

Article

Low-Cost Orientation Determination System for CubeSat Based Solely on Solar and Magnetic Sensors

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Abstract: CubeSats require accurate determination of their orientation relative to the Sun, Earth, and other celestial bodies to operate successfully and collect scientific data. This paper presents an orientation system based on solar and magnetic sensors that offers a cost-effective and reliable solution for CubeSat navigation. Solar sensors analyze the illumination on each face to measure the satellite's orientation relative to the Sun, while magnetic sensors determine the Earth's magnetic field vector in the satellite's reference frame. By combining the measured data with the known ephemeris of the satellite, the satellite–Sun vector and the magnetic field orientation can be reconstructed. The orientation is expressed using quaternions, representing the rotation from the internal reference system of the satellite to the selected reference system. The proposed system demonstrates the ability to accurately determine the orientation of a CubeSat using only two sensors, making it suitable for installations where more complex and expensive instruments are impractical. Additionally, the paper presents a mathematical model of a low-cost CubeSat orientation system and a hardware implementation of the sensor. The technology, using solar and magnetic sensors, provides a reliable and affordable solution for CubeSat navigation, supporting the increasing sophistication of miniature payloads and enabling accurate satellite positioning in space missions.

Keywords: CubeSat; satellite orientation; solar sensors; magnetic sensors; attitude determination; satellite–Sun vector; magnetic field orientation; quaternions



Citation: Nurgizat, Y.; Ayazbay, A.-A.; Galayko, D.; Balbayev, G.; Alipbayev, K. Low-Cost Orientation Determination System for CubeSat Based Solely on Solar and Magnetic Sensors. *Sensors* **2023**, *23*, 6388. <https://doi.org/10.3390/s23146388>

Academic Editor: Zvonimir Šipuš

Received: 12 June 2023

Revised: 7 July 2023

Accepted: 11 July 2023

Published: 14 July 2023



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1. Introduction

An important aspect of CubeSat operations is determining the satellite's orientation relative to the Sun, Earth, and other celestial bodies. The technology used in the development of CubeSat orientation sensors includes solar and magnetic sensors [1,2]. This information is necessary for spacecraft orientation [3,4], control, and collecting accurate scientific data [5]. The purpose of the solar sensor is to determine the coordinates of the satellite–Sun vector [6,7] in the reference frame associated with the satellite. This is achieved by processing photoelectric signals from solar sensors located on the six sides of the satellite [8,9].

Modeling shows that the precision of attitude determination can be better than 1°. Furthermore, the Radio Aurora Explorer 3U CubeSat [10] demonstrated, back in 2014, that it is possible to obtain information about the satellite's position with accuracy better than 1° (solar light) in orbit [11,12]. This is especially true when the satellite is on the sunny side, as multiple sensors are used for successful task execution. However, this determination is more difficult during eclipses [13]. Determining the orientation of CubeSat satellites remains a challenging task, as they are small and still lack active orientation and control systems [14,15]. Additionally, new miniature payloads for space-based missions are becoming increasingly complex and require accurate knowledge of a satellite's position.

One of the main goals of the SAT mission is to develop a CubeSat orientation algorithm that will exceed a few degrees of accuracy when using two sensors, particularly in sunlight. This objective aims to overcome the limitations of using complex and expensive tools like star sensors. Consequently, this paper presents an orientation system based solely on two sensors: a solar sensor and a magnetometer, which can be easily installed on any CubeSat. This system offers a practical alternative for situations where more elaborate instruments are not feasible.

Still, the utilization of solar and magnetic sensors in CubeSat orientation systems provides several advantages. Firstly, it is a cost-effective and reliable solution, making it accessible for a wide range of CubeSat missions. Secondly, the availability of solar and Earth's magnetic fields throughout most regions on our planet enables the utilization of this technology for CubeSat navigation, regardless of the mission's location.

In summary, this paper aims to present a comprehensive orientation system for CubeSats based on solar and magnetic sensors, highlighting its feasibility and advantages. The proposed system, utilizing only two sensors, offers a practical solution for determining CubeSat orientation and addresses the challenges posed by limited hardware and energy resources. Through its cost-effectiveness, reliability, and accessibility, the technology opens up new possibilities for CubeSat missions, supporting their growing complexity and enabling precise knowledge of the satellite's position in space-based operations.

The scope of this orientation system based on solar and magnetic sensors extends to CubeSat operations and scientific data collection, and also encompasses the development of a mathematical model, hardware implementation, and practical application of the orientation system.

The novelty of this work lies in the mathematical model, which is a new methodology for more accurate determination of the orientation of nanosatellites using budget sensors.

The article is structured as follows: Section 2 describes the mathematical model of the satellite orientation system and presents the sensor architecture. Section 3 discusses the operational algorithm and the hardware implementation of the sensor. In Section 4, a detailed presentation of the results obtained from studying the algorithm of the proposed system in laboratory conditions is provided. The concluding remarks are presented in Section 5.

2. Materials and Methods

This chapter presents a mathematical model of the orientation system and provides detailed descriptions of the hardware architecture of the sensors.

2.1. Theory of the Proposed Attitude Sensor

In this subchapter, a mathematical model based on the solar and magnetic sensors of the passive orientation system of the nanosatellite is constructed.

The solar and magnetic sensors are used to collect raw information about the CubeSat's orientation: the satellite–Sun vector and the magnetic field orientation. If the satellite's position in orbit is known, these data allow for the recovery of the satellite's attitude.

Solar sensors measure the orientation of the satellite relative to the Sun. These sensors measure the illumination of each face of the satellite, and the processing unit computes the direction of the satellite–Sun vector S [16,17]. Magnetic sensors are used to measure the Earth's magnetic field vector B in the satellite's reference frame.

If the ephemerides of the satellite are known, it is possible to determine the reference values of the magnetic field vector and the satellite–Sun vector from publicly available astronomical databases and models. By measuring the positions of the Sun and the value of the magnetic field using the satellite's sensors at a specific moment in time and comparing these data with real data, we obtain information about the satellite's position in the selected reference system. The attitude of a satellite can be conveniently expressed using quaternions. A quaternion is a mathematical object defined by four real numbers that represent a rotation in a three-dimensional space. The satellite's attitude is defined by a quaternion that rotates the internal satellite reference frame to align it with a selected reference frame (e.g., an

inertial geocentric frame). In this work, the selected reference frame for attitude expression is J2000.

Both reference vectors B and S are expressed in the J2000 geocentric inertial coordinate system and denoted as B_j and S_j . The satellite's sensors measure these same vectors in coordinates related to the satellite and denoted as B_s and S_s . The position of the satellite is determined by a quaternion that aligns the satellite's coordinate system with the J2000 system. This quaternion is defined by the rotation that aligns two pairs of vectors: B_s , S_s , and B_j , S_j . This rotation is calculated in two steps. In the first step, a rotation that aligns the vectors B_s and B_j calculated by determining the direction vector of the rotation axis using Equation (1). This vector is equal to the normal vector to the plane formed by vectors B_s and B_j .

$$\vec{n} = \left[\vec{B}_j \times \vec{B}_s \right] / \left(\frac{\vec{B}_j, \vec{B}_s}{\left| \vec{B}_j \right|, \left| \vec{B}_s \right|} \right) \quad (1)$$

Then, the angle between vectors B_s and B_j is calculated using Equation (2):

$$\vec{y} = \arccos \left(\left| \frac{\vec{B}_s}{\left| \vec{B}_s \right|} \times \frac{\vec{B}_j}{\left| \vec{B}_j \right|} \right| \times \cos \alpha \right) / \left(\frac{\vec{B}_s}{\left| \vec{B}_s \right|} / \frac{\vec{B}_j}{\left| \vec{B}_j \right|} \right) \quad (2)$$

And a quaternion for the first rotation can be expressed in form:

$$q1 = \left[\cos(y/2) \vec{n} * \sin(y/2) \right]. \quad (3)$$

During this rotation, vector B_s is transformed into vector B_j , while vector S_s takes a new value S_s' Equation (4):

$$S_s' = \begin{bmatrix} 1 - 2q_1^2 - 2q_3^2 & 2(q_1q_2 + q_0q_3) & 2(q_1q_3 - q_0q_2) \\ 2(q_1q_2 - q_0q_3) & 1 - 2q_1^2 - 2q_3^2 & 2(q_2q_3 + q_0q_1) \\ 2(q_1q_3 + q_0q_2) & 2(q_2q_3 - q_0q_1) & 1 - 2q_1^2 - 2q_2^2 \end{bmatrix} \begin{bmatrix} S_{s1} \\ S_{s2} \\ S_{s3} \end{bmatrix} \quad (4)$$

After the first rotation, vector B_s is transformed into vector B_j , and vector S_s takes on a new value, S_s' .

In the second step, it becomes necessary to rotate vector S_s' around the axis defined by vector B_j in order to align it with vector S_j . However, achieving perfect alignment is challenging due to measurement errors. The angles between the initial vectors B_s , S_s , B_j , and S_j are likely to differ, although they should ideally be the same in theory.

Therefore, a rotation of vector B_j is calculated to minimize the difference between the rotated vector S_s' and vector S_j 's norm. An optimization algorithm, such as the gradient descent method, can be employed to find the rotation angle that minimizes this difference. This is accomplished by defining a function $f(\alpha)$ that calculates the Euclidean difference between the rotated vector, S_s' , and vector S_j . The rotation is determined by the rotation axis, which is equal to B_j , and the angle α , using Equation (5):

$$f(a) = \|S_j - \text{rot}(S_j, \text{norm}(B_j), a)\|, \quad (5)$$

where, $\text{rot}(x, n, \alpha)$ is the result of rotating the vector x by angle α around the axis n . Using the optimization algorithm, α is found that minimizes the value of the function.

Now it is possible to calculate the second rotation quaternion, 'q2', using Equation (6):

$$q2 = \left[\cos(\alpha/2) \vec{B}_j * \sin(\alpha/2) \right]. \quad (6)$$

Finally, the quaternion expressing the orientation of the satellite is obtained by multiplying quaternions $q1$ and $q2$ using Equation (7):

$$q = q1 * q2 \quad (7)$$

The result is verified in two steps. First, one calculates the triple product of vectors using Equation (8):

$$\text{dot}(\text{cross}(\text{quatrotate}(q, Ss), Bj), Sj) \quad (8)$$

where, dot is a dot (x,y) product operator, $\text{cross}(x,y)$ is a cross product operator, $\text{quatrotate}(q,x)$ is a function rotating a vector x according to the quaternion q . If the calculation is correct, the result should be close to zero (it means that the aligned vectors and vector Sj are on the same plane).

The second verification step consists of comparing the vectors Bj and the rotated vector Bs using Equation (9):

$$\|Bj - \text{quatrotate}(q, Bs)\| \quad (9)$$

The result should also be close to zero.

2.2. Hardware Architecture

In this subchapter, the hardware architecture of the sensor connection to the microcontroller is implemented.

An orientation determination system for CubeSats based on solar and magnetic sensors can be implemented using the following hardware architecture, which is shown in Figure 1:

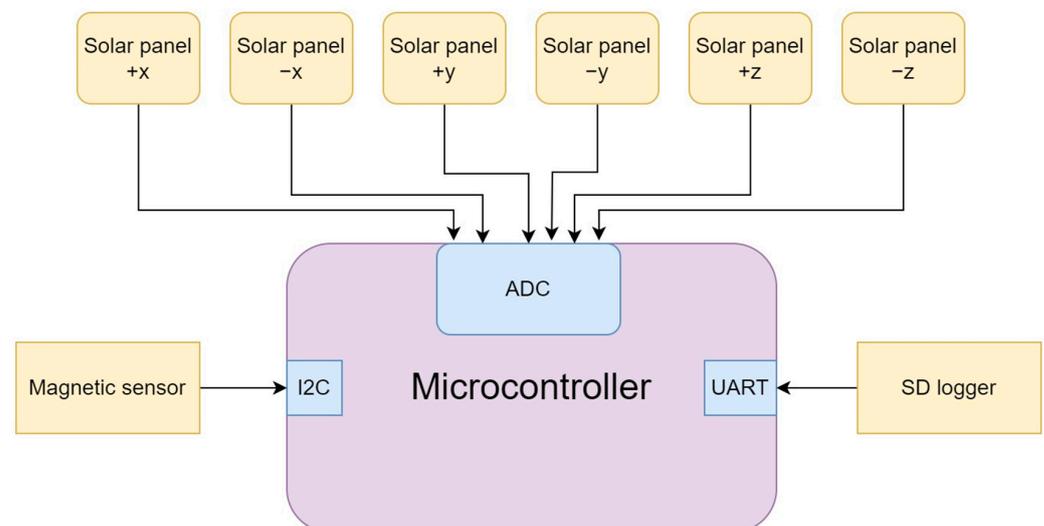


Figure 1. Architecture of the proposed CubeSat orientation system.

Six solar sensors, such as photodiodes, were placed on each face of the CubeSat to measure the intensity of sunlight. The 6 faces of the CubeSat were determined as follows $+x, -x, +y, -y, +z, -z$.

A three-axis magnetometer was used to measure the Earth's magnetic field. The magnetometer was placed in a suitable location on the CubeSat to measure the intensity and direction of the magnetic field.

A microcontroller was used to interact with the solar sensors and magnetometer for data processing. It was programmed to perform calculations to determine the satellite's orientation.

The overall system architecture is relatively simple and inexpensive as it only requires a few inexpensive sensors, a microcontroller, and power source components. The system can be integrated into a CubeSat during the design phase or added as an upgrade to existing CubeSat equipment.

2.3. Architecture and Model of Magnetic Sensor

In this subchapter, the architecture of the magnetic sensor used is presented.

Electronic three-axis magnetometers based on anisotropic magneto-resistive (AMR) technology are used as magnetic sensors on CubeSats to measure the magnetic field strength in different directions. The magnetometer used is the LSM303DLH, an inexpensive three-axis digital magnetometer capable of measuring magnetic fields in the range of ± 8 Gauss [18]. The LSM303DLH magnetic sensor is a digital compass that measures the Earth's magnetic field in three dimensions (X, Y, Z). The sensor is located such that its own coordinate axes coincide with the axes of the satellite's internal coordinate system, thus directly outputting the value of the B_s vector.

3. Practical Implementation of the Sensor Relative Attitude

In this chapter, a practical application of the orientation system is demonstrated, and the electrical circuit for sensor connections is presented. Additionally, a practical implementation in the form of a ready-made board is provided.

For the implementation of the above-proposed system, we used Arduino. The mathematical model of the CubeSat's orientation system was transformed into software code in the Arduino IDE. The block diagram of the system is shown in Figure 2.

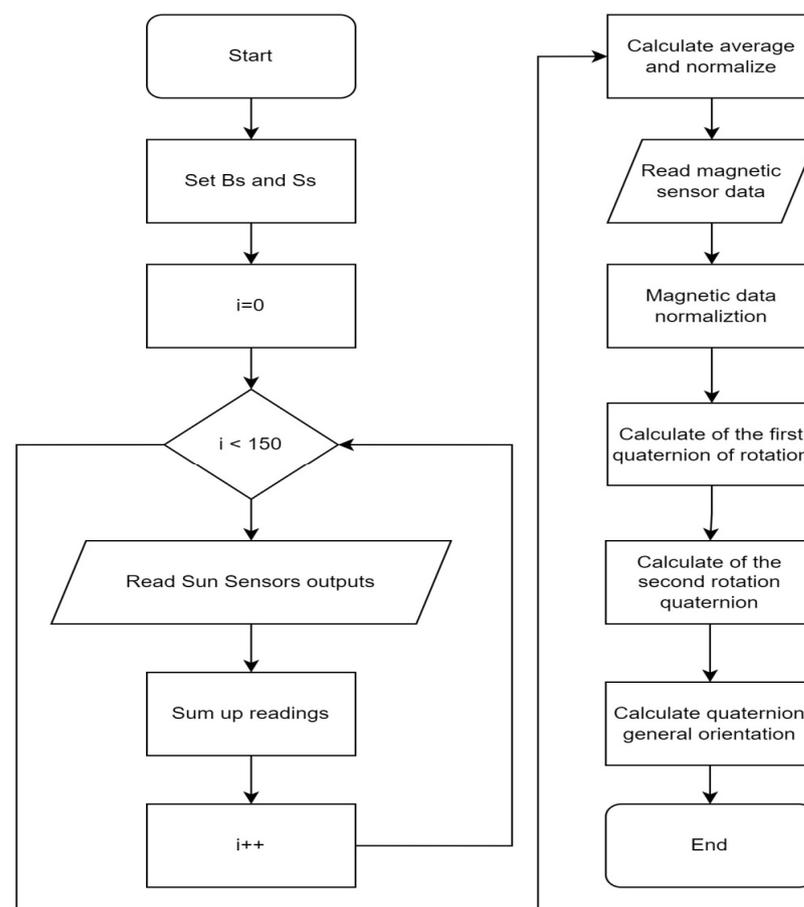


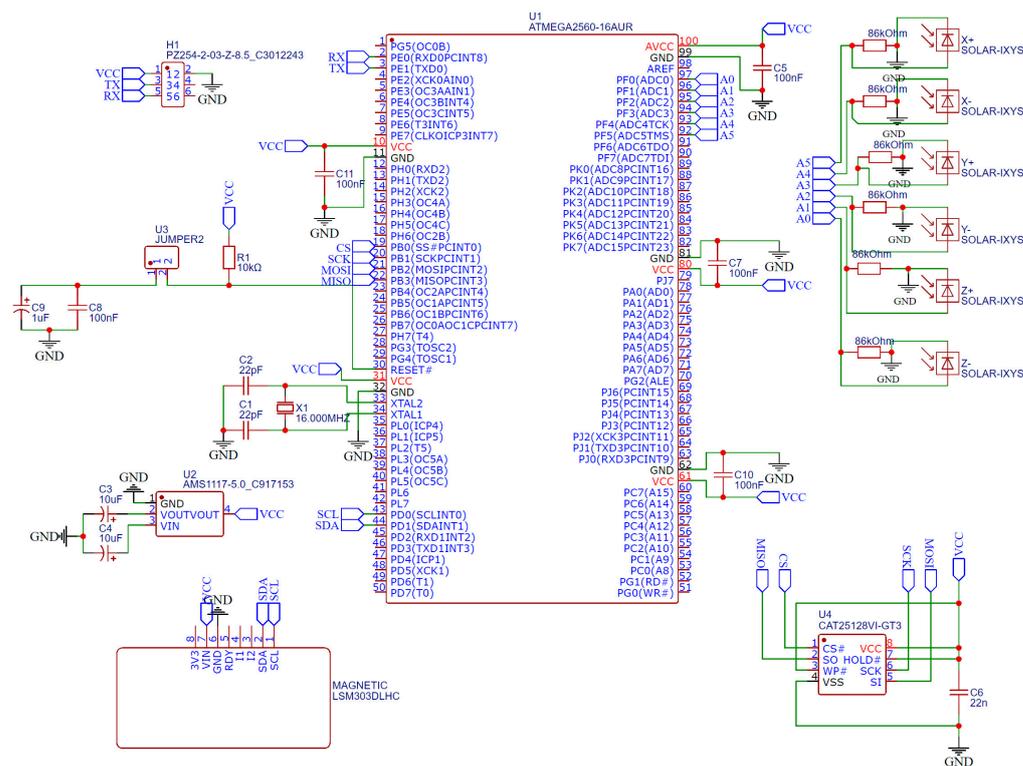
Figure 2. Orientation system computation algorithm.

The orientation system computation algorithm consists of several main steps:

- Reading variables from solar panels. For more accurate data, the program reads 150 values from each panel and outputs the average value. Then, the data from the solar panels are normalized.
- Reading variables from the magnetic sensor and normalizing them.

- Calculating the quaternion for the first rotation.
- Calculating the quaternion for the second rotation.
- Calculating the quaternion that expresses the overall orientation of the CubeSat.

Based on the constructed architecture of the CubeSat orientation system, a connection diagram of the sensors to the microcontroller was developed, as well as the manufacture of the orientation system board. The electrical circuit diagram of the system is shown in Figure 3.



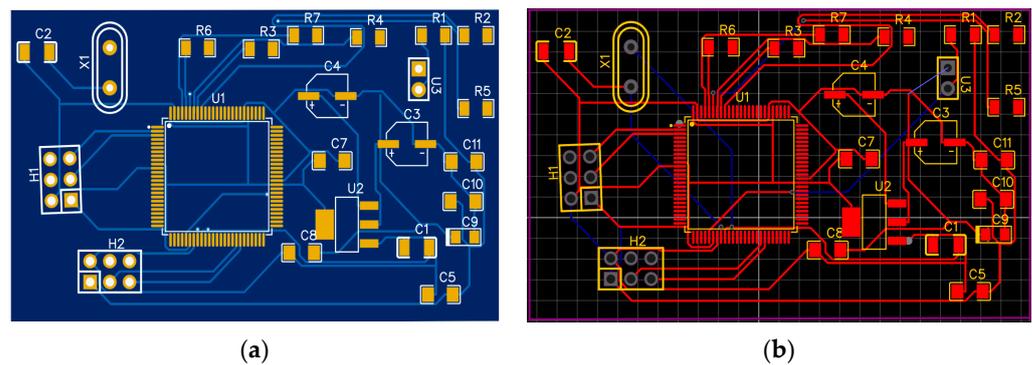


Figure 4. Parts setup diagram for making a double-sided circuit board. (a) First side of the board; (b) second side of the board.

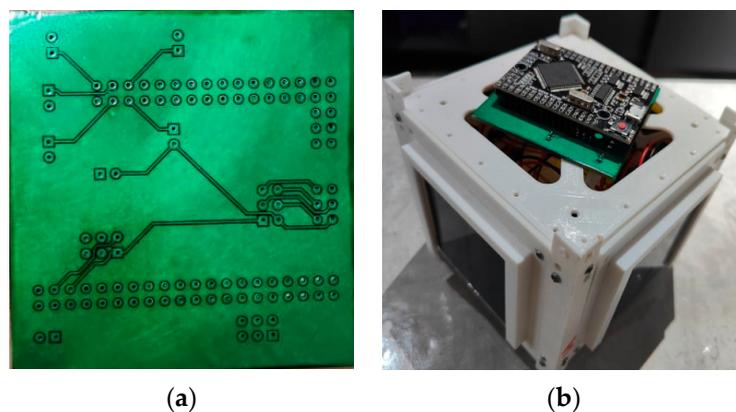


Figure 5. The board is completed using a CNC machine. (a) Printed circuit board; (b) ready-made board with a microcontroller.

4. Experimental Results

This chapter presents the results of experiments conducted to test the proposed passive orientation system of the nanosatellite in the laboratory conditions of the university.

The experiment was conducted in the university's laboratory. An electric lamp was chosen as a Sun emulator, and a supporting frame was used to install the CubeSat, which is shown in Figure 6.



Figure 6. Experimental study using Cubesat.

Before characterizing the developed orientation sensor, calibration of the measurement instruments was carried out. Using an online calculator, the data of the Earth's position in the heliocentric reference system for the year 24 April 2023 were calculated [19], as well as the magnetic field data in the geocentric reference frame at the laboratory location [20].

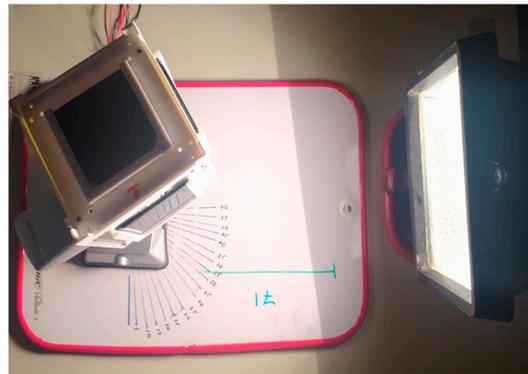


Figure 10. 1 experiment. The Sun's rays fall on only two faces of the Cubesat.

Table 1. Satellite orientation data for two panels.

Angle of Rotation		Quaternion	Angle of Rotation		Quaternion
0	Exp. Th.	0.95, −0.17, −0.07, −0.01 1, 0, 0, 0	200	Exp. Th.	−0.22, −0.28, −0.09, 0.98 −0.17, 0.0, 0.0, 0.98
20	Exp. Th.	0.94, −0.35, 0.01, −0.07 0.98, 0.0, 0.0, 0.17	220	Exp. Th.	−0.29, −0.23, −0.07, 1.00 −0.34, 0.0, 0.0, 0.93
40	Exp. Th.	0.92, −0.39, 0.02, −0.35 0.93, 0.0, 0.0, 0.34	240	Exp. Th.	−0.50, −0.25, −0.11, 0.89 −0.49, 0.0, 0.0, 0.86
60	Exp. Th.	0.89, −0.42, 0.02, −0.54 0.86, 0.0, 0.0, 0.49	260	Exp. Th.	−0.65, −0.25, −0.12, 0.79 −0.64, 0.0, 0.0, 0.76
80	Exp. Th.	0.76, −0.24, 0.01, 0.77 0.76, 0.0, 0.0, 0.64	280	Exp. Th.	−0.74, −0.26, −0.13, 0.68 −0.76, 0.0, 0.0, 0.64
100	Exp. Th.	−0.50, −0.18, −0.08, 0.97 0.64, 0.0, 0.0, 0.76	300	Exp. Th.	−0.84, −0.26, −0.14, 0.58 −0.86, 0.0, 0.0, 0.50
120	Exp. Th.	0.31, −0.20, −0.09, 0.88 0.50, 0.0, 0.0, 0.86	320	Exp. Th.	−0.91, −0.26, −0.13, 0.44 −0.93, 0.0, 0.0, 0.34
140	Exp. Th.	0.35, −0.22, 0.08, 0.95 0.34, 0.0, 0.0, 0.93	340	Exp. Th.	−0.96, −0.26, −0.14, 0.24 −0.98, 0.0, 0.0, 0.17
160	Exp. Th.	0.22, −0.26, −0.07, 0.99 0.17, 0.0, 0.0, 0.98	360	Exp. Th.	−0.98, −0.20, −0.09, 0.11 −0.99, 0.0, 0.0, 0.0
180	Exp. Th.	0.02, −0.27, −0.08, 0.99 0.0, 0.0, 0.0, 0.99			

Experiment 2: The objective of the second experiment was to illuminate three faces of the CubeSat simultaneously. The experiment was conducted as follows:

The satellite was positioned such that the Sun equally illuminated three panels adjacent to one of the vertices (Figure 12). Simultaneously, a magnetic sensor was installed inside the satellite, aligned with the local magnetic axis as the initial position. Illumination readings of the satellite panels were then taken. The experimental results corresponding to the satellite's vertices are shown in Table 2.

By comparing the analysis from the tables, it can be observed that the Sun's rays fell on the three satellite panels in a highly consistent manner. Additionally, this algorithm calculates the orientation of the nanosatellite, specifically the quaternion.

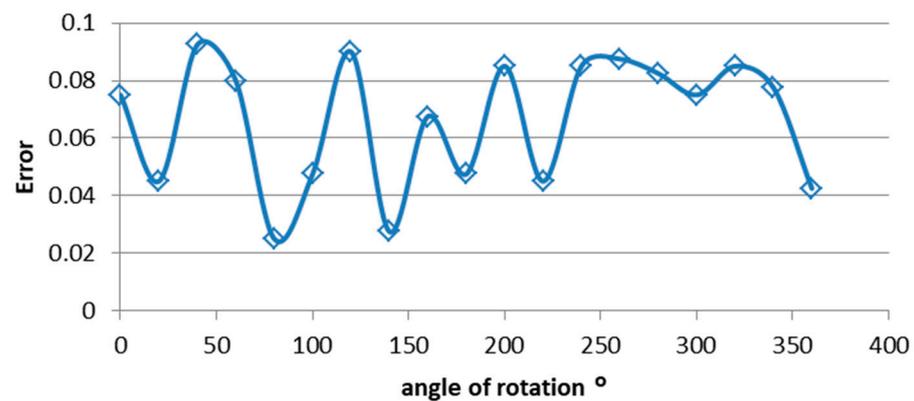


Figure 11. Sensor measurement error.

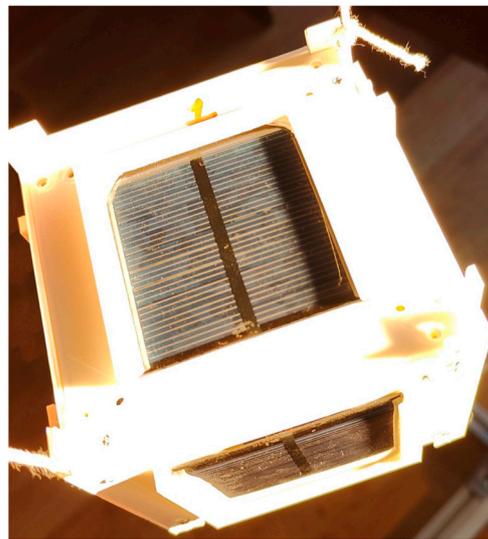


Figure 12. Experiment 2. The Sun's rays fall on the three faces of the CubeSat.

Table 2. Satellite orientation data for three panels.

CubeSat Facets	Quaternion
+z, +x, +y (+z: 0.54 +x: 0.60 +y: 0.58 -x: 0.12 -y: 0.07)	-0.34, -0.36, -0.11, -0.99
+z, +x, -y (+z: 0.61 +x: 0.57 +y: 0.08 -x: 0.08 -y: 0.56)	-0.52, 0.14, 0.02, -0.99
+z, -x, -y (+z: 0.53 +x: 0.08 +y: 0.08 -x: 0.61 -y: 0.57)	0.66, -0.15, 0.43, -0.89
+z, +y, -x (+z: 0.60 +x: 0.05 +y: 0.60 -x: 0.52 -y: 0.01)	-0.25, -0.50, 0.23, -0.84

5. Conclusions

This paper includes a discussion of the results obtained from laboratory tests conducted on an inexpensive CubeSat in the CubeSat format. The primary objective of these tests was to determine the coordinates of the satellite–Sun vector in the satellite's reference frame, using magnetic sensors and Sun sensors. These coordinates were then utilized to accurately determine the CubeSat's orientation. By incorporating a magnetic sensor and developing a mathematical model of the CubeSat's passive orientation system, experimental testing was conducted under controlled laboratory conditions. The results of these tests demonstrated the system's capability to accurately determine the satellite's orientation throughout the orbital day.

In the first experiment, the proposed sensor of the passive orientation system of the nanosatellite was tested. A comprehensive analysis of the solar panels was performed, and a mathematical model for the solar sensors was constructed. Additionally, experiments were conducted at various distances from the solar simulator. The detailed data and findings of this experiment can be found in the source provided [16].

In the second experiment, aimed at enhancing the accuracy of the nanosatellite's orientation, a second sensor was incorporated to measure the Earth's magnetic field. Following the integration of this second sensor, a mathematical model of the complete passive orientation system was developed. The outcome of this experiment yielded an orientation sensor with an error rate of 1.2%, which was a significant achievement in laboratory conditions.

In conclusion, the exclusive utilization of solar and magnetic sensors for orientation determination presents a cost-effective solution for CubeSats. These sensors are generally affordable and have low power requirements, making them particularly advantageous for CubeSats with limited resources. Moreover, the combination of information gathered from these sensors enables accurate orientation determination without the need for additional sensors or complex algorithms. This straightforward and cost-effective method of orientation determination is a noteworthy advancement in enhancing access to spaceflight for a broader range of organizations.

It is worth noting that this system exhibits potential for further expansion in the future. It can be adapted to accommodate various installations, incorporate various sensor types, facilitate scientific research, and investigate various anomalies. By harnessing the benefits of solar and magnetic sensors, CubeSat missions can continue to evolve and effectively address the increasing demands of space exploration and scientific investigations.

In summary, the results obtained from the laboratory tests validate the effectiveness and reliability of the proposed orientation system based on solar and magnetic sensors. These results instill confidence in the system's ability to accurately determine the CubeSat's orientation, thereby supporting the successful operation and data collection of CubeSat missions. With its affordability, simplicity, and adaptability, this orientation system offers a promising avenue for advancements in CubeSat technology and expands the opportunities for organizations to participate in space-based activities.

Author Contributions: Conceptualization, D.G. and Y.N.; methodology, D.G. and Y.N.; software, Y.N. and A.-A.A.; validation, Y.N.; formal analysis, Y.N.; investigation, Y.N.; resources, Y.N., G.B. and K.A.; writing—original draft preparation, Y.N.; writing—review and editing, D.G.; supervision, D.G.; project administration, D.G.; funding acquisition, Y.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP14869120—Development and creation of narrow-directional «satellite-satellite» antenna systems with the best and optimal characteristics for the CubeSat form factor).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that has been used is confidential.

Acknowledgments: This project was supported by the “Bolashak” funding.

Conflicts of Interest: The authors declare no conflict of interest.

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