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Attitude Control System for an Earth Observation Satellite

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Abstract

An Attitude Control System algorithm was developed to be included in the Earth Observation Satellite System Concept. The main task of the Attitude Control System is to execute attitude change manoeuvres required to point the axis of the image acquisition sensor to the fixed target on the Earth's surface, and to maintain a nadir orientation otherwise. The objective of the research is realized first by defining the high-level operational modes and control laws to manage the attitude control actuators, for which purpose magnetorquer and reaction wheel systems are used. The reaction wheels are used for rapid, precision attitude control during image acquisition, and the magnetorquers are used as a low-power stabilization system during the desaturation of the reaction wheels and may be also applied for detumbling after satellite deployment.

The operational modes were defined to generate the direction commands regarding the image sensor axis, and the actuators were commanded to perform actions whose aim was to attain these required directions. PID controllers were designed for each actuator. The system also monitors the status of the reaction wheels and automatically commands desaturation when necessary.

A six-degree-of-freedom satellite model was developed by customizing the Matlab Cubesat Simulation Environment. The realistic models of actuators and control laws were included in the spacecraft simulation model, which was used to verify the performance of the developed attitude control system.

The code tests and simulations at both the component and the system levels proved that the attitude control system fulfils the mission objectives with sufficient accuracy for a variety of combinations of orbital parameters and positions of surface target.

Keywords: Satellite, Satellite Controls, Attitude Control, Earth Observation, Trajectory Prediction

1. Introduction

A flight of two or more satellites with an accurately controlled position relative to each other, performing the same high-level mission objectives is defined as formation flying [3]. Compared to conventional monolithic satellite designs, the benefits of satellite formations are: additional mission flexibility, operational redundancy, and better damage tolerance. The satellites in formation may realize missions which otherwise would not be feasible [1].

A formation flying satellite system is being elaborated as the 'EOS-WUT Earth Observation System' concept [2]. The goal of the EOS-WUT Earth Observation System is to demonstrate the feasibility and efficiency of nanosatellite formations used for image acquisition in Earth observation missions [2]. The objective of this formation of two satellites is to perform image acquisition of a selected target on the surface of the Earth. The first satellite acquires a low-resolution image. A surface target is then selected for high resolution images to be registered by the second satellite flying in the formation.

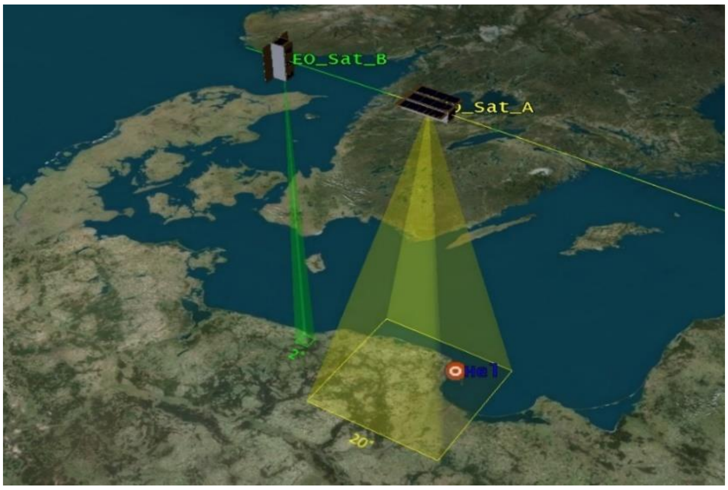

Figure 1: Visualization of the two satellites in formation [13]

The two satellites are capable of automatically controlling their attitudes.

The objective of this research was to develop a satellite attitude control system for this formation, profiting from the previous work of the research team at the Division of Automation and Aeronautical Systems (ZAiOL) at Warsaw University of Technology related to modelling actuators and the development of actuator control systems. This paper focuses on the development of higher-level control laws and operational modes of attitude control system to fulfil the mission profile.

2. Attitude control system requirements and architecture

The main task of an Attitude Control System (ACS) is to manage actuator controllers in accordance with the satellite's current and future orientation relative to the inertial reference frame to allow effective image acquisition.

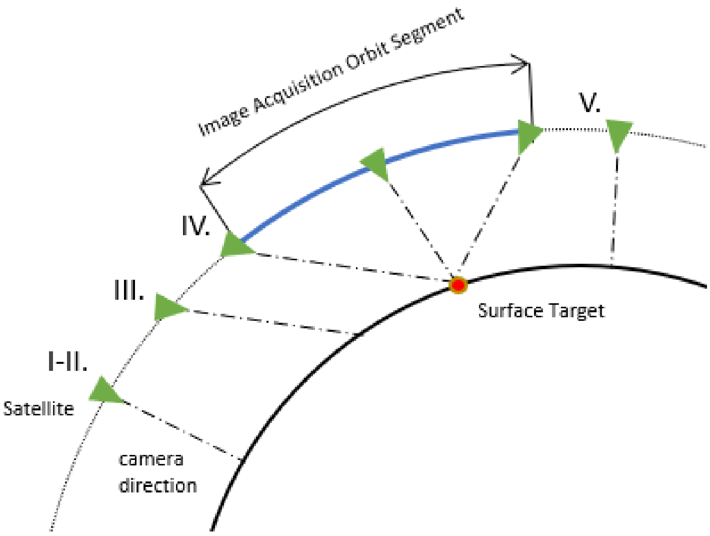

Figure 2: Satellite attitude control during the image acquisition

The segment of a satellite's orbit in which the image may be registered is referred to as "Image Acquisition Orbit Segment" (IAOS). Its length depends on the field of view and the resolution of a satellites' image sensor (Fig. 2). Within IAOS the axis of the image sensor points to the ground target, and otherwise it points towards the nadir direction.

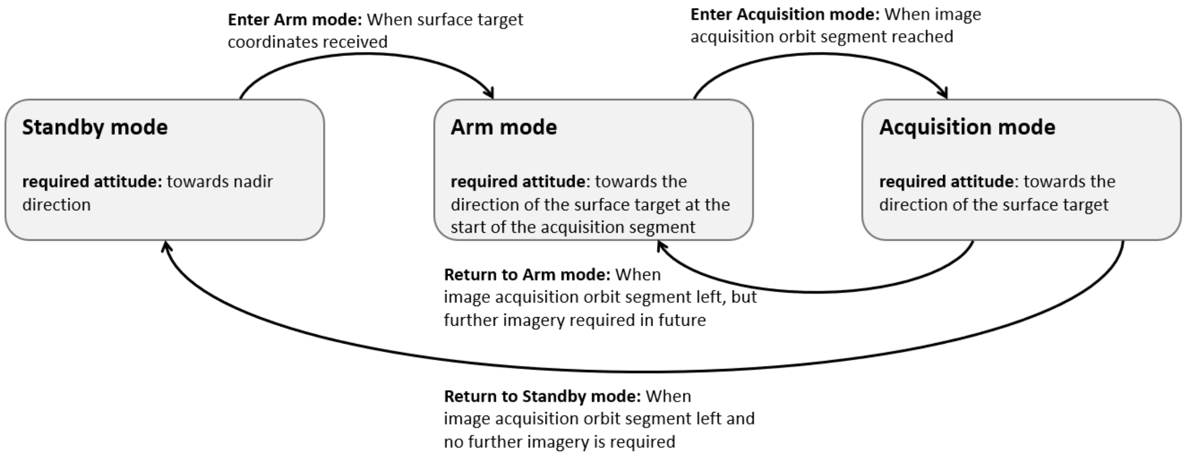

Figure 3: Attitude Control System modes of operation

The operation modes of control system depend on the satellite position on the orbit (Fig. 3):

I. Until receiving the coordinates of the Earth surface target, the satellite imaging equipment points towards the nadir direction (standby mode)
II. After receiving the target coordinates, the satellite attitude is adjusted to the required sensor axis orientation at the entry point of IAOS (arm mode).
III. Within the IAOS the satellite attitude is precisely controlled to point sensor axis towards the surface target (acquisition mode).
IV. After leaving the IAOS the attitude control system again orients the imaging equipment towards the nadir direction (standby mode).

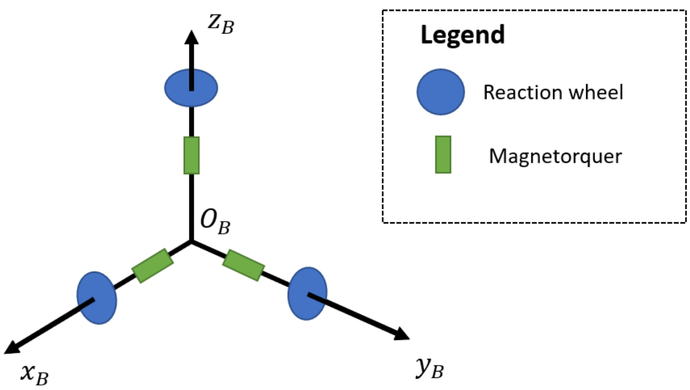

Figure 4: Orthogonal configuration of actuators

The spacecraft considered in this study is equipped with two types of actuators (Fig.4):

- reaction wheels for precision attitude control
- magnetorquers to support desaturating of the reaction wheels and to initially stabilize the satellite after deployment.

The orthogonal actuator configuration is used; the actuators control axes are positioned along the three axes of body frame; one magnetorquer and one reaction wheel are placed along each axis (Fig. 4).

Two levels of control system functionalities are defined, namely:

1. The Satellite **Attitude Control**. This system level defines the high-level control goals (the target attitude and target angular velocity of the satellite as well as based on the current and the required satellite states enabling/disabling commands for the actuators) for the lower-level Actuator Control System
2. The **Actuator Control**. This control level operates the actuators in accordance with the commands received from the Satellite Attitude Control Level.

3. System level test

The objective of this simulation was to evaluate the operation of the Attitude Control System for all modes. The following scenario was simulated:

1. At $t = 0$ the satellite has relatively high angular rates about all body axes; it imitates deployment.
2. The detumbling process is performed, during which the satellite may encounter the IAOS segment; since its angular velocities are still too high, the satellite continues the detumbling process.
3. When detumbling is completed, the satellite switches to the Standby-Nominal mode
4. Before reaching the IAOS boundary, the satellite switches to the Arm mode, and changes its attitude to the one required at the IAOS entry.
5. After entering the IAOS, the satellite switches to the Acquisition mode.
6. While in the Acquisition mode, the satellite follows the surface target.
7. After leaving IAOS, the satellite returns to the Standby-nominal mode.

The duration of the simulation:10000 seconds.

Operational modes throughout the simulation

The states set by the state machine during this simulation based on the analysed simulation results provide reference for the figures later:

Table 1: Operational modes during system level test

Interval start	Interval end	Operational mode	Commanded camera axis direction
0 s	3209 s	Detumble	Nadir
3209 s	7246 s	Standby-Nominal	Nadir
7246 s	7312 s	Arm	Initial acquisition direction
7312 s	7703 s	Acquisition	Acquisition direction
7703 s	10000 s	Standby-Nominal	Nadir

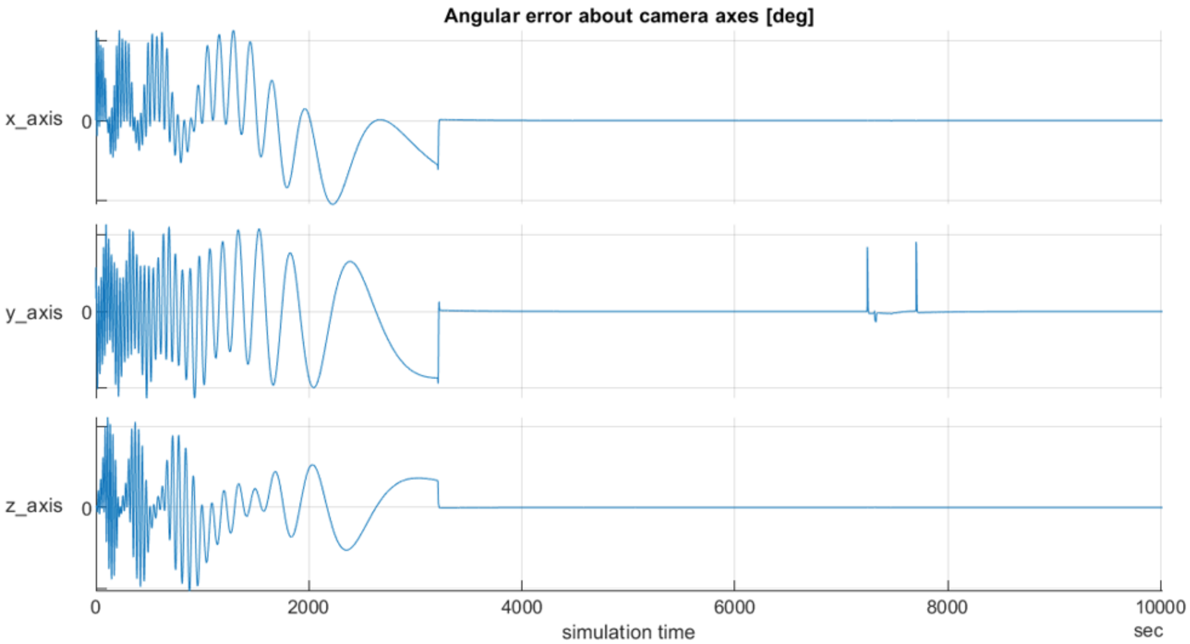

Figure 5: Angular errors in the system level test

The angular errors for the entire simulation can be seen in Fig. 5

Detumbling mode (0 s – 3209 s): During the initial detumbling, the angle errors were oscillating when the satellite performed the detumbling process using the magnetorquers only. After this manoeuvre was concluded, the satellite control system used the reaction wheels only, which resulted in significantly lower error values.

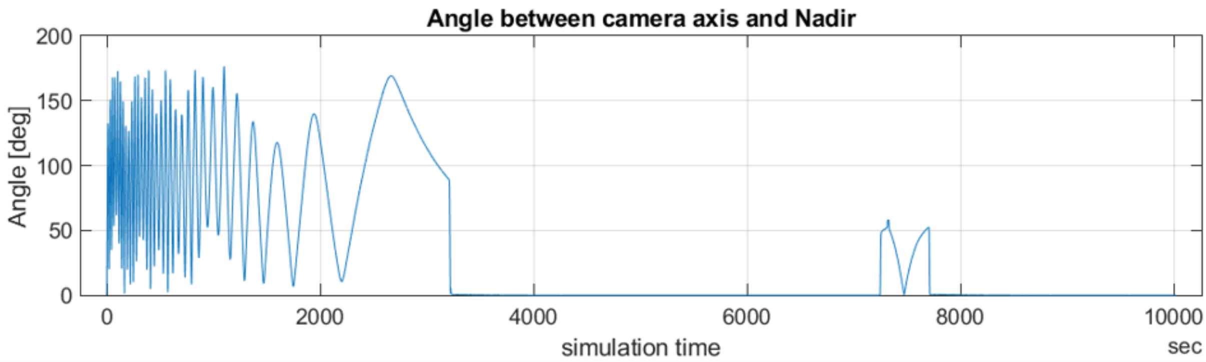

Figure 6: Angle between camera axis and Nadir direction for the system level test

Standby-nominal mode (3209 s- 7246 s and 7703 s- 10000 s): The angle between the camera axis and the Nadir direction is presented in Fig 6 to illustrate the efficiency of the controller in the nominal mode. The satellite follows the Nadir direction well when commanded in the standby-nominal mode.

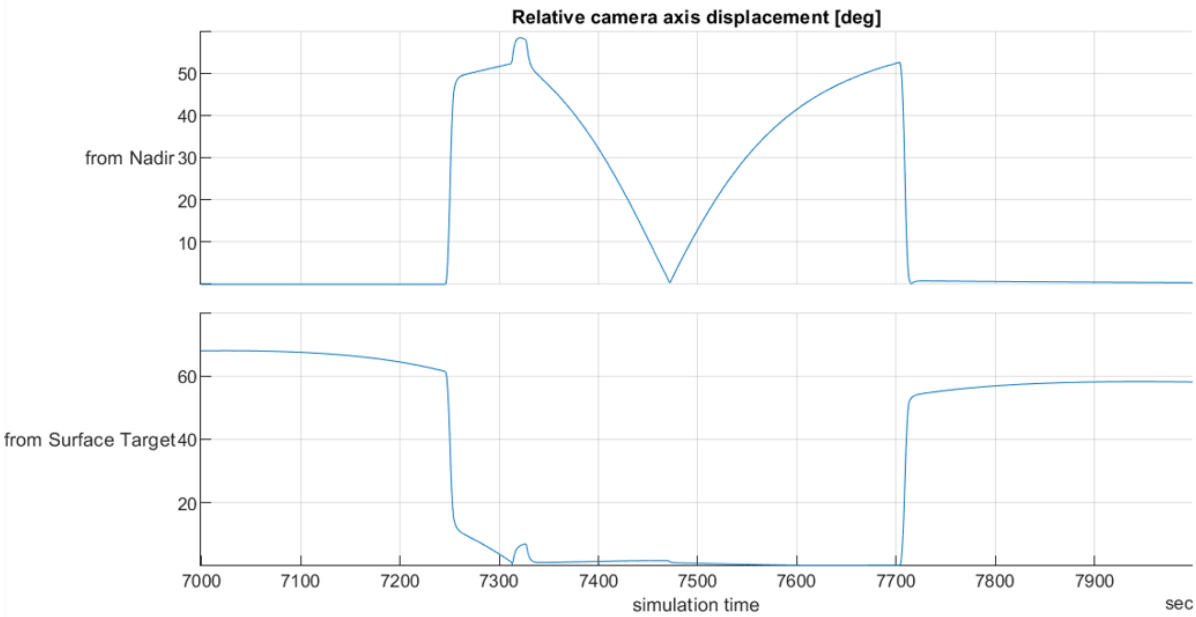

Figure 7: Camera angles in Arm and Acquisition modes in the system-level test

Acquisition mode (7312 s – 7703 s): When the satellite enters the Arm mode (Fig. 7), it attains the attitude that will be required at the beginning of the acquisition segment of the orbit. The camera's angle from the direction of the surface target decreases in an approximately linear manner in this mode, down to almost 0 degrees just before entering the Acquisition mode at 7312 s. When the satellite is in the Acquisition mode, the camera axis follows the direction of the surface target till 7703 s.

It can be concluded that the satellite performs the required mission objectives with sufficient accuracy: when it is within the acquisition segment, the mean error between the commanded and required attitudes is about 1 degree (Fig. 7). It is due to the rapidly changing direction of the surface target from the satellite's point of view when it is flying near the target. When the satellite is following the Nadir direction the angular error is 0.05 degrees.

The outcome of this test is that the satellite operational modes are set according to the assumed test scenario, and the manoeuvres of attitude variation are executed in an accurate and timely manner.

5 Conclusions

A Satellite Attitude Control System was developed to perform the mission objectives of the EOS-WUT satellite formation concept. High-level control laws and operational modes were defined to manage the attitudes of Earth Observation nanosatellites using magnetorquers and reaction wheels.

When the satellite was within the orbital segment where acquiring the pre-selected ground target was possible, it was controlled to point its camera axis towards the ground target; otherwise, the sensor axis was controlled to point towards the Nadir direction.

Two levels of control were defined. The high-level control laws were responsible for arbitrating between the control objectives and managing the actuators. The lower-level controls fulfil the control objectives (commanded directions) received from the higher-level controls, using PID- algorithms.

To be able to validate the developed Attitude Control System the satellite model was established by customizing Matlab's Cubesat Simulation Environment. The satellite model was expanded by the reaction wheel and magnetorquer models and controllers. The developed Attitude Control System and its implementation in Matlab were tested on both the component level and on the system-level, proving its efficiency.

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8. Copyright Statement

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