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Fuzzy attitude control for a nanosatellite in low Earth orbit

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ABSTRACT

In order to develop and introduce intelligent systems in the space field, an adaptive fuzzy logic controller is designed for a nanosatellite. Attitude determination and control subsystem (ADCS) and its performance and efficiency are compared with a traditional proportional integrative derivative (PID) controller. Fuzzy controllers have already been studied for satellite attitude control; however their performance has not been compared with the classical PID controllers typically being implemented on board spacecrafts currently. Both controllers have been designed and implemented in order to be tested on board a nanosatellite (QBITO) in a nearby mission (QB50), a constellation of 50 nanosatellites. Due to the requirements imposed by the mission, the orbit, and the significant limitations in the power available in these small spacecrafts, an efficient ADCS is required in order to fulfill the mission objectives. The comparison between the classical PID and the fuzzy controllers shows that the fuzzy controller is much more efficient in single maneuver (up to 65% less power required), achieving better precision in general than the PID. This shows that the use of this type of intelligent control systems is a great advantage over conventional control systems currently being used in satellite attitude control, and open new possibilities of application of intelligent controllers in the field of space technologies.

1. Introduction

The attitude determination and control subsystem is critical for the majority of space missions. Most space missions have attitude requirements in order to effectively operate their payloads; these requirements can range from a few degrees of pointing accuracy for the low cost communications missions, up to a fraction of arcsecond for some scientific missions. The stability and robustness of the controller also play an important role in the spacecraft performance. An unstable attitude control may lead to a mission failure or, at least, it may significantly impact its performances (Harland, & Lorenz, 2005). A robust controller ensures requirement conformance regardless of the environmental or internal disturbances. Finally, the power available for attitude actuations is usually tightly constrained. Thus, the attitude subsystem shall be as efficient as possible in order to maximize the mission return. The energy needed for attitude control can be either generated on board (electric power) or obtained by means of fuel consumption. In the best scenario possible, the electric power is generated on board but is shared among all the subsystems. Therefore, the less energy is required for attitude control the more energy is available for other subsystems (e.g. communications) and for the payload. In the worst case, only a limited amount of energy (i.e. fuel) is available during the whole mission for attitude actuations. Once the fuel is depleted, no attitude control is possible and the mission should be considered finished. Thus, an efficient attitude controller maximizes either the satellite lifetime or the available power for payload operations.

Many different controllers have been used or studied for space applications. From traditional satellite control (Wingrove, 1963) which have relied on classic control theories such as proportional integral and derivative (PID) (Sidi, 2000), or linear quadratic regulator (LQR) controllers (Gadelha de Souza, 2006), to intelligent control based on fuzzy logic (Guan, Liub, & Liub, 2005; Nagi, Ahmed, Abidin, & Nordin, 2010; Ortega, 1995; Steyn, 1994; Walker, Putman, & Cohen, 2015) or learning algorithms like neural networks (Fazlyab, Saberi, & Kabganian, 2016; Zou, Dev Kumar, & Hou, 2010;).

Fuzzy logic is a mature control theory (Zadeh, 1965; Lee, 1990; Jantzen, 2013; Takagi, & Sugeno,1985) already used in many commercial applications (Østergaard, 1977; Oshima, Yasunobu, &

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Sekino, 1988; Toshikazu, & Toshiharu, 1991) and is characterized by simplifying the design process taking advantage of the knowledge of selected experts (Østergaard, 1977; Oshima et al., 1988; Layne, & Passino, 1993). Satellite designers usually have extensive experience in satellite environment and dynamics, and small satellites, such as nano and pico satellites, usually have a very limited power budget. For those reasons the use of fuzzy logic for attitude control is highly suitable for nano and pico satellites as it reduces the design process by using the designer knowledge and, as we explain below, it requires significantly less power to meet the attitude control requirements. Although in space applications fuzzy logic has experienced a tepid adoption in global scale, it has shown good results when its application to space missions has been studied (Guan et al., 2005; Cheng et al., 2009; Nagi et al., 2010; Ortega, 1995; Steyn, 1994; Walker et al., 2015).

However, in the field of the space technologies, changes are introduced in a slow and careful way so, it is necessary not only to develop and implement intelligent controllers but also to compare and test their performance and efficiency with the traditional controllers through simulations and, of course, on board demonstration. In a previous work (Walker et al., 2015) an LQR control performance has been compared with a fuzzy controller in a CubeSat through simulations, finding that the fuzzy controller is a lower-cost solution than the LQR which also tends to settle faster than the LQR. In this work, a tailored adaptive fuzzy controller is designed for a nanosatellite mission, and its performance and efficiency are compared, for the same specific mission, with a traditional PID controller, which is the classic control theory most used and tested in ADCS of satellites . This comparison has not been carried out previously. Both controllers will be tested on board in a near future as part of the QB50 mission. A mission focused on the study of the lower thermosphere by launching together 50 nanosatellites. Both controller will be tested using the same hardware under the same external conditions, being a unique opportunity of in situ comparison of a classic controller and an intelligent one.

This paper is organized as follows: In Section 2 a brief mission overview is depicted emphasizing the constraints and the requirements to be accomplished. In Section 3 an overview of the attitude control is described, being the PID controller fully described in Section 4 and the fuzzy controller in Section 5. Both controllers are tuned using the same procedure, described in Section 6, and their performances are compared in Section 7. An adaptive fuzzy controller is described in Section 8. Section 9 compares performances of the PID, fuzzy and adaptive fuzzy controllers. Finally in Section 10, the conclusions of this work are stated and discussed.

2. Mission overview

QBITO is the first CubeSat developed by the Universidad Politécnica de Madrid (UPM), and the team responsible for it is part of the E-USOC (Spanish User Support and Operations Centre). E-USOC is one of the seven European centers delegated by the European Space Agency (ESA) for the preparation and execution of experiments aboard the International Space Station (ISS). QBITO is a 2 U CubeSat and is one of the satellites comprising the QB50 project currently lead by the Von Karman Institute (VKI) in Belgium. The QB50 mission consists of a network of 50 CubeSats distributed in a ‘string-of-pearls’ configuration. The starting point of the mission will be a circular orbit at 380 km of altitude and $i = 98^\circ$ of inclination (see Fig. 1 where the orbit frame is also represented), and due to atmospheric drag, the CubeSat orbits will decay until the spacecrafts burn in the atmosphere.

As part of the QB50 project, the main objective of the QBITO will be to operate the Ion Neutral Mass Spectrometer (INMS) that is the primary payload (PL) on board the CubeSat. Apart from the INMS, QBITO will carry three other payloads in order to take as much advantage of the mission as possible. Those PLs are: a phase change material (PCM), a medium wave infrared detector (MWIRD) and an ADCS experimental software (ESW), based on a fuzzy controller. The full overview of the QBITO hardware is shown in Fig. 2.

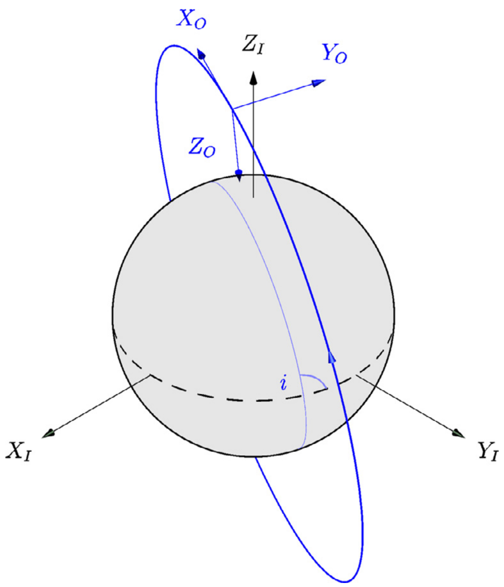

Fig. 1. QBITO inclined orbit representation along with the orbit (X_o, Y_o, Z_o) and inertial (X_I, Y_I, Z_I) reference frames (not in scale). i represents the orbit inclination.

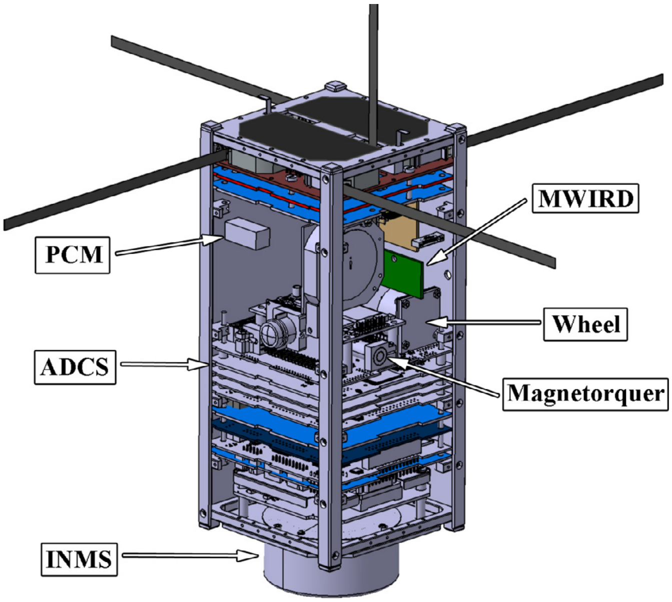

Fig. 2. Open view of QBITO with all the payloads and ADCS actuators labeled.

The INMS imposes some requirements on the mission which apply directly to the ADCS. The most restrictive requirement is to have a pointing accuracy of less than ± 10 degrees from the RAM velocity vector (represented as a cone with semi-angle (α) of 10 degrees in Fig. 3) when the scientific unit is acquiring data. Also, the actual attitude of the satellite shall be known with an accuracy of less than ± 2 degrees (represented as a cone with semi-angle (β) of 2 degrees in Fig. 3). Both requirements shall be achievable until a height of 200 km is reached, which implies that significant