Acta Astronautica 145 (2018) 515–527

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Discussions on attitude determination and control system for micro/nano/pico-satellites considering survivability based on Hodoyoshi-3 and 4 experiences

Shinichi Nakasuka [a,*], Kikuko Miyata [b], Yoshihiro Tsuruda [a], Yoshihide Aoyanagi [a], Takeshi Matsumoto [a]

[a] Department of Aeronautics and Astronautics, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo, 113-8656, Japan
[b] Department of Aerospace Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan

A R T I C L E I N F O

Keywords:
Micro-satellite
Attitude control system
Satellite survivability
Mode transition

A B S T R A C T

The recent advancement of micro/nano/pico-satellites technologies encourages many universities to develop three axis stabilized satellites. As three axis stabilization is high level technology requiring the proper functioning of various sensors, actuators and control software, many early satellites failed in their initial operation phase because of shortage of solar power generation or inability to realize the initial step of missions because of unexpected attitude control system performance. These results come from failure to design the satellite attitude determination and control system (ADCS) appropriately and not considering “satellite survivability.” ADCS should be designed such that even if some sensors or actuators cannot work as expected, the satellite can survive and carry out some of its missions, even if not full. This paper discusses how to realize ADCS while taking satellite survivability into account, based on our experiences of design and in-orbit operations of Hodoyoshi-3 and 4 satellites launched in 2014, which suffered from various component anomalies but could complete their missions.

1. Introductions

Thanks to the recent rapid advancement of miniature component technologies and ease of purchase, micro/nano/pico-satellites have become more and more important tools for space development and utilization [1], some of which even have realized high level missions such as space sciences, microgravity experiment, communications, or remote sensing. Examples include SNAP-1 [2], INDEX [3], SDS-4 [4], RISING-2 [5], BIRD [6] and BRITE constellation [7]. In order to carry out sizable missions, three axis stabilization is required in most cases, which has been realized to a sufficient level in these projects.

In contrast to these successful satellites, many “university satellites” which incorporated a challenging three axis stabilization design could not survive or fulfill their missions because of failure or low performance of their ADCS (Attitude Determination and Control System). The common tendency of these failed projects is that the system design was carried out assuming that all the components and software in the ADCS functions properly, which is a rarity for university-level satellites. For example, if a satellite with solar cells only on its large solar paddle cannot control its attitude to have sun light on its solar paddles, it eventually fails because of power shortage. Actually, three axis stabilization is a high level function which requires proper functioning of many sensors, actuators, and onboard software. Therefore, ADCS should be carefully designed, fully considering the satellite survivability even with unexpected performance. This is especially important for “university-level” satellites developed by less experienced development teams and lack redundant components. Recently it has become rather easy to buy miniature ADCS components. Even for CubeSats, various ADCS components including some basic software has been developed and used in many CubeSat projects such as QB50 [8]. Examples include “CubeADCS [9]” from “CubeSatShop,” “SatBus CR [10]” from “nano avionics,” or ADCS from “CubeSpace [11].” These components are considered “plug-and-play” and provide a certain level of attitude determination and control functions. This is one reason why many novice developers are challenged by three axis stabilization. The records on how such satellites behaved in space have not been published in literature thoroughly as developers do not want to make bad results open to the public.

A reliable and competent satellite cannot be built only by buying

* Corresponding author.
E-mail addresses: nakasuka@space.t.u-tokyo.ac.jp (S. Nakasuka), kmiyata@nuae.nagoya-u.ac.jp (K. Miyata), tsuruday@nsat.t.u-tokyo.ac.jp (Y. Tsuruda), aoyanagi@nsat.t.u-tokyo.ac.jp (Y. Aoyanagi), matsumoto@nsat.t.u-tokyo.ac.jp (T. Matsumoto).

https://doi.org/10.1016/j.actaastro.2018.02.006
Received 27 May 2017; Received in revised form 15 December 2017; Accepted 4 February 2018
Available online 10 February 2018

List of abbreviations

ADCS	Attitude Determination and Control System
AOBC	Attitude Control Onboard Computer
AOS	Acquisition of Signal
C&DH	Command & Data Handling
EPS	Electric Power System
FOG	Fiber Optical Gyroscope
GAS	Geomagnetic Aspect Sensor (i.e., Magnetic Sensor or Magnetometer)
GSD	Ground Sample Distance
HCAM	High Resolution Camera
HILS	Hardware In the Loop Simulator
H/K	House Keeping
IGRF	International Geomagnetic Reference Field
IRU	Inertial Reference Unit
LCAM	Low Resolution Camera
Li-Ion	Lithium Ion
LOS	Loss of Signal
LTAN	Local Time of Ascending Node
MCAM	Middle Resolution Camera
MOBC	Main Onboard Computer
MTQ	Magnetic Torquer
OBC	Onboard Computer
PCU	Power Control Unit
RCS	Reaction Control System
RW	Reaction Wheel
SAP	Solar Array Paddle
SAS	Sun Aspect Sensor (i.e., Sun Sensor)
SOI-SOC	Silicon On Insulator - System On Chip
SSO	Sun Synchronous Orbit
STT	Star Tracker (i.e., Star Sensor)
TLE	Two Line Element
UVC	Under Voltage Control

components and connecting them. For example, satellite developers should carefully design the attitude "mode sequence," that is, how the satellite can transit from initial tumbling mode to the final three axis stabilized mode in a safe way. In addition, "safe mode" and the transition sequence to safe mode should be properly designed to enable survival in various unexpected situations, even when the satellite cannot be contacted from ground.

This paper discusses the various considerations that should be made in order to design ADCS for university satellites, particularly considering satellite survivability. The discussions are based on our experiences to design and operate Hodoyoshi-3 and 4 satellites which were launched together in 2014 and have been successfully operated in orbit in three axis stabilization mode for more than one year. During in-orbit operations, several components' experienced temporal and permanent failures as well as other anomalies, which gave us much experience in tackling such anomalies, and the lessons learned taught us the importance of total system design combining the satellite subsystems and its ADCS. The objective of this paper is to share our experience with satellite developers, especially university teams who will start satellite development.

The discussion in this paper assumes the following types of satellites as targets.

1) Satellites are Hodoyoshi-3 and 4 class (50 kg) satellites which have three axis attitude control functions. Nano and pico-satellites which have similar functions can be included.
2) The attitude stability, determination, and control accuracy is for the level of remote sensing satellites with 3–30 m Ground Sample Distance (GSD) which requires Reaction Wheels (RWs) for precise control.
3) The satellite is in low Earth circular orbit with 500 km–800 km altitude.
4) Satellites have "timeline command" function, in which commands can be executed at the defined timing even when the satellite is not in direct contact with a ground stations.

Section 2 shows the overview of Hodoyoshi 3 and 4 satellites. Section 3 describes several considerations that should be made for three axis stabilization, and Section 4 discusses control system design strategy considering satellite survivability. Some of the lessons learned from our experiences through the operations of Hodoyoshi 3 and 4 are described in Sections 5 and 6, including additional ideas to improve the flexibility of ADCS.

2. Overview of Hodoyoshi-3 and 4 satellites

Hodoyosh-3 and 4 (Fig. 1 and Table 1) were developed by University of Tokyo together with several Japanese universities and small companies in the "Hodoyoshi Project" (2010–2014). The Hodoyoshi Project ("Hodoyoshi" stands for "just good") has been led by University of Tokyo and funded by Cabinet Office of Japan. The project aims to develop technologies and infrastructure for micro-satellite and to seek innovative utilizations [12]. Hodoyoshi-3 and 4's primary missions include Earth observation with 40 m and 240 m GSD (Hodoyoshi-3) and 6.3 m GSD (Hodoyoshi-4) optical cameras. New components developed through the Hodoyoshi Project were implemented for space demonstration, including a Silicon On Insulator, System On Chip (SOI-SOC) radiation hardened onboard computer, X-band transmitter with maximum 500 Mbps speed, reaction wheels, and ion thruster. "Store and Forward (low-power RF signal collection)" experiment and "hosted payload" business experiment were also tried as additional missions. At the beginning of the Hodoyoshi Project, the University of Tokyo had already developed and launched three satellites, including the world's first CubeSat "XI-IV" in 2003, "XI-V" in 2005, and 30 m GSD remote sensing satellite "PRISM" in 2009, but Hodoyoshi-3 and 4 were the first satellites for the University of Tokyo to attempt three axis stabilization using a full set of attitude sensors and actuators, including gyros, magnetic sensors, sun sensors, magnetic torquer, and reaction wheels. Fig. 1 shows the photos of Hodoyoshi-3 and 4, and some specifications of ADCS. Please take note that the moment of inertia matrix is almost diagonal by well-considered component placement.

The various specifications and attitude control requirements are summarized in Tables 1 and 2. These two satellites were launched by Dnepr launch vehicle on June 19 (UTC), 2014 from Yasny launch base, Russia. Though several anomalies were experienced, three axis stabilization was successfully achieved, and all the planned missions could be carried out. Fig. 2 shows an example of obtained images with 6.3 m resolution by Hodoyoshi-4.

3. Prerequisites of three axis stabilization

3.1. Required functions to realize three axis stabilization

The following requirements should be satisfied in order to realize three axis stabilization; if only one of these requirements is not satisfied, the three axis stabilization will not be realized.