed from any of the four feed tanks as in A380. Multiple jettison outlets can be tested for optimal fuel dumping or multiple bowsers for refueling or defueling. Similarly, multiple capacitance probes can be used at varying tank depths and locations for accurate Fuel On Board (FOB) measurement. The purpose of such architectural changes is to analyze the best configuration on the merits of complexity, performance, safety and cost.

In the preliminary design level activity, the hydraulic network topology, placement and sizing of the valves and pumps and redundancy schemes are expected to be frequently changing. Therefore, deriving new mathematical models becomes an arduous task and counter to the systems engineering activities that typically seek agile development. Thus, we use the system identification method [5] to determine new dynamics of the fuel system as the system is being incrementally developed. This is done by autonomously and iteratively identifying the underlying system transfer function from the output response and the input. The identification uses a learning algorithmic that "senses" the system behavior from step and impulse responses. As the network parameters or topology evolve resulting in new dynamics, autonomous identification gives a significant leverage in estimating the transfer function as opposed to using the first principles. Moreover, the algorithm can be given the desired output response as a requirement or performance criteria of the required over/undershoot, rise/settling times, peak or gain margin as well as closed-loop stability and order of the function. The requirement specification may be applied to estimate the transfer function of any closed-loop component e.g., a pump or engine. On the system-level scale, fuel flow dynamics from one wing to the other may be controlled for the entire fuel system for balancing the CoG. Both linear and nonlinear dynamics may be identified. We, however, estimate the flow network to be linear.

To determine fuel flow fluid dynamics and transfer performance, a high-fidelity tool like Simcenter Flomaster may be used [6]. A fine-grain tool, along with predictions of CoG based on precise geometric representations and complex fuel chemistries, achieves computational fluid dynamics simulations. A further advantage of the model-based approach is the flexibility to refining behaviors when the abstract models require exposure. For example, Physics-based descriptive models of real-life components can be used in place of behavioral blocks. The model-based development integrates executable system requirements and test harnesses into the system model. This integration is facilitated by a digital thread that ensures a consistent flow of information throughout the development cycle. Furthermore, once the system is validated in simulation, the controller code of the identified system may be machine-generated for real-time embedded hardware/software design of the fuel system computer. Optionally, the controller code may be qualified for hardware logic (DO-254) or software verification (DO-178C), bringing the preliminary design one step closer to airworthiness and certification.

These advantages of the model-based approach at a high simulation speed enable design alternates through

quick trade-offs and what-if scenarios, and wide test coverage encompassing a large domain of systems engineering lifecycle activities.

3. Current Practice in Aircraft Fuel System Modeling with the MBSE Methodology

MBSE and model-based design approach have been gaining popularity in all aspects of aircraft design [7] including components [8] and fuel system engineering [9-11] and for various phases of lifecycle analysis. An attempt to exploit multiple levels of abstractions in multidomain modeling including Physics behaviors for helicopter fuel system is described in [12]. The authors propose Functional Mockup Interface (FMI), XMI and APIs to integrate behaviors captures in diverse languages and tools, and exchange dynamic data via SysML federated backbone to achieve network simulation. An architecture design study for two-engine mid-size business aircraft using hydrogen fuel system is in [13]. This workflow is based on the System Composer toolbox of MATLAB. The work uses SysML for a rule-based architecture design flow that uses safety standards, rules, and regulations and best practices for ensuring fuel system safety. Quality Function Deployment (QFD) based stakeholders' needs and requirements for liquid hydrogen combustion engine propulsion systems employing a prioritization matrix has been demonstrated in [14]. No attempt at simulation capability or Physics modeling was reported. The authors [15] develop functional design of a control maintenance system in IBM Rational Rhapsody® tool and the proprietary Harmony® methodology and the fuel system design in a customized SysML based modeling approach. It is not readily obvious what this work achieved; however, the authors affirm the effectiveness of the MBSE methodology for different models developed by different users and at different levels. Patterns and libraries approach [16] of OOP paradigm has been applied for modeling behavior simulation and generic libraries developed in SysML for kinematic system design. Our approach is similar in that we developed fuel system components for network flow in C++ and converted to Simulink block with MATLAB s-function. MATLAB S-function API enables MATLAB language for creating custom blocks. These blocks can handle multiple input and output ports and signals produced by a Simulink model. The signals are complex data such as matrix and frame signals of any data type. SysML v2 is expected to enhance model interaction and interoperability and analysis tools [17]. This is shown for a hydrogen-powered aircraft.

4. Fuel System Model Design

The fuel system model illustrated in [Figure 1](#) is a scaled and highly configurable representation of a generic aircraft size in that the wing dimensions and therefore the fuel quantity in tank size can be scaled to any suitable dimensions. The model contains four main component types – bowser, valves, pumps, and twin engines – all connected to a fuel tank in each wing. The static model is simplified into an abstract drawing of the cross-sectional geometry of the wing and the fuel tanks within it. The primary and redundant components can be seen. The bowser B acts as a single coupling interface on the ground to the fuel intake – usually a refueling tank truck or an underground fuel tank. Following the bowser is a safety valve that connects the fuel system to the refueling tank source. Initially, the system was modeled to be an open loop system. Later, feedback paths were added to the relay of the status of components at the pilot's deck. There is a single fuel tank in each wing of the aircraft. Fuel is actively pumped into each engine. To ensure availability of fuel, there is a main and standby pump P for each engine. Although not shown, each pump is powered by a separate power supply [18]. Each engine has a fuel shut-off valve in case of engine bursting [19] or leakage. [Figure 2](#) shows the equivalent dynamic model for simulation and system design.

Note that all pumps are abstracted to be the same in [Figure 1](#) and [Figure 2](#). In a real system, the engine feed pumps are high pressure, and the airframe pumps are low pressure, and each pump type has different performance and installation specification [20]. The jettison pumps may be under high pressure as the requirement is dumping the fuel quickly and avoiding overweight emergency landing. As a further backup, fuel can be cross fed from one wing side to engine in the opposite wing via a central crossfeed valve. Cross feeding is a design requirement in multi-engine aircraft. In A380, any engine feed pump can cross feed to any of the other three engines. The pump locations of installation in the wing spar or tank bottom play a vital role in the preliminary design phase for flow performance and accessibility for maintenance. Fuel may not be usable due to pump placement in the mechanical configuration or structural design if the pump cannot develop the required suction to pump fuel out of certain locations and run dry.

4.1 Assumptions

The following statements apply during model development and analysis.

1. The development will suffice the needs of a variety of stakeholders: systems engineers, fuel system engineers, aircraft designers, safety specialists and subject area experts.
2. Design space exploration is paramount and will be ensued throughout the development through high abstraction such that the system architecture can be scaled and adapted to two-engine (A220 and A330 families and A350) and four-engine aircraft (A340, A380 and A400M).
3. Where possible behavioral blocks and components will be used.
4. The practical corollary that follows from the 2 and 3 is that the architecture will be of mixed type i.e., neither fully logical, nor physical but only as necessary in the essential areas and always functional and operational.
5. It follows from the above that behaviors of physical components will be utilized in essential areas of physics which directly relate to derived requirements driving subsystem, design refinement and critical design detail.
6. The physical components will be still adaptable to a variety of requirements such as flow rate, pressure, area and timing, and parameterized.
7. The model will be independent of the fuselage body types (narrow-body or wide-body).
8. The model will be independent of the engine technology (turboprop gas turbine or jet reaction).
9. The model will not accommodate wing configurations: straight, forward swept, gull, blended body, anhedral and delta. The wing configuration will be dihedral.
10. Engines will be taken at a height below the feed pipes.
11. During design exploration, which is the purpose of the model, the component weights will not be debated in safety, balance and performance analysis. The candidate baseline architecture selected for the particular aircraft type shall drive the structural design weight limits.

4.2 Gallery

Fuel may be transferred directly between the wings via a gallery consisting of pipes, pumps and valves. The aft gallery contains two pumps and valves symmetrically placed on each side. The valves and pumps are the primary devices for balancing CoG. Upon failures, both valves open during refueling. In such case, when the left side contains more fuel than the right side, the left pump would turn on and the right inlet valve would open to equate the fuel quantities in two sides. The forward gallery feeds the engines with fuel. Each engine has a cut-off valve as a safety measure and two feed pumps. One of the pumps on each side is redundant and would only turn on in case the primary pump fails or for cross feeding to the other side if the other side requires fuel flow from the working side. The directional cross feed valve in the middle connects the fuel network in both wings.

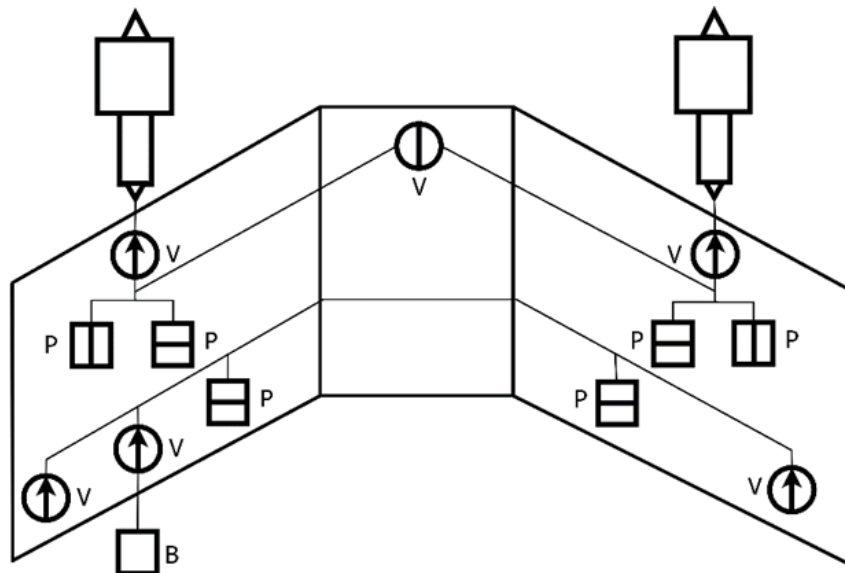


Figure 1 Diagrammatic view of the high-level system architecture of a fixed-wing aircraft fuel system. The architecture representation is a mix of functional and logical and yet physical to be realizable. The representation hides intermediary supporting components that facilitate connections between the major components such as engines, valves (V), pumps (P) and bowser (B). Note the peripheral outline of the wings - all of which comprise the two tanks inside the wings. A crossfeed valve in the central fuselage connects the two tanks.

Cross feed could occur when both right pumps fail, and the fuel needs to be fed using the two left pumps. Together with cross feed, the process of CoG balancing would occur in the aft gallery. The right pump would turn on and the left valve would open.

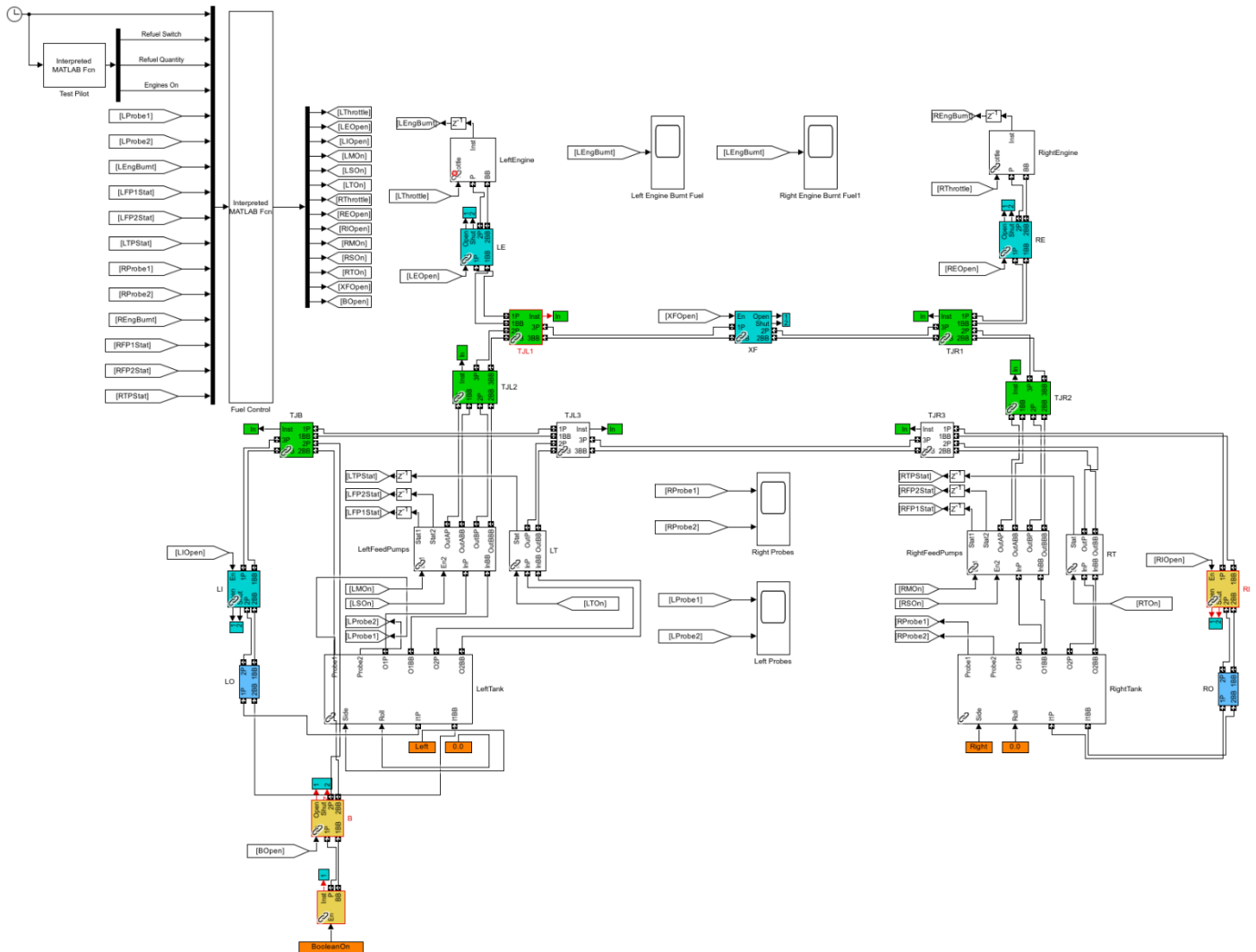


Figure 2 A corresponding simulation model is developed from the architecture description in Figure 1. The system feeds fuel to each engine with a pump through an emergency shut off valve. Each pump is redundant.

4.3 Tank Geometry and Volumetric Flow

The tank volumetric shapes and boundaries are usually not known until late in the design cycle [21]. Instead of computing complex definite integrals relating to irregular boundaries of the tank, we resort to abstract 2-D tank geometry. The outline of the tank geometry and abstraction as a simple triangle is shown in Figure 3. The volume is estimated to be a simple combination of smaller triangular and larger trapezoid shapes. The depth of the tank was taken to be 1 m. Note the ullage volume in the tank to facilitate high pressure conditions or fuel expansion with rise in temperature.

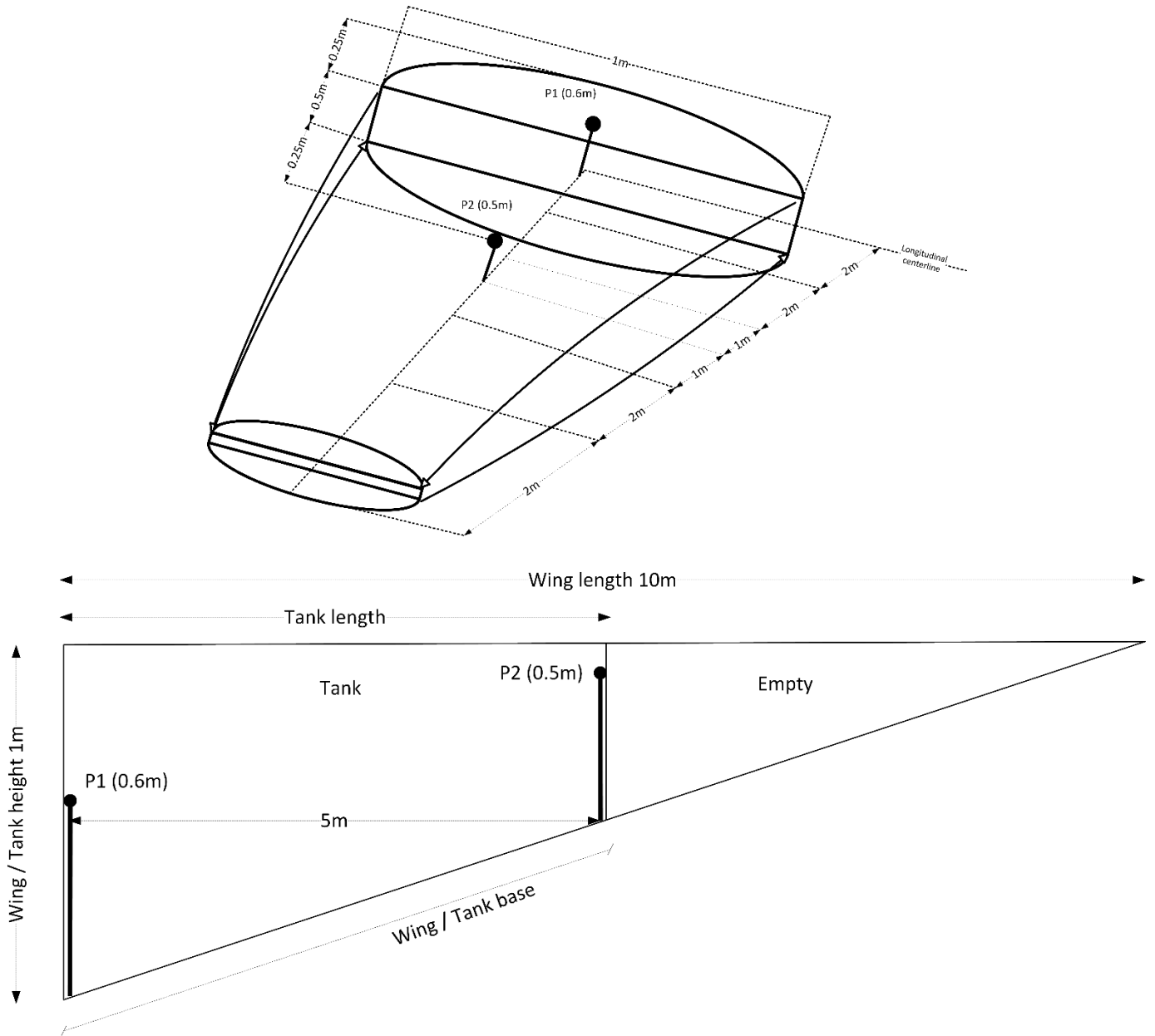


Figure 3 The top figure shows a 3-D curved semi-wingspan with leading and trailing edges and the wing tip and root. The planform and thickness tapers have been simplified to be symmetric. The accuracy of chord distribution, aspect ratio and the shape of the airfoil are ignored. Such abstraction is sufficient for our purpose of volume calculation for CoG balancing and fuel transfer. The bottom figure shows the tank volume in a 2-D view is half of 10 m^3 rectangular cube dissected diagonally. This illustration simplifies the calculation of wing area obtained by integrating the distribution of the wing chord along the span from one wing tip to the other. Probe P1 gauges fuel mass at a lower level of volume and Probe P2 gauges at a higher level of volume.

4.4 Fuel Gauging

The fuel quantity is gauged by two capacitance probes in each tank that report a “wetted ratio” (i.e., 0 equals totally dry, 1 equal totally wet). The two probes in each tank report values between 0 and 1 (empty and full, respectively). Probe 1 is mounted vertically at the bottom and far fuselage end of the tank. Probe 1 is 0.6 m long. Probe 2 is mounted vertically at the bottom and far wing-tip end of the tank. Probe 2 is 0.5 m long. Figure 3 shows that the tank is not homogeneously shallow along the length and the width. From the volume, the mass is calculated using nominal density 0.785 kg/liter . Typical density is $0.775\text{-}0.840 \text{ kg/liter}$ for Jet A and Jet A-1 fuels at 15°C [22-23].

Probe 2 cannot gauge in the ullage i.e., any fuel quantity above the Probe 2 tip is reported to be fully wet. The aircraft dynamic envelope presents a significant challenge in designing the probe network for accurate measurement during roll and pitch attitudes. In high attitude disturbance conditions, the fuel system may rely on the inertial reference system

[24] and multiple measurements from multiple probes. In a fixed-wing tank configuration and in absence of aft tanks, the roll attitude is more significant for CoG balance maintenance than other disturbances. In the current work, the roll moment of inertia has been rejected although provision has been kept as seen in [Figure 4](#).

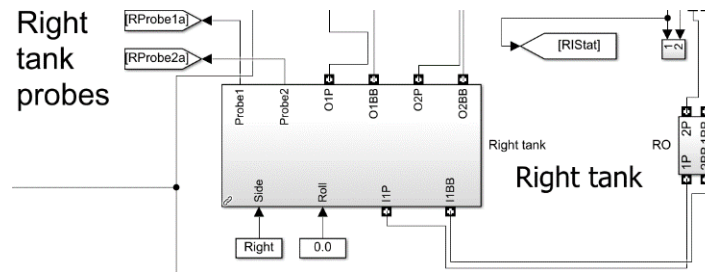


Figure 4 Tank model with two submerged probes.

The fuel gauging measurements would be more stable during refueling when the inertial reference is accurate than in flight mode. But the attitude sensitivity cannot be adequately measured with gyroscope and accelerometers, or when the reference system is unavailable. The residual fuel in the system usually cannot be measured [2] and can move around. Besides capacitive gauging, the behaviors of other measuring technologies such as resistive, float or level measurement, magnetic, sound or laser sensor are not modeled. Probe mounting locations and the number of probes is important consideration even in the early CoG analysis. The tank and probe arrangement gives linear gauging which is adequately accurate at the preliminary design level. For accurate measurements, additional probes are necessary. A330/A340 use as many 80 measurement devices including densitometers [19].

4.5 Data Communications Bus (Telemetry and Command and Control)

Electrical interfaces to the components for checking their current bi-level statuses, and sampling temperatures, flow rate and quantity gauging are based on a federated data communications interface to the cockpit. Note that the status of components is telemetered without a regard to data bus or communications protocol e.g., ARINC 429 and other complex interfaces such bus couplers, serial modules and Line Replaceable Units (LRU) to engine, pumps and valves have been abstracted away.

Pumps are switched on and off by a single discrete input (0 or 1). Each pump reports a discrete feedback signal, signifying if the pump is delivering fuel flow. Valves are driven open/closed by a single discrete input. Each valve reports two discrete feedback signals, signifying if the valve is open or closed respectively. Engines also accept discrete input; however, the throttle may be adjusted so that 1 is 100% and 0 is 0%. Each engine reports its burn rate in kg/sec in a feedback signal.

4.6 Test Pilot

The test pilot block supplies the inputs to the system and receives outputs e.g., components status of error signals from the system during both pilot-controlled operations e.g., refueling and automated operations e.g., maintaining CoG. The refueling of the aircraft by setting a desired refuel quantity and enabling of a refuel switch is seen in [Figure 5](#). The avionics open all necessary valves to allow fuel to flow into the tanks from the bowser until the requested quantity is on board. Running of the engines is set by an engine on switch. A clock signal provides a timing reference to keep track of all the test operations and timestamping of the statuses and measurements. The avionics automatically command the engines on and enable appropriate pumps and valves to feed fuel to the engines.

4.7 Fuel Management with Bang-Bang Controller

The fuel control block receives fuel quantities from both probes in each wing and the current burn rates from the engines. Based on this information, the pilot can manually turn on or off any component in either wing as necessary. An SR flip flop checks for fuel imbalance and corrects for it if out of limit.

4.8 Error Injection

Two error injection blocks, as seen in Figure 5, are used to force fail various components as required in tests scenarios. The components can be randomly turned off during their correct operation creating a failure condition or disbalancing the CoG. The network returns error codes upon encountering different conditions such as valve flap shut error, pump error, tank empty flow error or probe malfunction. The probes are failed by forcing out of range or undefined fuel quantities.

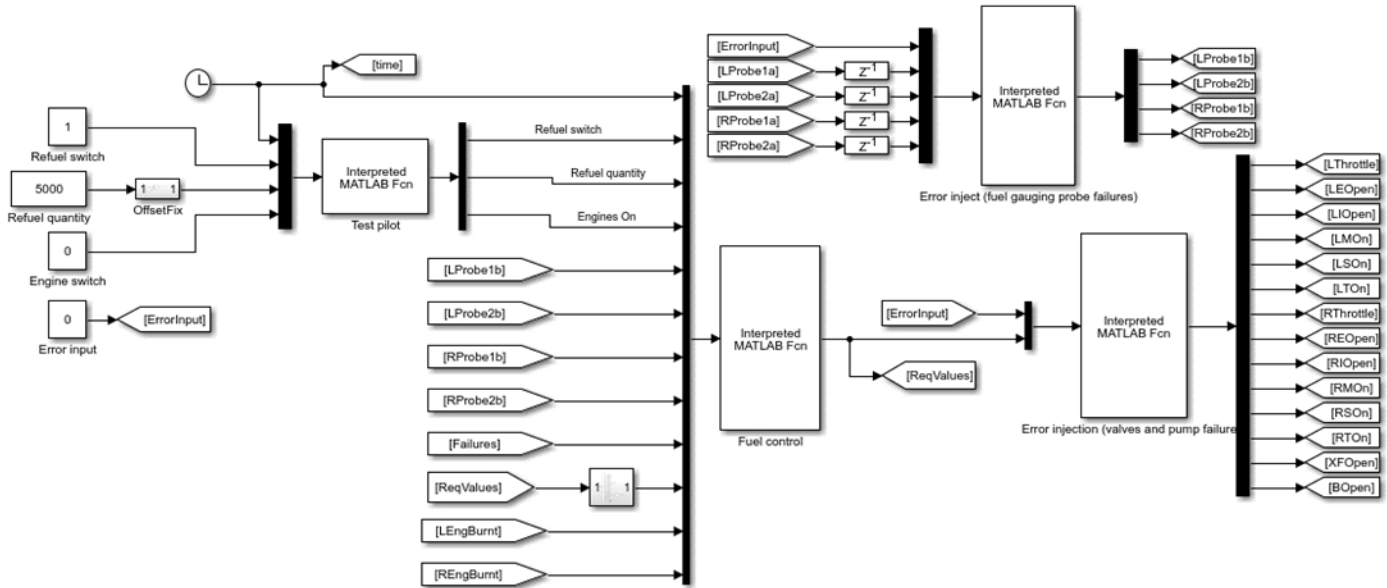


Figure 5 Test pilot provides crewed inputs to the fuel system such as the ordered fuel quantity, switching on refueling and igniting the engines.

4.9 Electronic Centralized Aircraft Monitor (ECAM)

The pilot's flight deck display or the Electronic Centralized Aircraft Monitor (ECAM) in Figure 6 shows the status of the components and fuel quantities in both tanks and the difference. Pre-flight test capability is provided through on/off test of each equipment. The error injection model is linked to the display. Upon successfully running the tests on components, the corresponding lamps light up and upon failure status is returned. In commercial aircraft, the in-flight fuel management is generally automatic but manual control at the flight deck is used when faults manifest [2, 19]. As per European Aviation Safety Agency (EASA) regulatory reference CS-25 [25] for large aircraft, a low fuel indicator is shown in Figure 6. This is also an airworthiness requirement. A measurement accuracy of 1-2% is considered acceptable [2, 21] using multiple probes.

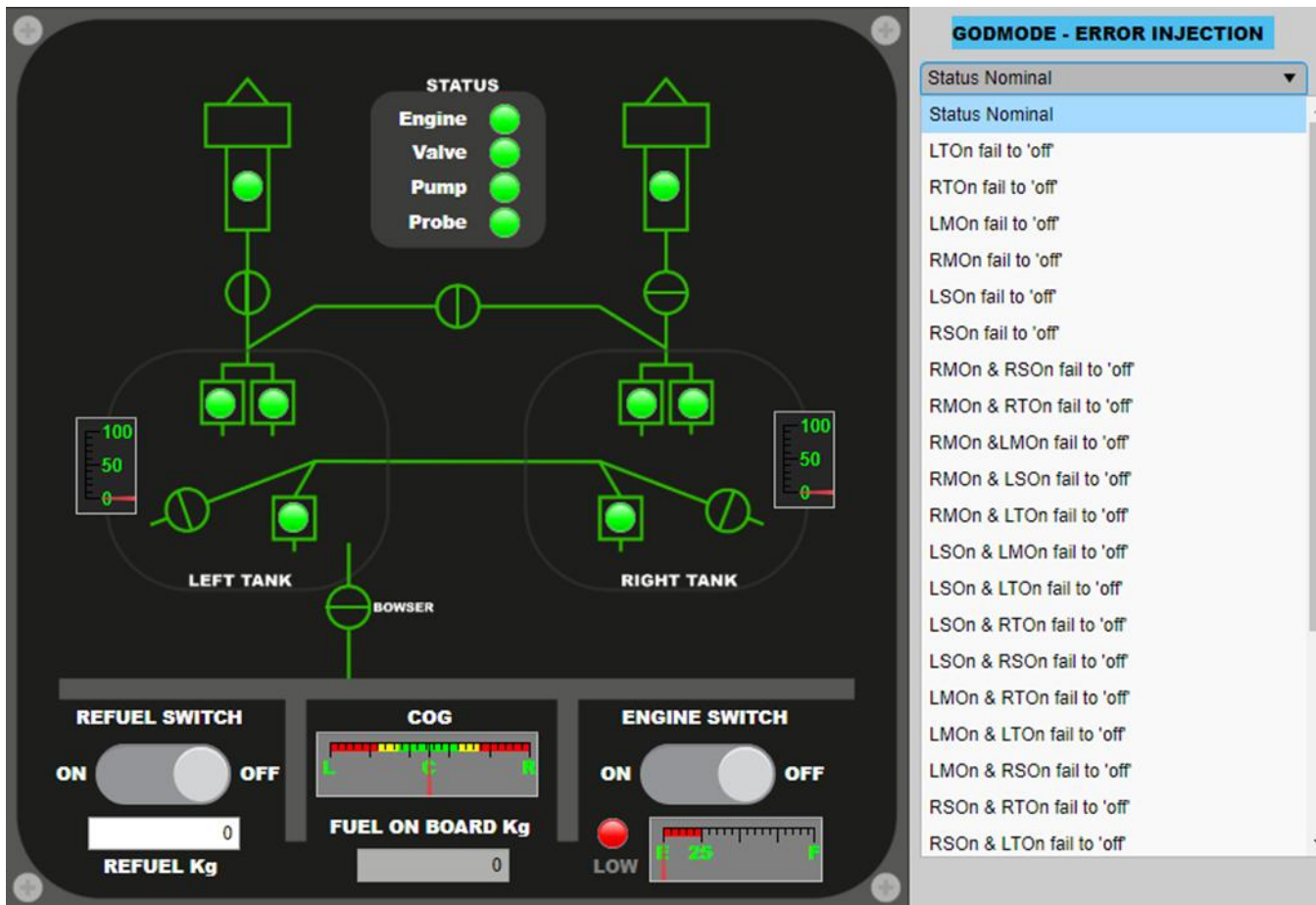


Figure 6 Fuel system display at the cockpit and instrument panel. Fuel Quantity Indicator (FQI) is shown between E (Empty) and F (Full).

5. System Configuration

The system is preset with fuel density, network temperature, typical flow rates, pipe parameters, pipe resistance, pump pressure and near-zero mass and flow values. The configuration depends on the aircraft type.

5.1 System Requirements

During all operations, the avionics must ensure the following safety conditions:

- An accurate FOB quantity in kg is reported to the flight deck.
- If the engine on switch is set, fuel is continuously fed to the engines.
- To extend their life, pumps are only run when needed. (Rationale: in A310-300, the trim tanks' pumps shut off after minutes when the low-level sensor indicates dry volume [26]. This provision is for on ground and in-flight operations and was kept for preventing operator errors on ground of running the pump dry.)
- Each fuel tank must always maintain a minimum amount of fuel to avoid damage to aircraft components.
- The fuel pumps must maintain a minimum flow rate to ensure that the engines can receive sufficient fuel during all phases of flights.
- The fuel pumps must not exceed a maximum flow rate when transferring between tanks to ensure that the aircraft is not de-stabilized during any flight phase.
- Balanced CoG is always maintained: this is defined as the difference of fuel between both wings. During standard operations, there shall be no more than 20 kg difference in fuel between the two wings within a settling time of 5 sec and a maximum allowable overshoot of 10% (20 kg +/- 2 kg).

We should remark the safety of a well-maintained aircraft may be compromised by the quality of the fuel, its chemistry

and handling. The matters of such safety and related procedures are defined in ASTM MNL5 [27].

5.2 Simulation

Race conditions through the feedback signals gave rise to algebraic loops in the modeling which were solved by adding continuous-time unity delays (Z^{-1}). All physical effects in the model are discrete-event behaviors or continuous-time dynamics; therefore, fixed step discrete solver is sufficient.

6. System Analysis and Safety Tests

From the cross-sectional geometry (Figure 3 bottom), for fuel density ρ and probe reading $P_{reading_1}$ in the rectangular section of the tank and $P_{reading_2}$ in the triangular section, the fuel quantity is

$$Fuel\ Quantity = \left(\left(\frac{\left(\frac{P_{1reading}}{2} \right) \left(\frac{P_{1reading}}{2} \right)}{2} \right) \times 10 + \frac{P_{2reading}}{2} \times 5 \right) \times \rho$$

The maximum fuel mass in one tank is

$$Fuel\ Quantity_{max} = \left(1.25 \times P_{1reading}^2 + 2.5 \times P_{2reading} \right) \times \rho$$

The fuel gauging equation is programmed in the model. Note that the overlapping area of probe P_1 and P_2 measurement is ignored in the calculation which is negligible for the probe lengths. For large overlapping area or additional probes, the overlapped quantity can be substantial and must be subtracted in the calculation.

In cruise, the fuel consumption rate is nearly constant assuming a steady speed and environmental conditions. The FQI system indicator may show continuous discrepancies for a certain time, or the capacitive probe may malfunction. The flight crew should keep a record of the best estimate of FOB in the aircraft logbook based on the available information. The information and estimate should be updated regularly. Estimates may be developed from the particular aircraft's FOB equations [28]. When all probes report dry condition, an estimate of maximum remaining FOB can be predetermined at ground with low level sensors. For A320 this quantity is approximately 750 kg [28]. A full uncertainty estimate of FOB quantity requires accurate probe overlap analysis, density range, temperature variation as well as fuel uplifted (the amount of fuel indicated by the refueler added during refueling) at the latest refueling event, the crosscheck between the expected uplifted and actual uplifted, fuel quantity from the refueler and fuel burnt during flight. Such estimate is beyond the scope of this work.

Refueling: The refueling automatically first switches off all the valves and pumps that participate in fuel transfer, and they remain continuously off while the only valve on is the bowser valve. Next, the right inlet valve is turned on allowing the fuel to move to the right wing. Both completely dry tanks are filled with a maximum of 5978 kg of refueling quantity. From the modeling perspective, the fuel mass can be any numerical figure. The refueling can start at any level below the full capacity of tanks. If a higher quantity is entered, filling goes to the maximum capacity and upon which the bowser valve is automatically shut off. During refueling, the bowser valve continuously indicates on status. Fuel in both tanks simultaneously rises with the smaller probes (Probe 2) reach 1, see Figure 7. If the engine is turned on, the system returns error that refueling is on. The low fuel indicator stays on at $\frac{1}{4}$ or below tank quantity. The refueling flow rate and timing can be adjusted in the system configuration. Delay blocks were utilized to ensure the system accurately detects and responds to pump failures.

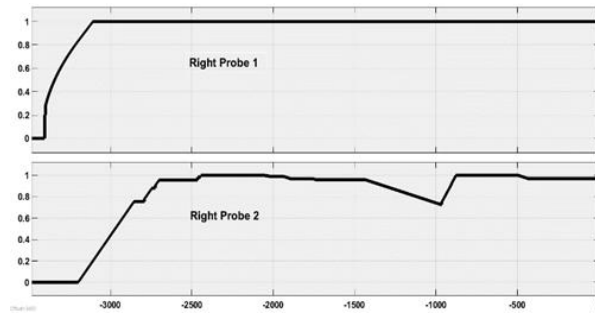
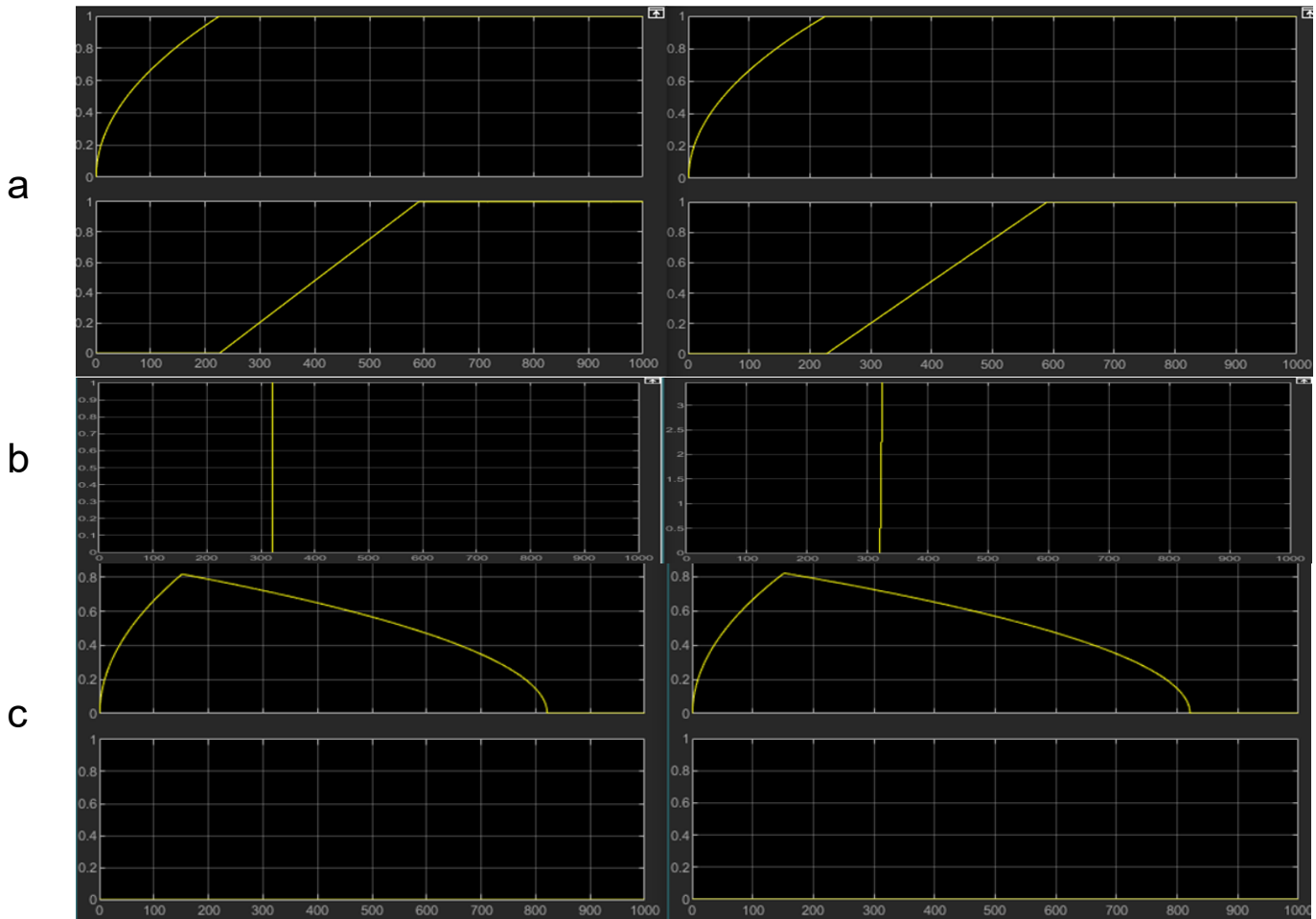


Figure 7 The probe indicates fuel quantity change during refueling and engines running. The x-axis signifies time in seconds, and y-axis shows fuel probe wetted ratio referring to the wet height percentage or the wetting fraction of a fuel quantity probe.

A few refueling and engine on scenarios are shown in Figure 8. The left and right tanks are shown on the left and right sides. The side-by-side plot in illustration 'a' shows the two left and two right probes during refueling. Probe 1, the large probe indicates full tank status at about 220 time units at which instance the smaller Probe 2 kicks in. The side-by-side plot in illustration 'b' shows the left and the right engines are turned before refueling is finished i.e., at 150 time units when the larger Probe 1 had not reached 1 while Probe 2 was still at 0. The shape of the tank causes an unsymmetric shape of the filling curve. Notice that Probe 1 indicates nonlinear rise in the fuel level which is consistent with the quadratic term of the fuel gauging equation in the rectangular section of the tank geometry, while Probe 2 indicates a linear slope in the triangular section. As soon as the engines are turned on in illustration 'c', the larger Probe 1 indicates a fall in fuel quantity on both sides (illustration 'c'). As with the refueling, the decline curve is consistent i.e., very linear in the Probe 2 section and nonlinear in Probe 1 section.



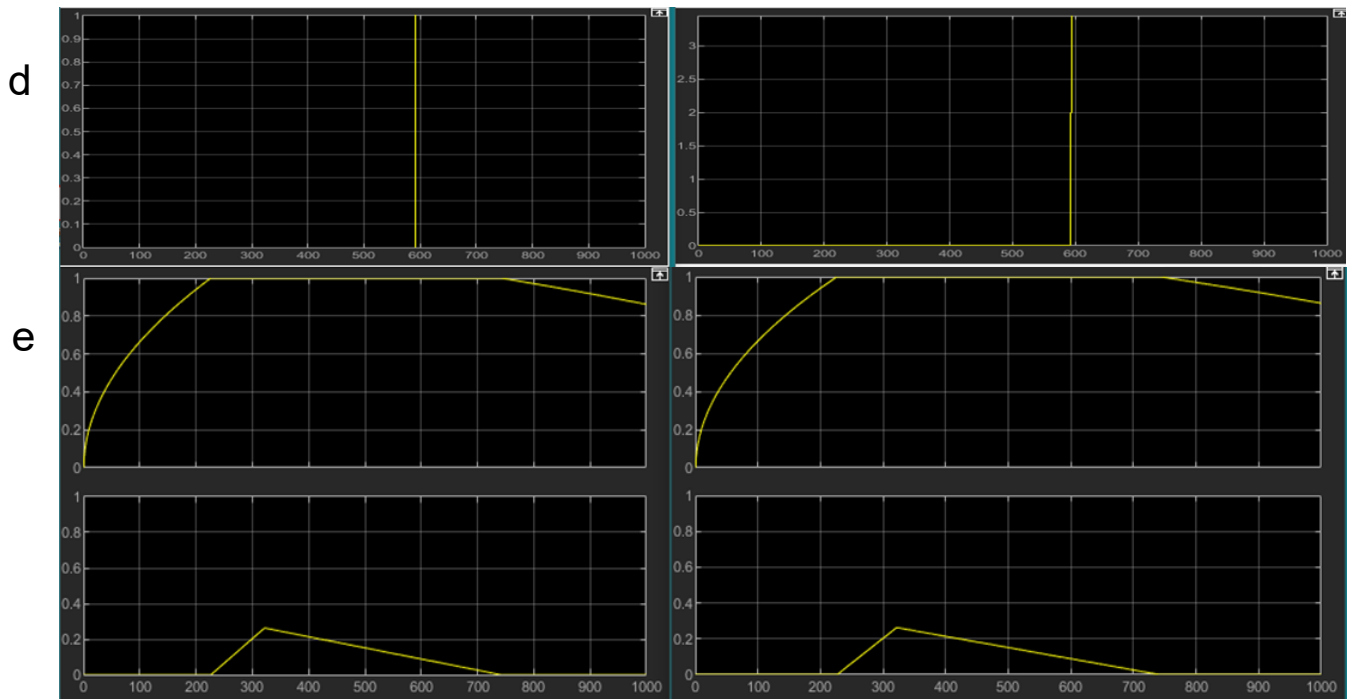


Figure 8 Refueling and engine on scenarios with time in seconds and probe wetted ratio between '1' and '0'.

The Illustration 'e' is a case when the Probe 1 sides of the tanks are full and Probe 2 sections have not reached full capacity, and the engines are turned on (illustration 'd'). Probes 2 immediately begin indicating a decline in fuel quantities at about 320 time units. At about 760 units, Probes 2 become completely dry. Right at this instance, the fuel from the Probe 1 sides of tanks starts getting consumed and Probes 1 show declining fuel quantities. At all times in the illustrations, the symmetry in both sides in fueling and consumption behaviors reflects that the weight distribution is kept in balance in both sides preventing the aircraft wing from deflecting on the ground.

Engines on: The single switch simultaneously turns on both engines. The main pumps and the engine on indicators are lit. The on-board fuel quantity steadily decreases. If refueling is turned on, an error returns that both refueling, and engines cannot be on at the same time.

The current implementation is a constant throttle resulting in a steady burn as seen in [Figure 9](#). Although the pump model is not entirely a physical description, the non-ideal behavior as seen in [Figure 10](#) gives sufficient slew rate during turning on and off and the running is at full capacity. The engine pump is a high-pressure positive displacement pump [29]. Typically, a low-pressure system with its own pump filters fuel and maintains temperature before feeding the high-pressure pump [30].

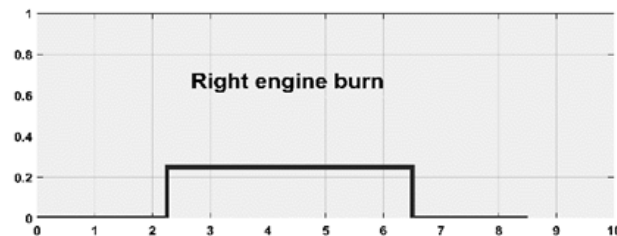


Figure 9 The engine burning at a constant rate at 1/4 throttle versus time where '1' is full throttle power.

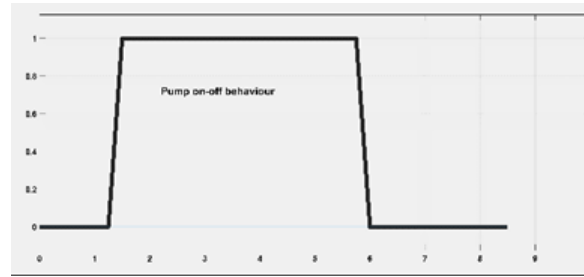


Figure 10 The engine pumps are modeled with physical effects of resistance and delay. Pump operation at full pressure is indicated by '1' with respect to time.

CoG balancing: The CoG shifts fore as fuel is used up in aircraft that only have wing tanks for fuel. The trim tab or horizontal stabilizer must be used to counteract this effect and maintain a continuous, albeit slight, relationship between positive lift at the wing and negative lift at the empennage. We ignore the effect of CoG shift due to fuel consumption [31]. Balancing CoG relates to lateral stability i.e., keeping the mass moment of inertia of the aircraft close to zero about the roll principal axis. The distribution of fuel mass causes imbalance in the wings which offsets the lateral CoG resulting in either the nose or tail being heavy, disturbing both the longitudinal and lateral balances. The lateral CoG continuously shifts with the flight as the fuel gets consumed and with that heaviness in the wings also keeps changing and requiring re-balancing of the CoG. If the flight control system cannot provide enough roll control power, then the onus lies on the fuel management system and flight stability becomes a safety-critical task of the fuel system [1-2]. A380 trim storage may contain 10,500 kg of fuel in horizontal stabilizers which are scheduled for forward transfer toward the end of flight in approach and descent phases. In commercial aircraft, the in-flight CoG regulation is generally automatic in cruise phase [19].

In the current fuel storage model, there are no trim tanks. The wing tanks are contiguous and are not split into compartments or central, feed, outboard, aft or surge tanks, therefore, the shifting of fuel is required from the gallery side toward the feed side or between the wings. This abstraction simplifies the in-flight fuel transfer scheme, and the fuel burn sequence. However, the single compartment scheme must be refined to multiple compartments as the design matures. The reason is the pitch attitudes require controlled shifting of the fuel forward or rearward in the tanks, which can be done if the fuel mass is constrained by the walls of the compartments. However, this scheme is still not sufficient unless non-return valves or check valves are used to restrict flow into the downstream direction. Furthermore, the collector cells must store the required fuel during the climb phase. Additional boost pumps may be needed for keeping the collector supply full. A multi-compartment tank system architecture is a remarkably complex fuel system and therefore can be taken as a follow-on activity.

The CoG balance is manually achieved with 14 kg, exceeding the mass and overshooting requirements as seen in [Figure 11](#) and can be improved with pilot training. This scheme is limited authority supported by manual overrides. The balance is in the lateral axis. Further lateral stability of the flight can be adjusted by deflecting the aileron in the heavier wing until its fuel gets consumed or shifted to the other wing equating the weight on both sides. The penalty is paid with additional drag. Note the lack of smoothness in [Figure 11](#) due to the pilot's manual effort.

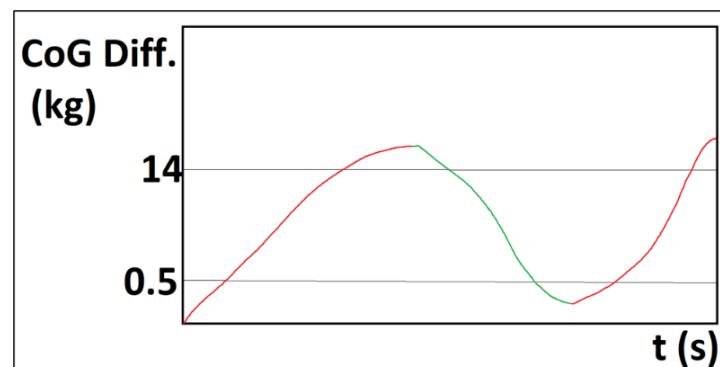


Figure 11 Manually achieving fuel mass difference in both wings within 20 kg for stability.

A settling time as seen in Figure 12 illustrates automatic CoG control band. This scheme is full authority and replaces manual flight controls. The automatic bang-bang controller reduces the undershoot to a stable steady-state for the rest of the duration of the flight with a settling time of at most 5 sec. Note the fine control in Figure 12 due to automatic control scheme.

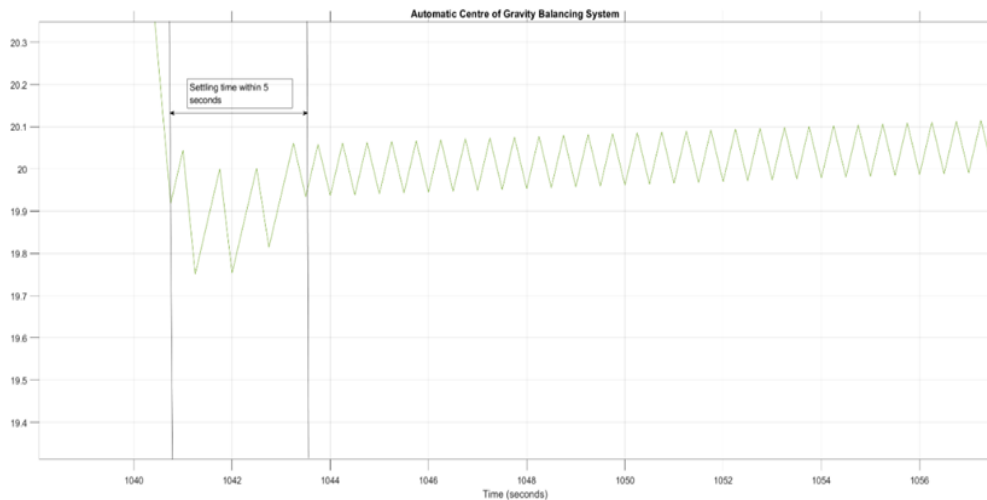


Figure 12 Y-axis indicates 20 kg fuel difference. The settling time requirement is met with CoG control band. Without the control of the CoG, the trace could rise or fall destabilizing the flight.

When there are no faults in the system, all transfers and balances are through automatic fuel management. The automatic control is transferred to the crew when a system fault appears. The crew can transfer fuel using alternate valves that are not used in regular operations because most valves are motor controlled. This is the fuel authority philosophy at Airbus [2]. In commercial aircraft, autonomous fuel management is desired for better handling qualities and relaxing piloting workload. Autonomous fuel management can work in conjunction with fly-by-wire that automatically controls the flight control surfaces and achieve reduced aircraft weight and hence lowering the fuel consumption and CO₂ emissions [21].

7. Identification of the Fuel System Plant and Controller Tuning

The bang-bang manual control scheme is sufficient for safety analysis; however, it wears out the components. Therefore, autonomous control is desired. Let's investigate aspects of modeling the transfer function of the fuel system plant.

7.1 Control Dynamics and Model Linearization

The fuel network is a bespoke design. Each pump, pipe and valve are selected for its precise location and flow requirements. High-pressure pumps with varying power drive fuel through conduits with changing cross-sectional areas. This flow is influenced by network friction and results in fully turbulent flow with high Reynolds numbers, indicating a dominant inertia force and a significant viscosity [32-33]. Aerodynamic forces on the flight and continuous moving of the lateral and longitudinal centers of gravity as well as the fuel sloshing vibrations add to turbulent nature of fuel mass flow. The flow from the feed tanks to the engines is even turbulent. A380 can burn 200 kg/min during cruise. These flow characteristics pose a significant difficulty in mathematical modeling even in a high-abstraction system model. The description involves nonlinear differential equations with algebraic constraints.

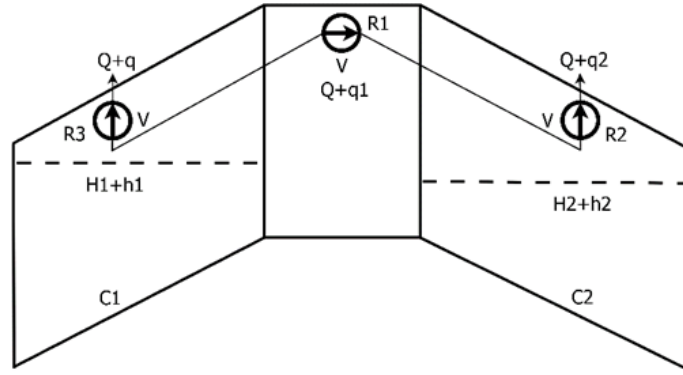


Figure 13 Dynamic quantities during crossfeed from right to the left tank.

Figure 13 shows that the right tank volume is lower than the left tank. The system is said to be coupled as the levels in each tank influence the other [34]. Consider that a slight roll maneuver is made to transfer fuel from the left tank to the right tank through the crossfeed valve. The capacitance is the cross-section area of a tank (C_1 and C_2) given as change in fuel volume per unit change in the head (analogous to potential energy in a spring-mass system where displacement is the head in the fluid system). The resistance R of the flow is the change in level difference of the two tanks divided by the change in the flow rate. These load resistances occur at the restricting valves (2x emergency cutoff and crossfeed valves). The steady-state turbulent flow is Q and H is the steady-state hydraulic head. Small changes q and h occur in the flow rates and the heads. For example, q_1 is the inflow deviation in the steady-state flow through crossfeed valve and h_1 is a small deviation in the left tank head in its steady-state.

If the crossfeed valve was shut off, we could have derived the transfer function of the two tanks separately. But here we have two tanks joint through the fuselage interface and therefore transfer functions arise depending on the direction of the flow and heads. We are tempted to solve this system in a linear fashion if the deviations remain small. Using the notation by Ogata [32], we write the equations of flow, fuel head and head changes

$$q = \frac{h_1 - h_2}{R_1}; Q + q_1 = \frac{H_1 + h_1 - H_2 - h_2}{R_1}; q_1 = \frac{h_1 - h_2}{R_1}$$

$$C_1 \frac{dh_1}{dt} = -q - q_1; q_2 = \frac{h_2}{R_2}; C_2 \frac{dh_2}{dt} = q_1 - q_2$$

$$dH = h_2; dQ = q_2; q_2 = \frac{h_2}{R_2}; \frac{dq_2}{dt} = \frac{1}{R_2} \frac{dh_2}{dt}$$

The first-order dynamics are

$$\frac{dh_2}{dt} = R_2 \frac{dq_2}{dt}$$

$$C_1 \frac{dh_1}{dt} + \frac{h_1}{R_1} = -q + \frac{h_2}{R_1}$$

$$C_2 \frac{dh_2}{dt} = q_1 - q_2$$

$$C_2 R_2 \frac{dq_2}{dt} = q_1 - q_2$$

We can define Laplace domain transfer functions for any desirable input and output. The head of the right tank is related to the head of the left tank as

$$\frac{H_2(s)}{H_1(s)} = \frac{1}{R_1} \left(\frac{1}{C_2 s + \frac{1}{R_1} + \frac{1}{R_2}} \right)$$

The deviation in flow in the right engine is related to the head in the left tank as

$$Q_2(s) = \frac{1}{R_1} \left(\frac{H_1(s)}{C_2 R_2 s + \frac{R_2}{R_1} + 1} \right)$$

The first-order lag or the RC time constant indicates the fuel transfer time or how quickly the fuel level in the right tank comes to a steady-state or stabilizes following a step change in the input in the left tank. The time constant turns out to be

$$C_2 R_2 = \left(q_1 R_2 - \frac{h_2}{R_2} \right) \frac{dq_2}{dt}$$

The delayed response may be traded off for tank capacity, resistance and the head level ($1-5 \times RC$ step input change corresponding to 63.2-99.6% of the target in the steady-state change). The time constant tells how fast the output will change and the steady-state gain tells by how much the output will change for a given change in the input.

While at first sight, these elementary formulations may appear to lend easy to a steady-state solution, a few fine points must be noted. The turbulent flow through the restriction is modeled by Darcy's law as $Q = K\sqrt{H}$ where K is the conductivity. We know the resistance $R = \frac{dH}{dQ}$, therefore $R = \frac{2H}{Q}$. The relationship in Q and H is nonlinear. Therefore, R is determined by Taylor series linearization of the $Q - H$ curve at some operating point [35]. The original forms of the transfer functions are usually complex which are converted to understandable canonical forms by applying manipulation rules [36] or using a signal flow graph solver. The flow considered is un-pressurized i.e., gravity-driven, lacking a dynamic pump model. Finally, transfer functions for several cases will be derived based on where the input and outputs are read in the system. All this is a significant job. Consequently, these complications led us to turn to system identification method [37-39] which enables identifying dynamics for any output and input. To develop the identification theory, we simplify the system identification process for engine dynamics.

7.2 Engine System Identification

We use the engine throttle input and the fuel mass burn rate output shown in Figure 14 to estimate the transfer function of the engine plant as a Single Input and Single Output (SISO) system [40] and develop a suitable Proportional Integrator Derivative (PID) controller for it. The engine throttle or uneven fuel burn can affect the aircraft stability. The model-based approach simplifies this task as follows.

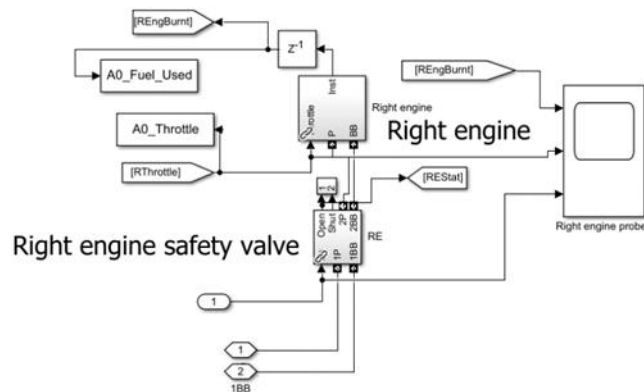


Figure 14 Input and output time history is used for the engine system identification.

The system is allowed to simulate under the bang-bang scheme to generate dynamics when the components run at their full capacities. The $RThrottle$ input and delayed output $REngBurnt$ are written to the simulation workspace. This copies the signal history to internal buffers while the simulation is paused. The amount of data can be controlled by specifying logging intervals. The data of the input and output time-domain signals is imported into workspace variables in the systems identification app and transfer function model is estimated. The transfer function is specified in continuous-time with the required number of poles and zeros. Figure 15 illustrates that the right engine dynamics is abstracted with the 2nd order plant.

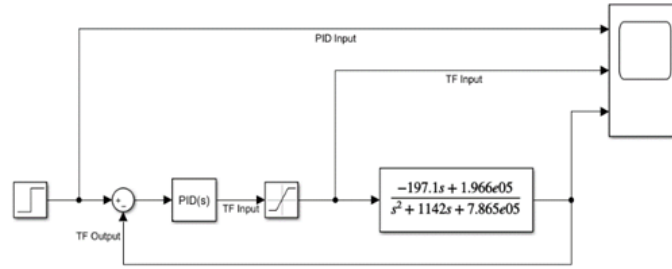


Figure 15 The engine fuel consumption and burnt rate is modeled with a 2nd order transfer function.

The identification algorithm uses nonlinear least square estimation and selects a suitable line search method such as gradient, damped Gauss-Newton or Levenberg–Marquardt iteration [41-43] for converging to the fit. The iterative method depends on the matrix formulation (rank and condition). The fitness goal is to minimize prediction or simulation error. We use two poles and one zero achieving 97.6% fitness. Higher order functions may be identified for faster damping incurring a complex controller code for fuel system computer. For completeness, we remark that Ikonen and Najim [44], have identified a two-tank nonlinear flow under constraints with a similar equation system as we have shown. However, they excited the system with pseudo-random data to take almost 400 measurements. The model parameters were estimated by constraining the process such as head of the right tank, outputs, gains values, and poles within the unit circle. The model was trained for 8000 runs and with 228 constraints. The model was tested with inputs varying more than the training inputs. Ikonen and Najim were able to identify a dynamic model satisfying the constraint and concluded the model performs well when constrained. Using the Levenberg-Marquardt method, the unconstrained output prediction was poor. Their analysis is complex and dependent on user inputs for a great deal. In a network flow system, it is difficult to determine constraints. It is, therefore, feasible to run the fuel network at full throttle and let the identification algorithm autonomously determine and apply constraints, select the number of iterations and extrapolate the output for the desired reference.

7.3 Full Authority Digital Engine Control (FADEC)

Once the plant has been identified, the controller is determined with a first estimate of forward gains. The controller is tuned which starts a linearization of the plant function. The system is triggered with discontinuous Heaviside step function. This leads to a dynamic response shown in Figure 16. The transient response is satisfactory in the gain indicated by the solid line, so the proportional action of the control was estimated. The proportional gain is unity which suits our need of not amplifying noise or highly dynamic or random inputs causing CoG disbalance. The rise time is slightly delayed but considering the equipment response time and fluid motion, this is negligible. The steady-state response warrants attention as this may cause instability. The steady-state error is controlled by shaping the response with a compensation action. The systems engineer can adjust the response to any desired settling time, overshoot or undershoot. The response time can be adjusted anywhere between slower and faster, and the transient behavior can be adjusted anywhere between aggressive and robust.

The controller turns out to be Proportional Integral (PI) with a strong integral gain. These dynamics can be further adjusted for a transient time or response behavior requirement by moving the bars, as seen in Figure 16, until matching with the reference is achieved. Visual modeling coupled with system identification and automatic linearization is huge productivity gain than first, mathematical modeling, and later in transfer function simulation.

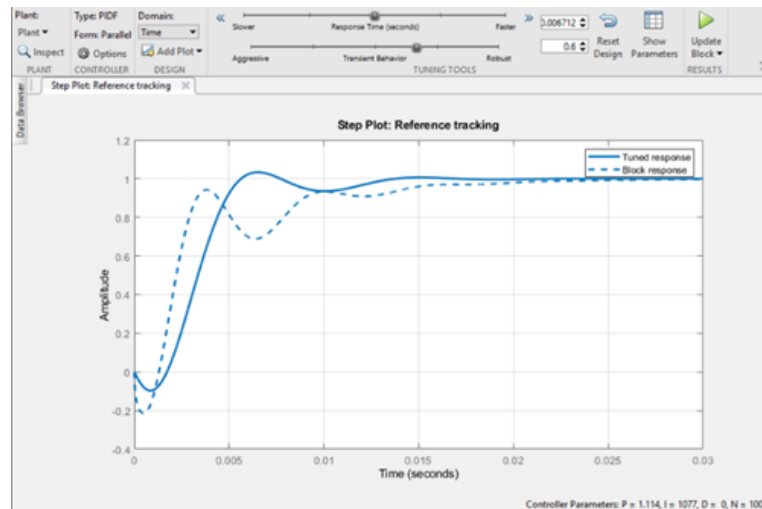


Figure 16 Engine controller is tuned visually for any desired response.

7.4 Autonomous Control

The autonomous CoG control is investigated by estimating the SISO dynamics of an engine running at full throttle. The method determined the systems transfer function using the system identification and the associated PID controller was automatically linearized. Moreover, the controller output can be tuned to the design overshoot, undershoot or settling time requirement. This is a great advantage to alternate scheme of a detailed physical-level modeling of plant components or mathematical derivation of dynamics. Our analysis has shown that dynamics of each component should be system identified severally, and a unique controller can be developed for the component plant. At the very least, this approach is suiting the pumps and the engines. The pumps are custom designed and have different requirements according to their locations, pressure requirement, tank size and pipe diameters. An alternative to SISO modeling of each component is the Multiple-Input and Multiple-Output (MIMO) [45] modeling in which the system dynamics are related to several actuators with variable gains, bandwidths and several sensors providing feedback for integral dynamic behavior, such as the full fuel system. We have noted the mathematical difficulty in deriving linear transfer functions when cross feeding fuel without pressure in a SISO system. The pump dynamics would even complicate mathematical formulation. If the objective is to control an output and several output variables by manipulating several inputs – all at the same time, the problem becomes multivariable modeling [46]. Another difficulty in MIMO control arises if there are multiple feedback control loops and the gain of one loop depends on the gain on the other [46]. A scenario for such dependency would be the two tanks interacting bidirectionally or if the crossfeed valve acts as a shuttle valve sensing a high-pressure bias and returning fuel to the sending tank during Dutch roll [47]. Such conditions in a MIMO controller leads to severe mathematical complications, such as which input to use to control the head in left tank or the head in the right tank. The race condition of the two coupling first-lag time constants is an added complication. The coupling constants results in an s-shaped response. These advanced techniques can be best explored in sequel study.

8. Architectural Improvements

We next improve the system with defueling and fuel jettison capabilities. Our goal is to achieve these capabilities with sufficient reliability with minimal design complexity and minimal additional equipment as to not increase aircraft mass.

8.1 Defueling

For defueling, the existing equipment in the refueling gallery (pumps, valves, bowser interface and fuel lines) can be used. A procedure and modeling logic opposite refueling is needed. Effectively, the refueling differential pressure is required to be reversed for defueling. From the modeling perspective, defueling is achieved by using logic gates to reverse the flow direction. In Figure 17, Inport is set to 1 for defueling without changing the input for refueling. This ensures that the final signal is always inverted, activating defueling. Defueling can only occur when refueling and

engines on are set to 0. It is also possible to add a bowser interface in the right wing for refueling and defueling.

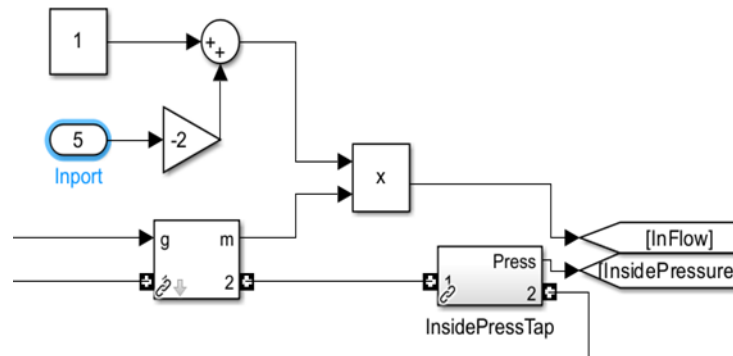


Figure 17 Defueling logic only requires software changes.

8.2 Jettison

Unlike defueling the aircraft on ground where engines and the other equipment are turned off, the initiation of a fuel jettison is a safety-critical procedure due to the flight being airborne and engines and the rest of equipment being active. Therefore, for jettison, it is generally required to host separate equipment in the gallery to avoid the reuse of existing equipment and potentially propagate further failures. The system architecture was improved for redundancy with dual bowzers and an additional cross feed between the jettison pumps. This is for contingency if one fails during a jettison. The system was then tested, and it was found that the second bowser significantly reduced the time it took to refuel the aircraft, and that the jettison crossfeed was able to automatically open and operate in response to a pump failure. Shown in Figure 18 are the additional bowser and two symmetric jettison outlets and accompanying crossfeed valve XF1. Each side can be activated individually. An automatic stop is placed on the system when the on-board fuel quantity reaches 500 kg for remaining endurance. The rate of jettison is controlled by the pump flow rate. The fuel difference on both sides and therefore the lateral CoG is actively maintained during the jettison keeping the flow rates equal in both wings. The system model is not concerned about the physical placement of the outlets or the installation of the jettison pump and outlets at a distance above the feed tank bottom to guarantee a minimum fuel quantity. The crew starts the jettison procedure. The maximum landing weight will be the amount of leftover fuel.

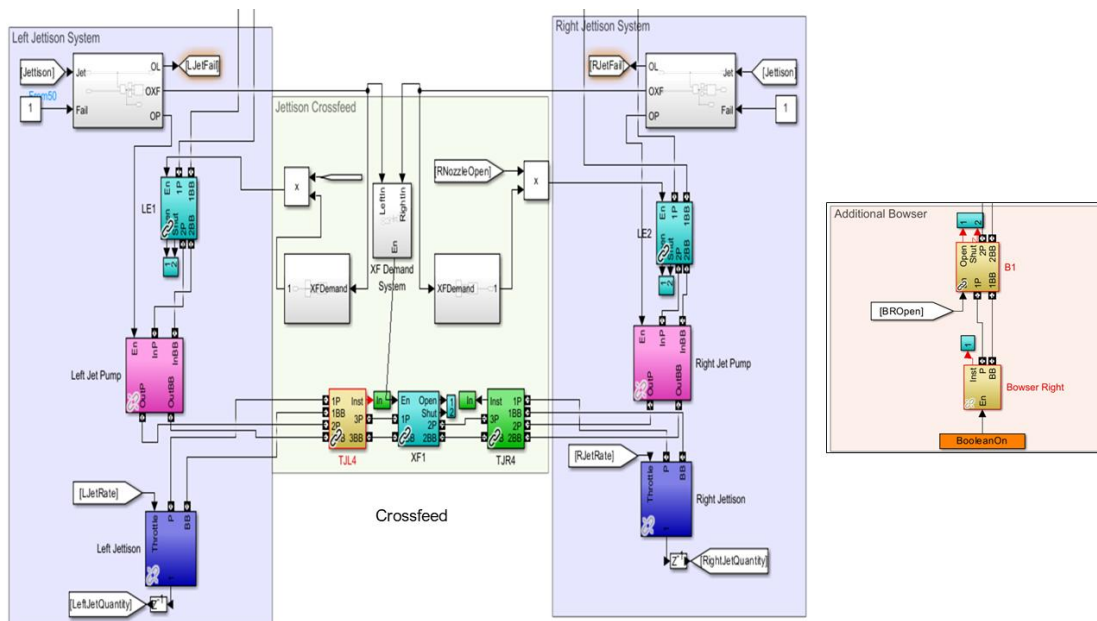


Figure 18 Fuel jettison network with additional bowser in the right wing.

Throughout the cruise flight and during fuel jettison, the endurance is tracked considering the fuel burn and jettison rates. Although endurance time for an aircraft to stay aloft is higher at lower altitudes, for the bare bone fuel system analysis, we ignore the altitude factor in determining endurance.

9. Flight Mission for Jettison

We have analyzed the fuel dumping capability of a standalone fuel system. We now develop a flight mission and provide realism and validation to the system model's performance through aircraft design and flight parameters. A regional jet flight plan was modeled using the AGI STK aviator as seen in [Table 1](#) configuration parameters and [Figure 19](#). A business jet model's performance parameters were used. The fuel quantity is based on tank dimensions, and the fuel system model was determined by rearranging the two fuel tanks so that each wing had a single 2989 kg fuel tank. The system model's maximum fuel flow at 100% throttle, while the default fuel flow was kept at its lowest. The system model assumes that the aircraft is fueled to its maximum capacity (about 5978 kg). The mission employed the jettison procedure. The amount of reserve fuel was approximately 10 % of the full tank capacity. A fixed quantity is set to dump. Other options are dump to a specific weight and dump to fuel state. Acceptable jettison mass-flow rate must be at least 1% of the maximum weight per minute, as per Federal Aviation Authority (FAA) regulation 23.1001. The requirement for the engine flowmeters is to measure mass flow directly within 1 %or better in cruise [2]. The amount of fuel to dump depends on time available. The weather conditions must be considered in the dumping area. Large aircraft may take longer than an hour to dump fuel. A typical rule is a rate of 2% of the All Up Weight (AUW) per minute. FAA § 23.1001, the primary regulation pertaining to fuel jettisoning, is applicable to aircraft in the regular and utility categories. Similar but more stringent requirements for fuel jettisoning are found in § 25.1411 or its predecessors, which are used by transport category aircraft. However, the regulations for turbine-powered aircraft are more stringent, and the performance and handling standards for larger aircraft are more comprehensive. The UK Civil Aviation Authority recommends in CAP745 Aircraft Emergencies that the entire jettison procedure be carried out safely for fuel to evaporate and spread in the sky rather than impact the ground in a liquid form.

[Figure 20](#) shows the weight profile during the jettison scenario. The mission allows a trade space for refining the jettison network, jettison outlet size and pump specification for dumping fuel in real flight conditions.

Table 1 Jettison mission

Mission and system configuration	
Level turns	2 G Sea Level
Bank angle	60°
Turn acceleration	0.01679 km/sec ²
Max pull up G	2 G Sea Level
Max push over G	0.5 G Sea Level
Wind bearing	180°
Wind speed	20 nm/hour
Attitude transition	
Roll rate	30°/sec
Angle of attack / pitch rate	15°/sec
Sideslip / yaw rate	20°/sec
Weight and balance	
Empty weight	14,061 kg
Max landing weight	18,143 kg
Fuel weight	5,978 kg
Total weight	20,039 kg
Base drag index	0
Characteristic length	11.144 m
Refuel/Dump	
Mode	Dump
Quantity	~1200 kg
Rate	120 kg/min



Figure 19 970 km flight path based on the fuel tanks configuration.

Credit: Google Earth. This map includes data from: Google, Landsat / Copernicus, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, GeoBasis-DE/BKG (©2009), IBCAO. Imagery from the dates:14/12/2015–01/01/2021. Some visible imagery has unknown date information.

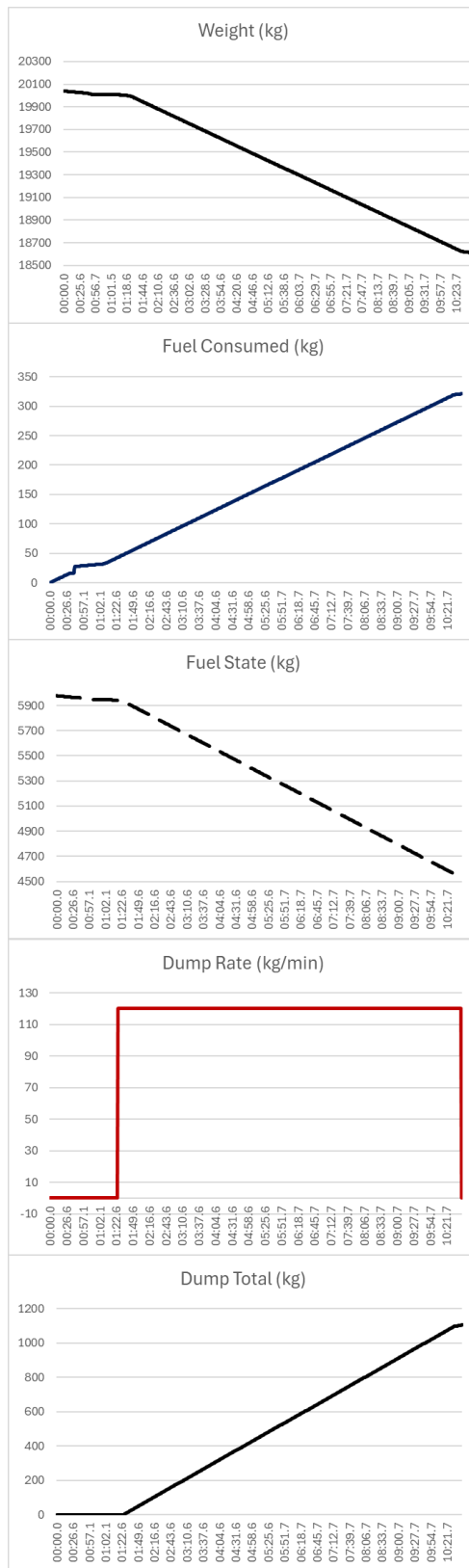


Figure 20 MTOW and the fuel state follow a negative constant linear rate that matches with the positive rise in dump fuel total and fuel consumed. Both behaviors are timely with the jettison process indicated by the red trace. About 1200 kg fuel is dumped and 320 kg burnt. This leaves the FOB at 4,448 kg and aircraft weight 18,600 kg at the end of jettison.

10. Model-Based Systems Engineering (MBSE) Activities

We now turn to MBSE activities [9] in the modeling workflow.

10.1 Requirements Annotation

The system requirements are two types, logical or temporal. The logical requirements set maximum or minimum bounds on signals and logical expressions or set a logical expression to hold true or false. The thresholds for the bound checks are less than, greater than, always inside, and always outside. Temporal requirements set a signal response when a trigger is detected. The requirements are authored, annotated and linked to the implementation blocks directly onto the model. This process ensures digital traceability of requirements and test cases to the system model blocks. [Figure 21](#) shows the requirement statements of the secondary engine pump activation and reading a valid data type from the capacitance probe sensor. The arrow link ties the requirement statements to the owner entity block that implements the requirement.

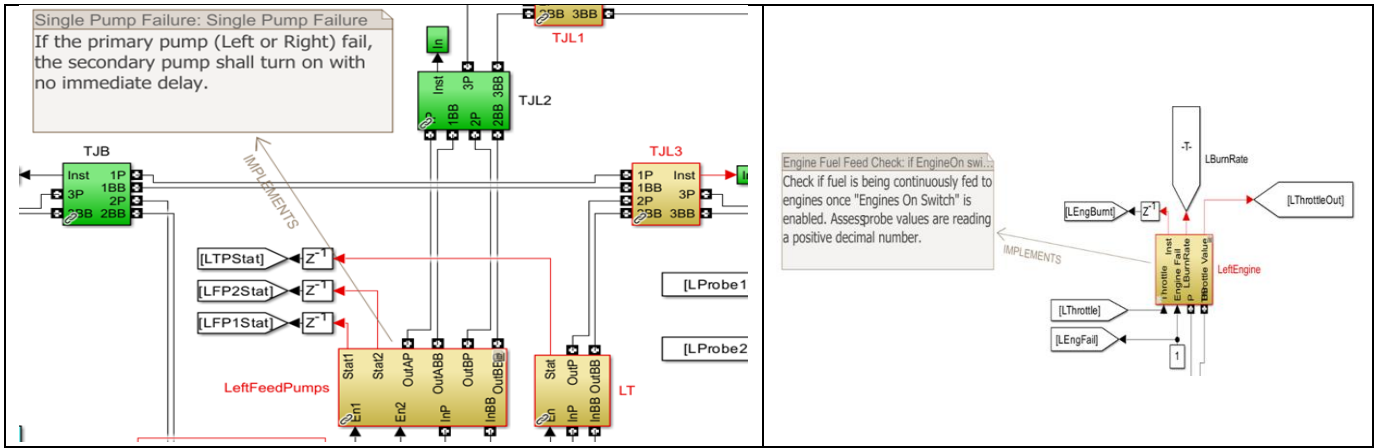


Figure 21 Requirements annotation right in the modeling blocks.

10.2 Requirements Verification

The assessment of requirements verification is according to their logical or temporal type. In the logical assessment conditions logical operators (&, |, and ~), relational operators (<, <=, ==, ~=, >=, and >), arithmetic operators (+, -, and *) or cast operators for floating-point, un/signed integers or conversion of an array, vector or matrix to logical (True/False) values can be used. Verifying the requirement of whether the avionics in the system infrastructure immediately activate the secondary engine fuel feed pump is the logical assessment utilized to confirm the single pump failure. This puts the system avionics capabilities to the test during a period of 2000 sec during which the main engine fuel supply pump continuously fails. The verification of the requirement supported by a repeated activation test was successful. [Figure 22](#) shows this process.

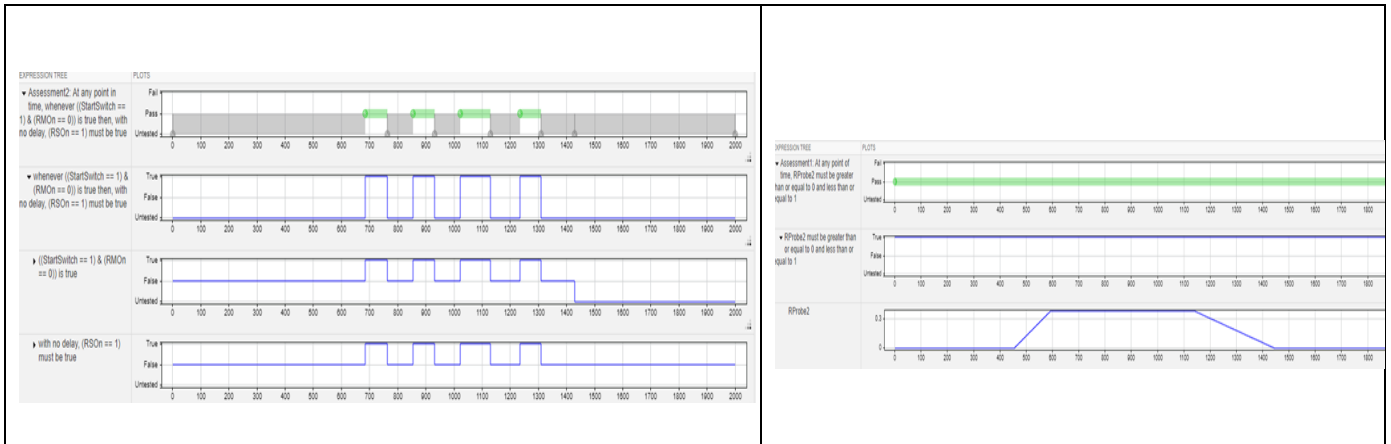


Figure 22 Logical requirement verification is confirmed by the green trace indicating pass when the pump switch pulses are high and the secondary pump instantaneously activates. For fuel gauging, the right probe measures a positive decimal quantity indicated by a green pass trace.

A summary of requirement statements, IDs, implementation and verification status is shown in the requirements toolbox's Requirement's Manager. Refer to Figure 23.

Index	ID	Summary	Implemented	Verified
1	#2	Left Engine On	<div></div>	<div></div>
2	#4	Right Engine On	<div></div>	<div></div>

Index	ID	Summary	Implemented	Verified
1		Single Pump Failure	<div></div>	<div></div>
2		Fuel Probe Check	<div></div>	<div></div>
3		Engine Fuel Feed Check	<div></div>	<div></div>
4		GoG Balance	<div></div>	<div></div>

Figure 23 Requirements implementation and verification traceability is a requisite capability in MBSE.

10.3 Test Harness

Testing is a different process than requirements verification. The purpose of a rigorous test procedure is to validate the system for resultant or desired system behavior and rule out the manifestation of any emergent behavior. Accurate fuel tank readings are provided to the pilot's front deck throughout standard operations. To test an accurate FOB quantity, the fuel calculations logic is isolated as a subsystem and tested in a test harness. In Figure 24, a test sequence block generates simulation testing scenarios, function calls, and assessments and provides inputs to the system under test which is the fuel quantity calculation logic that has been isolated from the full fuel system model. An assessment block is connected to the output of the system under test and assesses and verifies the behavior of system under test.

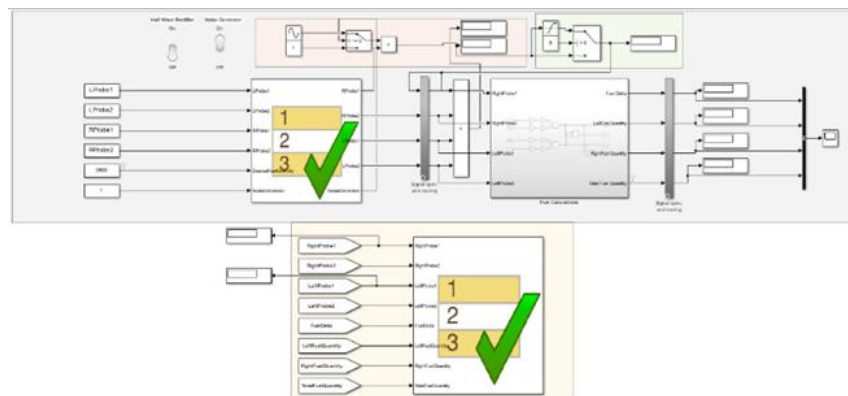


Figure 24 Test harness for testing the FOB calculation logic is achieved by isolating the system of interest (system under test) from the large system. Any system block may be tested in isolation, refined and integrated back into the system.

Inputs to the subsystem can be previously recorded from simulations during the standard refueling procedure. These inputs are passed through the test sequence block to the system under test, as well as new test cases and tests vectors can be written in the sequence block. Figure 25 shows the assessment conditions. To test the subsystem and determine whether the fuel calculations are reliable in the event of a capacitance probe failure, a noise generator switch is included. The assessment block was used to process the outputs to confirm consistent performance.

Step	Transition	Next Step	Description
Assessment_1 when t == 0			Start Time = 0 Check if Probe values have been initialised at the start of the refueling procedure.
Assessment_2 when 100 > t > 0			100 > Time > 0 Check that the left and right probe's are reading a value larger than zero at the start of refueling procedure. Ensure all probe values are not negative Ensure FuelDelta is below normal operation limit (20kg) Ensure probe readings are being correctly calculated by the subsystem to a display correctly showing the pilot and accurate "fuel on board" value.
Assessment_3 when t > 100			Time > 100 Ensure correct assessment for rest of flight time
end			

Figure 25 Test assessment block shows different assessment condition entered to make the system pass and fail.

As seen in Figure 25, the test assessment block made it possible to write and record a prompt response. Before refueling, the block examined the subsystem to make sure all probe values were set to 0. To make sure the initial fuel calculations were accurate, the system was tested within 100 sec of the refueling process. The assessment block identified the conditions that were not met by the subsystem. The test verification code failed at certain time intervals. Figure 26 illustrates failure and Figure 27 passed assessment histories.

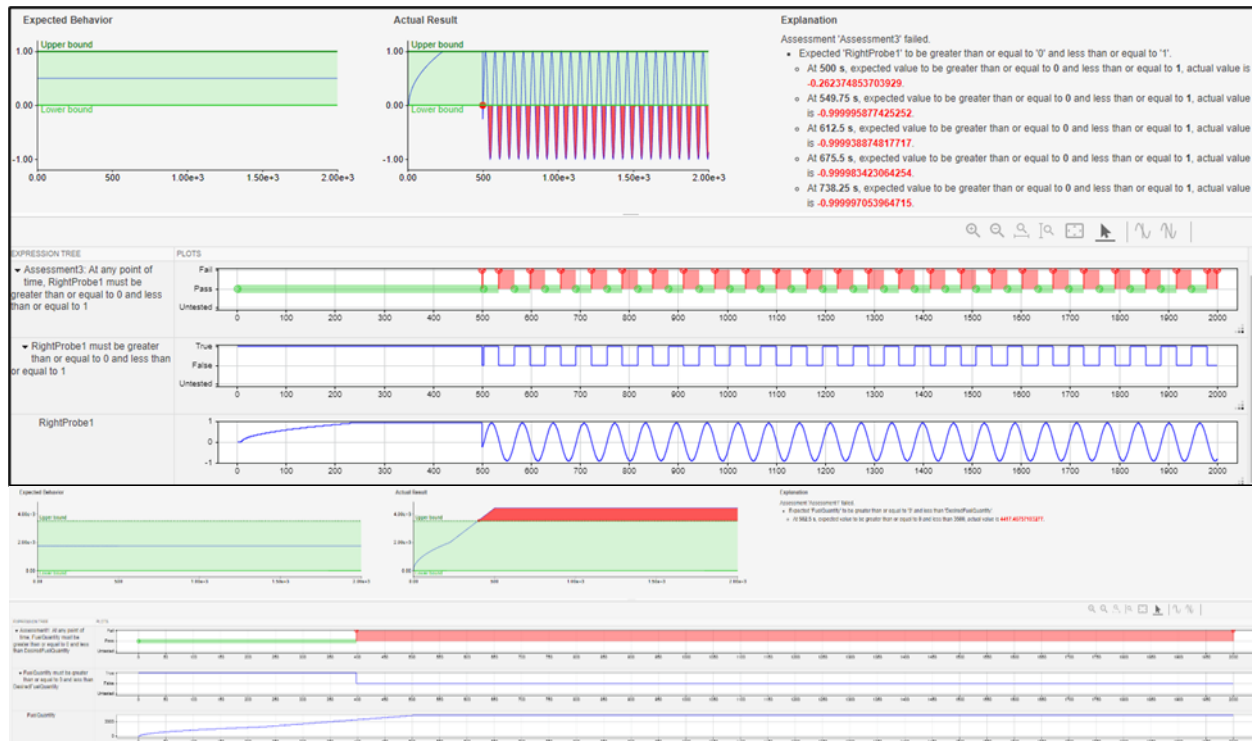


Figure 26 Failed assessments during testing of the fuel quantity calculation subsystem.

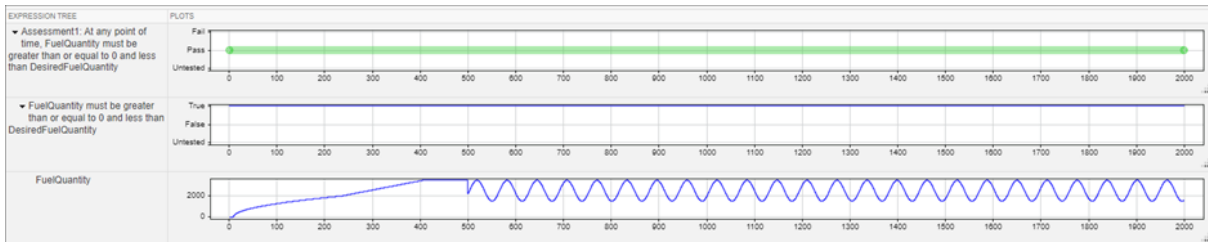


Figure 27 Passed assessments during testing of the FOB calculation subsystem.

It must be remarked that the validation considers no attitude disturbance assumption, linearized gauging with two probes in each tanks and linearized flow of the fuel dynamics.

10.4 Code Emittance

Simulink Coder is used to generate standalone C code from the CoG balancing subsystem block for a target embedded hardware. The code can be used to check the system's hardware functionality and, thus, its compliance with the DO-178C standard, if it has been previously validated by the assessments. Figure 28 illustrates this process. The executable code can run inside the MathWorks environment or can be ported to the target fuel management processor and run on a test rig, hardware-in-the-loop system or iron bird for prototyping, verifying and validating, physical real-time testing and deploying. It is important to note that code synthesis is suited for discrete-event models or blocks. The code can be analyzed with Code Analyzer for Design Assurance Level (DAL) and follow-on DO-178C certifiable production. Alternatively, the code can be emitted in a hardware description language (VHDL, Verilog, SystemVerilog) for Field Programmable Gate Array (FPGA) or System on Chip (SoC) target device and checked for DO-254 compliance.

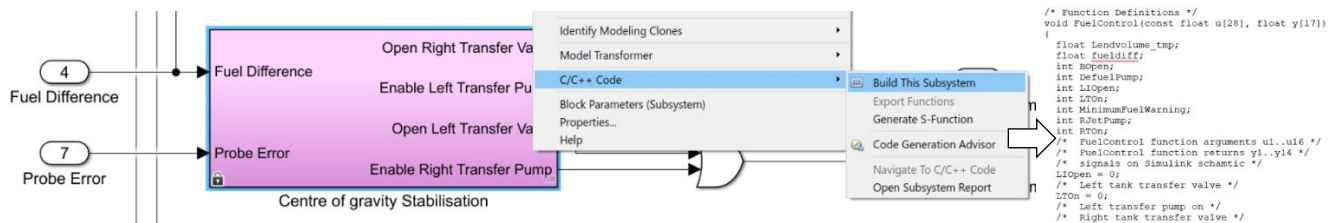


Figure 28 Fuel system microprocessor code emitted directly from the model block.

11. Limitations and Outlook

The current model has several limitations. We list these and future directions for improvement of CoG and safety analysis.

1. Each tank currently uses two probes which are inadequate. For accurate FOB gauging and redundancy, additional probes of varying lengths installed at disperse geometric deflection of the wing are necessary. Doing so adds significant complexity to the model in calculating the overlapping head volume.
2. Currently, in the system model, the FQI at the front deck uses the on-board fuel quantity. The flight altitude is not a factor in this computation. The altitude can be provided from the GPS or Air Data Inertial Reference System (ADIRS).
3. Quantization noise can be added to the least significant bits of the gauging process.
4. A slight roll can be added while gauging the fuel quantity. This adds significant complexity to the model.
5. Consideration for the Non-Return Valves (NRV) or check valves in the architecture is necessary for additional safety for one-way fuel flow and preventing reverse flow.
6. System's component sizing e.g., fuel lines, and various types of pumps (tank, feed, transfer) and valves (emergency, feed, transfer) sizing for timing, and flow rates are necessary for detailed design.
7. The altitude and atmospheric factors impact endurance to increase the simulation's accuracy and realism.

8. Because the model-based design space is huge and exploration problem in architecture is exponential in terms of design objectives and trade space analysis such as complexity, performance weight, a more parametric configuration would be highly useful where the top-level design parameters such as tank dimensions, mass flow rates, pump and pipe parameters, valve open times, resistances and pressure can be allowed to be configured from graphical display.
9. The model used single failures. Although the number of components is small and with two tanks the number of failure scenarios and mitigation of their effects is manifold. Having said that, consideration of two back-to-back failures is worth investigating for determining alternative paths for keeping the fuel mass in balance in both wings. Two failures is further necessary to analyze the emergence of uncontrollable cyclic flow in the two sides.
10. The CoG shifting may be tracked in the flight plan [48]
11. The model may be validated by adaptation and calibration to a real aircraft fuel system.

12. Discussion

When the secondary right pump fails to turn off or suddenly turns on, the system can turn off the left main pump and enable crossfeed. Another reaction is to turn off the right main pump and leave the system running with the secondary pump. If the left transfer pump fails to turn off the fuel is shifted into the fuel gallery and pumped back into the left tank through the left transfer valve. This creates a loop of fuel being pumped up and then transferred back down into the same tank. Thus, the CoG returns to nearly 0 kg difference condition. It is difficult to distinguish whether the tanks or probes have failed. Thus, the reliance is on last values to determining the present fuel level. Moreover, the probes cannot detect fuel quantity changes due to maneuvers such as a roll. Another way of calculating the fuel level during capacitance probe failure would have been to use the burnt fuel by subtracting it from the refuel quantity. While this would only work if the refuel quantity had been reached, this implementation would create a more accurate estimate of fuel in the tank with the failure, and it is not dependent on the probes. Additionally, the transfer pumps also can fail, however, in most cases, this failure would have little impact on CoG. An emergency scenario is a dual throttle failure of both engines. The system does nothing in this case, and this would mean an emergency landing in gliding mode.

MBSE activities of requirements annotation, V&V and testing enable a wide range of system design and analysis after the initial investment of effort in model development. The main advantage is an assorted array of stitching the digital thread connecting various views and viewpoints of the simulation and submodels and achieve a single simulation model with a consistency and single source of truth of the simulation data. In the MathWorks' MBSE workflow, the entire design can be based on shared models. Through the digital thread, all system artifacts can be traced back to the single source of truth which is the system model. If any error manifests in an artifact it is likely that it originates from the system model. The Data Inspector tool allows comparing data streams. The variables can be ported to any view of the simulation into the workspace. This feature allowed generating an isolated plant model of the engine and its PID controller from the main system model while both models were digitally linked and rendered the same consistent behavior at the top-level.

13. Conclusion

A fuel system model was developed and controlled at component level for proper system operation using a pilot's deck interface. The model was implemented in the MBSE methodology and workflow. The system architecture was explored. Several considerations for fuel management and flight stability were presented. The focus is on flight safety. The analysis began with creating different logical tests. After passing safety, the system was analyzed for balancing the CoG manually in bang-bang control scheme. With switching the appropriate pumps and valves the fuel quantity can be maintained within a difference of 100 kg between the two wings. The bang-bang or manual control of the system allowed a variety of safety tests. The scheme serves as a starting point for control autonomy.

Acknowledgements

The authors are grateful to Dr. Steve Wright, formerly of the University of the West of England, Bristol and Airbus Operations Ltd., Filton, United Kingdom.

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2025-12-31

Society of Automotive Engineers (SAE)

<https://doi.org/10.4271/01-18-03-0015>

Zaidi Y, Michalek O. (2025) Architecting ATA 28 with model-based systems engineering: center of gravity balance and system performance. SAE International Journal of Aerospace, Volume 18, Issue 3, 2025, Article number 01-18-03-0015