# MODELING AND SIMULATION OF A SATELLITE PROPULSION SUBSYSTEM BY PHYSICAL AND SIGNAL FLOWS

**Leonardo Leite Oliva**

National Institute for Space Research, INPE
Av. dos Astronautas, Jardim da Granja, 1758
São José dos Campos, SP, 12227-010
leonardoleite.oliva@gmail.com

**Marcelo Lopes de Oliveira e Souza**

National Institue for Space Research, INPE
Av. dos Astronautas, Jardim da Granja, 1758
São José dos Campos, SP, 12227-010
marcelo@dem.inpe.br

**Abstract**: *Modeling and Simulation (M&S) of dynamic systems based on computers is a diverse field that involves several knowledge areas and tools, and is used in all development areas of space industry such as rocket and satellites construction. Since the space systems are divided into several subsystems for ease of engineering, their models are divided accordingly for the same reason. Such models may be done using different computational tools that are based on either physical flows, informational flows, or hybrid flows, depending on the subsystem nature. This is specially true for a satellite propulsion subsystem, and its physical (volume, mass, energy, enthalpy, entropy, linear momentum, etc.) flows. This paper presents the modeling and simulation of a satellite propulsion subsystem by physical and signal flows. To accomplish this task, two different computational tools were used: AMESim and MatLab. The first part gives a general view of M&S, showing its importance in modern engineering. After that, there is a brief description of the space subsystem (propulsion subsystem of the MultiMission Platform - MMP), with its main components and tubing. The third part presents briefly the mathematical and simulation models. Conclusions describe what kind of simulation results are expected, and how data analysis will be done.*

***Keywords:*** *Modeling, Simulation, Monopropellant propulsion system, Simulink, AMESim, Hydrazine.*

## 1 Introduction

Modeling and Simulation (M&S) of dynamic systems based on computers is a diverse field that involves several knowledge areas and tools, and is used in all development areas of space industry such as rocket and satellite construction. Since the space systems are divided into several subsystems for ease of engineering, their models are divided accordingly, for the same reason. Such models may be done using different computational tools that are based on either physical flows, informational flows, or hybrid flows, depending on the nature of the subsystem.

In general, systems can be analysed by three ways: (a) Mathematical models; (b) Simulation models; (c) Prototype construction (Fig. 1).

Mathematical models are very general and accurate. However, for complex systems, that have several parameters and variables to be measured, it is very difficult to have a satisfactory analytical solution. They can be static, in witch the main object of interest is the movements cause (forces and moments); kinematic, that is focused on the effects caused by the actuating forces and/or moments (displacements and speeds); or dynamic, that combine both static and kinematics models. This is the most general approach.

The prototype construction enables a high fidelity model. But it is too difficult to build if the main goal is analyse complex aerospace systems. Additionally, there are problems after each experiment, because there is a direct interference in the system, demanding replacements and adjustments after each physical simulation. This makes this kind of approach expensive and human demanding.

Therefore, the final solution is adopting simulation modeling techniques.

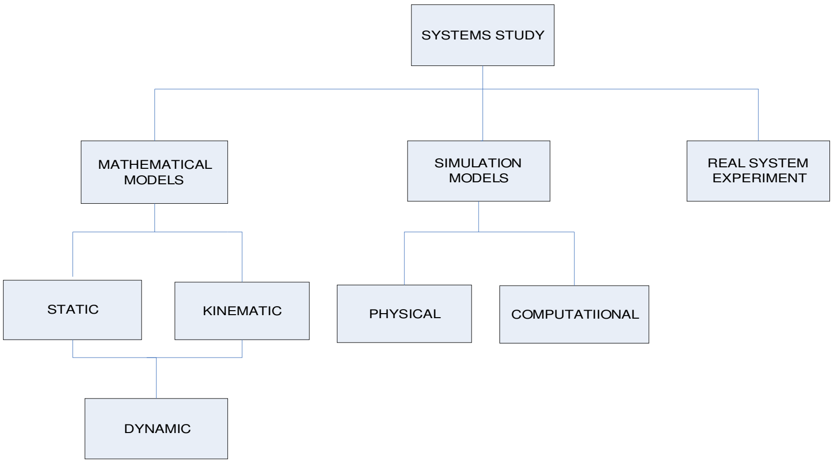

**Figure 1: Approaches for system study.**

Simulation models can be physical or computational. The first model uses real components to represent interactions, while the second uses only computers to represent the system behaviour (virtual).

Virtual based simulation is used in industry for many reasons. One of it is main advantages is the possibility to run simulations rapidly, enabling fast data acquisition. This allows the develop team to analyse more situations that the system may encounter during operational lifetime.

Simulation models may have 4 kinds of solutions:

- Acceptable
- Satisfactory
- Optimal
- No solution

Acceptable solutions usually have models that are very easy to build. However, they can be unsatisfactory because their response has low fidelity, compromising further analysis.

An optimal solution is highly desirable, but not possible to achieve due to financial costs involved - besides time for model development.

Obviously, a simulation that brings no solution is useless. Therefore, considering what was told before, the model capable of deliver a satisfactory solution is the best. It balances simplicity and fidelity, enabling its construction and providing results of high reliability.

After defining the M&S approach, it is important to define what is a physical and informational model. The theory related to them is widely used in this work.

## 2 Physical and signal modeling and simulation

Physical based modeling is generally made by components and it is connections that are based in physical laws and physical flows. When this is energy flow we use Bond Graphs (BG) representation. This kind of notation is capable of representing physical systems of different domains without need of specific notation. Therefore, physical systems or subsystems that have components of different domains, but that have the same function (for example, mass and electric inductor), can be represented with the same notation. This turns the M&S work easier to visualize and understand, as well as to run simulations.

Signal based modeling has another kind of approach: the variables that flow are adimensional (they can have real or integer values, or be Boolean). The flow goes in one direction.

An informational model can be built using Block Diagram and Signal Flow Diagram (often used in continuous electronic or control systems); State Machines or Fluxograms (in M&S by events); or by UML (Unified Modeling Language) diagrams (used in the software development).

To build the simulation model of the space subsystem we decided to adopt the Block Diagrams using Simulink environment to build the informational model; and to use AMESim, a modeling tool based in components, to build the physical model.

Before introducing the mathematical formulation, the main subsystem will be described in order to give an general view of its operation.

## 3 MultiMission Platform propulsive subsystem

The choice to study the propulsive subsystem of the MMP has several reasons, which are listed below.

- The lifetime of a satellite is dependent of it is capacity to keep correct orbit and attitude (orientation). This is done using actuators, that commonly include chemical monopropellant systems, commanded by the Attitude and Orbit Control System (AOCS);
- Depending on the mission to be accomplished, several types and configurations of propulsive subsystems can be chosen. For this, there must be an detailed study of the subsystem using modern techniques, such as M&S;
- The MMP is a modern concept in satellite architecture, whose main goal is to gather in a single platform all essential equipments for a satellite operation, independently of it is orbit and mission. Therefore, in Brazil, this is an entirely new project;
- The physical architecture of the MMP allows a separate development of the platform and the payload of the satellite, enabling that both modules can be developed, built and tested in separate, before integration and final tests. This is a completely new approach for INPE;
- There are employees at INPE directly involved in the construction, integration and test of the MMP propulsive subsystem, that are able to provide all required data to build the simulation models.

A simplified architecture (Fig. 2) shows the relation between propulsive subsystem and others. It can be seen that all subsystems must respond to the On Board Control System (OBCS) that is responsible for processing commands and sending information in signal form for all satellite. The tank is connected to the thrusters through tubing and control valves.

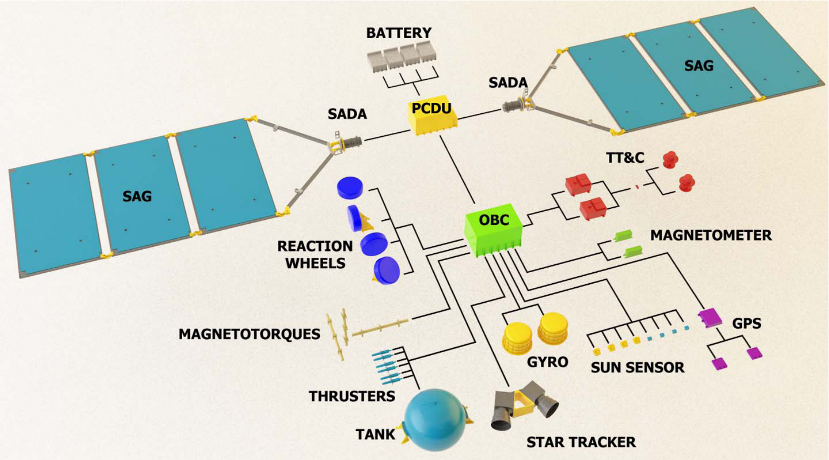

**Figure 2: Functional architecture of the MMP. Source: ETE/INPE.**

Although the propulsive subsystem has great importance, the reaction wheels are the fine actuators in the MMP. But they saturate after turning a certain number of times, being unable to correct moment after that. Consequently, there is the need to use different actuators in order to keep the satellite attitude. That is the purpose of the chemical propulsion subsystem.

Besides its importance in attitude correction, the propulsive subsystem of the MMP can be used to correct satellite orbit. This is done using all thrusters that accelerate the satellite, increasing it is tangential speed[1]. As consequence, the altitude is increased. Therefore, the propulsive system have two functions: attitude correction (as substitute for the reaction wheels) and orbit correction (a unique function).

### 3.1 MMP propulsive subsystem main components

MMP propulsive subsystem is composed of components and tubing. Those can receive energy form the electrical system (valves operation), while the entire system responds to the commands given by the AOCS. Table 1 lists all components and respective masses of the propulsion subsystem.

Those components form the propulsive subsystem, with tubing and components surrounding the tank (Fig. 2).

**Table 1:List of components of the MMP and their weights, without thrusters. Source: ETE/INPE (2011).**

| COMPONENTS (NUMBER / LENGHT) | MASS (kg) |
|---|---|
| Flow Control Valves - FCV (4) | 1.336 |
| Tank (1) | 6.000 |
| Latching Valves - LV (2) | 0.800 |
| Pressure Transducer (1) | 0.227 |
| Filter (1) | 0.150 |
| Service Valves - SV (2) | 0.079 (N2H4) + 0.070 (N2) |
| Tubing (1.500 mm) | 0.475 |
| Subsystem Total | 8.837 |

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[1] According to gravitation theory, that theorized the relation between gravitational forces and the kinematics of objects subjected to gravitation field, tangential speed is directly related to the satellite altitude.

Each component is briefly described below.

### 3.1.1 Thrusters

The MMP thrusters are built by the Brazilian company Fibraforte, and can deliver a maximum thrust of 5 N with maximum operating pressure. They are divided in two main parts: (1) the FCV, that dictates the flow of Hydrazine; and (2) the engine, composed of catalytic chamber, where the Hydrazine decomposes into Ammonia, Nitrogen and Hydrogen, and the nozzle, that accelerates the flow in order to provide thrust.

### 3.1.2 Tank

As said, the tank is placed in the center of the MMP subsystem. It is filled in Earth with Hydrazine (fuel) by a tubulation and with Nitrogen (pressurant gas) by a separate connection, up to 22 bar.

### 3.1.3 Latching valves

These are valves that control the propellant flow through the system. They make the connection between the pressured Hydrazine in the tank and all thrusters valves. They are fed by the electric system, with a range of 21-36 V, and consume 10 W each.

### 3.1.4 Pressure transducer

Enables the measure of system pressure. The power consumption is 0,9 W.

### 3.1.5 Filter

It is placed after the exit channel of propellant. It is function is to filter the passing fluid, avoiding the passage of solid particles that may affect thruster performance.

### 3.1.6 Service valve

They are two, one for each element (Hydrazine and Nitrogen). They allow propellant and pressurant gas passing to fill the tank while in Earth.

### 3.1.7 Tubing

They connect all components. Basically makes the connection between the tank and the thrusters.

With the complete description of each component, it is possible to present a mathematical model.

## 4 Mathematical model

A monopropellant Hydrazine subsystem has a reasonable complexity. It demands a simulation model to know its behaviour, but equally it needs theoretical formulation because the informational model, built using Block Diagrams, uses equations.

The main equations used are related to thrust. This force is directly related to the inlet pressure in a linear relation (1). The gas exhaust velocity is also related to the inlet pressure and two coefficients (2).

$$F = k_1 \cdot p_i + k_2 \tag{1}$$

$$c = k_3 \cdot p_i^{k_4} \tag{2}$$

Due to difficulties in getting information related to the constants, the alternative was to calculate those coefficients based on available information. These data were the expected thrust and flow rate for three inlet pressures. With force and flow rate it is possible to obtain three exhaust speeds using a simplified version for thrust equation (3)[2].

$$F = \dot{m} \cdot c \tag{3}$$

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[2] It is clear that Equation 3 is a simplified version of the general thrust equation, that considers relative velocity between vehicle and gas ejected, besides the pressure difference.

Other important equations are based on: physics gas theory (4); fluid mechanics, with mass balance (5), Reynolds number (6) and friction factor for laminar flow (7), and pressure difference (8).

$$p_t^{\ j} = \frac{V_{N_2}^{\ 0} \cdot p_{MEOP} \cdot \rho_p}{\rho_p \cdot (V_t - V_p^{\ 0}) + m_p} \tag{4}$$

$$\dot{m} = \rho_p \cdot A_x \cdot v_p \tag{5}$$

$$\mathrm{Re} = \frac{\rho_p \cdot v_p \cdot \phi}{\mu_p} \tag{6}$$

$$f = {}^{64}\!/_{\mathrm{Re}} \tag{7}$$

$$p_i = p_t - \Delta p \tag{8}$$

Equation 4 establishes the relation between the tank pressure in function of propellant properties and tank volume. Equation 5 relates propellant flow properties with mass flow of exhaustion gases[3]. Reynolds number is important to calculate the friction factor (7) that allows the calculation of the pressure drop in the tubing (8). This last equation makes a direct connection between tank pressure and inlet pressure that is directly related to thrust, the main variable of analysis of this work.

Equations 1 to 8 serve as base to build the signal flow model in Simulink. The energy flow model, in other hand, is based on the physical architecture provided by employees involved in MMP project.

## 5 Simulation models

Simulation models are important to represent the behaviour of complex systems that cannot be solved analytically. They can be built using several kinds of notations such as energy flow, block diagrams, flowcharts, among others.

This work has as main goal establish an comparison between two forms of simulation models (signal flow and energy flow) of the same space subsystem based on their outputs and data obtained from subsystem test.

### 5.1 AMESim model

The model built in AMESim is based on subsystem architecture (Fig. 3), and uses components of four domains (thermal, hydraulic, pneumatic and signal) to represent the components, tubing, propellant and gases, besides the commands given by the control system to the valves.

At the moment the energy flow model is in elaboration phase. This is the most critical part of M&S study due to the importance of having a high fidelity model. Therefore, model build is a critical part in any project of complex systems. Any modeling error, such as wrong representation of component or physical phenomena can put in risk simulation, verification and validation phases.

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[3] The first analysis considers permanent flow. Consequently, the Hydrazine flow can be considered the same as the Hydrogen, Ammonia and Nitrogen being expelled in form of gas.

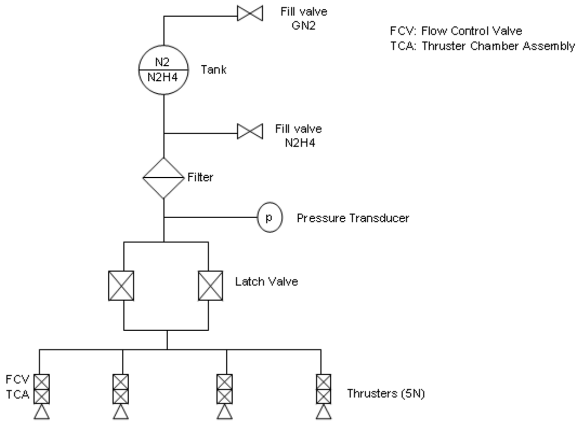

Figure 3: MMP propulsive subsystem diagram.

An initial AMESim model of the propulsive subsystem can be seen in Figure 4.

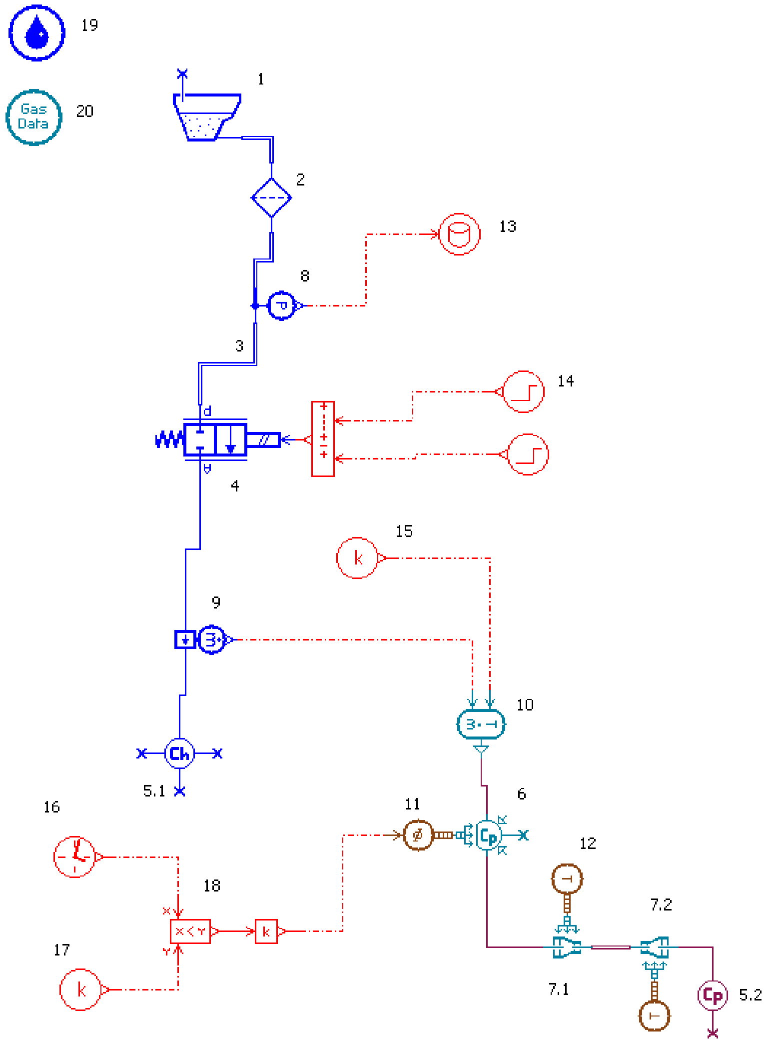

Figure 4: Simplified AMESim model of MMP Propulsive subsystem.

The hydraulic part of the model (blue) represents tank, tubing and components, with exception of the thrusters, witch are represented by light blue (thermal-pneumatic library). Signal flows controls (red) dictate the opening regime of FCV. Space environment was created with use of a chamber with very large volume and small pressure. The model of Figure 4 is still in study.

## 5.2 Simulink / MatLab model

The signal flow model is being developed. Equations 1 to 8 will serve as basis to Block Diagram construction. Due to its considerable size, the model will be divided into several submodels – each one representing physical phenomena (equation). In order to give an idea, Block Diagram of Equations 1, 2 and 3 is represented (Figure 5). This is one of the five basic propulsive subsystem submodels. The others will be built using Equations 4 to 8.

This phase will use code programming to support Simulink model, providing parameters and other logic relations to be used in the simulation model.

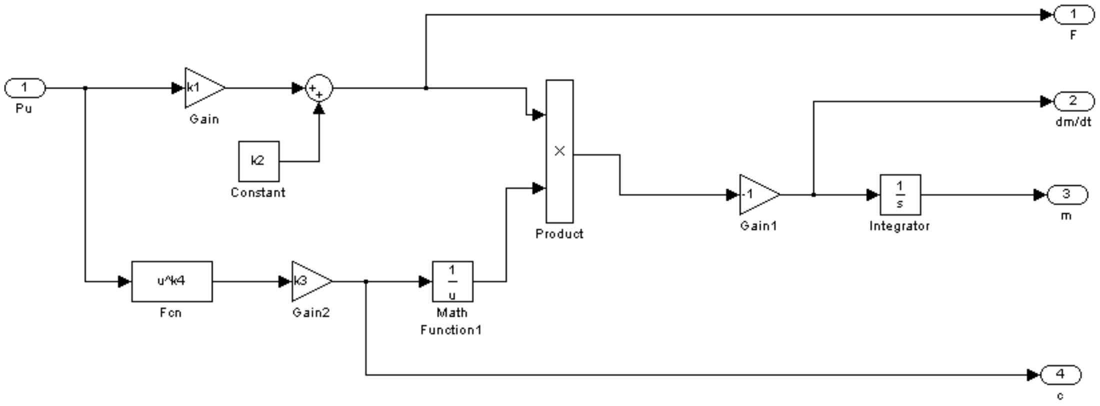

**Figure 5: Simulink model of thrust equation**

Figure 5 represents thrust equation subsystem. Inlet pressure is the only input. From this variable value, thrust force and exhaust speed are obtained, according to equations 1 and 2. Using (3) flow mass is obtained. This value is integrated in order to obtain mass. Therefore, from this set of equations 4 output variables are obtained.

## 6 Conclusions

After the two models are built, the simulation phase will take place. At first, several variables such as gas exhaust speed, thrust, tank pressure, propellant mass, among others, will be measured and compared with expected results (given by the company responsible by thruster development).

The final part of the study intends to list advantages and disvantages of M&S by signal and energy flows.

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