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Bump Reduction for the Reconfigurable Control Architecture of the MultiMission Platform

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ABSTRACT

Many control systems switch between control modes according to necessity. That is often simpler than designing a full control to all situations. However, this creates new problems, as determining the composed system stability and the transient during switching. The latter, while temporary, may introduce overshooting that degrade performance and damage the plant. This is particularly true for the MultiMission Platform (MMP), a generic service module currently under design at INPE. Its control system can be switched among nine main Modes of Operation and other submodes, according to ground command or information coming from the control system, mainly alarms. It can acquire one and three axis stabilization in generic attitudes, with actuators including magnetotorquers, thrusters and reaction wheels. In this work, we will begin to analyze, design and simulate a reconfigurable control architecture with focus on reducing the bump on the switching between at least two modes of the MultiMission Platform, as part of a larger work in progress. It will be done by creating a virtual plant for the unused controls, which will keep their outputs close to the actual control, minimizing differences at the switching times. The tests are planned to be based in simulations with the MatrixX/SystemBuild software, from National Instruments, which support developers with tools to model, analyze and test a control system. They focused mainly on the worst cases that the satellite is supposed to endure in its mission, be it during modes or transitions between modes and submodes. Being able to withstand them, the control system is considered apt to other simpler situations.

INTRODUCTION

Many control systems switch between control modes according to necessity. That is often simpler than designing a full control to all situations. This is the case of hybrid control systems. Figure 1 shows an example of such a control system, where a discrete switching signal σ selects which control block C will be used for the plant P.

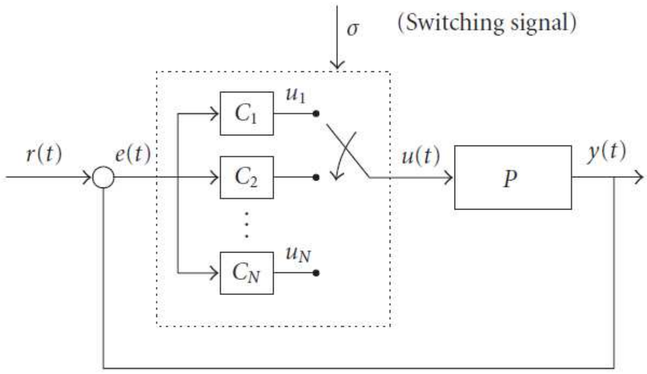

Figure 1 (Source: Yamé and Kinnaert, 2007).

Besides its obvious advantages, this also creates new problems, as determining the composed system stability (Liberzon and Morse, 1999) and the transient during switching (Graebe and Ahlén, 1996), (Yamé and Kinnaert 2007). The latter, while temporary, may degrade performance and damage the plant due to overshooting or discontinuities. It is often desirable to attenuate this, even at the expense of a slower transition.

In this paper, we will begin to analyze, design and simulate a reconfigurable control architecture with focus on reducing the bump on the switching between at least two modes of the MultiMission Platform, as part of a larger work in progress. While it is a relatively simple example, it is a real case, and we expect it to be a starting point for more complex works.

THE MMP

This work presents the beginning of the analysis, design and simulation of the reconfigurable control architecture of the MultiMission Platform (MMP). The MMP is a generic service module currently under design at INPE. Its embedded real time control system can be switched among nine main Modes of Operation and other submodes, according to ground command or information (mainly alarms) coming from the control system. The MMP can acquire one and three axes stabilization in generic attitudes, with actuators including magnetotorquers, thrusters and reaction wheels.

The implementation followed the specifications when they were found; otherwise, it was designed. The MMP enters in the Contingency Mode right after the launcher separation, or if there is an emergency, according to the following sequence: it stops any rotation using magnetotorquers; opens the solar panels, if it is not done yet; points them to the Sun using thrusters; and acquires gyroscopic rigidity using reaction wheels. If the stopping with magnetotorquers is not achieved in a predetermined time, the MMP will enter in a submode for trying to achieve it with thrusters. As there is thruster control for only two axes, it will also wait for the best moment to make a maneuver.

OPERATION MODES

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 for 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 dessaturation with magnetic actuators also happens.
- Wheel Dessaturation Mode with Thrusters (WDM). In this mode the reaction wheel dessaturation 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.

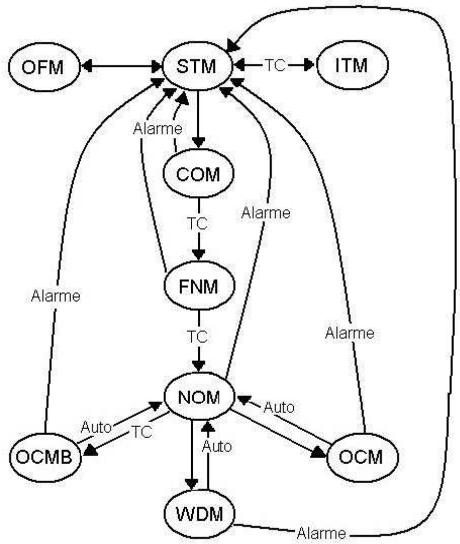

Figure 2. Transition logic of the operation modes of the MMP. INPE (2001)

THE BUMPLESS TRANSFER PROBLEM

The bump phenomenon is caused by a discontinuity of the plant input and its derivatives. The rapid variation may excite the derivative components of the plant transfer function, and cause overshootings at its output.

Also associated with that is the wind up phenomenon (Peng et al. 1998), which is happens when the control loop is opened, as during actuator saturation, and the integral component of a controller accumulates too much, causing an overshoot. While not a bump by itself, and it was for a long time the main problem relate to transitions, and will also be considered here.

The strategies to avoid the bump include input blending, output blending and controller initialization, while the strategies to avoid the wind up try to detect and compensate the integrator build up. Also, a proper bumpless transfer may eliminate the risk of wind up.

As we are dealing with a relatively simple system, we will attempt first to reduce the transient by treating the unused controller as a plant, and forcing it to approach the primary control output signal at the instant of the switching (Figure 3).

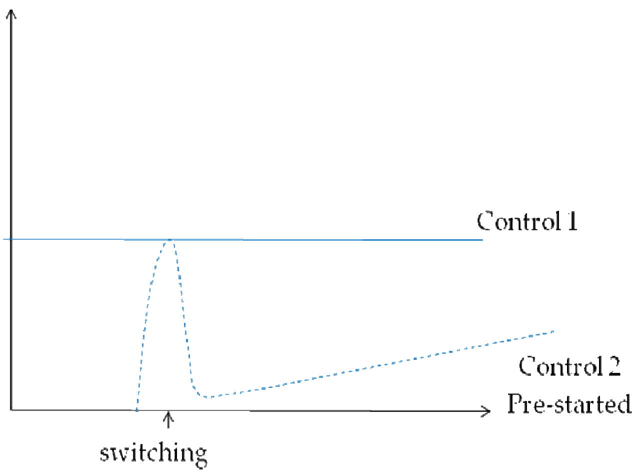

Figure 3.

Thus, both outputs will have not only close values, but also close derivatives at the switching time (Figure 4). If the primary control is not saturating the actuators by itself, the transition will not saturate them as well.

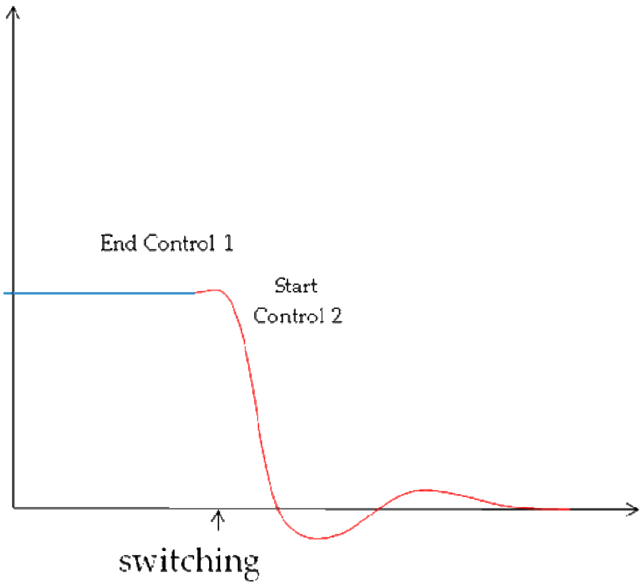

Figure 4.

There are different methods in the literature to treat this, according to the complexity and requirements: from nonlinear plants with bidirectional switching during transients (Graebe and Ahlén, 1996), to linear systems at steady states (Yamé and Kinnaert, 2007). In particular cases, the performance can be maintained with just an anti wind up design.

As an example of the bump problem, Figure 5 shows the module of the angular velocity during the Fine Navigation Mode of the MMP. Each peak is a rotation for a nominal attitude acquirement. The first two exhibit clear "bumps" (marked with blue arrows) during the switch from coarse to fine control.

Even if there is not an impact, the unnecessary oscillation of the module of the angular velocity means a slower acquirement. We will test different approaches to enhance the smoothness and even duration of the transition.

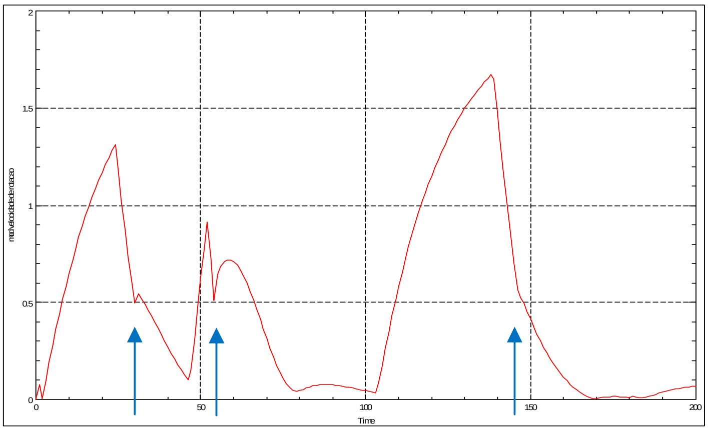

Figure 5. Module of the angular velocity during three consecutive rotations for nominal attitude acquirement during the Fine Navigation Mode.

TESTS

The tests are based in simulations with the MATRIXx/SystemBuild software, from National Instruments, which supports developers with tools to model, analyze and test a control system. They focused mainly on the worst cases that the satellite is supposed to endure in its mission, be it during modes or during transitions between modes and submodes. The plant includes simulators such as orbit propagation, air drag, and variations in inertia moment. They were taken from (Amaral 2008).

DINAMICS

A reference system A of the type VLHL represents the origin of the mass center of the satellite, and has unitary vectors (a_1, a_2, a_3), being: a_1 on the direction of the orbit, a_2 perpendicular to the orbit plane, and a_3 towards Earth. The angular speed of A related to the inertial referential is

$$\vec{w}^{A/N} = w_0 \vec{a}_2 \tag{1}$$

where w_0 is the orbital speed. The angular speed of the referential B fixed to the body, with base vectors (b_1, b_2, b_3) is given by

$$\vec{w}^{B/N} = w^{B/A} + w^{A/N} = w^{B/A} - w_0 \vec{a}_2 \tag{2}$$

where wb/a is the angular speed of B related to A.

The rotational equation of movement of a rigid body with angular moment H =Iw$^{B/N}$ is given by:

$$\left\{\frac{d\vec{H}}{dt}\right\}_B \equiv \left\{\frac{d\vec{H}}{dt}\right\}_N + \vec{w}^{B/N} \times \vec{H} = T_P \qquad (3)$$

where w$^{B/N}$ is the angular speed vector of the satellite (reference of the body B in relation to the inertial reference N), I is the inertia matrix of the satellite, and T_p is the torque due to the external perturbations

The model of the MultiMission Platform follows the movement equations of a rigid space vehicle (Wie 1998), considering the presence of the reaction wheel and its coulpling with the satellite (Wertz 1978). Therefore, the dynamic equation of the plant is

$$I\dot{\vec{w}} + \vec{w} \times (I\vec{w}) = \vec{w} \times h - \dot{h} + T_P \qquad (4)$$

Where I is the inertia matrix of the satellite, w is the angular speed vector of the satellite (reference of the body B related to the inercial reference N), h is the angular moment of the reaction wheels, $\dot{h}$ is the variation of the angular moment of the reaction wheels, which represents the controllable part of the equation (also called control torque), and T_P is the torque due to external perturbations.

FINE NAVIGATION MODE

The initial tests focus of the Fine Navigation Mode. The purpose of this mode is to bring the MMP to its nominal attitude and then switch to the Nominal Mode. In this simulation, the nominal attitude is towards the Earth. The MMP executes a maximum of three rotations. Each rotation (Figure 6) starts guided by a bang-bang coarse control block, which is reversed when the absolute error is under a predetermined value ε, and then is switchd to a PID fine control block when the absolute speed is under a predetermined value ξ.

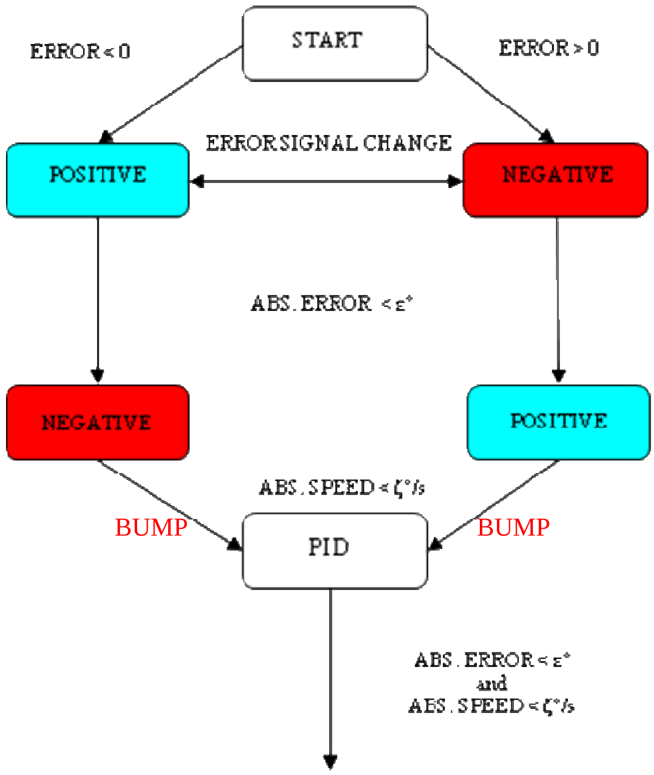

Figure 6: Block diagram of control submodes of a single rotation.

The switching usually causes a bump, and is a good opportunity to test anti-bump strategies. The cases here show the first rotation, around the z-axis, and each value is displayed in pairs with and without an anti-bump design. There is a switch between the primary to secondary controls near 30 seconds.

RESULTS

Figures 7 and 8 show the control signal as seen from the plant. Figure 8 shows the full difference between outputs reaching saturation at -10 V, likely to induce wind up problems. The anti-bump counterpart shows a much smoother transition, inside the +/-10 V range.

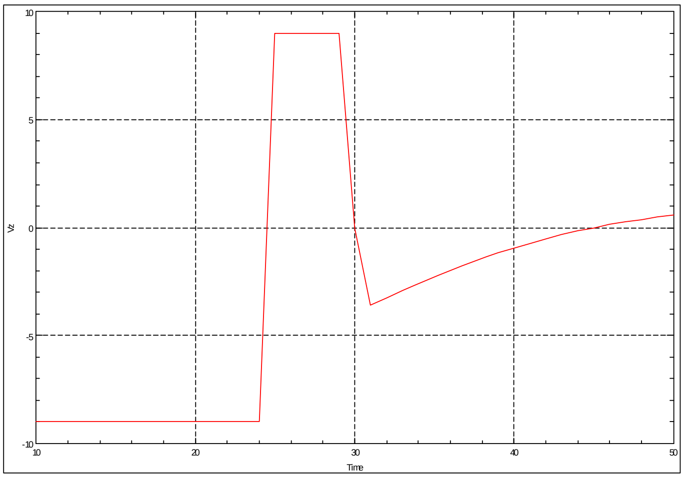

Figure 7: Control signal

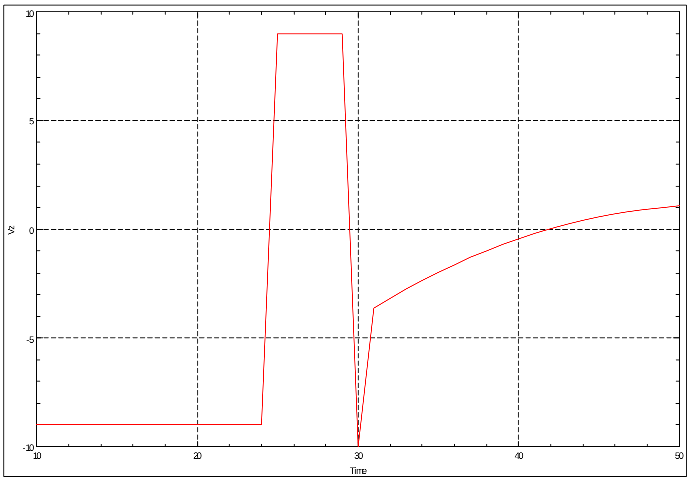

Figure 8: Control Signal

Figures 9 and 10 show the module of the angular velocity. The anti-bump implementation was able to eliminate the oscillation. The transition results only in a decrease in acceleration at 30 seconds.

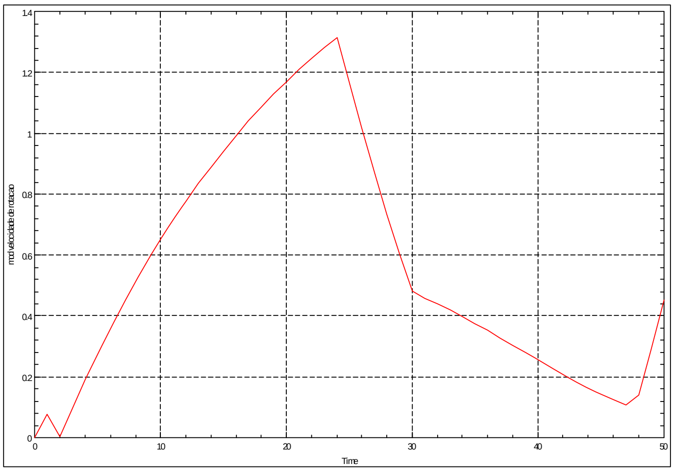

Figure 9: Angular speed

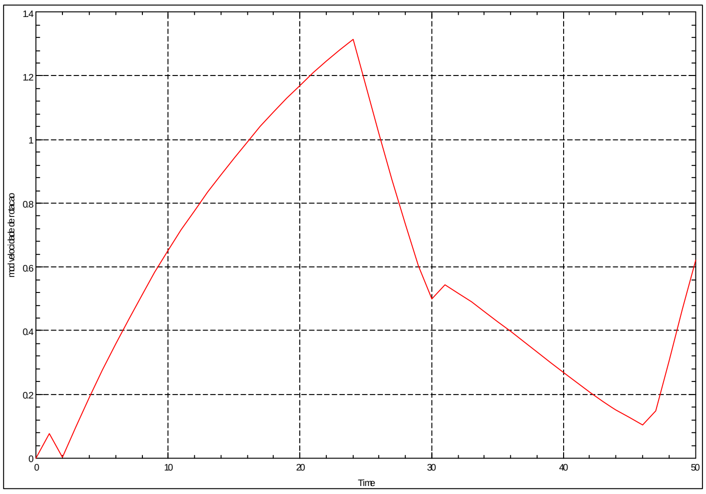

Figure 10: Angular speed

Figures 11 and 12 show the error of pointing. The bump is not readily visible, but causes a bigger overshoot. Using an anti-bump implementation acquires a quicker pointing.

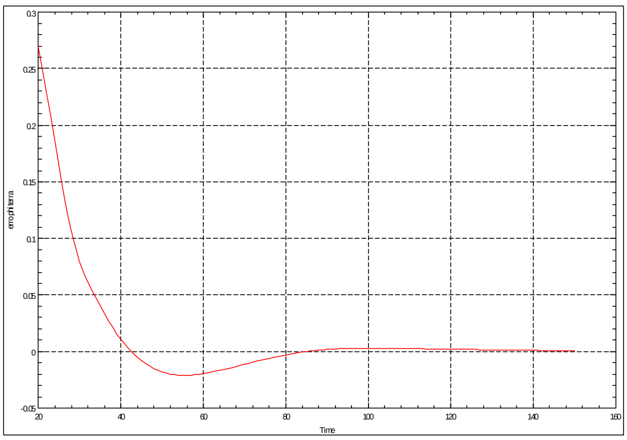

Figure 11: Error signal

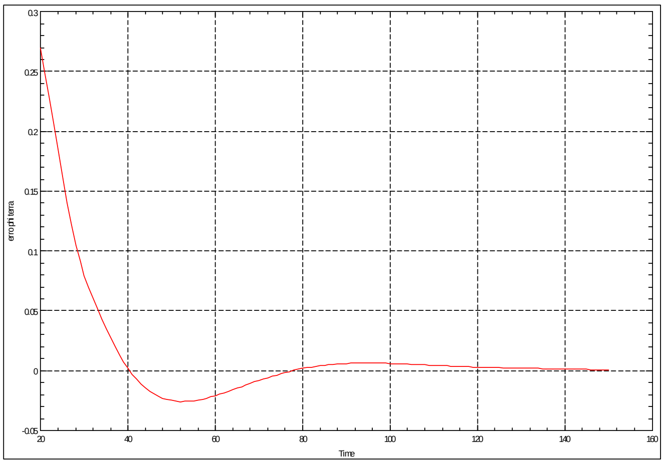

Figure 12: Error signal

SUMMARY/CONCLUSIONS

It was possible to force the control signal to come closer to the primary control signal, reducing the bum phenomenon at the switching. It was also possible to avoid the signal saturation of the secondary control, eliminating the risk of wind up phenomenon.

FUTURE OBJECTIVES

As there is a switch in the error signal as seen from the secondary control block, this is another situation where a discontinuity can be smoothed. Besides that, we intend to use other techniques, as anti-windup and mixing outputs; transfer between more complex control signals; study types of signal to preset the secondary control, and criteria for the switching time; and test about the observation of the control signal. Additionally, we intend to reduce the bump phenomenon also at the error signal on the secondary controller.

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