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Attitude Control of a Satellite by Using Digital Signal Processing

Adrielle C. Santana[1], Luiz S. Martins-Filho[1,*], Ricardo O. Duarte[2], Gilberto Arantes Jr.[3], Ivan S. Casella[1]

[1] Universidade Federal do ABC - Santo André/SP - Brazil

[2] Universidade Federal de Minas Gerais - Belo Horizonte/MG - Brazil

[3] Universität Bremen - Bremen - Germany

Abstract: *This article has discussed the development of a three-axis attitude digital controller for an artificial satellite using a digital signal processor. The main motivation of this study is the attitude control system of the satellite Multi-Mission Platform, developed by the Brazilian National Institute for Space Research for application in different sort of missions. The controller design was based on the theory of the Linear Quadratic Gaussian Regulator, synthesized from the linearized model of the motion of the satellite, i.e., the kinematics and dynamics of attitude. The attitude actuators considered in this study are pairs of cold gas jets powered by a pulse width/pulse frequency modulator. In the first stage of the project development, a system controller for continuous time was studied with the aim of testing the adequacy of the adopted control. The next steps had included an analysis of discretization techniques, the setting time of sampling rate, and the testing of the digital version of the Linear Quadratic Gaussian Regulator controller in the MATLAB/SIMULINK. To fulfill the study, the controller was implemented in a digital signal processor, specifically the Blackfin BF537 from Analog Devices, along with the pulse width/pulse frequency modulator. The validation tests used a scheme of co-simulation, where the model of the satellite was simulated in MATLAB/SIMULINK, while the controller and modulator were processed in the digital signal processor with a tool called Processor-In-the-Loop, which acted as a data communication link between both environments.function and required time to achieve a given mission accuracy are determined, and results are provided as illustration.*

Keywords: *Satellite Attitude Control, Linear Quadratic Gaussian Control, Digital Signal Processor, Pulse Width/ Pulse Frequency Modulation.*

INTRODUCTION

The development of satellites in Brazil has become, in the last decades, a subject of extreme importance. The economic relevance and strategic role for the nation are appealing. There are scientific and technological efforts from the government in order to stimulate the space research. There are also in research centers and in the private sector. Nowadays, many activities are associated with the achievements and technological breakthrough in space. The applicability of satellites can be found for a large number of purposes, e.g., terrestrial, maritime and aerial navigation by using GPS, communication, weather forecasting, etc.

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*author for correspondence: luiz.martins@ufabc.edu.br - Av. dos Estados, 5001- Bangú - Santo André/SP - Brazil

The frequent manifestations of authorities from the Brazilian Space Program confirm their intention to dedicate financial and human resources in activities that can place the country in an autonomous level. Those activities include the creation of an infrastructure for launch, operation, and development of their own satellites. It is worth to mention that the costs of images from weather satellite, or the use of communication satellites, represent relevant sums and boost investments in the global economy sector. Moreover, the space research provides important achievements for several areas into science and technology.

To illustrate the economic relevance, one can mention the 47-million-dollar contract, which was signed between Brazil and an Argentinean company (INVAP) for the development of attitude control and data handling (ACDH) system for the Multi-mission Platform (MMP) mission satellite. The MMP consists of a carrier module that can incorporate different payloads for different applications, such as the Amazon-1 satellite for Earth observation and surveillance.

The MMP satellite is being developed at the National Institute for Space Research (INPE, acronyms in Portuguese). According to the director of INPE, Gilberto Camara, the Brazilian space industry is characterized by the specialization in different areas, such as cameras for remote sensing, structures, etc. However, there is no company in the country able to develop or that holds the technology of an ACDH system. This is a result of no specialized manpower. The actual educational formation is focused on the development of hardware, but not software (Mileski, 2009).

In this context, the objective of this paper was to contribute to overcome this lack of technological capability. This paper studies an attitude control system (ACS), more specifically, a digital system for attitude control for three-axis stabilized satellites. The development on an embedded system is addressed. In this case, the information obtained by the sensors is performed by a digital signal processor (DSP). The controller design is based upon a linear-quadratic Gaussian (LQG) optimal control, which is a well-known control theory in terms of space applications. The design combines a Kalman filter and a linear quadratic regulator (LQR) control law.

In addition, within the synthesis of the control law, we adopted a pulse-width pulse frequency (PWPF) modulator, which is responsible for modulating the signal control sent to the reaction thrusters that are considered in this work. The quality of an ACS using propulsion controllers is strongly influenced by the modulation of the control command. Therefore, the practical issue of translating the continuous desired signal to an on/off signal is done.

THE MMP SATELLITE

The MMP satellite is a project based on an advanced concept in terms of architecture of a satellite. It intends to bring together in one versatile platform all equipment that are essential to the operation of a satellite, such as power generation and distribution, attitude control, and propulsion, etc. It can accomplish a variety of applications with different orbits and mission requirements.

In this architecture, there is a physical separation between the platform and the payload module. Thereafter, both modules can be design, built and tested separately before the integration and final assembly and testing of the satellite. The advantage associated with the MMP concept is the cost reduction in manufacture of the satellite, i.e., the navigation module would be the same unless any updates and upgrades are implemented, regardless of the payload hosting the MMP. Figure 1 illustrates the MMP (INPE, 2010).

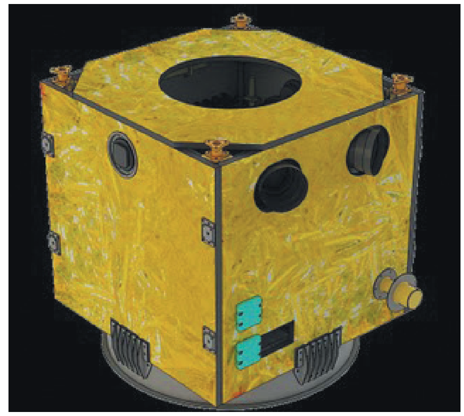

Figure 1. Illustration of the Multi-Mission Platform (INPE, 2010).

Some applications are already planned for the MMP, including the first Remote Sensing Satellite (SSR-1), also named Amazonia-1. The Amazonia-1 will be equipped with instrumentation for imaging a wide field imager (AWFI) full developed in Brazil. It is also equipped with transponders for collecting data from data-collecting platforms (DCPs), which can be used for Weather Forecasting and Climate Studies in Brazil (INPE, 2004). Its applications include evaluation and estimation of productivity in cultivated areas, and monitoring of pollution in coastal areas. The main objective of the mission is the acquisition of data for monitoring the Amazon system. The Remote Sensing Satellite 2 (SSR2), also known as Multi-Application Purpose SAR (MAPSAR), is another candidate to a future mission based on MMP. MAPSAR is the result of a joint study conducted by INPE and the German Aerospace Center (DLR) targeting a mission for assessment, management and monitoring of natural resources, comprising cartography, forestry, geology, geomorphology, hydrology, agriculture, disaster management, oceanography, urban studies, and security (Schröder *et al*., 2005).

Attitude model: kinematics and dynamics

In order to model the attitude of the satellite, we have considered two reference systems: the orbital frame or the Local-Vertical-Local-Horizontal (LVLH) and the satellite frame. The coordinate frame LHLV (x_0, y_0, z_0) moves with the satellite. Its origin coincides with the center of the mass of the satellite. The axis z_0 of the LVLH frame is defined by the satellite radius vector, the axis y_0 by the orbital normal, and the axis x_0 completes a right handed coordinate frame.

The body or satellite coordinate frame (x, y, z) has its origin in the center of mass of the satellite.

Their axes coincide with the principal axes of inertia of the body. The nominal or the desired attitude is one that the axes of the reference body are aligned with those of the reference frame LVLH (Wie and Arapostathis, 1989). The Euler's angles are used to parameterize the attitude, the sequence of rotations 3-2-1 is chosen. The rotation matrix is given by Equation 1 (Shuster, 1993):

$$\mathbf{R}_x^X = \begin{bmatrix} c\psi c\theta & s\psi c\theta & -s\theta \\ -c\phi s\psi + s\phi s\theta c\psi & c\phi c\psi + s\phi s\theta s\psi & s\phi c\theta \\ s\phi s\psi + c\phi s\theta c\psi & -s\phi c\psi + c\phi s\theta s\psi & c\phi c\theta \end{bmatrix} \tag{1}$$

The kinematics equation is obtained by the time derivative of the rotation matrix equation (Shuster, 1993), then (Eq. 2):

$$\dot{R}(t) = S(\omega(t))R(t) \tag{2}$$

The kinematics equation can be simplified if one considers small angle maneuvers, in this case we can approximate: $\sin\phi, \sin\theta, \sin\psi, \cos\phi, \cos\theta$ e $\cos\psi$ to $\phi, \theta, \psi, 1, 1$ e 1, respectively. Moreover, the non-linear terms $(\dot{\psi}\theta, \dot{\psi}\phi, \dot{\theta}\phi)$ are very small compared to the linear ones. The velocities $\dot{\psi}$ and $\dot{\theta}$ are also small compared to the orbital velocity ω_0 (Arantes Jr. *et al.*, 2009). Considering those approximations, the kinematic equation is given by Eq. 3:

$$\omega_{ib}^{b} = \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} + \omega_0 \begin{bmatrix} -\psi \\ -1 \\ \phi \end{bmatrix} \tag{3}$$

In this paper, the satellite is modeled as a rigid body. Therefore, the dynamic model can be obtained with Euler's equation that describes the rotation of a rigid body. The dynamic equation is given by Eq. 4:

$$\tau_{ext} = \left[\frac{dh}{dt}\right]_b + \omega_{ib}^{b} \times h_b \tag{4}$$

We rewrite the expression as Eq. 5:

$$\mathrm{J}\dot{\omega}_{ib}^{b} + \mathrm{S}(\omega_{ib}^{b})\mathrm{J}\omega_{ib}^{b} = \tau_d^b + \tau_p^b \tag{5}$$

where:
J is the inertia matrix of the satellite; τ_d^b represents the torques from external perturbations acting on the satellite; and τ_p^b represents the control torques (τ_x, τ_y, τ_z).

All vectors described in the body frame, ω_{ib}^{b} is the angular velocity of the body with respect to the inertial frame written in the body frame. The gravity gradient is the only external perturbation considered in this work. Its effect cannot be neglected in a low-orbit satellite, an asymmetric body subject to the Earth gravitational field will experience a torque tending to align the axis of minor inertia with the field direction. The gravity gradient torque is modeled as Eq. 6:

$$\tau_g^b = 3\omega_0^2 \begin{bmatrix} (J_z - J_y)\phi \\ (J_x - J_z)\theta \\ 0 \end{bmatrix} \tag{6}$$

Substituting the applied torques and the kinematic equation (Eq. 3) into the dynamic equation, and representing the dynamic equation in the state space form, we have (Arantes Jr. *et al.*, 2009) Eq. 7:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{7}$$

CONTINUOUS-TIME LQG CONTROL

The LQG is designed upon the linearization of the dynamic model. The theory is developed for linear systems. However, the simulation takes into consideration the complete non-linear model of the satellite.

The optimal control approach consists of minimizing a quadratic cost function and computing a feedback gain matrix (Dorato *et al.*, 1998). The optimization problem aims at obtaining a control law expressed by a linear relationship between the state variable ***x*** (expressing the Euler's angles and the angular velocities) and the control variable ***u*** (applied torques) given by Eq. 8:

$$\boldsymbol{u} = -\mathbf{K}(t)\boldsymbol{x} \tag{8}$$

with a gain **K** that minimizes a quadratic cost function formulated as Eq. 9

$$\mathbf{J}_{lqr} = \int_0^T \left[\mathrm{x}^T \mathbf{Q}_c \mathrm{x} + \mathrm{u}^T \mathbf{R}_c \mathrm{u}\right] dt \tag{9}$$

where, $\mathbf{Q}_c$ and $\mathbf{R}_c$ are the weight matrices of state and control vectors, respectively. The gain matrix K for the optimal control law is obtained by solving the algebraic matrix Riccati equation for a time-invariant system and considering an infinite horizon context (Eq. 10).

$$A^T P + PA - PBR_c^{-1} B^T P + Q_c = 0 \qquad (10)$$

where, **A** and **B** are the matrices of the linearized attitude model. The optimal control gain is given in terms of the solution **P** of the Riccati equation (Eq. 11):

$$K = R^{-1} B^T P \qquad (11)$$

Due to the presence of noise, a filter is needed to obtain more reliable information about the states measured by the sensors. For the inclusion of a sensors signals filtering, we adopted the controller design based on the theory of LQG. The LQG regulator problem can be described as the synthesis of a control law, which stabilizes the system and minimizes a quadratic error criterion (Dorato *et al*., 1998). We consider in this work the presence of white noise in the observations, and that the system is observable. In the LQG issue, we want to minimize the cost function as in Eq. 12:

$$J_{lqg} = \int_0^T \left(\mathrm{x}^T Q_f \mathrm{x} + \mathrm{u}^T \mathrm{R}_f \mathrm{u} \right) dt \qquad (12)$$

where, $\mathbf{Q}_f$ is the covariance matrix of the measurements noise, and $\mathbf{R}_f$ is the covariance matrix of the dynamics noise (to represent the inaccuracy of the model). The solution of the LQG problem will be given by dividing the main problem into two sub problems: setting the controller for the linear quadratic deterministic problem, previously defined; setting the Kalman-Bucy filter for optimum estimation of $\hat{x}$ state x.

The formulation of the Kalman-Bucy filter is given by Eq. 13:

$$\dot{\hat{\mathrm{x}}} = \mathrm{A}\hat{\mathrm{x}} + \mathrm{Bu} + \mathrm{L}(\mathrm{y} - C\hat{\mathrm{x}}) \qquad (13)$$

where L is the Kalman filter gain that is obtained by solving the algebraic Riccati matrix equation (Eq. 14):

$$\mathrm{A^T S} + \mathrm{SA} - \mathrm{SCR}_f^{-1} \mathrm{C^T S} + \mathrm{Q}f = 0 \qquad (14)$$

The gain of the optimal filter is given by Eq. 15:

$$\mathrm{L} = \mathrm{R}_f^{-1} \mathrm{C}^T \mathrm{S} \qquad (15)$$

After obtaining L, it is possible to obtain the transfer function of open loop LQG controller, according to (Arantes Jr. *et al*., 2009).

$$K_{lqg} G(s) = K(sI - A + BK + LC)^{-1} LG(s) \qquad (16)$$

where, is the transfer function of the attitude dynamics.

The matrices Q_c and R_c are computed by adjustments from the values obtained by using the rule of Bryson (1994), and Q_c and R_c are obtained by heuristic iterative adjustments. The complete control system implemented and tested in MATLAB/SIMULINK environment is illustrated in Fig. 2.

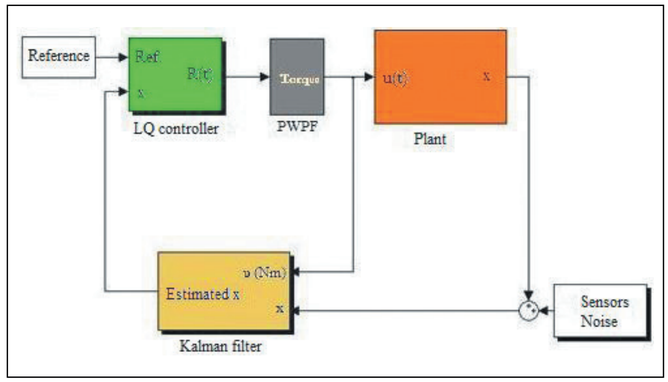

Figure 2. The Linear-quadratic Gaussian control system developed in MATLAB/SIMULINK environment.

Gas jets actuation

The linear quadratic controller action can be implemented using actuators, such as reaction wheels and magnetic actuators for a continuous control command. However, during orbital operations, such as rapid detumbling maneuvers, the required torques are usually too high for reaction wheels. Therefore, on-off propulsion strategies are used for such operations (Arantes Jr. *et al*., 2009). The choice of cold gas jets actuation in the present study aims at testing the control in a most critical situation in terms of the small attitude adjustments difficulties. Future works should use other actuator types (e.g. reaction wheels, magnetic torquers), including combined use with gas jets. It is important to mention that gas jets are also used for reaction wheels desaturation.

The firing of gas jets is controlled by a PWPF modulator (Buck, 1996). The PWPF is an interesting option for the thrusters control system due to its advantages over other types of pulse modulators. PWPF is designed to provide propulsion output proportional to the input command. The modulator optimizes the use of propellants; it provides a smoother control and increases the equipment life. The PWPF structure is shown in Fig. 3 (Arantes Jr. *et al*., 2009).

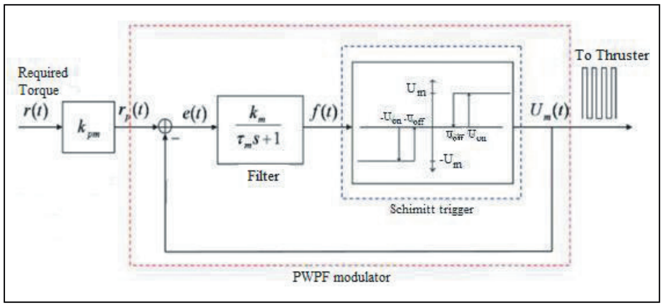

Figure 3. Scheme of the pulse width/frequency modulator.

When the positive input in the Schmitt trigger is greater than U_{on}, the trigger output is U_m. If the input falls below U_{off} , the trigger output becomes null. This response is also reflected for negative inputs. The error signal *e(t)* is the difference between the output of Schmitt trigger U_{on} and system input *r(t)*. This error is sent to a pre-filter, whose input *f(t)* feeds the Schmitt trigger (Arantes Jr. *et al*., 2009).

Simulations results for continuous-time LQG controller

The results obtained in the case of continuous time LQG controller in MATLAB/SIMULINK environment, considering an initial error of 10º in the three Euler's angles, are shown in Fig. 4. It can be seen that even for a fairly large deviation in the stabilization mode context, the controller meets the specification of 0.5º upper error limit. This error can be improved by using other types of actuators, like reaction wheels, which have higher resolution in action.

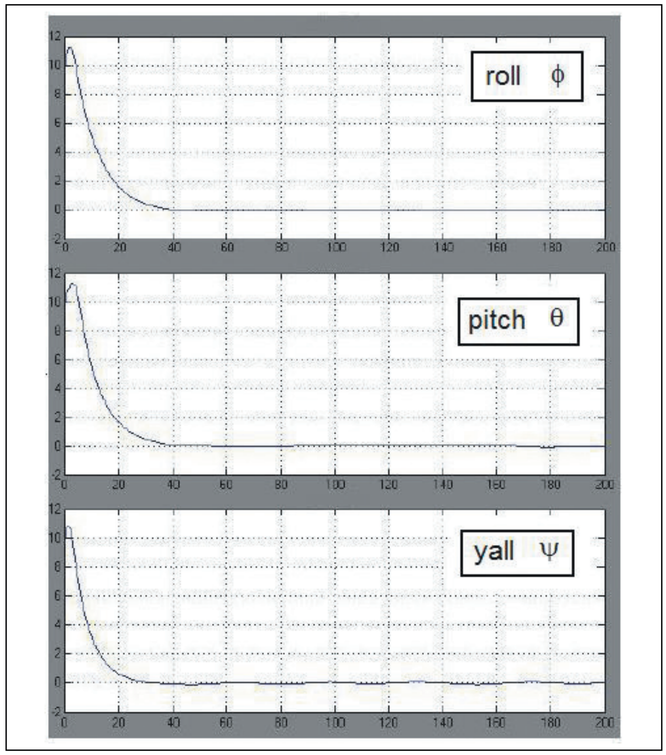

Figure 4. Simulation results of attitude control for three angles (roll ϕ, pitch θ, yall ψ) .

DIGITAL LQG CONTROLLER

The LQG controller design in a digital version requires some study steps of major importance for a successful implementation of the algorithm in an embedded DSP. In this section, we present the main design analysis and decisions with respect to time of sampling, technique of system discretization, and adaption of the LQG controller, originally designed for continuous time systems, to discrete time application.

Selection of the sampling time

The appropriate selection of the sampling period *T* is a crucial factor in the digital controller design, since if this period is too large there are problems in the signal reconstruction, and if it is too small, system instability and processing capacity problems can occur. In principle, one can believe that smaller sampling period is the best digital approximation. However, if the sampling period is too small, the controller poles approach the unit, causing instability. According to the equation mapping from s and *z* spaces, where $z = e^{sT}$, we can see that if *T* is very small, tending to zero, the poles of the controller in z tend to 1, which are those of a marginally unstable system, making the closed-loop system unstable. However, it is not necessary that *T* approaches zero to start the problems, if it is small enough the poles at *z* cannot be anymore distinguished by the computer unit. Furthermore, small sampling periods can introduce significant distortions in the system dynamics behavior (Soares, 1996).

Very large sampling periods may result in violation of the rule established by the sampling theorem, which says that the sampling frequency ω_s must be twice greater than the highest signal component frequency ω_M (Ǻstrom and Witternmark, 1997). If the condition of the theorem is not satisfied, there are information losses in the signal reconstruction.

A reasonable choice for the sampling rate is 10 to 30 times the bandwidth of the system ω_B in closed loop (Ǻstrom and Witternmark, 1997). A suggestion of Franklin *et al*. (1998)

is to adopt a sampling frequency greater than $20\omega_B$, in order to have a fairly smooth control response. In Dorf and Bishop (2008), the indication is to adopt the sampling period $T = 1/(10\, f_B)$, where $f_B = \omega_B/2\pi$ and f_B is the bandwidth of the closed loop continuous system. In this work, we adopted the sampling period corresponding to $20 f_B$, which is an average value of the literature suggestions. In order to analyze the system frequencies, we consider the linearized equation of the dynamics of attitude, according to Euler's angles (roll ϕ, pitch θ, yall ψ)

For each dynamics equations, we calculated the open loop transfer function of LQG controller. The closed loop transfer function is obtained by considering a unity feedback. Next, we performed a frequency analysis of the system by the Bode plot of the three transfer functions, and the bandwidth was identified for each equation separately.

For each transfer function, a different value of bandwidth was obtained. The obtained bandwidth values for roll, pitch, and yaw angles were respectively 0.4480, 0.0013 and 0.4200 rad/s. The highest value of bandwidth was chosen for this work, since the LQG control law approximates a continuous-time control when the sampling period approaches zero. Taking this into account, the choice of the higher bandwidth will provide a sampling period closer to zero. The obtained maximum sampling period was approximately 0.7 seconds.

This reference value of sampling period serves as a starting point to a tuning and adjustment procedure, thereafter a better sampling time value is adopted in this work. It was observed that values higher than 0.7 seconds resulted in a bad dynamic behavior, with the appearance of large oscillations around the reference (zero). Values smaller than 0.7 seconds resulted in a considerable improvement of this dynamics. After several recursive adjustments, the value of 10 ms was considered as a quite satisfactory value, considering the desired pointing accuracy. Furthermore, since the maximum speed of the adopted DSP core is 600 MHz, a sampling period of 10 ms is a reasonable value; it can process the received signal and compute the control signal in the co-simulation in the interval between samples.

System discretization

The design of control systems in the continuous domain is mathematically simpler and allows the use of a large set of tools. In the case of control system design in discrete domain, the mathematical problem is quite more complicated. In addition, in the continuous time domain, the visualization of the relationship between physical reality and mathematical representation of a control system is more evident. Therefore, the usual starting point for a discrete time control design is the continuous time control system study, followed by discretization procedures.

There are several methods of discretization of a given continuous time system, and they are basically divided into open loop methods and closed loop methods. In the open-loop methods, the discretization essentially consists of turning the transfer function *G(s)* in *G(z)*. This transformation is performed by substituting the terms in s by z ones to satisfy some criterion. In the closed loop methods, the discretization of a controller function *G(s)* is obtained taking into account information from the operation of the closed-loop system, and also the knowledge of all the transfer functions involved in the system, including the plant that is intrinsically continuous.

In Soares (1996), several methods of discretization are presented and compared. Among them, the open loop method of transformation of Tustin, also called bilinear transformation, giving satisfactory results even when compared to closed loop ones – which often have better results by taking into account the whole system –, when applied to systems of low order, and also compared with the system of Grenoble, which is of order 9. The Grenoble system consists of a plant considered as a benchmark, developed by the Automatic Control Laboratory of Grenoble. Another well-known discretization method is of retaining elements where the most used is the zero order holder (ZOH).

One of the most popular methods is Euler's, also known as forward difference (Soares, 1996). This method consists of approximating the mapping of the z plane z in the s plane as a truncated series expansion, like in Eq. 17:

$$z = e^{sT} \approx 1 + sT \Rightarrow s \approx \frac{z-1}{T} \tag{17}$$

In the stability analysis of this method, it could be observed a problem: it is possible that a stable system in s is mapped to an unstable system in z. Although simple, this method is very often adopted.

The method of Tustin's bilinear transformation is not based on the approximation of s, as in the case of other methods. It is based on the approximation of the integral represented by the factor *1/s* (Soares, 1996). Approaching the integral by trapezoidal integration method, we obtain Eq. 18:

$$s \approx \frac{2z-1}{Tz+1} \tag{18}$$

Design of the digital controller

The dynamics of the satellite plant in the case of discrete control remains the same as in the continuous time case. Figure 5 illustrates the LQG controller scheme after its discretization. The main change observed in this scheme is the addition of a ZOH in the output signal, which is sent to the satellite's block, as indicated by the output named "torque". The sensors signals are received by the "measured states" gateway. Finally, the controller subsystem was changed by the discretization in terms of its integration function.

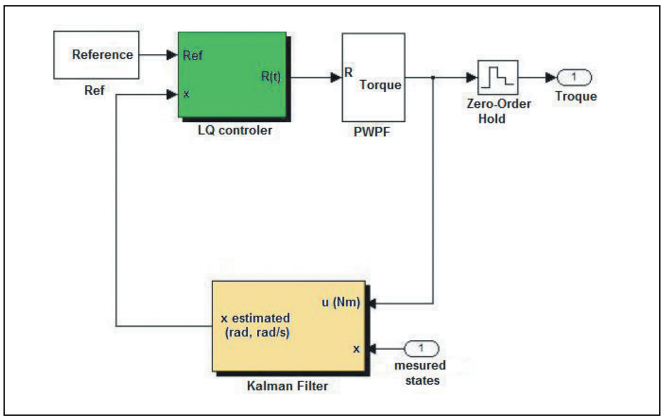

Figure 5. Scheme of the discret linear-quadratic Gaussian controller.

Results of digital LQG control simulations

Figure 6 shows the results of simulations carried out exclusively in MATLAB/SIMULINK environment, using the discrete LQG controller previously obtained by the method of Tustin's transformation, and the controlled plant modeling the non-linear artificial satellite. Figure 6 also shows the variation of the three attitude Euler's angles. This simulation considered the same initial deviation of 10º for each of the three angles.

VALIDATION TESTS

The validation of the digital attitude controller was carried through a scheme of co-simulation, where a computer performs the simulation of the satellite's motion, in MATLAB/SIMULINK, using models of attitude kinematics and dynamics, and a Blackfin 537 DSP device (installed on ADSP-BF537 kit, Analog Devices) plays the digital LQG controller processing, and also the PWPF modulator.

This type of validation scheme has been used as a way to move beyond on strictly computer simulations, giving opportunity to study realistic problems related to communication and to exchange data between the embedded processor and the controlled system, such as time delays, reliability of transmitted and received data, processing time of the controller, among others.

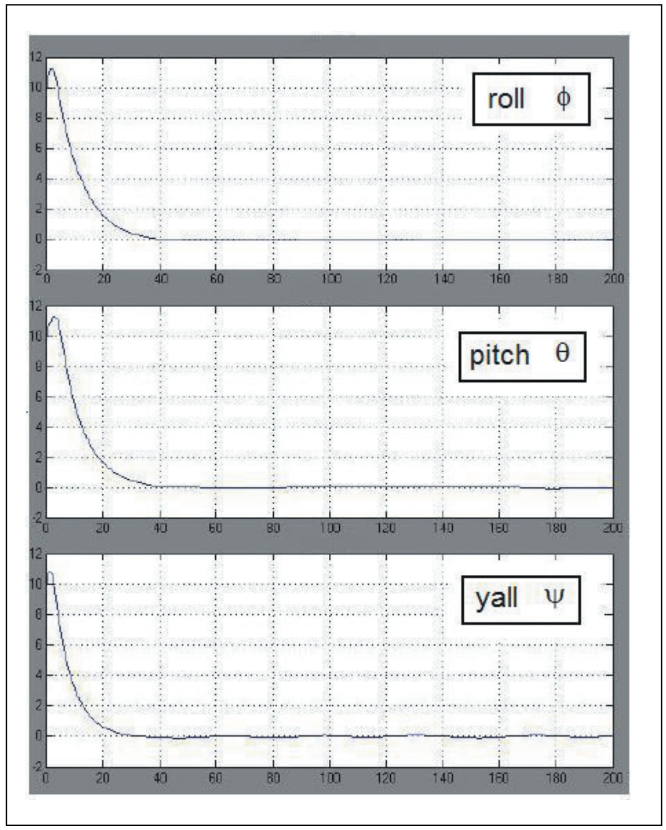

Figure 6. Simulation results of discrete time attitude control, in terms of the Euler's angles.

An example of this kind of application can be found in Seelaender (2009), where a field programmable gate array (FPGA) processor performs the attitude control of a satellite simulated in computer, combining the MATLAB/SIMULINK and LabVIEW-RT tools. This attitude control uses reaction wheels as actuators.

The validation tests comprise two distinct scenarios. In the first one, the tests consider the same case studied in the precedent sections, i.e., three axes attitude stabilization. In the second scenario, the attitude control is aimed at performing a maneuver to achieve a new orientation, that is, a task of attitude tracking.

Co-simulation scheme

The co-simulation scheme is based on the computer communication with the DSP (Fig. 7), which is facilitated by

MATLAB/SIMULINK tool, allowing integration of several external processors, including the BF537, by creating a block Processor-In-the-Loop (PIL) in the simulation diagram in SIMULINK. This communication is made possible through the interaction of the MATLAB/SIMULINK with the BF537 development environment, the Visual DSP ++.

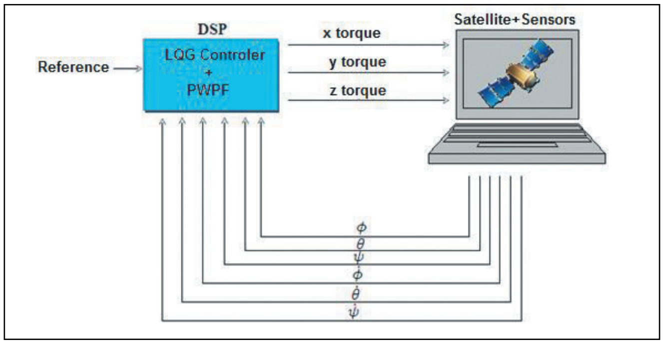

Figure 7. Co-simulation scheme, with the digital signal processor processing linear-quadratic Gaussian controller and the pulse width/frequency modulator, and MATLAB/SIMULINK simulating the motion of the satellite attitude.

The block PIL is inserted into the block diagram developed in the SIMULINK environment. It is responsible for the communication with the DSP, it is in charge of sending the information of the satellite attitude and of receiving the commands related to the control action (the gas jets driving from the PWPF modulator).

Tests results for attitude stabilization

Figure 8 shows the results for the three Euler's angles of the validation tests for the case of three-axis stabilization scheme using co-simulation. The considered initial deviation is 10º for each three Euler's angle, as in the case of the previous simulations.

A comparative analysis of the obtained results in the case of continuous LQG controller, shown in Fig. 4, and those obtained in the scheme of co-simulation (Fig. 8), can be made from a plot of the differences of the results. This plot of differences is shown in Fig. 9.

The differences are smaller than 0.1º for the three angles. However, we cannot conclude about the best precision scenario. Both simulations met the accuracy specifications, nevertheless the simulation of continuous-time system lacks of realism for an experimental application. In fact, the small difference between the two cases shows only that the co-simulation scheme works very similarly to the idealized

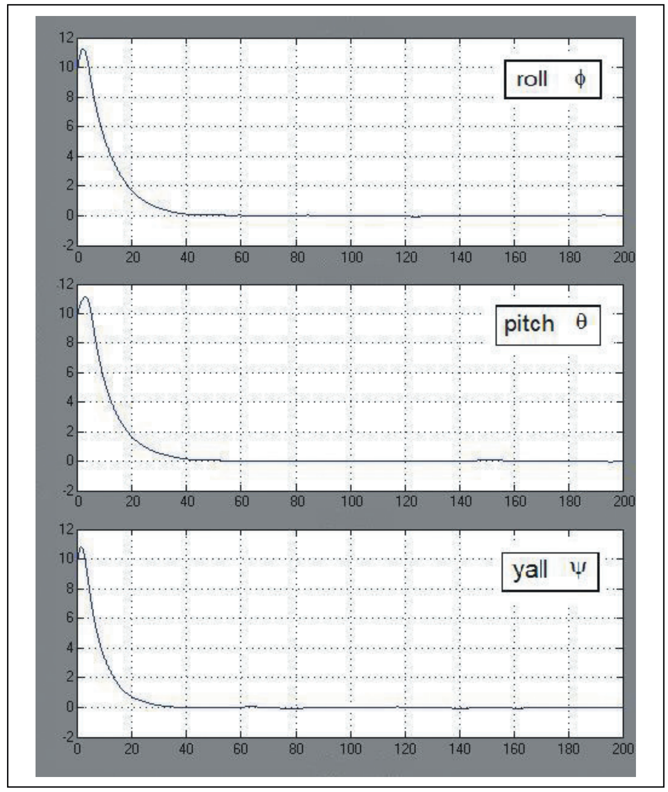

Figure 8. Co-simulation results of attitude control using a digital signal processor for the three angles.

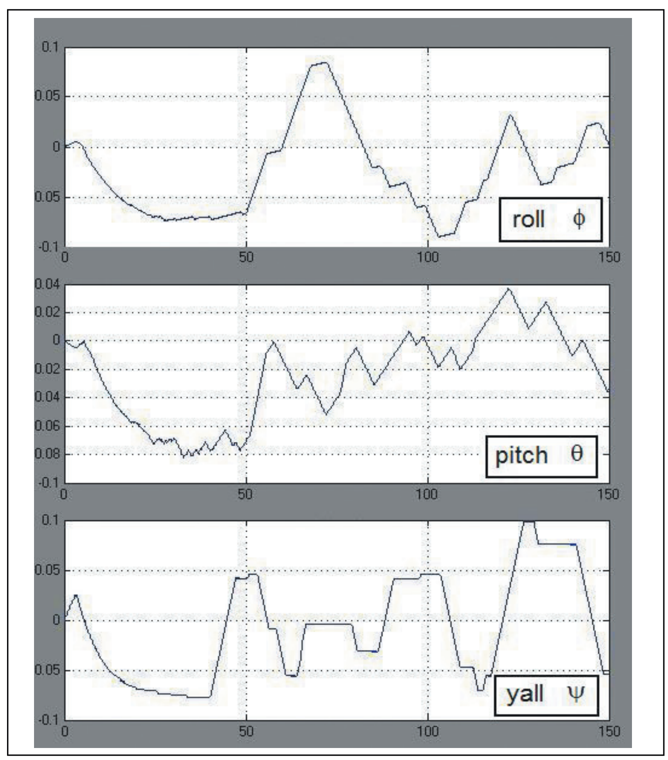

Figure 9. Difference between the simulation results of the continuous controller and co-simulation of digital control for the three angles, in degrees.

one, suggesting an optimistic outcome in relation to the expectations of an experimental application.

In terms of adopted sampling time, it was observed that the simulation in MATLAB/SIMULINK waits the DSP processing to continue the calculations, preventing it from some problem related to the interval between two controllers processing and actuation. However, there is a DSP development platform tool that allows the measurement of processing time and data traffic. Consequently, it is possible to verify that the DSP processing time remains inferior to the maximum period provided for sampling (10ms in this study). This tool is the Cycle Counter, which considers the frequency of the DSP core, 500MHz. The obtained result was processing and traffic time of 8.72×10^{-5}, which is much smaller than the time available, due to the sampling period. It is possible to conclude that there are no problems in this application related to the aspect of the controller discretization and the use of a digital processor to perform the function of controlling and modulating the actuators.

Tests results for attitude maneuver tracking

In this second test case, the satellite is commanded to change its attitude, initially with three angles (roll, pitch, and yaw) at the same value of 10º, for a new attitude defined by the values 50, 60 and 45º, respectively. The results are shown in Fig. 10.

It was observed that the controller performs satisfactorily its task, with tracking maneuver time of about 45 seconds. An important remark: the gap angles between initial and final attitudes are relatively large for the considered approximations in the synthesis of LQG control law. In the controller design, we adopted a linearized model for small angle values, whereas in the simulation of the motion of the satellite attitude we used nonlinear models of kinematics and dynamics. These models, in the case of large angles, exhibit very different behaviors of the linearized model, especially for higher angular velocities. It shows that the adopted controller achieves adequate performance even with this difference between models, and it presents interesting features of robustness, suggesting further studies on this issue.

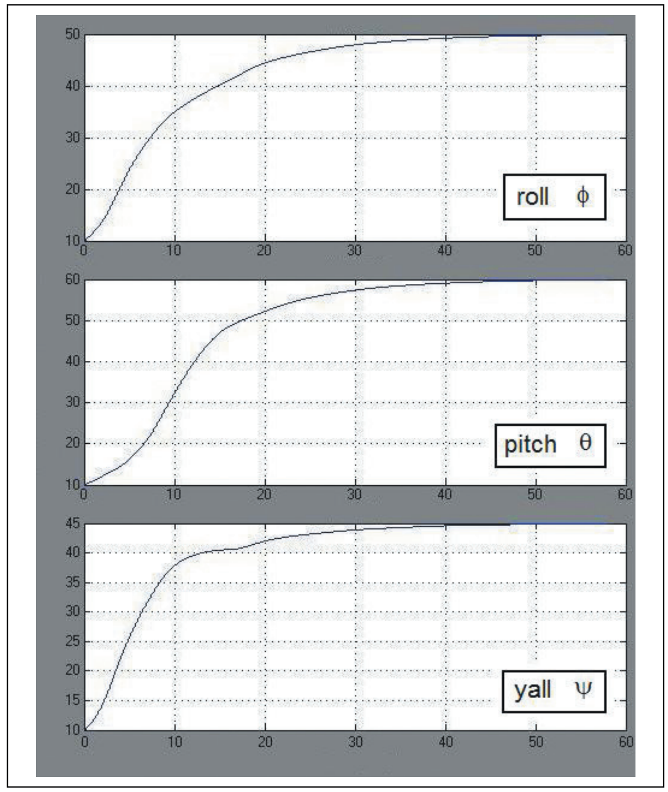

Figure 10. Co-simulation results of attitude control for the three Euler's angles, considering a tracking maneuver.

CONCLUSIONS

This paper presents different stages of designing a digital controller for artificial satellite attitude, based on the theory of LQG regulator, defined from the linearized model of the attitude dynamics. The satellite considered in this study was the MMP, developed at INPE. In order to deal with more realistic features, the controller was developed and implemented in a digital processor, and tested within a co-simulation scheme in MATLAB/SIMULINK (simulation of the satellite motion) and DSP (PWPF controller and modulator). The results of numerical simulations, for the three stages of the study development, show the suitability of the LQG controller, as well as the process of discretization of the designed controller and the implementation in a DSP.

Continuity of the project can consider three main possibilities. The first will be the designing and test/validation of variant controllers, based on different approaches and theories. The second one involves the use of other types of actuators, such as reaction wheels and magnetic torquers, considered also in use combined with gas jets and other modes or phases of stabilization of the satellite. The latter alternative is to continue the study using experimental platforms, possibly in simplified experimental arrangements in relation to a real satellite in flight. This option allows the performance analysis of the controller in action in an experimental system. The co-simulation scheme adds aspects of realism in the simulations that could not be entirely done in the computing environment, but it does not replace the opportunity to verify aspects of the typical physical experiments.

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