Speed PID controller simulation of a reaction wheel for CubeSat orientation applications

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Speed PID controller simulation of a reaction wheel for CubeSat orientation applications

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Abstract. CubeSat technology is a low-cost alternative for space research in universities worldwide, promoting research areas in tele-detection, Earth and space observation, telecommunications, meteorology, etc. In this sense, Attitude and Determination Control Subsystem (ADCS) plays a key role in order to achieve a fast and precise orientation of the satellite, aiding the system by acquiring the specific and critical angles they require to accomplish the space mission. Therefore, choosing adequate actuators is key for the correct manipulation of the CubeSat, and it must consider size, weight and electrical power usage limitations of the CubeSat Standard. ADCS actuators must generate a quick response to generate an active momentum that modifies the satellite attitude. This work proposes a speed PID controller for a reaction wheel using low-cost materials for its implementation in 1U CubeSats.

1. Introduction

CubeSat technology is in constant growing due to their relatively easy development and low costs, compared to larger satellites, making them ideal for research purposes in universities globally. CubeSats' basic unit (1U) have standard dimensions of 10 cubic centimetres, and are able to increase in size and units, making a modular solution for several applications [1]. They are intended for operations in Low Earth Orbit (LEO), from 300 to 650 km of altitude, completing one Earth's orbit in about 90 minutes (orbital speed $\approx$ 8 km/s), providing Line of Sight (LoS) from the ground station point of view of $\approx$ 5 to 10 minutes, optimally [2, 3, 4].

Nowadays, the growing necessities of satellite communications as higher data rates motivate innovative data transmission methods, proving that current Radio-Frequency methods (RF) are deficient for the upcoming market requirements in terms of system size, cost, energetic consumption and RF licenses, providing only data rates of approximately 3 Mbps [4, 5, 6].

Considering the evident limitations of RF, there are numerous proposals for satellite laser communications (lasercom), the wireless counterpart of optic fibre communications, offering: higher data rates, higher bandwidth, small weight and size components, low power transceivers, etc [7, 8]. Lasercom technology in Cube Sat's has already being implemented. The NASA Optical Communications Sensor Demonstration (OCSD) has achieved a LEO – OGS (Optical

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Ground Station) link, with higher data rates and lower power consumption [9, 10, 11, 12, 13]. However, the main drawback of lasercom is the design, programming and selection of actuators for ADCS, responsible for aircraft attitude corrections. Widely used actuators for CubeSats are reaction wheels (RWs), since are able to attain a fine and continuous pointing. This work proposes the simulation of a speed PID controller for a low-cost RW to be implemented as a slave controller in a cascade control loop system. This will allow the ADCS to have a fast control response of the actuators, acquiring the desired angular modification, aiding to guarantee higher precision, thus providing better pointing for optical or RF communication systems working with narrow beams.

2. Attitude Determination Control Subsystem (ADCS)

There are two classifications for orientation control systems: active and passive ADCSs. Passive ADCSs take advantage of the environment and the satellite dynamics to obtain the wanted orientation, without the necessity of any power. On the other side, active ADCSs require an energy source to accomplish its function, and use actuators' controllers [14, 15, 16]. Active ADCSs consist on a closed loop control constituted of three different stages [14, 16],

(i) Measurement and determination of current orientation,
(ii) Current orientation and desired orientation comparison, error calculation,
(iii) Actuator control to reduce the orientation error.

The mission's goals indicate the conditions to select adequate sensors and actuators. The ADCS design greatly influence the performance of other satellite subsystems. Therefore, some indispensable functionalities must be offered [15, 16], like

- To protect the power system performance and
- To adjust or maintain the desired orientation.

3. ADCS-like feedback control system

The stability and orientation determination of the satellite is calculated via appropriate readings, obtained from different sensors, determining the current orientation of the satellite's three axes.

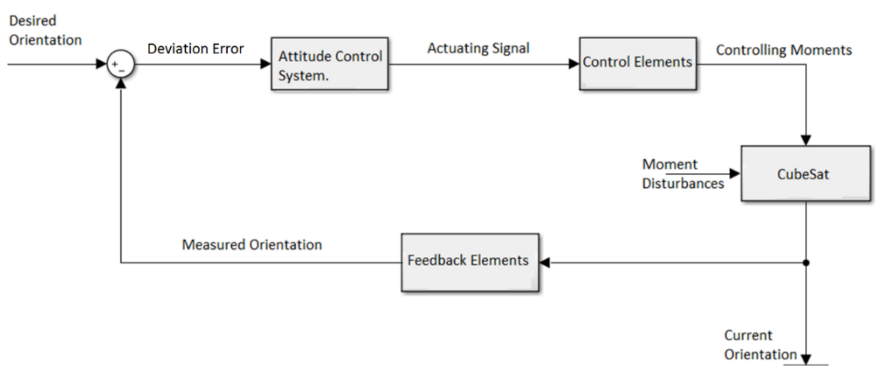

Figure 1. CubeSat orientation feedback control system [16, 17].

Figure 1 shows the ADCS feedback control system, for the satellite to keep a desired orientation, which can be established through an algorithm processed by the on-board computer or by telemetry from the ground station. The desired orientation is compared to the current orientation measured in the satellite, resulting in a deviation error, so the control algorithm to generate a signal for the actuators, as shown in Table 1. Actuators generate a momentum, actively changing satellite's orientation. The control system must be exact and precise in the pointing, acquisition and tracking stage [16].

Table 1. CubeSat actuators advantages and disadvantages [15, 16, 17].

Actuator	Advantages	Disadvantages	Power consumption	Momentum
Propulsors	Altitude insensitive Can adapt to any operative orbit in any referential axis High momentum	Fuel dependent On-off operation	Active	External
Solar sail	Fuel independent Useful for high orbits	Needed for panel control Low momentum	Passive	External
Reaction wheels	Continuous and fine pointing Variable magnitude	Non-linear at zero velocity Internal friction issues	Active	Internal
Momentum control gyroscope	Fitted for three axis stabilisation Very high momentum	Mechanical complexity Fidelity issues High cost	Active	Internal

4. ADCS considerations

This work proposes a speed PID controller for a RW for its implementation in 1U CubeSat prototypes endowed with hybrid communications system (lasercom and RF).

A cascade control loop system is proposed as controller configuration. The controller is responsible of improving the response time of the RW to acquire the angular modifications required by the mission, and it is driven by the aircraft's ADCS. Thus, it is important to consider the transitory and stable regimes of the controlled variable.

P, PI and PID controllers have the next features:

- In the Proportional (P) controller, the control action is directly proportional to the gain,
$$V(t) = k_p e(t) \ . \tag{1}$$
The P controller (Equation (1)) lightly reduces the elevation time, compared to PI and PID controllers, presenting an overshoot.
- The Proportional-Integral (PI) controller is proportional to gain and to its time integration,
$$V(t) = k_p e(t) + \frac{k_p}{T_i}\int e(t)dt \ . \tag{2}$$
The PI controller (Equation (2)) reduces the damping time of the system and elevation time, thus improving time response. However, the maximum overshoot is increased and there could be several ripples and oscillations before stabilisation.
- The Proportional-Integral-Derivative (PID) controller is proportional to gain, time integration and time derivative (Equation (3)). It improves the maximum overshoot, the elevation time and the signal damping, which are drastically reduced, reducing oscillation time and improving the proportional band ratio.
$$V(t) = k_p e(t) + \frac{k_p}{T_i}\int e(t)dt + k_p T_d \frac{de(t)}{dt} \tag{3}$$

In this sense, the best choice for the proposal of a slave controller for a RW is the PID controller. Thus, the elevation and peak times that could affect the system are reduced.

5. Speed control PID of the Reaction Wheels

In order to obtain angular modifications for a standard 1U CubeSat, the relevant variables are its moments of inertia (Figure 5(a)), the angular acceleration, the moment of inertia of the RW and RW's mass. RW's geometry is that of a disc, drilled in the centre to be fastened to the brushless motor's shaft (Figure 5(b)). Table 5 shows the equations used for the calculation of the mentioned variables, assuming the specifications of a 1U CubeSat [1].

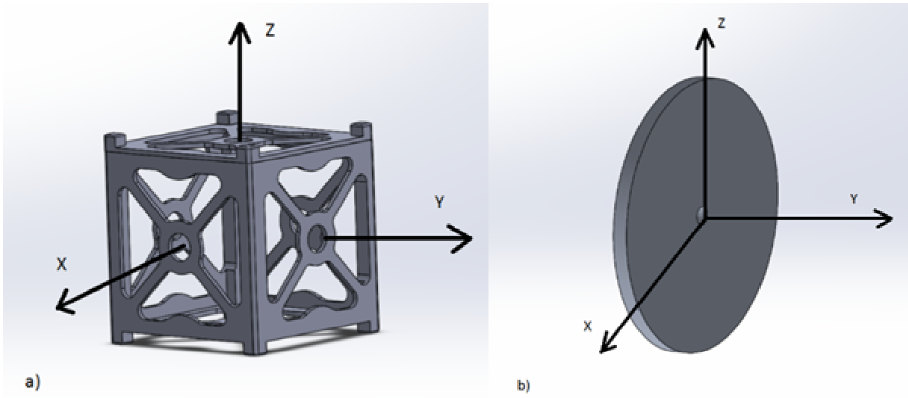

Figure 2. (a) 1U CubeSat moment of inertia. (b) Moment of inertia at the motor wheel.

Table 2. Considerations to obtain the angular modification for a 1U CubeSat, considering a brushless motor of 7353 rpm ≈770 rad/s and a RW made of anodised aluminium.

Parameter	Moment of inertia	Angular acceleration of reaction wheel	Moment of inertia of reaction wheel	Reaction wheel mass
Equation	$I_{\text{CubeSat}} = \frac{1}{6}ml^2$	$\ddot{\theta}_{\text{RW}} = \frac{\ddot{\theta}_{\text{RW}}}{nt}$	$I_{\text{RW}} = \frac{T}{\ddot{\theta}_{\text{RW}}}$	$m_{\text{RW}} = \frac{2I_{\text{RW}}}{r_{\text{RW}}}$
where	m: Satellite's mass l: Arista length	n: wheel activation % t: operation time ≈ 10s	T: Nominal torque	$r_{\text{RW}} = 30$ mm radius

The development of a low-cost RW must consider the mentioned parameters as well as the brushless motor shown in Figure 5(a). RW has a mass of 72 grams a diameter of 60 mm. Thus, a speed controller is proposed as a slave controller, in order to accelerate the response of the RW, reducing response times and guaranteeing a fast ship stabilisation. The modelling and motor transference function are represented by Equation (4), derived from the mathematical model of the equivalent electric circuit of a brushless motor, shown in Figure 5(b).

$$G(s) = \frac{29.79}{2.3 \times 10^{-5}s^2 + 0.01359s + 1} \tag{4}$$

6. Results

The RW's design was performed in SolidWorks®, and the speed controller behaviour for the low-cost RW was simulated in Matlab®, in order to analyse the transient response so to adapt it to the mathematical model of the motor. The latter contemplates a load of a 30 mm radius disc and 72 grams of weight. The system's response in open-loop is shown in Figure 6(a). The Zielger-Nicholls method was used to tune the obtained data. Actually, the behaviour of P, PI and PID controllers was simulated (Figure 6(b)).

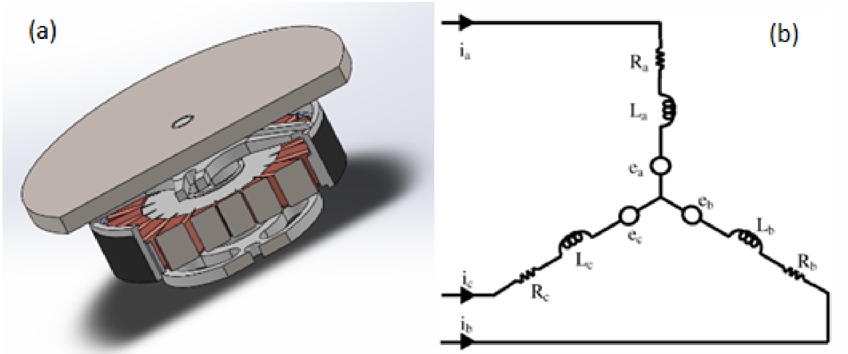

Figure 3. (a) Cross-section of brushless motor coupled to the reaction wheel. (b) Brushless motor equivalent circuit [18].

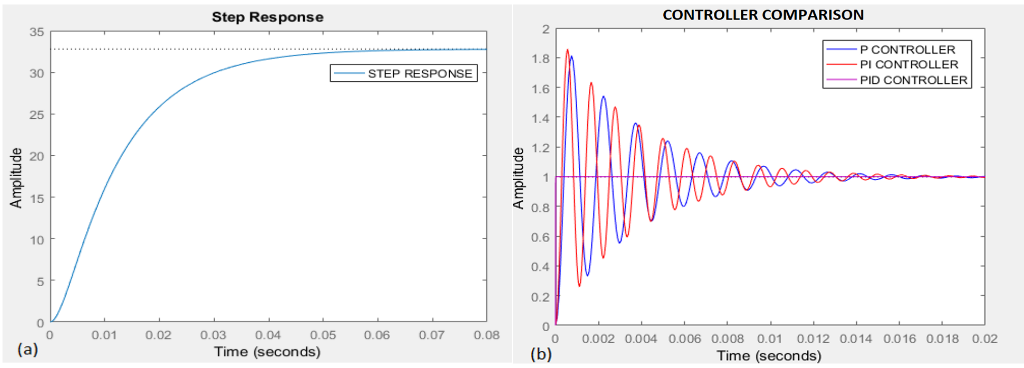

Figure 4. (a) System response to a unitary step function. (b) Speed controllers' comparison.

7. Discussion

The PID controller proposal was compared to a brushless motor speed controller, showing similar results between them for short times (Figure 7(a)). However, tuning reduces the peak shown in Figure 7(b). The PID controller designed for a low-cost RW guarantees a fast response which if considered along with the master orientation controller, improves CubeSat's stability, providing a fast acquisition and tracking response for an uplink/downlink narrow beam application.

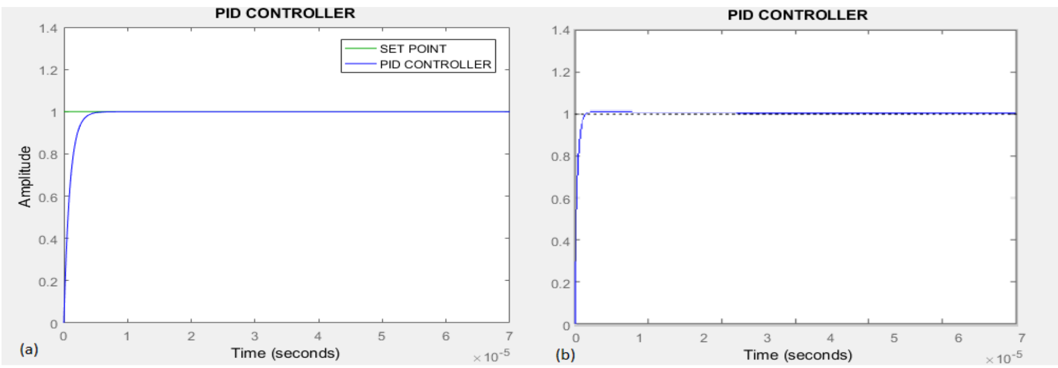

Figure 5. (a) PID controller response time. (b) PID controller response time after tuning.

8. Conclusions

Narrow beam technologies as lasercom add essential benefits to wireless transmissions, such as higher data rates. However, their implementation involves several issues, as it is imperative to achieve a precise and fast pointing in order to establish optical links in very short sighting periods. Bearing these ideas in mind, in this work we proposed the use of low-cost reaction wheels for 1U CubeSat transcieving through a narrow beam channel. Three speed controllers were tested. The PID speed controller for the reaction wheel as a slave controller reduces drastically the stationary response time, and it eliminates the peaks and oscillations in the actuators' response, providing a fast response to the master controller. This work, still in progress, sets the precedent to the development of ACSs specially designed for the very stressing and demanding task of precise pointing for lasercom in nano-satellites as those built under the CubeSat standard [1].

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