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# ACHIEVEMENTS AND PROSPECTS OF CREATING SYSTEMS FOR DETERMINING THE ORIENTATION OF SMALL SPACE SATELLITE

**Ua** Досягнення у сфері створення малих супутників разом із доступністю недорогих запусків призвели до збільшення кількості космічних польотів. Оскільки космос стає більш доступним, ніж будь-коли раніше, виникають нові та новаторські місії.

Показано сукупність досягнень у галузі автоматичних систем, приладів систем управління, обчислювальних систем, виконавчих органів систем управління, способів та методів комплексування систем управління, що дозволили створити багатоцільові, багаторежимні системи з тривалим циклом активного життя, системи з максимальною автономністю та автоматизацією процесів управління.

У цій статті представлені досягнення та перспективи систем управління космічних апаратів за останні три десятиліття. Розглянуто проблемні питання підвищення точності орієнтації та стабілізації.

**En** Advances in the development of small satellites, combined with the availability of low-cost launches, have led to an increase in the number of space flights. As space becomes more accessible than ever before, new and innovative missions are emerging.

A set of achievements in the field of automatic systems, control system devices, computer systems, control system executive bodies, methods and methods of control system integration, which made it possible to create multi-purpose, multi-mode systems with a long active life cycle, systems with maximum autonomy and automation of control processes, is shown.

This article presents the achievements and prospects of spacecraft control systems over the past three decades. The problematic issues of increasing the accuracy of orientation and stabilization are considered.

## Introduction

Achievements of scientific and technological progress, first of all, modern electronics and mathematics, computer technologies, which today have greatly increased our ability to collect information, have allowed us to create adequate means for storing, searching, processing, distributing and analyzing it. First of all, this applies to the direction of creating small-sized spacecraft of micro- and nano-classes, which can significantly reduce the cost of creation, as well as the time spent on development while maintaining all the functionality of space in-

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formation systems. A broad understanding of trends in satellite reliability can lead these future missions to success. As a result, more and more space enterprises are paying special attention to reliability in the early stages of design. The purpose of the study is to analyze the achievements and prospects of creating systems for determining the orientation of small satellites in orbit, taking into account the type of mission, the developer, the service life of the design and the reliability conditions of satellite operation.

**The state of development of orientation detection systems**

Currently, the space industry is experiencing a growing demand for small satellite platforms, ranging from microsatellites to nanosatellites. These small space systems, despite their size, are currently technologically mature and are entering the market for complex space missions with strict system requirements.

The orientation system interacts with the center of mass motion control system and other onboard systems: energy supply, communications, navigation, telemetry. The successful development of technical means (primarily on-board computers) has led to a significant modernization of control systems and to a significant expansion of their capabilities while improving the quality of these systems.

The satellite industry is currently not designed to support explosive growth. Space enterprises face three main problems — large initial costs, long time to market due to specialized production of components and unusable assets that are created for one-time use. Thus, it is necessary to find a compromise between developing your own satellite or grouping and sharing resources with limited capabilities in the case of a hosted payload.

The focus was on the new opportunity provided by the emerging technology of reusable satellite systems, which will facilitate access to space and the associated prospects for the commercialization of space will become a reality over the next decade, including new efficient technologies such as in-orbit maintenance and repair. The paper [1] presents the architecture of the orientation and orbit determination system (AODS) with built-in fault detection and isolation functions, as well as autonomous management of redundant components and reconfiguration for basic recovery after a failure. The development and implementation of the system were designed for small satellite platforms characterized by limited computing power and a reduced level of autonomy.

In [2], the authors used the Kaplan-Meyer estimate to calculate nonparametric reliability functions.

A new semi-analytical algorithm specially developed for the rapid design and optimization of turning maneuvers in accordance with a flexible set of operational constraints (for example, forbidden guidance directions, maximum angular velocities, maximum viewing angle of the Sun, etc.) is presented in [3]. The authors also discuss the results of the entire verification campaign, SIL tests with a high-precision GNC orbital simulator in the contour.

The paper [4] describes the design, testing and implementation. Radio Aurora Explorer (RAX) satellite, including discussion of orientation determination requirements, specific sensors used, equipment configuration, methods and results of pre-flight calibration of sensors, as well as planned orientation determination algorithms. The RAX orientation detection subsystem uses magnetometers, solar sensors and high-speed gyroscopes.

Employees of the University of Wuerzburg investigated the details of the ADS implementation (Attitude Determination System) [5, 7, 9, 10]. The results of performance evaluations in modeling and tests are presented. Specific aspects of orientation determination are considered on the example of a standardized microsatellite platform related to technology demonstration and space research. The UWE-1, USE-2, and UWE-3 picosatellites have been in orbit since October 2005 and have successfully completed their telecommunications experiment missions. The paper [6] presents a detailed discussion of the dynamics of the HokieSat position and the orientation control system (ADCS). An overview of the entire Orientation Detection and control system (ADCS) is given. This system provides accurate and reliable information about the position of the nanosatellite and control during ionospheric observations. Methods of normalization of the orientation quaternion in two extended Kalman filters – multiplicative and additive – are presented in [8].

In [11], two different methods for determining the Sun's vector to the solar panel flow are compared and the triad method is used to determine the position along three axes. The problems of stabilization and orientation determination are investigated, as well as solutions for achieving partial flight capability with a magnetometer as the only sensor.

Over the past two decades, many antenna designs have been proposed and implemented for CubeSat missions. Recently, there has been a tendency to use antenna arrays that provide a higher gain and reconfigurable and controllable directional patterns. [12] provides an overview of the antennas used in 120 CubeSat missions from 2003 to 2022, as well as a set of single-element antennas and antenna arrays. A graphical method for selecting antennas is proposed.

[13] presents the results of the creation of a picosatellite DPS-1 A, Zhejiang University with a triaxial stabilization system and guidance to the nadir by magnetic coils. The orientation system includes two three-axis magnetometers, a three-axis gyroscope and two sun sensors.

An improved observation mode for determining the field of view (FOV) of a satellite in a sun-synchronous orbit is considered in [14]. An increase in satellite coverage up to 95% is shown. The COMPASS-1 picosatellite of the Aachen University of Applied Sciences performed the task of verifying the operability of the magnetic orientation system in orbit [15].

The Tien Tuo 1 nanosatellite (TT-1) [16] uses three magnetic coils as control drives to control triaxial stabilization. Solar sensors, magnetometers and a three-axis gyroscope are used as measuring sensors. To determine the orientation, the quaternion estimation method (QUEST) and the Kalman filter were used. Declared good test results. By 2009, more than 60 university micro- and nano-satellites had been launched. Their main tasks were technology demonstration, scientific measurements and radio communication.

The developments of the Orientation and Control Determination System (ADCS) of student CubeSat satellites of Tallinn University of Technology are shown in [17]. Satellites use magnetic sensors and flywheels on three axes as actuators to control rotation speed and position.

In [18], the prototype model approach is presented, in which there are two spacecraft models: the Engineering Qualification model (EQM) and the Flight model (FM) to test functional tests for the creation, testing, launch and operation of the first Irish satellite, as well as the demonstration of payloads in orbit. The launch and deployment of picosatellites from the OPAL microsatellite of Stanford University [19] in 2000 demonstrated the feasibility of a new era of space experiments. CubeSat microsatellites weighing less than one kilogram with dimensions of 4x3x1 inches were built as test platforms for DARPA, designed and delivered for launch in less than nine months expanded capabilities with small platforms for space experiments with low cost of creation and launch.

It is emphasized in [20] that the multiplicative extended Kalman filter remains the method of choice for the vast majority of applications. However, it can fail in cases where the dynamics or measurement models are highly nonlinear, or when there is no good a priori assessment of the state.

[21] presents an approach to the design of a system for determining the orientation and control of picosatellites, the results of preliminary operational tests in orbit. The necessity of optimizing the orientation detection and control system by improving the calibration of sensors, as well as adjusting the coefficients in the Kalman filter is shown.

An autonomous miniature nanosatellite orientation system, including magnetoregulators, reaction wheels, sensors and control electronics, is shown in [22]. The system works as a real-time maneuvering system, or as an autonomous orientation control system.

A passive magnetic orientation system developed for the Swedish nanosatellite MUNIN with the results of mathematical modeling is described in [23].

[24] shows the implementation of a control system for the orientation and rotation of a mini satellite, the influence of the residual magnetic moment on it. During the tests, the ESTCube-1 satellite achieved the highest known rotation speed of 841°/s for small satellites.

In [25], an electromagnetic control system for the rotation speed and orientation of the axis of rotation of ISIS ionospheric satellites is described. The satellite, whose rotation is stabilized at a nominal speed of 3 rpm, is characterized by flexible crossed dipole antennas in a plane perpendicular to the axis of rotation, with one dipole 240 feet long and the other 61.5 feet. The design of the control system uses a single coil with an air core along the periphery of the satellite, the axis of which is perpendicular to the axis of rotation. To control the rotation, the magnetic moment of the coil is switched by signals coming from a ferrosonde magnetometer. To control the orientation, the coil current is switched by signals received from four solar sensors. An essential feature of this orientation control method is that the direction of precession of the axis of rotation does not depend on the rotation or position of the Earth's magnetic field vector relative to the satellite and, therefore, does not depend on the position of the satellite in orbit.

In [26], a classical orientation control scheme with full magnetic guidance to the Sun is considered. Modeling has shown that the upgraded solar orientation control scheme on a magnetic basis is able to meet the requirements of pointing at the Sun.

The study of the possibility of a single-axis guidance maneuver of a spacecraft with insufficient drive in the presence of a non-zero residual angular momentum vector is devoted to the work [27].

Advances in the field of control systems for small spacecraft and satellites have made it possible to solve several complex problems related to orientation determination, reliable control, optimal maneuvers or precise guidance. It is assumed that the number of actuators is equal to or exceeds the number of degrees of freedom of the system in which the drives can use different physical principles. In an attempt to extend the service life or increase the stability of the mission in the recent past, the problems of orientation stabilization in the event of a failure of the executive mechanism have attracted increasing attention. The problem is especially relevant for small satellite platforms, for which a combination of restrictions on mass, volume and/or budget may lead to the adoption of a non-redundant orientation system architecture, and possibly based on inexpensive equipment.

## Conclusions

Prospects for further development of orientation instruments and precision guidance of spacecraft are becoming the norm for future space missions, mainly due to the ever-growing demand for high-resolution images of various celestial objects and phenomena required by the scientific objectives of the mission. In this regard, the problems of stabilization and orientation determination, as well as their solutions for achieving systems for determining the orientation of small spacecraft, are investigated.

The achievements, prospects and creation of systems for determining the orientation of small satellites over the past three decades and the conditions for the reliability of satellite operation are presented. The successful development of technical means has led to a significant modernization of control systems and to a significant expansion of their capabilities while improving the quality of these systems.

Research is needed to create systems for determining the orientation of small satellites with high-precision determination of their spatial position. High-quality images of celestial objects are also needed to achieve high precision guidance of the spacecraft.

**References**

1. *Andrea Colagrossi* and *Michèle Lavagna*. Fault Tolerant Attitude and Orbit Determination System for Small Satellite Platforms //Journal/*Aerospace*/Volume 9(2), 46; 2022.
2. *Perumal, R. P.*; *Voos, H.*; *Vedova, F.D.*; *Moser, H.* Small Satellite Reliability: A decade in review. In Proceedings of the AIAA/USU Conference on Small Satellites: Mission Operations & Autonomy, Virtual, 7–12 August 2021. Number SSC21-WKIII-02.
3. *Colagrossi, A.*; *Prinetto, J.*; *Silvestrini, S.*; *Orfano, M.*; *Lavagna, M.*; *Fiore, F.*; *Burderi, L.*; *Bertacin, R.*; *Pirrotta, S.* Semi-analytical approach to fasten complex and flexible pointing strategies definition for nanosatellite clusters: The HERMES mission case from design to flight. In Proceedings of the 70th International Astronautical Congress (IAC 2019), Washington, DC, USA, 21–25 October 2019 pp. 1–8.
4. *Springmann, J. C.*; *Sloboda, A. J.*; *Klesh, A. T.*; *Bennett, M. W.*; *Cutler, J. W.* The attitude determination system of the RAX satellite. Acta Astronaut. 2012, 75, 120–135.
5. *Schmidt, M.*; *Ravandoor, K.*; *Kurz, O.*; *Busch, S.*; *Schilling, K.* Attitude determination for the Pico-Satellite UWE-2. IFAC Proc. Vol. 2008, 41, 14036-14041.
6. *Makovec, K. L.*; *Turner, A. J.*; *Hall, C. D.* Design and implementation of a nanosatellite attitude determination and control system. In Proceedings of the 2001 AAS/AIAA Astrodynamics Specialists Conference, Quebec City, QC, Canada, 30 July–2 August 2001. Number AAS 01-311.
7. *Barza R., Aoki Y., Schilling K.* (2006), Cubesat UWE-1 – Technology Tests and in Orbit Results. In: 57th International Astronautical Congress, IAC-06-B5.3.07.
8. *Deutschmann J.*, *Bar-Itzhack I.* and *Galal K.* (1992), Quaternion Normalization in Spacecraft Attitude Determination. In: AIAA/AAS Astrodynamics Conference.
9. *Schmidt M., Zeiger F., Schilling K.* (2006), Design and Implementation of In-Orbit Experiments on the Pico-Satellite UWE-1, In: Proceedings 57th International Astronautical Congress, IAC-06- E2.1.07 Google Scholar.

10. *Zeiger F., Schmidt M., Schilling K.* (2006), A Flexible Extension for Pico-Satellite Communication Based on Orbit Operation Results of UWE-1, In: 57-th International Astronautical Congress, IAC-06- B5.2.05.
11. *Joseph B. Robinson* et al. Stabilization and Attitude Determination Methods for FalconSAT-3 //Journal of Spacecraft and Rockets, 2016.
12. *Sining Liu, Panagiotis Theoharis, Raad Raad* et al. A Survey on CubeSat Missions and Their Antenna Designs// Special Issue "Antenna Designs for 5G/IoT and Space Applications" 1 June 2022 / Revised: 20 June 2022 / Accepted: 22 June 2022 / Published: 27 June 2022.
13. *Tian Xiang, Tao Meng, Hao Wang, Ke Han, Zhong-He Jin* Design and on-orbit performance of the attitude determination and control system for the ZDPS-1A pico-satellite// Acta Astronautica, 2012.
14. *Dandan Xie, Yawei Huang* and *Changxiang Yan*. Determination of Field of View of a Dawn–Dusk Sun-Synchronous Orbit Satellite Based on Improved Observation Mode // MDPI. *Applied Science*. Appl. Sci. 2022, 12, 7475.
15. *A. Scholz, W. Ley, B. Dachwald, J. J. Miau, J. C. Juang*. Flight results of the COMPASS-1 picosatellite mission // Acta Astronautica. Volume 67, Issues 9–10, November–December 2010, Pages 1289-1298.
16. *Ran Dechao, Sheng Tao, Cao Lu, Chen Xiaoqian, Zhao Yong*. Attitude control system design and on-orbit performance analysis of nano-satellite – "tian Tuo 1" //Chinese Journal of Aeronautics, 2014.
17. *Anton Rassõlkina, Toomas Vaimanna, Peeter Orgb, Alar Leibakc, Rauno Gordond* and *Eiko Priidelb*. ADCS development for student CubeSat satellites – TalTech case study. Tallinn University of Technology, Tallinn, Estonia// Space Systems, Aerospace Sciences and Engineering. Dynamical Systems and Robotics.10 August 2021.
18. *Sarah Walsh, Maeve Doyle, Jack Reilly* et al. Development of the EIRSAT-1 CubeSat through Functional Verification of the Engineering Qualification Model// *Aerospace* 2021, *8*(9), 254.
19. *Hank Heidt, Jordi Puig-Suari, Augustus S. Moore, Shinichi Nakasuka, Robert J. Twiggs*. CubeSat: A New Generation of Picosatellite for Education and Industry Low-Cost Space Experimentation // Small Satellite Conference. 2000.
20. *John Crassidis, Landis Markley, Yang Cheng*. Survey of nonlinear attitude estimation methods// Journal of Guidance, Control, and Dynamics 30(1):12-28 January 2007.
21. *Philip Bangert, Stephan Busch* and *Klaus Schilling*. Performance characteristics of the uwe-3 miniature attitude determination and control system // Journal of Geodesy. October 2010.
22. *Gian Paolo Candini, Fabrizio Piergentili, Fabio Santoni*. Miniaturized attitude control system for nanosatellites// Acta Astronautica Volume 81, Issue 1, December 2012, Pages 325-334.

23. *Michael Ovchinnikov, Vladimir Pen'ko, Olle Norberg, Stas Barabash*. Attitude control system for the first swedish nanosatellite “MUNIN”// Acta Astronautica Volume 46, Issues 2–6, January–March 2000, Pages 319-326.
24. *Hendrik Ehrpais, Johan Kütt, Indrek Sünter, Erik Kulu, Andris Slavinsk, Mart Noorma*. /Nanosatellite spin-up using magnetic actuators: ESTCube-1 flight results //Journals & Books. Acta Astronautica Volume 128, November–December 2016, Pages 210-216.
25. *H. Kowalik*· A spin and attitude control system for the Isis-I and Isis-B satellitesUn systeme de commande de rotation et d'attitude pour les satellites Isis-I et Isis-BDrall- und lage-regelungssystem für die Isis-I und Isis-B //Journals & Books. Automatica. Volume 6, Issue 5, September 1970, Pages 673-682.
26. *Nuo Xu, Xiwang Xia, Yonghe Zhang, Jun Jiang, Yuchi Ding*. PD-type Magnetic-based Sun-pointing Attitude Control Scheme//Chinese Control Conference (CCC). 11 October 2022.
27. *Giulio Avanzini, Alessandro Zavoli, Guido DeMatteis, Fabrizio Giulie*. Single axis pointing for underactuated spacecraft with a residual angular momentum// Journals & Books. Aerospace Science and Technology Volume 124, May 2022.