Nanosatellites attitude estimation and control using norm-constrained Extended Kalman Filter and quaternion PD-like controller

UNITED NATIONS
Office for Outer Space Affairs

Eduardo Lacerda Campos*, **Kurios Iuri Pinheiro de Melo Queiroz, Samaherni Morais Dias**

Universidade Federal do Rio Grande do Norte

*edulacerda@ufrn.edu.br

UFRN UNIVERSIDADE FEDERAL DO RIO GRANDE DO NORTE

1. Introduction

Recently, nanosatellites have gained great attention as an alternative solution to space exploration. Although, this new approach can provide a reduced cost and a short development time, the size and mass constraints of nanosatellites create several difficulties that should be evaluated.

Hence, the main purpose of this poster is to present the results achieved in the Masters dissertation, which the objective was to develop a simulator that supports the implementation of an attitude control in future nanosatellites in INPE.

2. Methodology

A navigation system was implemented to estimate the attitude and the angular velocity of a nanosatellite, which possesses only two sensors, a magnetometer to measure the direction of the Earth's magnetic field and a solar sensor to measure the direction of the Sun. Hence, the following steps were developed to obtain the navigation system :

- Implement the equations that inform the apparent movement of the Sun around the Earth [1].
- Study the IGRF (International Geomagnetic Reference Field) version 12, capable of providing the direction of the Earth's magnetic field [3].
- Study the SGP4 (Simplified General Perturbations) to propagate the orbit of the nanosatellite [5].
- Estimate the attitude and angular velocity of the nanosatellite through the norm-constraint extended Kalman Filter.

3. References Frames

To represent the Earth frame, this work chosen the Earth-Centred Inertial, which is fixed at the Earth center and do not rotate.

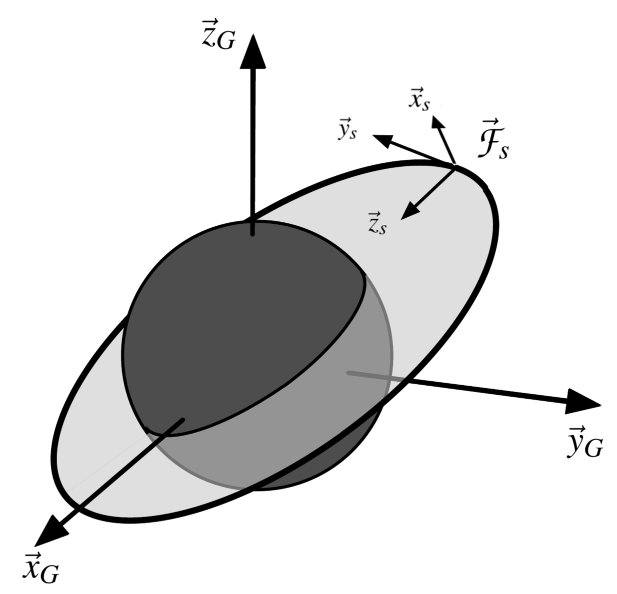

Figure 1: *Fixed frame on the nanosatellite body $\vec{\mathcal{F}}_s$ related to the Earth-Centred Inertial frame $\vec{\mathcal{F}}_G$. Source: Adapted from [4]*

4. Nanosatellite Model

As present by [2], the kinematics using quaternion and the dynamics equations of a nanosatellite can be described by:

$$\underbrace{\begin{bmatrix}\dot{\omega}_{sG}\\ \dot{\epsilon}\\ \dot{\eta}\end{bmatrix}}_{\dot{x}} = \underbrace{\begin{bmatrix} J^{-1}(-\omega_{sG}^{\times}J\omega_{sG}+\tau_{s,c}+\tau_{s,p}) \\ \frac{1}{2}(\eta\mathbf{I}+\epsilon^{\times})\omega_{sG} \\ -\frac{1}{2}\epsilon^{\intercal}\omega_{sG}\end{bmatrix}}_{f(x,\tau_{s,c},\tau_{s,p})} \qquad (1)$$

5. Sensor Emulation

To emulate the sensor measurement, the solar and magnetometer was calculated within the frame $\vec{\mathcal{F}}_G$ and then was rotated to the frame $\vec{\mathcal{F}}_s$ and a noise γ was applied, given by:

$$v_s = \mathcal{R}_{s\leftarrow G}v_G + \gamma \qquad (2)$$

6. Navigation System

The purpose is to estimate the nanosatellite attitude and angular velocity using only a magnetometer and a solar sensor. To estimate the spacecraft angular velocity and the quaternion attitude, a norm-constrained Extended Kalman Filter was used.

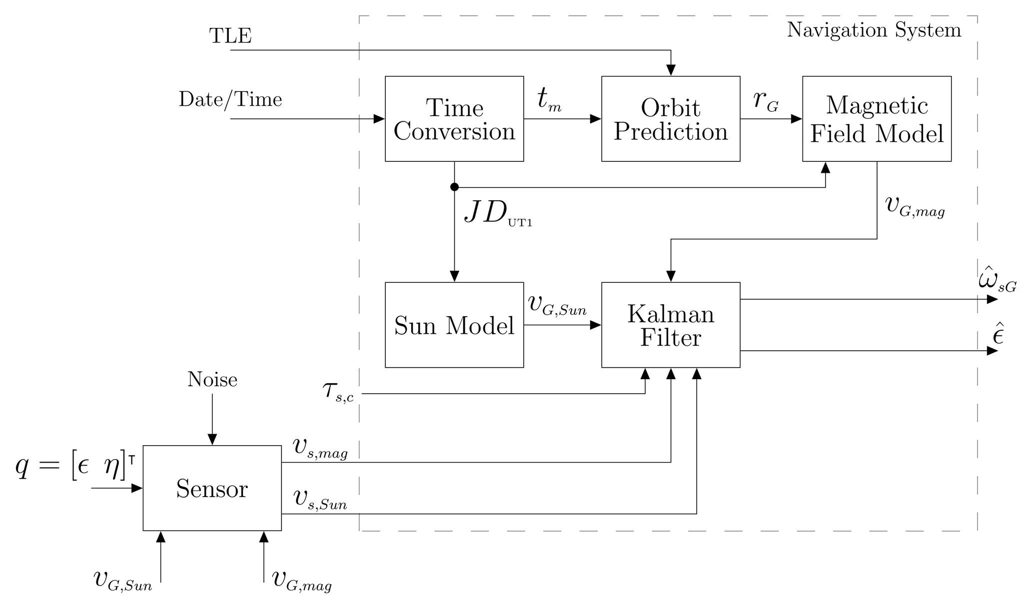

Figure 2: *Navigation System (Attitude Estimation) for a nanosatellite equiped with magnetometer and solar sensor to estimate its attitude and angular velocity*

By using these information, the Kalman Filter should estimate the quaternion attitude $\hat{q} = [\hat{\epsilon} \;\; \hat{\eta}]^{\intercal}$ and keep its unit length

$$\hat{\epsilon}^{\intercal}\hat{\epsilon} + \hat{\eta}^2 = 1 \qquad (3)$$

7. Closed loop structure

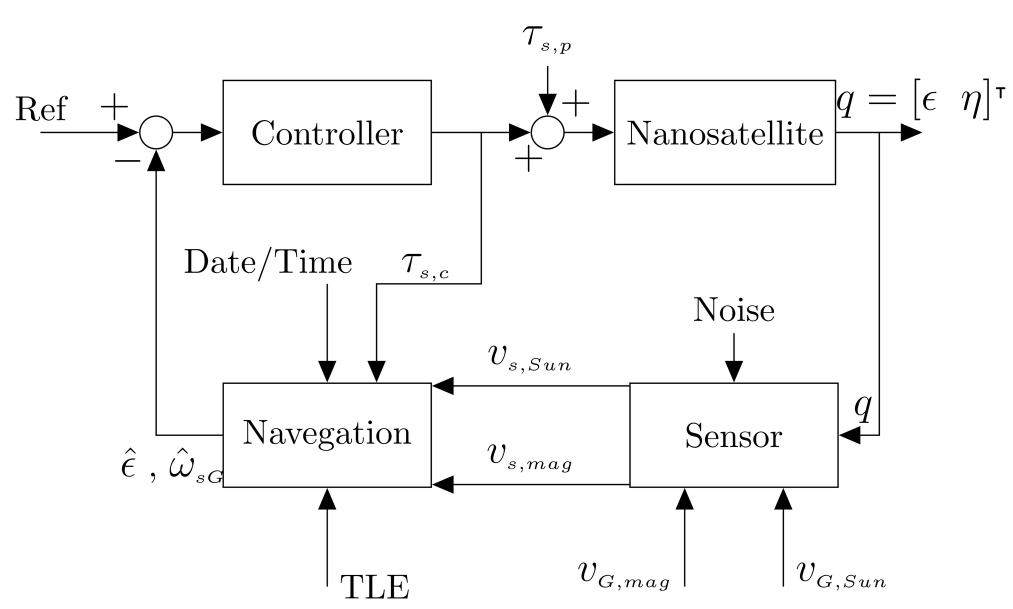

Figure 3: *Closed loop structure for a nanosatellite to correct its attitude and angular velocity*

Thus, by using the vector quaternion component and the angular velocity estimate by the Kalman Filter, the control law adopted is given by the following expression [2]:

$$\tau_{s,c} = -K_p\epsilon - K_d\omega_{sG} \qquad (4)$$

8. Simulations

The purpose of this simulation is to evaluate the behavior of the nanosatellite in the presence of disturbances and noise, when the initial attitude has a large angle deviation and the initial angular velocity is high.

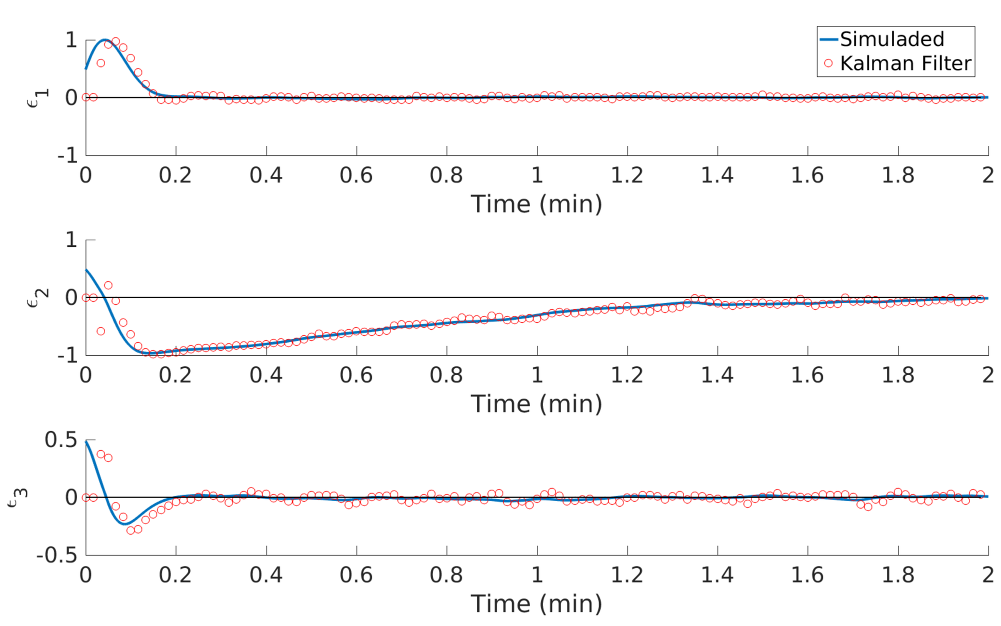

Figure 4: *Quaternion vector component $\epsilon = [\epsilon_1 \;\; \epsilon_2 \;\; \epsilon_3]^{\intercal}$. A large maneuver correction was carried through, which leads in this situation the values of ϵ toward zero*

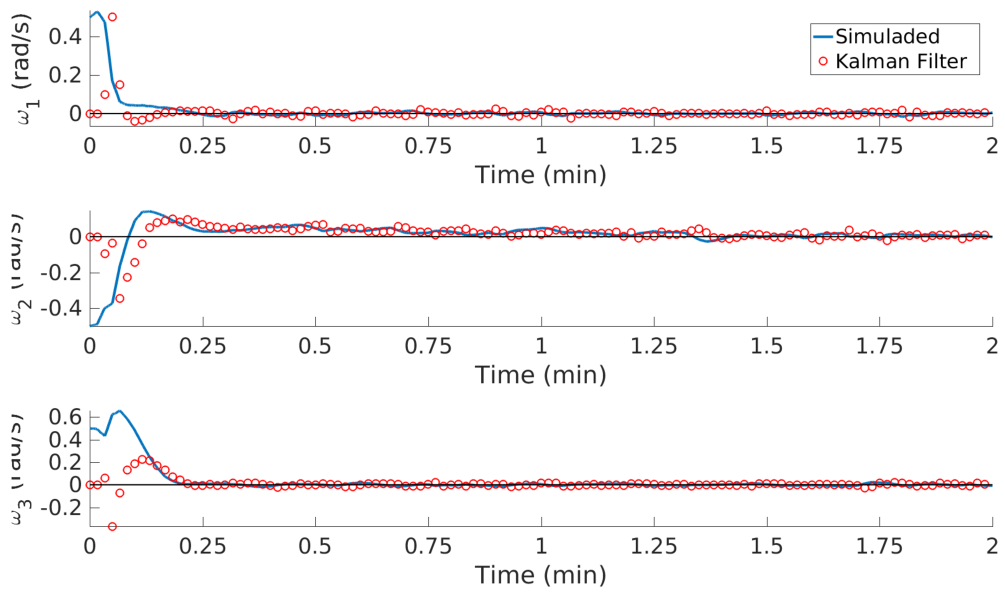

Figure 5: *Angular velocity $\omega_{sG} = [\omega_1 \;\; \omega_2 \;\; \omega_3]^{\intercal}$. The initial values was chosen to emulate the a initial condition where the nanosatellite has been launched with a angular velocity*

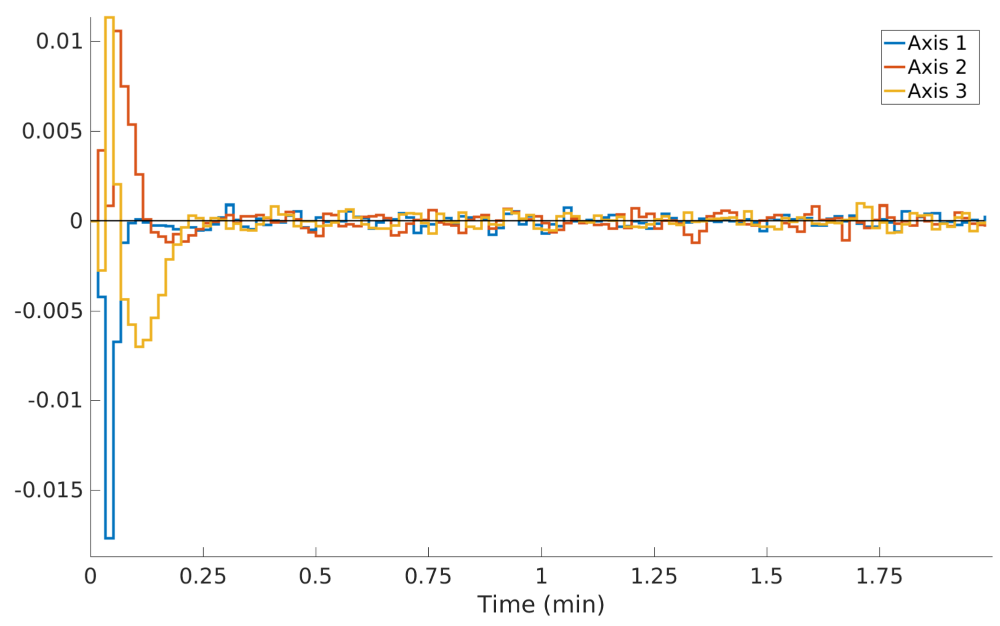

Figure 6: *Torque applied by the controller to keep the desired attitude and angular velocity*

9. Conclusion

The navigation system was tested in a closed loop, where simulations were performed with different initial conditions of operation and disturbances. It is possible to observe that the set of algorithms used to simulate, to estimate and to control the attitude of the nanosatellite presented a stable answer.

In all tests, the controller has presented a convergent behavior, respecting the desired performance requirements, in which the attitude and angular velocity were estimated and corrected as expected.

Finally, one of the objectives of this poster is to present the results achieved in the master dissertation, which contributes to the technological advance of Brazil, by providing a basis for simulations of control strategies in nanosatellites.

References

[1] W.D. McClain and D.A. Vallado. *Fundamentals of Astrodynamics and Applications.* Space Technology Library. McGraw-Hill Companies, Incorporated, 2 edition, 1997.

[2] A.H. Ruiter, C. Damaren, and J.R. Forbes. *Spacecraft Dynamics and Control: An Introduction.* Wiley, 1 edition, 2013.

[3] Erwan Thébault, Christopher C. Finlay, Ciarán D. Beggan, and et al. International geomagnetic reference field: the 12th generation. *Earth, Planets and Space*, 67(1):79, May 2015.

[4] Andrew James Turner. An open-source, extensible spacecraft simulation and modeling environment framework. Master's thesis, Faculty of the Virginia Polytechnic Institute and State University, 2003.

[5] David Vallado. Astrodynamics software. Avaliable in: `https://celestrak.com`, June 2017.