ISSN (Print): 2476-8316
ISSN (Online): 2635-3490
Dutse Journal of Pure and Applied Sciences (DUJOPAS), *Vol. 5 No. 1b June 2019*

Co-simulation of Fault Resilient Aircraft Fuel Management System Using Vienna Development Method (VDM), and 20-Sim

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Abstract
This paper presents a co-model of seven tanks aircraft fuel management system that provides fuel transfer between the fuel tanks and the engine of the aircraft in order to control the centre of gravity of the aircraft within its defined region in a normal or during components' failure. We used DESTECS[1] tools for the co-modelling and co-simulation to guarantee the reliability of the system. The paper describe the co-modelling and co-simulation of the discrete-event descriptions in Vienna Development Method (VDM), with continues time descriptions in 20-sim[2].

Keywords: Modelling-Simulation, Fault-tolerance, Aircraft-fuel system, Embedded systems

INTRODUCTION
The design of complex safety-critical embedded systems presents many challenges ranging from rules formulated in one domain (such as electronic and mechanical domains) to be use by an expert from another domain (e.g Software engineer); presenting evidence to the assurance process demonstrating that important operational tasks have been taken into account right from the initial stage of the design; and above all achieving fault resilient system (Fitzgerald et al., 2011; Pierce et al., 2012).

Addressing such challenges requires building models and running simulations so that early phase of the design can be proven to avoid experiments using real objects which is costly and time consuming (Fitzgerald et al., 2011; Pierce et al., 2012). We intend to present model of aircraft fuel management system for a 7 tanks aircraft. Fuel in the aircraft can be transferred from one tank to another for a different reason. Some of these reasons include engine feeds and keeping the aircraft's center of gravity (CoG) within a defined region (Heifang, Bifang, and Fangyi, 2011; Beno and Adamcik, 2012; Long and Song, 2009; Moir 2008). The fuel system in the aircraft is being monitored and controlled by a computer aircraft fuel management system. It decides how and when fuel can move from one tank to another. Many situations arise in this process, for instance failure of fuel component. It is therefore important to present a flexible and intuitive computing

[1] www.destecs.org
[2] www.20sim.com

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platform to investigate the logic to be use by the computer in dealing with all circumstances. Failure in aircraft fuel system could lead to the failure of engines which might eventually lead to failure in operation and crashing of the aircraft. Sixty percent of "In-Flight Shut-Down" from 1964 to date, were caused by fuel system (Heifang, Bifang, and Fangyi, 2011). According BBC News (2019) preliminary investigation into recent crashes of Ethiopian airline Boeing 737 Max 8 revealed that two sensors that measured the flight angle began to report different readings. This implies that the aircraft's CoG is out of its defined region before the plane finally crashes killing all the 157 people on board.

This work introduces DESTECS tools for the study of the aircraft fuel management system. DESTECS is a collaborative multidisciplinary modeling environment that allows early model validation using co-simulation and provides ways for fault modeling and fault analysis at the early stage (Pierce et al., 2012). The ability of DESTECS to utilize domain specific analysis and cross-disciplinary capability, dealing with wider range of faults as well as handling different fluid flow complexity problems (Pierce et al., 2012) makes this work unique than the existing co-models.

The previous work on DESTECS platform was limited to few number of tanks, valves and fuel pumps, which does not fully address complex fuel flow problems. Using latest edition of DESTECS guidelines and tools, this paper advances in modeling an aircraft fuel system with complex piping network, complex fuel flow components and complex program in the controller that ensures successful fuel flow in a normal or when there is a problem along the flight.

Description of the process to be simulated

Large aircrafts mostly intended for intercontinental flights, are designed with a trim tank in the tail. This tank is filled with extra fuel which helps to get a good aircraft trim angle along a flight and also sustain aircraft steadiness thereby shifting the CoG of the aircraft backward (Jimenez et al, 2008). Figure 1 show the aircraft fuel system used in for this research. The aircraft has 2 engines LE and RE and 7 tanks. In each of the tanks, there is a level sensor to gauge the quantity of fuel in any flight stage. There are also 3 fuel pumps and 13 valves used for fuel transfer.

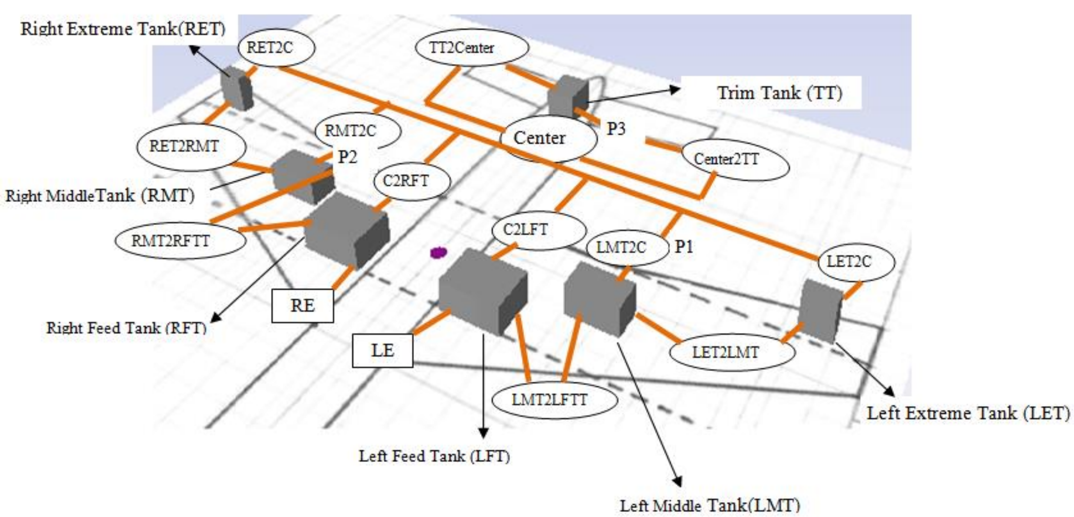


Figure 1: Schematic of Aircraft Fuel System

In the remaining part of this paper, the following acronyms are used for the following valves and pumps: P1= pump1, P2 = pump2, P3 = pump3, V1=LMT2C, V2=RMT2C, V3 = CENTER2TT, V4 = TT2C, V5 = CENTER2LFT, V6 = CENTER2RFT and Vc = CENTER.

LFT and RFT are two tanks supplying fuel to the left and right engines respectively. LMT and RMT supplies fuel to the feed tanks and to the tail tank depending on controller's decision. LET and RET works against the upward bending of the wings, hence fuel transfer from these tanks is not common since there must be enough fuel in these tanks along a flight.

Fuel transfers are mostly between the wing tanks and the trim tank, although wings transfer do occurs but not often. The following notation is being use to represent fuel transfer between the tanks.

LMT ⟶ (P1)(V1) ⟶ (Vc) ⟶ (V3) ⟶ (TT).

This notation represent fuel transfer from left middle tank through V1, Vc, V3 using P1 into the trim tank.

Fuel transfers were carried out using different modes (corresponding to the flight phases) in the controller. Below are the descriptions of the fuel transfer occurring at each flight phase.

TAKE_OFF mode: There is no fuel transfer in this mode. This mode begins from taxiing until the Aircraft reaches FL255(25500 ft). At this mode, the fuel consumption by the engine is at high rate reaching almost 2000kg per simulation second.

MTS_TO_TT mode: As the Aircraft reaches FL255(25500 ft), this mode is activated pumping fuel from the middle tanks to the trim tank as shown below. There is less fuel consumption rate in this mode.

LMT ⟶ (P1)(V1) ⟶ (Vc) ⟶ (V3) ⟶ (TT).
RMT ⟶ (P2)(V2) ⟶ (Vc) ⟶ (V3) ⟶ (TT).

MTS_TO_FTS mode: This is activated when the quantity of fuel in the feed tanks reaches a minimum of 4000kg. The mode pumps fuel from the middle tanks to the feed tanks and stops when there is no fuel to pump out from the middle tanks. The fuel transfer can be shown below:

LMT ⟶ (P1)(V1) ⟶ (V5) ⟶ (LFT).
RMT ⟶ (P2)(V2) ⟶ (V6) ⟶ (RFT).

TT_TO_FTS mode: Three conditions activates this mode: when the quantity of fuel in the engine feed tanks reaches minimum amount of 4000kg and there is no fuel in the middle tanks, when the aft limit is reached and when it is one hour to the landing time. Although it is necessary to keep trim tank full of fuel during the flight as it balance the aircraft longitudinally, it will be more dangerous to allow the feed tanks to run out of fuel, this makes the first condition necessary. The pumping of fuel due to the second condition is to avoid the CoG crossing the security region and third condition is to ensure there is no fuel in the trim tank during the landing. This mode continue until there is enough fuel for engine feed, or when the position of the CoG is slightly far away from the aft limit. The Fuel transfer is shown below.

TT → (P3)(V4) → (Vc) → (V5) → (LFT).
TT → (P3)(V4) → (Vc) → (V3) → (RFT).

DO_NOT_PUMP mode: This mode stops pumping fuel to any tank, therefore. It activates when the quantity of fuel in TT is 10000kg. The temporary suspension of fuel transfer stops when a particular mode is activated. For example, when the quantity of fuel in the feed tanks reaches 4000kg and there is fuel in the middle tanks, it automatically switches to MTS_TO_FTS mode.

Movements of the fuel between the engines and tanks causes the motion of the CoG. The CoG should remain within security zone along a flight. The allowable CoG range is expressed as a percentage of mean aerodynamic chord (MAC) (Duncan, 2007; Houghton and Carpenter, 2003). Our main goal in the simulation environment is to mimic a complete flight and observe the motion of the CoG position.

DESTECS Simulation Process

In general, the design of embedded control systems such as fuel management system is a combination of two parts, namely the controller and plant (Ni and Broenink, 2012). Co-model and co-simulation are two concepts use in DESTECS to express and accomplish embedded systems model (Fitzgerald et al., 2011; Pierce et al., 2012; Ni and Broenink, 2012; Broenink et al, 2012). A co-model consists of a discreet event (DE) part, and continuous time (CT) part as well as a contract that links DE and CT parts. DESTECS uses VDM-RT (VDM Real-Time) which is a dialect of VDM to formally denotes DE models. For building the CT model, 20-sim[1] tool was used which provides features for modelling the dynamics of the plant through different ways, and the most powerful way is bond graph notation which is being used for this work. "*Bond graphs are a network-like description of physical systems in terms of ideal physical processes*" (Kleijan, Groothuis and Differ, 2013). Using bond graph in building CT model requires splitting the system characteristics into an (imaginary) set of constituent elements with individual element portraying an idealized physical process.

Developing fuel system management model involves several stages. The plant section (CT-part) was done in the 20-sim environment where 3 submodels (Controller, Plant and CoG) where developed and connected to form the model of the fuel system. **Figure 2** depicts the submodels connected together.

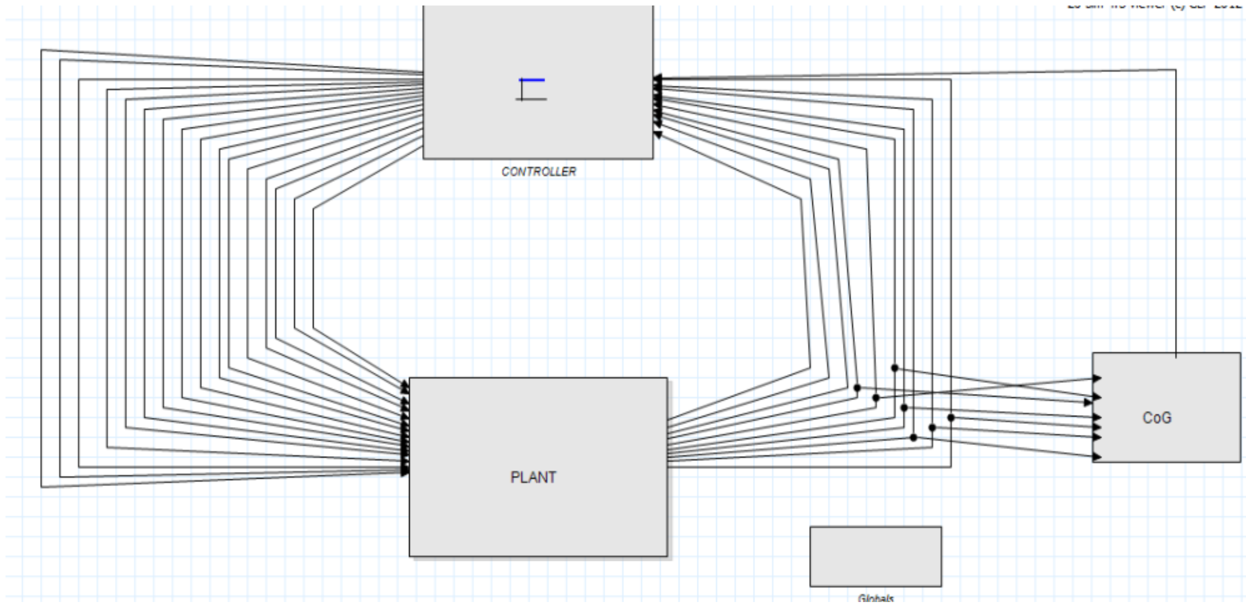


Figure 2: Controller, Plant and CoG submodels connection in 20-sim

Controller submodel contains monitored and controlled variables which receives information such as quantity of fuel in a tank, current state of a valve and so on from CT to the DE part and receives control such as, set a valve ON/OFF, shut down a pump and so on from the DE to the CT part. The plant submodel contains all the fuel components and their connection. Figure 3 shows the content of the Plant submodel. CoG submodel calculates the centre of gravity of the Aircraft at any time along a flight. CoG is calculated longitudinally and laterally. For the longitudinal position of the CoG, we need the distance of each tank from the datum, weight of the aircraft when empty of fuel and the weight of each tank. The datum is chosen from the forward nose of the aircraft in order to minimise computational errors (Duncan, 2007). The product of the distance of each tank from the datum and its weight are stored in a variable "Total_moment". The weight of the aircraft is continuously added to the total weight of the tanks at any point along the flight, the result is stored in a variable "total_weight". Having this information at hand, the longitudinal CoG is calculated as: CoG = Total_moment/ total_weight. However, in computing the lateral position of the CoG, we ignored the weight of the plane as we assumed the aircraft balances at y- direction. We compute new "Total moment" and new total weight using the same procedure as in longitudinal CoG. In each case, the longitudinal and lateral positions of the CoG are exported to the DE part for the controller's decisions.

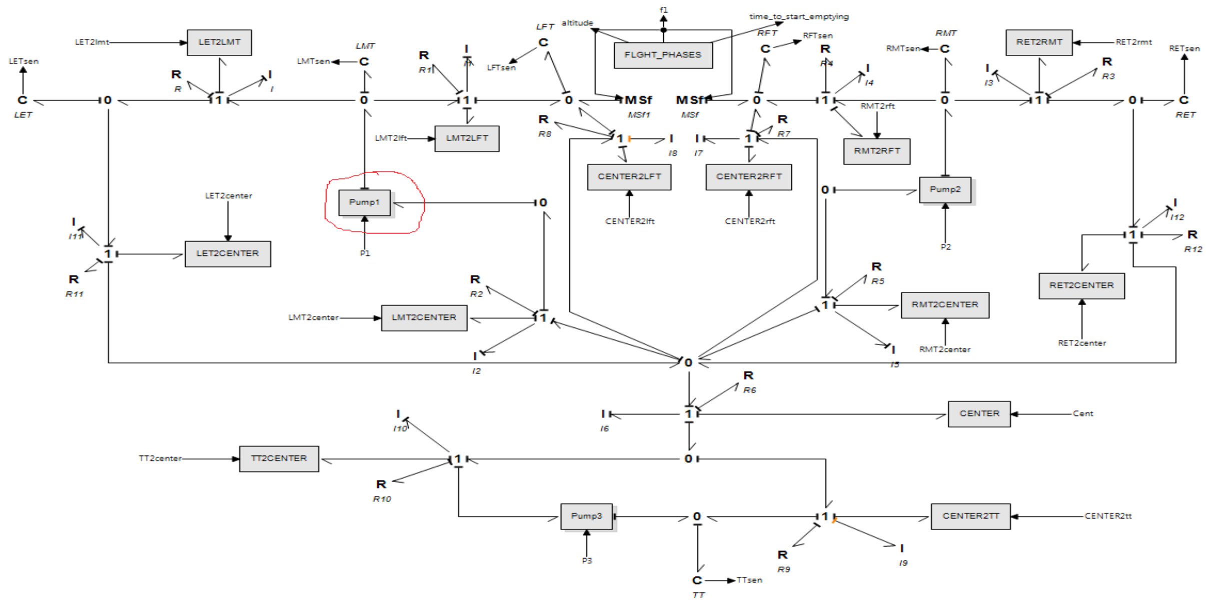


Figure 3: The Plant model from the 20-sim

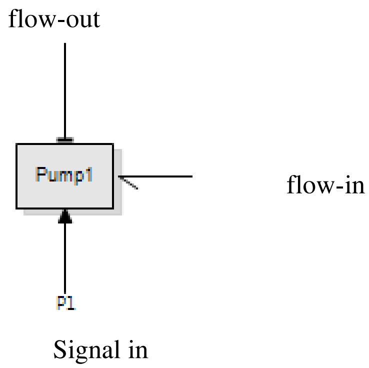
In figure 3, arrows pointing in or out of the model represents signal for the use of the controller in the DE part. By clicking any of the icons representing fuel components, a window opens showing equations and calculations representing the icon's model. For modelling engine fuel consumption rate, we uses *Modulated source of flow* (MSF) element of the 20-sim library. It receives an input altitude signal from the flight phase submodel and decides the quantity of fuel to be use by the engine at particular flight level.

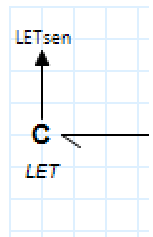
Fuel components

Fuel pumps were modelled using modulated transformer element (MTF) from the 20-sim library. The pumps are ON/OFF. They are usually set "ON" by producing high pressure and "OFF" when the pressure is low. Figure 4a shows the typical model of the pump with its ports.

A proportional valve which behaves as ON/OFF to allow or prevent passage of fluid through them was used in this work. High and low resistance mimics OFF and ON behaviour of the valves respectively. Figure 4c shows a valve between LET and LMT.

Capacitance (c-element) represents the fuel tanks due to its ability to store energy in the form of potential energy (Shearer, Kulakowski and Garder, 2007; Durfee and Sun, 2009). Flow into and out of the tanks were modelled by positive and negative flow respectively. By default, C-element does not recognise the point at which the positive or negative flow should stops fuel. Using the default construction of C-element in 20-sim allows flow to go below zero (negative flow) which is not possible in real sense. In this model, this situation is been managed by using a high resistance value to stop the flow when the level reaches zero. Figure 4b shows a model of a fuel tank. State variables in the capacitance element stand as the quantity of fuel in each tank at a particular time along the flight, hence state variable exports the quantity of fuel to the DE-part at each flight-time. Inductance (I-elements) and resistance (R-elements) elements were used for modelling the fuel pipe. I-elements models the inertia of the fluid in the pipe, while R-elements models fluid resistance on the pipe wall due to the motion of the fluid.





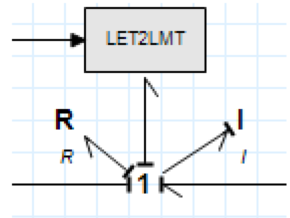


Figure 4a: Model of pump1 **Figure 4b:** Model of Left Extreme tank **Figure 4c:** Model of LET2LMT valve

Using the Simulation

All the icons used for modelling fuel components in 20-Sim can be edited by clicking on the items and changing the parameters. For example, the c-element used as fuel tank (fig 4b) can be click and change the value of its initial fuel quantity.

Global submodel in fig. 2 contains the initial values of some flight parameters such as fuel consumption rate at each flight phase, cruise altitude, pumps pressure value and so on. These values can be modified by clicking and editing the global submodel.

After checking the entire model (by clicking the "check model" icon) to ensure no error from the 20-sim environment, simulation can be run from the DESTECS platform by clicking on the run icon. As the simulation begins, three simulation windows appears. Fig. 6 shows the movement of fuel from different tanks, fig 7 shows the motion of the CoG and Mac percentage along a flight.

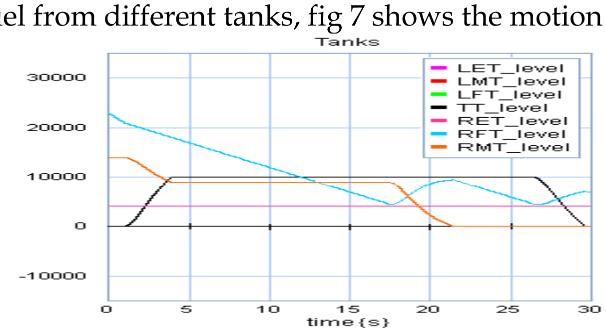


Figure 6: Evolution of fuel tanks.

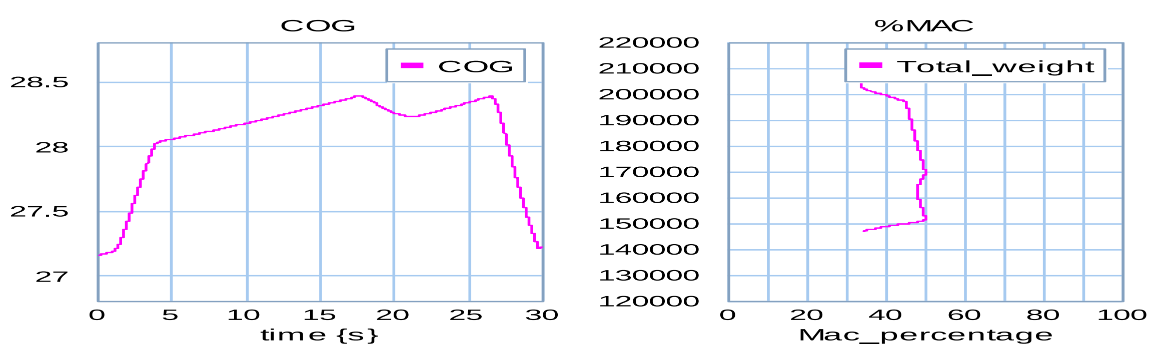


Figure 7: shows the evolution of the CoG and %Mac.

Some Experiments

Fig. 5 and 6 shows the results of a typical flight. We will present result when there is failure of a component. Although only P1 failure was modelled in this paper, however the control modes used in this section can be modified to model different types of components failure.

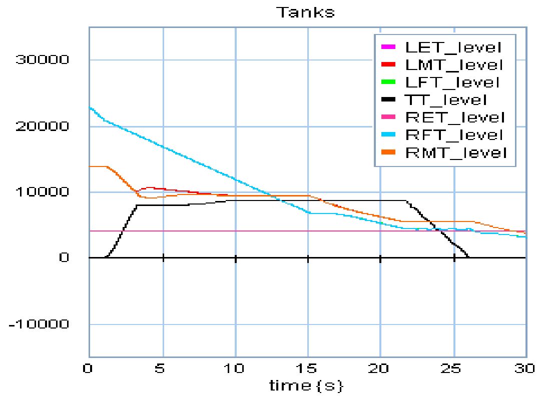


Figure 8a: Evolution of fuel contents when P1 failed.

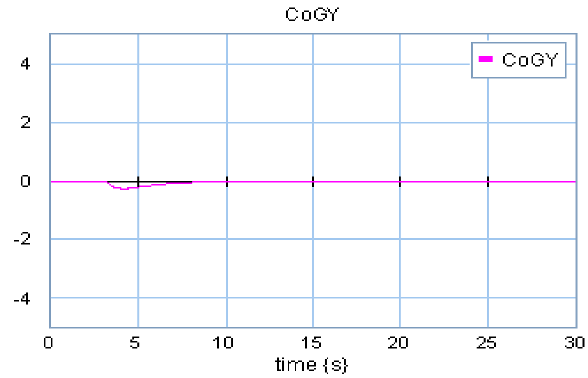


Figure 8b: Lateral deviation of the CoG position as P1 failed

P1 fails when pumping fuel from the middle tanks to the trim tanks. The failure causes the CoG to slightly move to the left wing of the aircraft since there is more weight in the left wing than in the right wing. This failure could be detected by the fuel management system through the routine checks by the controller to compare the quantity of fuel between the middle tanks. When there is any variation in the quantity that reaches some threshold value of 500 kg, the controller reports failure of P1. In order to maintain a normal flight as well as keep the CoG within a security zone despite the P1 failure, the following fuel transfer occurs:

1. When the fuel in the feed tanks reaches minimum of 7000kg, the following fuel transfer occurs:

LMT → (V1) → (V5) → (LFT).
RMT → (P2)(V2) → (V6) → (RFT).

This fuel transfer is possible because there is more pressure in the middle tanks than in the feed tanks due to the variation in fuel quantity in both two tanks. This will ensure that there is available fuel for the engine in the feed tanks and also moves the CoG slightly backward by reducing the amount of fuel in the middle tanks.

2. When the fuel quantity in the feed tanks reaches a minimum level of 4500kg, the following transfer starts

TT → (P3)(V4) → (Vc) → (V5) → LFT.
TT → (P3)(V4) → (Vc) → (V6) → RFT .

This transfer stops when the quantity of fuel in the feed tanks reaches 7000kg, and the control is switched to 1 above.

It is important to note that, both the engine feeds and position of CoG are maintained whether in a normal flight or when there is a problem in the fuel system.

CONCLUSION AND FUTURE WORK

A co-model of aircraft fuel management system for an aircraft with seven fuel tanks and two engines have been designed and implemented. The co-model performed two major important tasks simultaneously, keeping the aircraft's CoG within its defined region and ensuring available fuel for engine feed at any time in the flight. Furthermore, the work modelled some fault analysis by injecting fault on a particular component and providing fault resilient mechanism that will keep the system to continue with its intended operation in the presence of fault. An in-depth research on areas related to co-modelling and co-simulation of aircraft fuel system has been conducted. In addition to this, all the required functionality of the co-models have been implemented, tested and evaluated. The work could be extended to model other parts of the aircraft other than fuel system only.

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