# A RECONFIGURABLE CONTROL ARCHITECTURE FOR THE NOMINAL MODE OF THE MULTIMISSION PLATFORM

**Jairo Cavalcanti Amaral**

**Marcelo Lopes de Oliveira e Souza**

National Institute for Space Research (INPE/DMC)
S J dos Campos – Brazil

***Abstract:*** *In this work, we executed the study of a reconfigurable control architecture for the MultiMission Platform (MMP). The problem chosen was implementing a control system which can deal with a loss of quality in the reaction wheels during the Nominal Mode (NOM). We used a mixed adaptive controller, based in Gain Scheduling and Model Following. The simulations were done with the SystemBuild tool of MatrixX. A brief introduction of the system will be presented.*

***Keywords:*** *MultiMission Platform, reconfigurable control, adaptive control, satellite attitude control, reaction wheel.*

## 1 Introduction

The capacity of detecting a fault and reconfiguring to accomodate it without the necessity of human help allows robustness to the satellite, and can be an a more economical alternative than adding redundances. A difficulty associated with this is guaranteeing the stability of the transition between the different modes of control. This is already used in many technologies, and had succes includingly in space engineering. We choose the PMM as a base for this study because it is a service module in development in INPE. Except for the control system, the modeling of the PMM and environment used here already exist, and came from the work o Amaral (2008), which is na extension of the works of Moreira (2006) and Prudêncio (1997).

## 2 What is the PMM

The MultiMission Platform, object of this work, is a modern concept in satellite architecture, and consists in reuniting in a single, versatile platform the equipments essential to a satellite's opperation, independent of its orbit or mission. In this architecture, there is a physical separation between the platform and the payload module, allowing both to be developed, constructed and tested sepparately, before the integration and final testing of the satellite.

Due to the diversity of conditions that a satellite will face during its entire life, there is a separation in many Operational Modes, where each mode is defined by the environment and conditions in which the satellite will be. Those modes are divided in two major groups, defined by the environment where the satellite is:

Ground Modes:

- Off Mode (OFM). In this mode, all the equipments are shut off (with disconnected batteries). This mode is to storage and transport.

•Integration and Test Mode (ITM). This mode is used during the assembly and integration tests, or in the launch platform. During the assembly and integration, all the tests are done, while at the launch platform, only the tests of functional verification will be done.

Flight Modes:

•Start Mode (STM). This mode can be used on the ground, during the flight phase, and at any time during the useful life of the satellite.
•Contingency Mode (COM). The objective of this mode is to automatically take the satellite and its payload from STM to a safe mode after the launcher separation, or in case of an anomaly.
•Fine Navigation Mode (FNM). This mode is used to acquisition of attitude, position and time in a precise way to allow the transition from the COM to the nominal mode.
•Nominal Mode (NOM). This is the operational mode of the satellite, where the payload can perform its objectives. In this mode the wheel desaturation with magnetic actuators also happens.
•Wheel Desaturation Mode with Thrusters (WDM). In this mode the reaction wheel desaturation is done by the action of thrusters. This proceeding aims to reduce the angular speed of the wheels back to nominal levels of operation.
•Orbit Correction Mode (COM). It is used to execute orbital maneuvers on the orbital plane, or from it.
•Orbit Correction Mode Backup (OCMB). If one of the thrusters fails, the orbital maneuvers will be executed with only two of the symmetric thrusters, to minimize the disturbing torques.

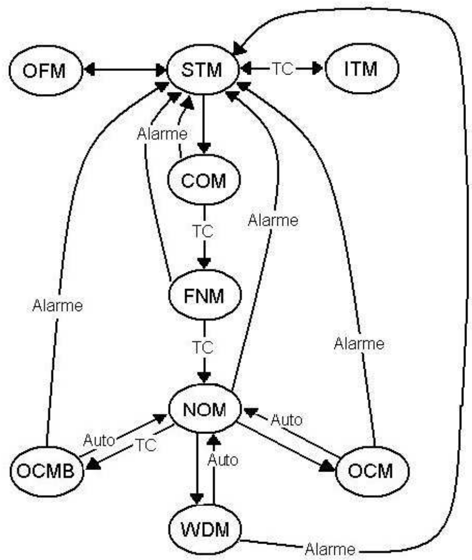



**Figure 1. Transition logic of the operation modes of the PMM. INPE (2001)**

For the chosen type of mission in this work, the Nominal Mode is encharged to mantain the axis of the PMM alighned with the axis of the referential Local Vertical Local Horizont (VLHL). This is a referencial turning in the orbital plane of the satellite, whose coordinate system has its origin in the satellite's center of mass. The z-axis points towards the Earth's center, the y-axis points towards the direction normal to the orbital plane, and the x-axis is obtained by the right-hand rule, and coincides with the direction of the velocity vector, for a circular orbit.

The satellite attitude and its variation rate must be controled in the three axis to accomplish the following requisites:

•Pointing precision: $< 0.05°$ ($3\sigma$);
•Drift: $< 0.001°/s$ ($3\sigma$);
•Attitude determination: $\leq 0.005°$ ($3\sigma$);

•Off-pointing of at most 30º in 180 s.

## 3 Implementation

The implementation of the PMM used as base of this work was made by Amaral (2008), using the tool SystemBuild from MATRIXx.

The mathematical modeling considers the PMM as a body without flextion, nule internal torques, nule wheel atrite and nule inicial moment. It propagates the attitude and the orbit, and includes models for the gravitational gradient, atmospheric drag, eclipses, massa variation due to propelent expenditure, and variation of intertia moments due to the solar pannel extension. Besides, it includes fixed perturbatory torques of 0.00015 $Nm^2$ in all three axis.

### 3.1 Attitude Control System

We decided to adopt an attitude control system based in the linear quadratic regulator, but able to detect a deterioration of functioning of one of the reaction wheels, and to adapt accordingly. Due to the size of this work, the monitoring and adaptation were designed only for the wheel of x-axis.

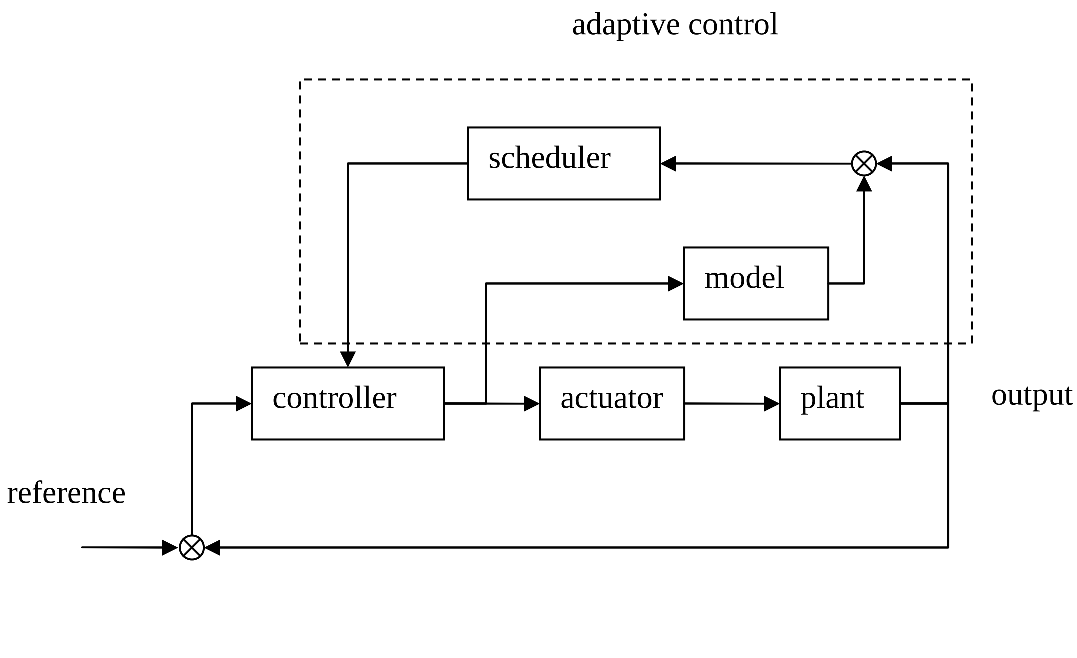



**Figure 2. Block diagram of the attitude control system.**

### 3.2 Actuators

The actuators used in Nominal Mode are three reaction wheels, aligned with the PMM's axis. They are already implemented from previous works. The model of the reaction wheel is similar to the one suggested by Souza (1980). It is based in a linear approximation of the characteristic curve of a DC servomotor.

The calculation of the wheel's parameters can be done according with Souza (1980), in the following way:

$$T_W = \frac{I_R \cdot \omega_{R\max}}{M_{R\max}} \tag{1}$$

$$K_W = \frac{M_{R\max}}{V_{R\max}} \tag{2}$$

where $T_W$ is the time constant, $K_W$ is the gain.

For didatic purposes, we decided to adopt the values of a reaction wheel more strong and quick, also used in the works of Amaral (2008), Moreira (2006) and Gobato (1997). Using the simplifications suggested by Souza (1980), we have the following equation for the system:

$$\dot{\vec{H}}_S + \vec{\omega}_S \times [(\vec{I}_W + \vec{I}_S)\vec{\omega}_S + \vec{I}_W \vec{\omega}_{WS}] = \vec{M}_{Ext} + \dot{\vec{H}}_W \tag{3}$$

which can be further reduced to three independent equations for each axis.

## 4 Linear quadratic regulator

The implementation of the linear quadratic regulator is similar to the one which can be found in Gobato (2006). The state vector contains the angles, angular speeds and wheels' speeds of each axis, and will be defined as follows:

$$x(t) = \lfloor \phi \quad \dot{\phi} \quad \omega_{Rx} \quad \theta \quad \dot{\theta} \quad \omega_{Ry} \quad \psi \quad \dot{\psi} \quad \omega_{Rz} \rfloor \tag{4}$$

The control vector contains the control tensions of each reaction wheel, and will be

$$u(t) = \lfloor V_{Rx\_s} \quad V_{Ry\_s} \quad V_{Rz\_s} \rfloor \tag{5}$$

In each of the three rotation axis, the set angle, angular speed and reaction wheel's rotation speed is not completely controlable. However, this last one was included in the state vector so that the dynamic of the wheel be considered, and the output of the controler be tension $u(t) = -Kx(t)$ , instead of torque.

In the space state form, we have the following result:

$$
\begin{bmatrix} \dot{\phi} \\ \ddot{\phi} \\ \dot{\omega}_{Rx} \\ \dot{\theta} \\ \ddot{\theta} \\ \dot{\omega}_{Ry} \\ \dot{\psi} \\ \ddot{\psi} \\ \dot{\omega}_{Ry} \end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -\frac{I_R}{T_W I_{Sx}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -\frac{1}{T_W} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\frac{I_R}{T_W I_{Sy}} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\frac{1}{T_W} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{I_R}{T_W I_{Sz}} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_W}
\end{bmatrix} \cdot
\begin{bmatrix} \phi \\ \dot{\phi} \\ \omega_{Rx} \\ \theta \\ \dot{\theta} \\ \omega_{Ry} \\ \psi \\ \dot{\psi} \\ \omega_{Ry} \end{bmatrix} +
\begin{bmatrix}
0 & 0 & 0 \\
\frac{K_W}{I_{Sx}} & 0 & 0 \\
\frac{K_W}{I_R} & 0 & 0 \\
0 & 0 & 0 \\
0 & \frac{K_W}{I_{Sy}} & 0 \\
0 & \frac{K_W}{I_R} & 0 \\
0 & 0 & 0 \\
0 & 0 & \frac{K_W}{I_{Sz}} \\
0 & 0 & \frac{K_W}{I_R}
\end{bmatrix} \cdot
\begin{bmatrix} V_{Rx\_S} \\ V_{Ry\_S} \\ V_{Rz\_S} \end{bmatrix} \qquad (6)
$$

The matrix K is calculated by the function LQR of MatLab, but an algorithm for its solution can be found in Kwakernaak (1972). The values of the adjust matrices will be chosen empirically. As suggested by Arantes (2005), a first choice for the parameters Q and R can be made as

$$
q_i = \frac{1}{(\Delta x_i^{\,2})} \qquad (7) \qquad\qquad r_i = \frac{1}{(\Delta u_i^{\,2})} \qquad (8)
$$

The values of $\Delta u_i$ are based in the maximum signal of the actuators, and the values of $\Delta x_i$ are based in the state's operation of interval.

**5 Gain Scheduling**

The gain scheduler is one of the simplest methods of adaptive control, and is used since the first uses of adaptive control in high altitude airplanes during the 60s (Aström 2006). It consists in obtain informations from the plant, and switch to the most adequate control parameters, from a conjunt of pre-established parameters.

More sophisticated methos of adaptive control, as pole alocation, dependes on the solution of polinomial diophantine equations, and the estimators associated to this dependes on inversion of big matrices during the work of the system (Aström 2006), demanding a great computational load, uncommon for the attitude control of a satellite.

According to the implementation of this work, it starts using a matrix K, calculatad for three reaction wheels with nominal parameters. This matrix K was the same of Gobato (2006), which was already done for a nominal case:

$$
K = \begin{bmatrix}
5.2087e{+}001 & 8.0875e{+}002 & -1.2500e{-}002 & -8.2276e{-}012 & -2.5735e{-}006 & 7.6988e{-}011 & -1.7673e{-}010 & 9.3877e{-}005 & -3.8426e{-}009 \\
-1.9573e{-}011 & -2.3215e{-}003 & 1.1776e{-}007 & 5.2087e{+}001 & 1.1264e{+}003 & -1.2500e{-}002 & 1.0793e{-}007 & -1.4259e{+}000 & 5.8629e{-}005 \\
-4.1344e{-}010 & -2.6859e{-}003 & 1.3627e{-}007 & 1.2451e{-}007 & 1.0589e{+}000 & -3.1681e{-}005 & 5.2087e{+}001 & 9.2140e{+}002 & -1.2571e{-}002
\end{bmatrix}
$$

obtained with the following matrices Q and R:

$$
Q = diag\left( \frac{1}{(11^o)^2} \quad \frac{1}{(10^o/s)^2} \quad \frac{1}{(6800r.p.m)^2} \quad \frac{1}{(11^o)^2} \quad \frac{1}{(10^o/s)^2} \quad \frac{1}{(6800r.p.m)^2} \quad \frac{1}{(11^o)^2} \quad \frac{1}{(10^o/s)^2} \quad \frac{1}{(6800r.p.m)^2} \right)
$$

$$
R = diag\left( \frac{1}{(10V)^2} \quad \frac{1}{(10V)^2} \quad \frac{1}{(10V)^2} \right)
$$

If an error signal surpasses a pre-determined value, it will switch to a K matrix calculated for nominal wheels for y- and z-axis, and a whell in x-axis with inferior time constants and gain ($K_w$ = 0,2 $Nm^2/V$ and $T_w$ = 100 s).

The disposition of the values of the matrix K for the fail case is showed here:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 9.5492e+001 | 3.8293e+003 | -7.5000e-003 | -3.0193e-015 | -3.3527e-006 | 1.0231e-010 | 1.8777e-014 | 5.5879e-007 | -2.2737e-011 |
| 2.8589e-015 | -1.1920e-005 | 6.0254e-010 | 9.5492e+001 | 3.6862e+003 | -1.2499e-002 | 3.9335e-015 | 1.5832e-006 | -7.3896e-011 |
| 1.4866e-014 | -1.4901e-006 | 6.8212e-011 | 1.6317e-013 | -3.7252e-007 | 2.8421e-012 | 9.5492e+001 | 3.6154e+003 | -1.2499e-002 |

and it was obtained using the following matrices Q and R:

$$Q = diag\left( \frac{1}{(6^o)^2} \quad \frac{1}{(30^o/180s)^2} \quad \frac{1}{(7500r.p.m)^2} \quad \frac{1}{(6^o)^2} \quad \frac{1}{(30^o/180s)^2} \quad \frac{1}{(7500r.p.m)^2} \quad \frac{1}{(6^o)^2} \quad \frac{1}{(30^o/180s)^2} \quad \frac{1}{(7500r.p.m)^2} \right)$$

$$R = diag\left( \frac{1}{(10V)^2} \quad \frac{1}{(10V)^2} \quad \frac{1}{(10V)^2} \right)$$

This represents a response of the control system when the wheel suffers from detteriorarion with time and use.

**6 Fault Detector**

Alterations in the reaction wheel of the x-axis are detected by the comparation with a model, which receives the same control signal. The specification of the PMM says that the angular speed of the reaction wheels are monitores. Therefore, we consider this value as available in the simulation.

The difference between the angular speed of the wheel and the model provides se error signal observed by the scheduler.

As the error takes some time to increase, this means that the switching is not immediate. However, as there is a limit of 10 Volts in the module of the control signal, and such big initial errors reach this threshold in the first moments, any of the possible matrices would resul in +10 or -10 in the begining. Therefore, this problem is minimized.

**7 Considerations about Stability**

Usually it is difficult to warrant analitically the stability of a non linear model. The system in question is linearized, but the parameter’s variation of the adaptive bloc can introduce instabilities. The analysis by phase (Poincaré 1967) plane permits determining the behavior of dynamic systems without the necesity of solving analytic equations, and authors like Popov developed analytical methods for non linear cases. But a simple way to warrant the stability or performance is to inspec the behavior of the system for the worst cases which can be found in nominal working. According to the specifications of the PMM, this worst case is when all the attitude angles are 30 degrees from the origin in the system LVLH. Thus, this will be the initial condition for the tests.

## 8 Test Cases and Results

The following six cases were done considering a circular orbit with a radius of 7000 km, and the inicial attitude was 30 degrees in all three axis, in relation to the referencial LVLH.

### Case 1

The linear quadratic regulator is projected for the nominal values of each reaction wheel (K = 0.06 $Nm^2/V$ e T = 20 s). There are no simulated failures.

### Case 2

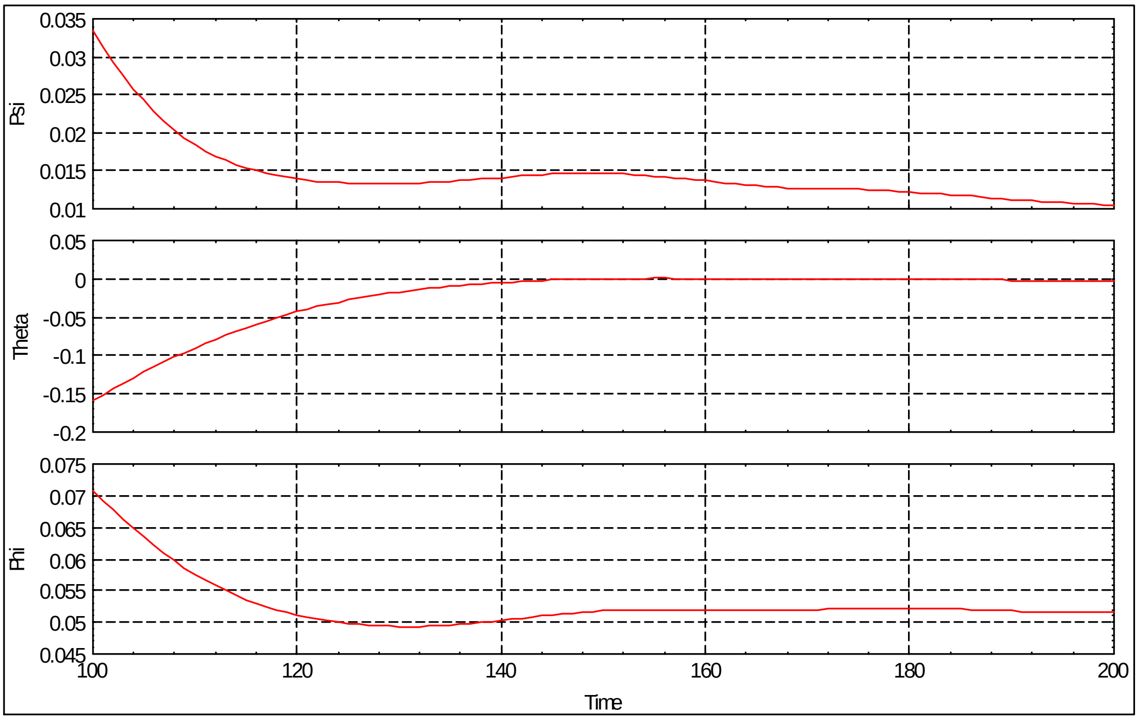
Linear quadrátic regulator designed for nominal wheels in y and z-axis, and a deteriorated wheel in x-axis (K = 0,2 $Nm^2/V$ e T = 100 s). The wheels used in the simulation are nominal. Tere is no adaptive control.

### Case 3

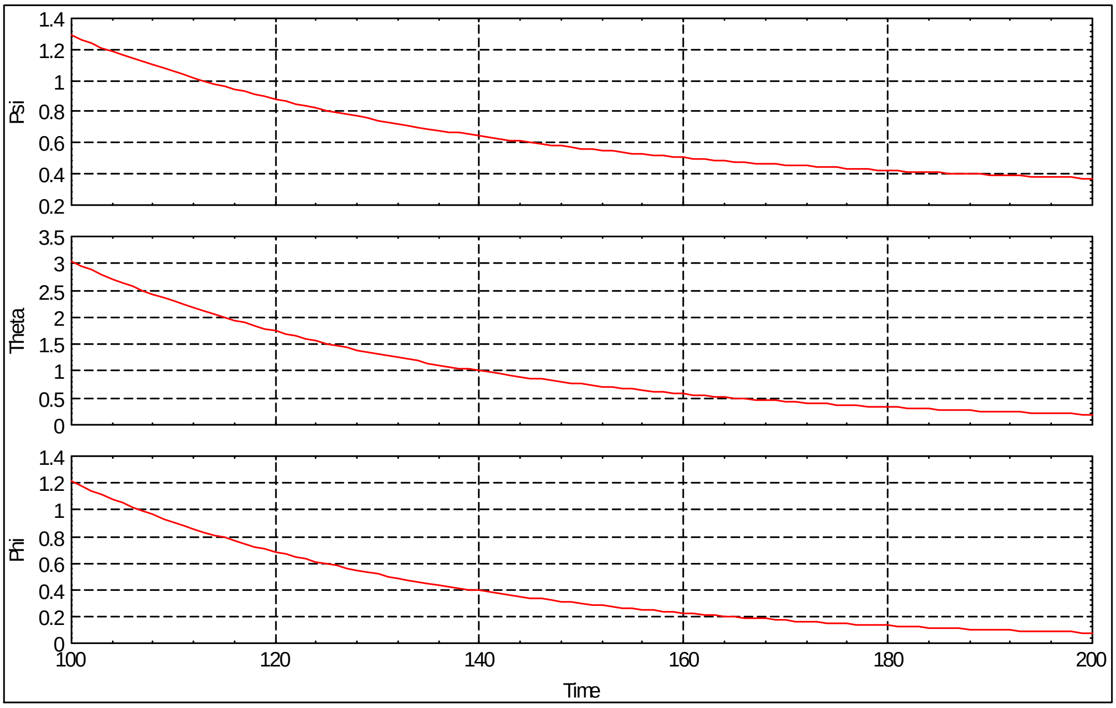
Linear quadratic regulator designed for nominal wheels in y- and z-axis, and for a wheel arbitrarily deteriorated in the x-axis (K = 0,2 $Nm^2/V$ e T = 100 s). There is no adaptive control.

### Case 4

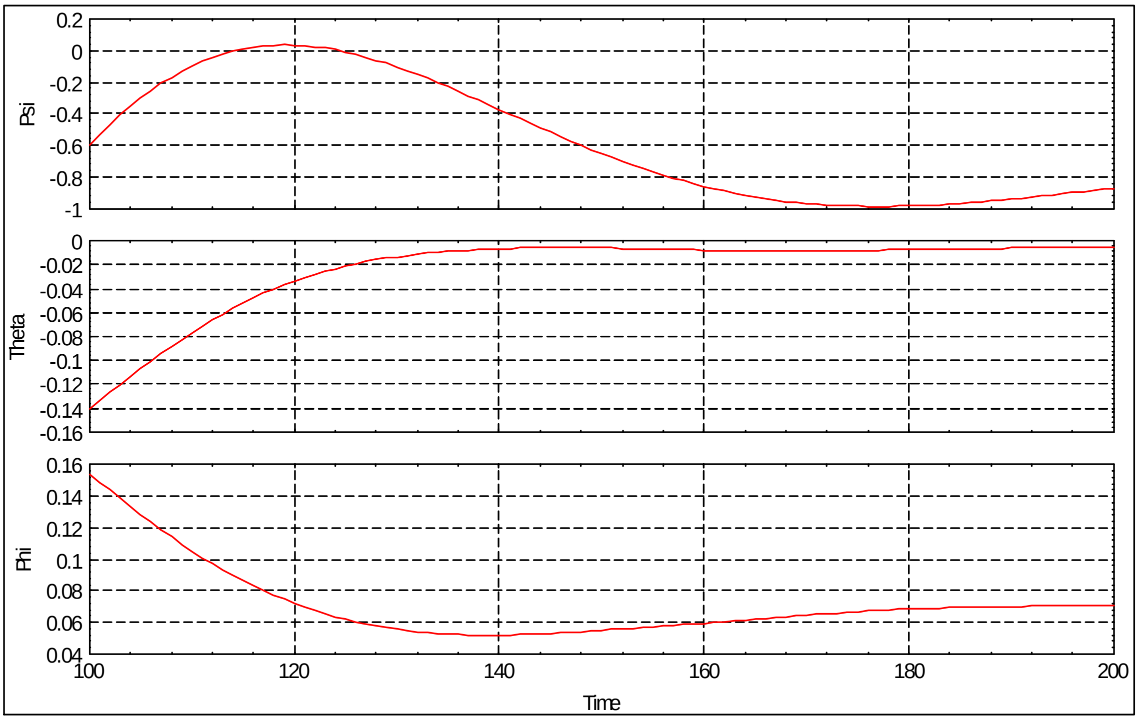
Complete control system, with wheel in x-axis with Kw = 0,2 $Nm^2/V$ e Tw = 100 s. The criteria for determining the switch of gain is when the module of the error signal between the angular speed of the reaction wheel and the model surpasses 100 rad/s.



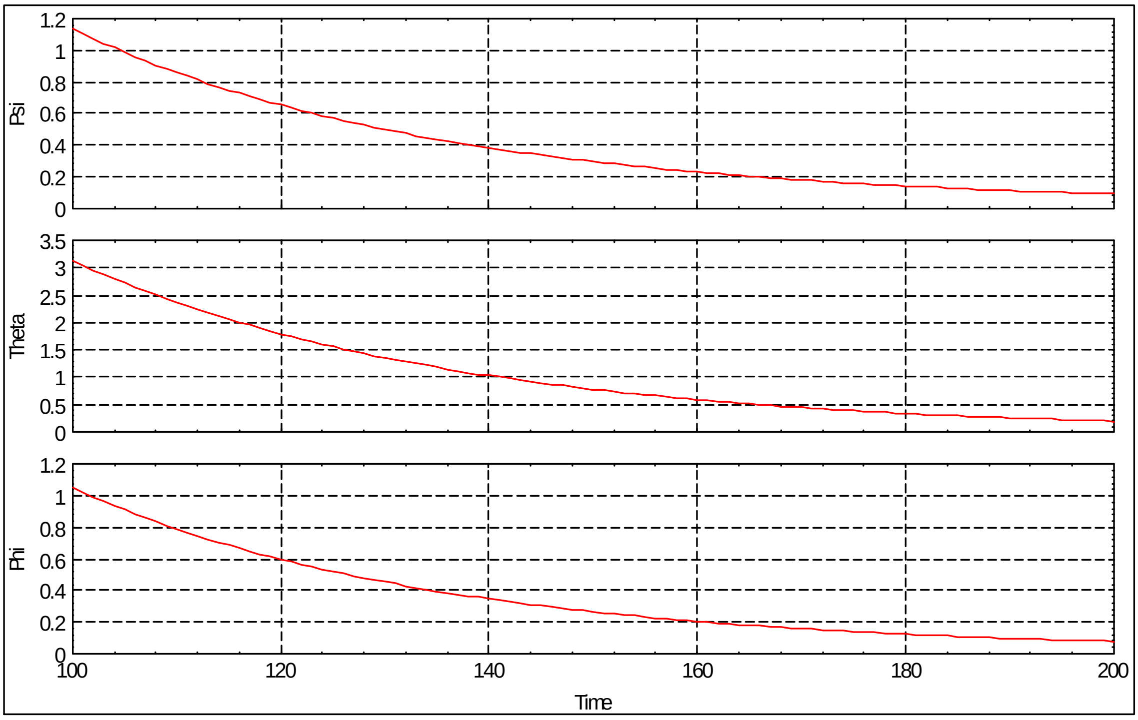

**Plot 1: Attitude in degrees in all axes in referential LVLH, as a function of time in Case 1**



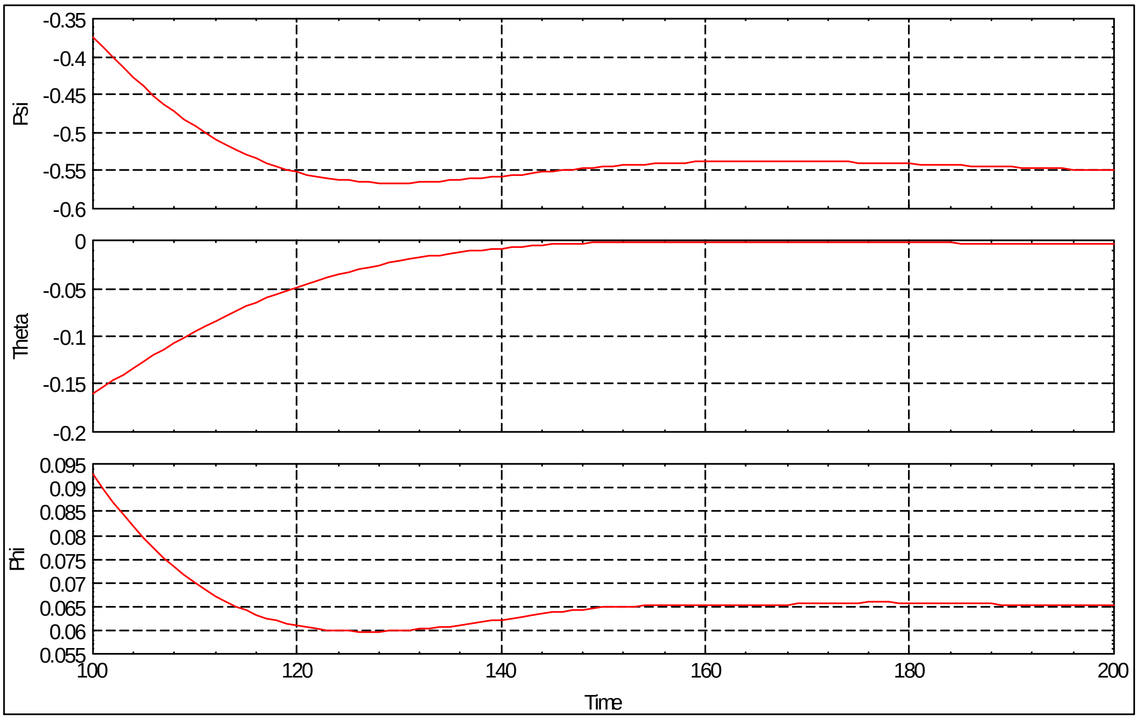

**Plot 2: Attitude in degrees in all axes in referential LVLH, as a function of time in Case 2**




**Plot 3: Attitude in degrees in all axes in referential LVLH, as a function of time in Case 3**




**Plot 4: Attitude in degrees in all axes in referential LVLH, as a function of time in Case 4**



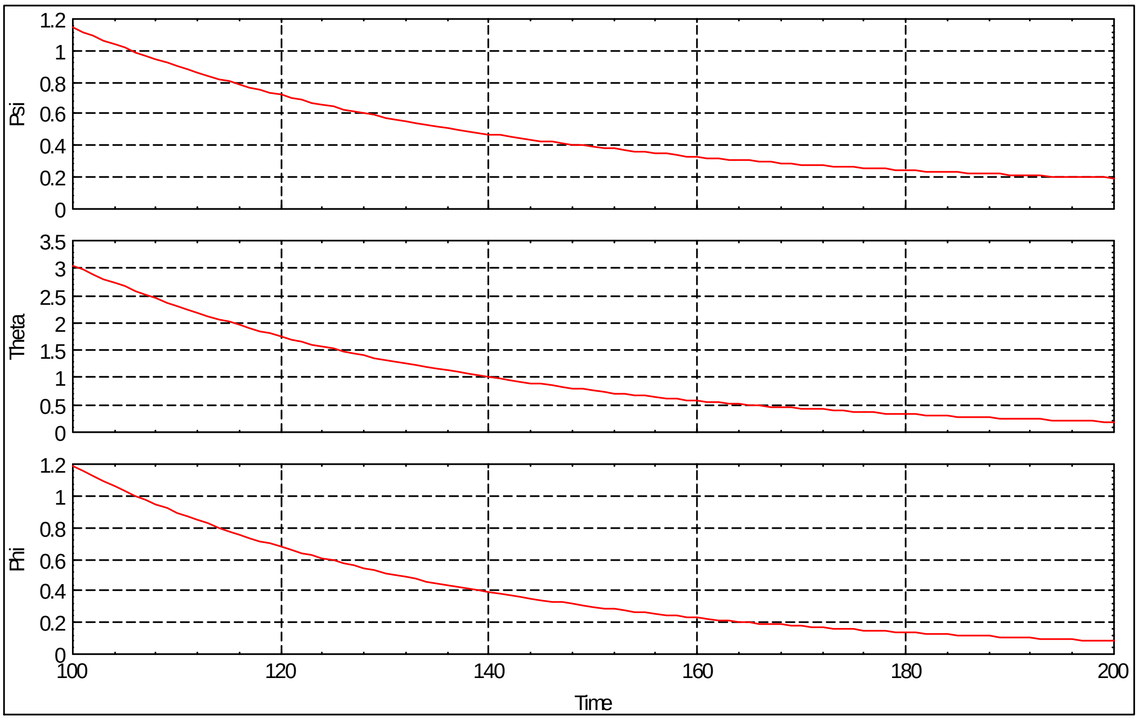

**Plot 5: Attitude in degrees in all axes in referential LVLH, as a function of time in Case 5**

**Case 5**

Similar to the fourth case, but with a reaction wheel of Kw = 0,4 $Nm^2/V$ e Tw = 40 s. The switch criterium is when the error modul surpasses 100 rad/s. Such a wheel is on the threshold of triggering the switching for a new K matrix, considering the worst case of an initial error of 30 degrees in every axis.

**Case 6**

Using the complete control system, with a reaction wheel with = 0,4 Nm2/V e Tw = 40s. The switch criterium is when the error module surpasses 50 rad/s.




**Plot 6: Attitude in degrees in all axes in referential LVLH, as a function of time in Case 6**

**Conclusions**

The plot of Case 1 show that the nominal behavior of the attitude control system does not satisfies the specified requisites, as after 180 s the atitude of the z-axis was still slightly over 0.05 degrees.

The plot in Case 2 show that the unecessary use of the fault mode results in a pointing worse than the nominal case. In 180 seconds, all the axis had errors between 0.2 and 0.5 degrees.

The plot of Case 3 show that the use of the nominal mode with a degraded wheel (Kw 0,2 $Nm^2/V$ Tw = 100s) results in a pointing worse than the nominal case.

The plot of Case 4 show that the appropriate use of the fault mode resulted in errors under 0.5 degrees after 180 seconds. It is not superior than the nominal functioning, but is still better than the nominal control during a fault.

The plot of Case 5 show that a wheel with (Kw 0,4 $Nm^2/V$ e Tw = 40s) does not trigger the switching, and the result is na error of 0,5 degrees after 180 seconds. Considering the error module of the three axis, it is an error bigger than the one obtained in Case 4. This indicates that the criterium of 100 radians per second is too tolerant.

The plot of Case 6 show that using a criterium of 50 rad/s produce better results in the control system. The error module in the three axis is similar to the one obtained in Case 4. This indicates that this criterium is better, because the threshold of triggering to the error mode should coincide with the threshold where its use is better than the nominal mode.

Although the control system does not satisfies the pointing requirements, the inclusion of an adaptive control enhances the performance, compared to fixed gains.

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