Satellite Attitude Control System Validation in an Air Beared Sphere

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***Abstract*— This paper presents the use of a testbed for satellite attitude control system (ACS), that can allow verifying and assessment of several control methods and algorithms for satellites in a frictionless environment. It consists on an air-bearing that keeps an aluminum sphere suspended in the air, while the sphere can rotate in three degrees of freedom. The system's software is projected in a module based pattern, with the data modules separated from the control module, and as such, the control algorithm can be altered or replaced easily by reusing the preexistent communication modules and protocols. To exemplify the uses of the testbed, a non-linear controller was used, composed by a component that provides linearization by compensating non-linearities and a linear component, a PD controller.**

Keywords*— *Satellite Attitude Control, Control Algorithm Verification.

I. Introduction

When developing control systems for orbiting satellites, there are few forms of analyzing attitude control systems(ACS) using the embedded hardware in a realistic manner. Most of the current evaluations of these systems are done through software simulation, which require a high capacity computer due to the large number of variables that are involved in a simulated environment, and do not provide an assessment as reliable as a real test would, as some problems in the algorithm can pass unnoticed when tested only in software.

Therefore, it is convenient to have a laboratory device that simulates the conditions found on an actual orbitating satellite, that is, a device that can be considered to be on a frictionless and gravityless environment[1]. With that goal in sight, a framework named MUSAT was developed.

This work's goal is to demonstrate how that framework can be used for assessing a satellite ACS, by showing the response of the system when under its default control algorithm.

A. The MUSAT testbed

A testbed was designed for simulating an environment that allows testing both the electromechanical systems and the attitude control algorithm in conditions closer to reality than in a software simulated environment. It consists on a air bearing that keeps afloat an aluminum sphere, that acts as an satellite model. Due to the thin layer of air that keeps the sphere in levitation, the sphere is free to rotate in three degrees of freedom[2]. The use of an air bearing on this test is justified, as pressurized air ensures a low friction environment and it also nearly nullifies the gravity's influence on the satellite model[3].

The sphere's attitude can be controlled through three reaction wheels placed orthogonally inside the model, by varying the rotational speed of each wheel. Fig. 1 is a photograph of the sphere over the air bearing, and Fig. 2 is a photograph of the reaction wheels inside the sphere.

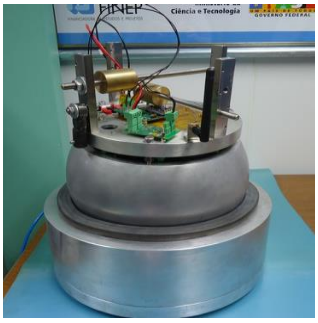

Fig. 1. Air bearing and sphere.

Fig. 2. Reaction wheels contained inside sphere.

An IMU located at the sphere's cap is used for measuring attitude and angular velocity. Along with data pertaining to the sphere's motors status, all data is sent through a UDP network to a computer acting as a ground station, which saves data collected by the system and sends commands back to the sphere.

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This computer acting as ground station runs the attitude control algorithm, which was developed in MATLAB and Simulink, performs all calculations necessary for attitude control, and then sends the results back to the sphere. The Simulink model is procedurally separated into several modules for each task, such as data reception and logging, control, and transmission. Therefore, it is easy to modify or replace the system's control method by simply replacing or modifying the control module while reusing the remainder of structure.

Fig. 3 shows all modules in the Simulink Model. The leftmost, red block is the data logging and reception module, the blue block at the center is the control module, and the green is the data transmission subsystem.

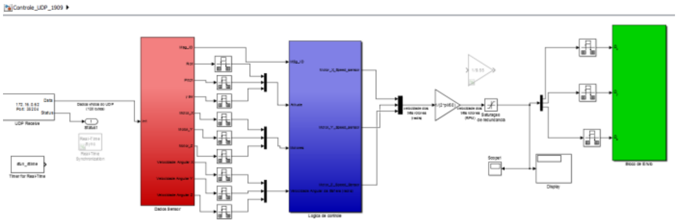


Fig. 3. Simulink control loop model running on ground station.

II. Default Control Algorithm Implementation

The sphere can be used for testing several control methods and algorithms. To demonstrate that, the sphere will be under control of a default control algorithm, described in [2].

An algorithm for controlling the sphere can be obtained by observing the sphere's dynamics model.

$$\dot{\omega} = I^{-1}\left[-(\omega \times I\omega) - J\dot{\mathbf{\Omega}} - (\omega \times I\mathbf{\Omega})\right] \tag{1}$$

Where ω is the angular rate of the sphere and Ω is the rotational speed of the rotor, I is the moment of inertia of the MUSAT and J is the moment of inertia of each reaction wheel. By isolating the derivative of the rotor's rotational speed, it can be found an expression for the reaction wheel acceleration.

$$\dot{\mathbf{\Omega}}_{ref} = \mathbf{a} + \mathbf{b} \tag{2}$$

Where terms **a** and **b** are:

$$\mathbf{a} = \frac{1}{J}\left[\mathbf{K_r}\omega + \mathbf{K_p}\left(\theta^{\mathbf{ref}} - \theta\right)\right] \tag{3}$$

$$\mathbf{b} = -I^{-1}\left[-(\omega \times I\omega) - (\omega \times I\mathbf{\Omega})\right] \tag{4}$$

Where **θ** is the vector representing satellite attitude**, Kr** and **Kp** are respectively the gains of the derivative for a modified PD controller, as the **Kr** acts on angular rate rather than the derivative of error defined by **(θ^{ref} - θ).** This prevents sudden changes on the reference angle from causing a large variation on the output of the PD controller[4].

It must be noted, however, that the control equation (2) yields the reaction wheel's acceleration, while the actual input variable is actually the target reaction wheel speed, therefore, the calculated acceleration must be integrated numerically before being sent back to the sphere. This control was then implemented onto the Simulink model, as shown in Fig. 4. Fig.4 shows only the implementation for the reaction wheel in the X axis, as the implementations for the other two axes are done similarly.

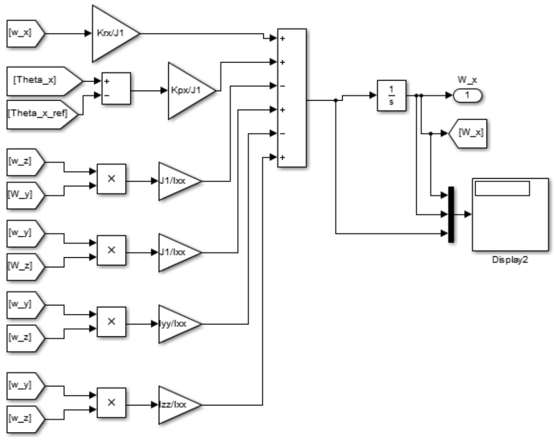


Fig. 4. Implementation of the control equation for the reaction wheel in the X axis.

III. Results

After implementing the control block on the Simulink model, a practical experiment was performed to verify the efficiency of this control system.

The sphere was initially positioned on a leveled inclination, and several reference signals were sent to the sphere, spaced out 75 seconds between each signal.

First, it was sent a command for the sphere to rotate to 5 degrees in the roll axis, and then rotate to -5 degrees in the same axis, then returning to level at 0 degrees. The same signals are then repeated at the pitch axis, and the test is then finished. Control in the yaw axis was disabled for this test.

Fig. 5 and Fig. 6 shows plots of the attitude angles Roll and Pitch vs. time. The large spike seen at the end of the experiment was a result of motor saturation on the roll axis, which caused the spike seen on both plots. Fig 7 and 8 presents the reaction wheels speed over time. The motor saturation can be seen at Fig 7, at the 425 seconds mark. Fig. 9 shows a picture of the MUSAT sphere leveling itself at the 200 second mark.

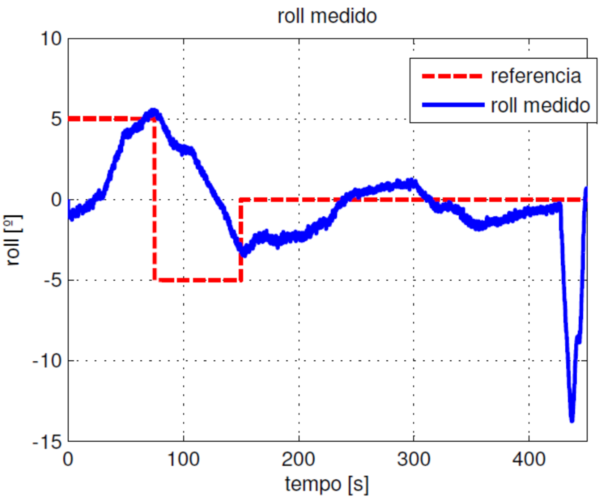
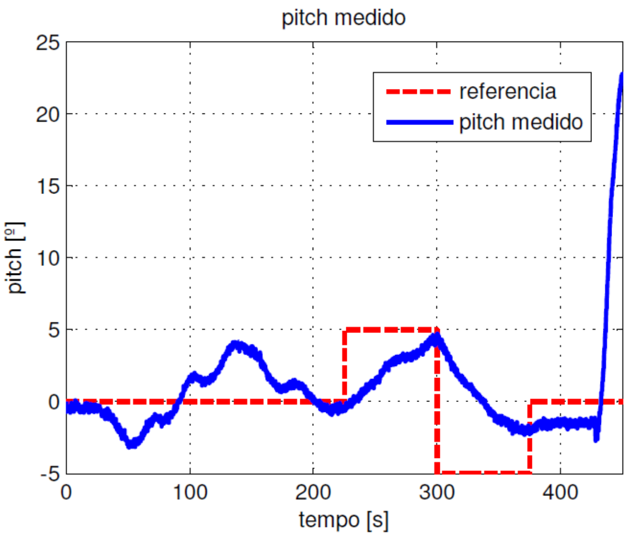
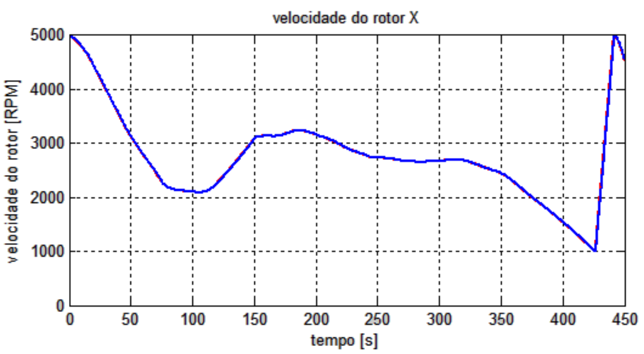


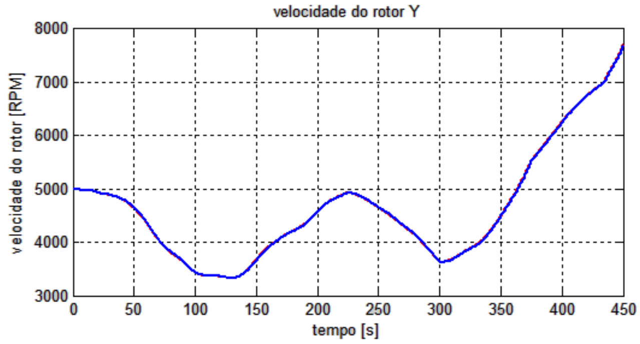
Fig. 5. Roll vs. time plot



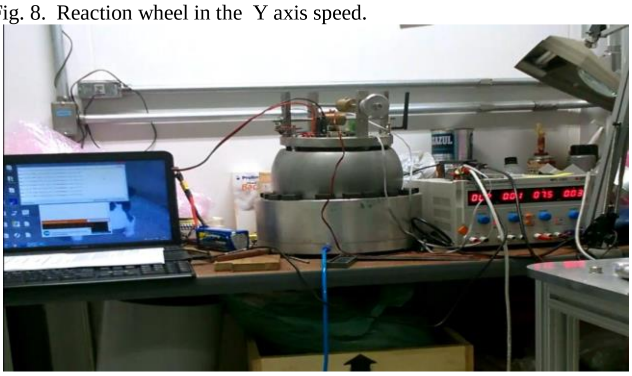
. Fig. 6. Pitch vs. time plot



. Fig. 7. Reaction wheel in the X axis speed.



. Fig. 8. Reaction wheel in the Y axis speed.



. Fig. 9. MUSAT sphere leveling itself.

IV. Conclusions

The work presented a technique and an environment for testing satellite ACS. It is possible to test different control systems simply by replacing the control subsystem in the ground station. Using this testbed, one can design an ACS aiming for improvements over the original algorithm, such as the prevention of reaction wheel saturation, reaction wheel desaturation techniques, integrator windup prevention, and overall attitude tracking.

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