Attitude Determination Algorithm Using Earth Sensor Images and Image Recognition*

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This paper describes a new algorithm to determine the attitude of micro-/nano-satellites using an Earth sensor. For recent micro-/nano-satellites, the requirements for attitude determination accuracy are becoming more stringent, despite its limited volume. Since Earth sensors have the advantage of smaller size, some studies have presented using them as attitude sensors; however, they could not achieve fully automatic processing in real-time. Therefore, we have developed an algorithm that effectively combines geometrical consideration and image recognition technology, thus realizing high autonomy, robustness, and real-time processing. The validity of this algorithm is confirmed through ground experiments. The algorithm operates at a rate of 0.2 Hz and achieves an accuracy of 0.1°–1 deg, which is similar to the accuracy of a coarse sun sensor. Furthermore, it is capable of determining the three-axis attitude using only an Earth sensor and a GNSS receiver for position information. This study proves that the bus equipment required for attitude determination systems in micro-/nano-satellites can be reduced, thereby contributing to increased design freedom.

Key Words: Astronautics, Attitude Determination, Earth Sensor

Nomenclature

(X, Y, Z): position on the Earth fixed coordinate in rectangular way
(a, β, A): position on the Earth fixed coordinate in latitude, longitude and altitude
O: origin of the Earth fixed coordinate
(x, y, z): position on the sensor fixed coordinate
o: origin of the sensor fixed coordinate
(u, v): position on the image coordinate
(r, Ψ): position on the FoV screen
(θ, φ, ψ): three-axis attitude parameters
a, b, c: coefficients of plane equation
C: center of the circle on a unit sphere
D: distance between o and C
f: focal length of the Earth sensor
L: distance between p and O
p: point on Earth surface
R: radius of the Earth
θs: angle between op and oO
θE: angle between Op and Oo

1. Introduction

In recent years, the importance of attitude systems has increased even for micro-/nano-satellites. The missions of the world’s first CubeSats, launched in 2003, were satellite bus demonstration. Since the 2010s, the number of micro-/nano-satellites that have been launched has increased dramatically, and the types of missions have also diversified at the same time. As a result, the requirements for attitude systems have increased. In particular, some micro-/nano-satellites for science and Earth observation missions require high accuracy, which is not much different from that required for large satellites. Going forward, more and more micro-/nano-satellites are expected to require attitude systems with greater accuracy.

We focussed on Earth sensors using small cameras as the attitude sensor for micro-/nano-satellites since they have advantages in terms of volume and weight. Star Trackers (STTs) are the most popular attitude sensors at present. The advantages of STTs include high accuracy and the ability to determine three-axis attitudes by themselves. However, STTs require optical systems larger than a certain size to detect stars that are fainter than some threshold. On the other hand, Earth sensors do not require large optical systems, since the Earth is sufficiently bright when sunlight strikes it.

The studies of Refs. 8)–10) have utilized Earth sensors with a small camera. The methods proposed in these studies involve determination of the nadir vector using Earth Edge detection. In particular, in Ref. 10), three-axis attitude determination is performed using the waxing and waning of the Earth. In order to use this method, it is necessary to see a wide area of the Earth; however, this is difficult for micro-/nano-satellites, which often take a low Earth orbit.

Another method for detecting three-axis attitude is to utilize the information on the surface of the Earth. In Refs. 11) and 12), three-axis attitude determination is performed by matching the image taken with an Earth observation camera and the image captured by another satellite. This method,

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however, requires a very large calculation cost if no a priori attitude information is obtained from the other sensors. In addition, given the impact of disturbances such as clouds on the image, it is difficult to use without human intervention. Therefore, it is difficult to make fully autonomous on-board real-time attitude determination.

To achieve such robustness, we adopt image recognition technology. In recent years, research on image recognition has been very active, and it is becoming faster and more accurate. Especially, in the field of automated driving, on-board real-time object recognition has become more realistic.\textsuperscript{13,14}\textsuperscript{15} We optimize these technologies for space use and use them for solving the above problem. In addition, we propose a new algorithm for image matching to reduce the amount of calculation.

In order to realize an attitude sensor using these technologies, we started a project named “Deep Learning Attitude Sensor (DLAS).”\textsuperscript{15} DLAS is a project adopted as a mission component of the satellite “Innovation Satellite Technology Demonstration-1” led by JAXA. It was launched in January 2018 and is now in the on-orbit demonstration phase. DLAS has three missions: i) to demonstrate an attitude sensor using an Earth sensor, as described in this paper; ii) to demonstrate an in-house-made STT; and iii) to realize the attitude sensors at a low cost using commercial off-the-shelf (COTS) devices. The algorithm described in this paper is now being demonstrated through this project. The progress of the experiment has been reported in Ref. 16).

In this paper, a new method is proposed to determine the three-axis attitude of a spacecraft using an Earth sensor. This method makes effective use of image recognition technology, and is capable of working fully autonomously under a wide range of conditions. Furthermore, some ingenuity is introduced to reduce the calculation cost and realize real-time use. We also describe the experiment that was conducted on the ground using the proposed algorithm.

This paper is organized as follows. Section 2 introduces the problem settings and the notations used in this paper. Section 3 describes the proposed algorithm in detail. Section 4 discusses the ground experiment used to evaluate the algorithm and its results. Finally, Section 5 presents our concluding results.

2. Setup

In this section, some assumptions and parameter definitions are specified.

2.1. Coordinate frame

Consider the position of a spacecraft in the Earth fixed coordinate system shown in Fig. 1. It is represented in two ways: a rectangular coordinate system \((X, Y, Z)\) and polar coordinate system \((A, \alpha, \beta)\), which indicate the altitude, latitude, and longitude, respectively. Here, taking a picture with a camera is modeled as projecting a three-dimensional object onto a two-dimensional plane. Let us define coordinate systems in perspective projection model,\textsuperscript{17} indicated in Fig. 2. \((x, y, z)\) is an Earth sensor fixed right-hand orthogonal coordinate system, where \(-z\) is the sight direction of the Earth sensor and origin \(o\) is the optical center of the Earth sensor lens. Next, we consider an imaginary screen at the location \(z = -f\). We take a two-dimensional coordinate frame \((u, v)\), named the “image coordinate system” corresponding to the \(x, y\) direction. A three-dimensional point \(x = (x, y, z)\) is projected onto the intersection of the imaginary screen with the ray incident at the origin \(o\), as shown in Fig. 2. Now, the image coordinates \((x, y)\) of the point \(x\) are given by

\[
u = f \frac{x}{z}, \quad v = f \frac{y}{z}. \tag{1}\]

2.2. Attitude parameters definition

The attitude parameters used in this paper are defined as shown in Fig. 3. An azimuth angle \(\theta\) and an elevation angle \(\phi\) describe the nadir direction from the sensor fixed coordinate system. The azimuth angle \(\theta\) is the angle formed by the \(-z\) direction (sight direction) and a vector obtained by projecting the nadir vector on the \(xz\) plane. The elevation angle \(\phi\) is the angle between the nadir vector and the \(xz\) plane. Next, we define the last attitude parameter \(\psi\), which describes the angle around the nadir vector. \(\psi\) is the angle formed by a plane including the \(y\)-axis and the nadir vector, and a plane including the Earth’s axis and the nadir vector, as shown in Fig. 4.

2.3. Other assumptions

In this paper, we make the following assumptions:

\begin{itemize}
  \item We ignore the ellipticity and the unevenness of the Earth.
  \item In other words, we consider that the diameter of the Earth is a known constant \(R\).
\end{itemize}
The position of the spacecraft can be obtained using orbital information, Global Navigation Satellite System (GNSS), and so on.

The parameters of the Earth sensors such as focal length \( f \) are available since they are measured in advance.

We use a small camera with a wide-angle field of view for the Earth sensor, but its lens is not the fish-eye type.

3. Attitude Determination Algorithm

In this section, we propose an attitude determination algorithm with an Earth sensor. This algorithm is for determining the three-axis attitude of the Earth sensor with respect to the Earth. It also provides the attitude of the spacecraft with respect to the inertial system, since the attitude of the camera with respect to the spacecraft and the attitude of the Earth with respect to the inertial coordinate system can be modeled in advance.

In general, the surface pattern of the Earth essentially includes three-axis attitude information; however, determining all three of the attitude parameters from only this information requires a large calculation cost. In order to reduce the calculation cost, the proposed algorithm is configured using the following two steps: nadir vector determination and determination of the angle around the nadir vector. In the step of nadir vector determination, we use the edge between the Earth and space to determine two parameters: \( \theta \) and \( \phi \). In the step of the angle around the nadir vector determination, the surface pattern of the Earth is used to detect the last parameter \( \psi \). The step of nadir vector determination significantly reduces the total calculation cost. These algorithms are described in detail in Sections 3.1 and 3.2.

3.1. Nadir vector determination

Here, we present the method to determine the nadir vector using an Earth sensor. For this, we have to determine the nadir vector from an image that shows only a part of the Earth. Since it is not assumed that the nominal attitude is Earth oriented or the lens of the Earth sensor is the full-circumference fish-eye type, only a part of the Earth may be pictured.

As the first step, the edges of the Earth are detected in a conventional way.\(^8\) Although not described in detail in this paper, the simplest way would be to apply a derivative filter (i.e., detect points where the gradient of the pixel value is larger than some threshold). Note that it is sufficient to detect some points of the Earth edge, as shown in Fig. 5, and not all of them. In other words, it is also possible to shorten the time by reducing the image. Even if there are some misdetections, they can be removed by the method described later.

Next, we describe the algorithm used to calculate the nadir direction from the edge points. It consists of three steps:

1) Project the edge points of the Earth onto a unit sphere as shown in Fig. 6(a).

2) Consider a circle formed by extending the points made in Step 1) along a spherical surface, as illustrated in Fig. 6(b). The circle on the unit sphere is a part of a plane that includes the edge points \( (\hat{x}, \hat{y}, \hat{z}) \). Therefore, the plane can be obtained from the least squares solution of the following simultaneous equation using \( n \) of the edge points:

\[
\begin{bmatrix}
\hat{x} \\
\hat{y} \\
\hat{z}
\end{bmatrix}
= \frac{1}{\sqrt{u^2 + v^2 + f^2}}
\begin{bmatrix}
u \\
v \\
f
\end{bmatrix}.
\]

3) Then, the vector to the center of the circle, named \( OC \), is the nadir vector, as indicated by Fig. 6(c). The vector \( OC \)
is a perpendicular from the origin \( O \) to the circle on the unit sphere. Hence, the parameters of the nadir vector \( \theta \) and \( \phi \) are obtained using the following equations,

\[
\begin{align*}
\theta &= \arctan2(a, -c), \\
\phi &= \arctan2(b, \sqrt{a^2 + c^2}),
\end{align*}
\]

where \( \arctan2(y, x) := \arctan(y/x) \).

Although this procedure appears to be indirect, it has advantages in that it automatically satisfies the constraint conditions, such as the need for the major axis of the ellipse to pass through the origin. Furthermore, the circle on the unit sphere studied here is convenient when removing misdetection.

Here, we explain the algorithm used to eliminate misdetection of the edge points. The above procedure should be performed after eliminating misdetection, as described here. The method introduced here is based on RANSAC. Conventional RANSAC excludes samples with large fitting errors; however, it can choose the boundary between shade and daytime areas. Therefore, we propose a method to choose edges that would lead to the likely curvature radius. As shown in Fig. 7, we can obtain the distance \( D \) between the circle on the unit sphere and the origin from the Earth’s diameter and satellite altitude using

\[
D = \cos\left(\sin^{-1}\left(\frac{R}{R + A}\right)\right)
= \sqrt{1 - \frac{R}{R + A}}.
\]

Then, the points that form a circle with a distance \( D \) that is different from the true value should be removed. The specific procedure is as follows.

1) Calculate the true \( D \) using Eq. (5).
2) Choose three points randomly from the edges set.
3) Calculate a circle on the unit sphere with the chosen points using Eq. (3), and then find the distance \( D \) to the origin using

\[
D = \frac{|d|}{\sqrt{a^2 + b^2 + c^2}}.
\]

4) Repeat 2)–3) and find a set of three edge points with the nearest \( D \) to the true value.
5) Consider a plane that consists of the points chosen in 4). Then, choose the edge points whose distances to the plane are smaller than some threshold.
6) Using the edge points thus selected, determine the nadir vector using the procedure described in the previous paragraph.

This method can remove arc features that do not appear to be the Earth edges. The boundary between the day and night areas are therefore expected to be eliminated in the edge detection step and in this step.

3.2. Determination of angle around the nadir vector

In this section, we present the method for determining the attitude angle around the nadir vector. This algorithm is based on matching between the contour of a coast pictured by the Earth sensor and preloaded map data. In other words, we find the attitude parameter \( \psi \) that makes the image and the map coincide the most. Using the spacecraft position data and the result of the nadir vector determination to reduce the degree of freedom of matching, we reduce the calculation cost. Otherwise, searching all cases would require considerable processing cost.

We cannot simply match the picture taken by the Earth sensor and the preloaded map data because of two factors: color and features. The color appearance of the pictures depends on the weather, season, and so on. In addition, when we take a picture of land on a sphere, its shape will be distorted. To process the matching successfully, these problems must be solved.

As a measure against the color problem, we use image recognition technology to detect land/sea in the picture. By identifying them in some way, we can perform robust matching with the preloaded map data, which can be a binary of the...
land/sea. We developed a fast algorithm with neural networks; however, the details are reserved for related documents.\(^{15,19,20}\)

To solve the problem of distortion, we utilize projection for both the image obtained using the Earth sensor and the preloaded map data. There are two types of distortion between the image and map data. One is between the planar map and the spherical Earth, or in other words, distortion of the map such as that in equidistant cylindrical projection. The other distortion occurs when projecting the sphere of the Earth onto the plane of the picture. One way to realize matching in this condition is to perform the matching process on the map, Earth, or image. For example, the matching process on the image is shown in Fig. 8. However, it requires very large calculation cost because two of the projections described above are repeated in this process. In order to improve the matching speed, we present a matching method on a new plane called a “FoV (Field of View) screen,” as shown in Fig. 9. The FoV screen is located between the Earth and the spacecraft. Then, project both the image and the map onto the screen. The images taken from the spacecraft can include views only up to the horizon. Therefore, when we project all of the ranges that can appear in the picture onto the screen, it will be circular. As shown in the upper part of Fig. 10, matching is performed while rotating the projected image along this circle to determine the attitude \(\psi\) around the nadir vector. This method requires only one projection in the entire matching or \(\psi\) determination process.

For speeding up the process further, we devise a coordinate system for the FoV screen. The heaviest processing in the method presented above is rotation transformation of the image of the Earth sensor on the FoV screen. This transformation is required to repeat for each update of \(\psi\). As a measure for this problem, we utilize a polar coordinate system for the FoV screen. In other words, the projected image of the Earth sensor and the preloaded map are expressed on the polar coordinate. Therefore, since the data are rectangular in appearance, we can increment \(\psi\) simply by sliding the image in the \(\Psi\)-axis direction and perform matching, as shown in the lower part of Fig. 10. Thus, we can omit the rotation conversion and significantly reduce the calculation cost.

The projections on the FoV screen are written with the nadir vector and the satellite position. Using the nadir vector determination results \((\theta, \phi)\), the position of a point \((r, \Psi)\) on the FoV screen is written as

\[
\begin{pmatrix}
  x \\
  y \\
  z
\end{pmatrix} = R_x(\theta)R_y(\phi)R_z(\Psi)
\begin{pmatrix}
  0 \\
  r \\
  1
\end{pmatrix}, \tag{7}
\]

where \(R_x(\cdot)\), \(R_y(\cdot)\), and \(R_z(\cdot)\) are the rotational matrices around the \(x\), \(y\), and \(z\)-axis, respectively. Thus, the projection from the polar coordinate on the FoV screen \((r, \Psi)\) to the image coordinate \((u, v)\) is written as

\[
\begin{pmatrix}
  u \\
  v
\end{pmatrix} = f R_x(\theta)R_y(\phi)R_z(\Psi)
\begin{pmatrix}
  0 \\
  r \\
  1
\end{pmatrix}. \tag{8}
\]

On the other hand, the projection from the preloaded map to the polar coordinate on the FoV screen \((r, \Psi)\) can be obtained as follows. First, we obtain the distance \(L\) between the origin of the sensor coordinate system \(o\) and the surface of the Earth, such that it passes through a point on the FoV screen \((r, \Psi)\), as indicated in Fig. 11. Using the cosine formula and the quadratic formula, it is obtained as
We performed an experiment to validate the proposed algorithm and evaluate its accuracy using the configuration shown in Fig. 12. In this experiment, the target attitude determination accuracy and the execution time are set to 1 deg and 10 s (0.1 Hz of update rate), respectively. The devices are the same as those used in the on-orbit demonstration, and they are selected from COTS products after conducting environmental tests, such as radiation tests to achieve both low cost and on-orbit availability. The algorithm is implemented on a COTS single-board computer (SBC) with a quad core 1.2 GHz CPU and 1 GB RAM. As the Earth sensor, we use a small, 3 × 3 cm visible-ray camera with a resolution of 3280 × 2464 pixels. Rather than using a fisheye-type lens, a wide-angle lens with a fixed focal length of 3.04 mm and a diameter of 1.5 mm is used. Accordingly, the FoV is 62.2° × 48.8° deg. The camera took photographs of the simulation images displayed on a monitor instead of being launched into the orbit and photographing the Earth. The monitor is 1.65 × 0.93 m in size and has a resolution of 3840 × 2160 pixels, which covers the FoV and the resolution of the camera at the minimum focusing distance of 1.00 m. The camera has to be installed in front of the monitor with the optical axis aligned precisely. We aligned the position and attitude with a precision of under 1 mm and 3 pixels, respectively, using a six-axis fine movement stage, a laser distance meter and a test pattern displayed on the monitor. This alignment corresponds to an attitude accuracy of 0.06 deg between display and camera. The actual experimental image is shown in Fig. 13.

The simulated Earth images were created using a 3D rendering software “Maya,” and a high-resolution image of the Earth, “Blue Marble: Next Generation,” published by NASA. In the actual photographs, the Earth’s surface near the horizon appears white and the horizon appears blurred due to the influence of the atmosphere. In order to reproduce them, we laid a white gradation over the surface of the Earth and put a blue gradation along the edge to express the atmospheric layer. The position of the spacecraft was randomly selected with an altitude of 500 km from the surface.
of the Earth. This assumes a low Earth orbit, which is often used for micro-/nano-satellites. However, the position is limited to the day side since this method is not valid on the night side and the simulation image cannot reproduce the boundary area between the day and night sides well. The attitude was also chosen randomly, but was limited so that the Earth edge is within the FoV.

In this experiment, Earth-edge detection and image recognition are performed using the methods of Ref. 9) and Ref. 20), respectively. The image recognition is performed every square window $16 \times 16$ pixels, resulting in an output resolution of $205 \times 154$ pixels. The window size is directly related to the $\psi$ determination accuracy and the processing time for image recognition. In this experiment, a window size with an average resolution of 0.3 deg (i.e., less than half of the target accuracy) is selected in order to achieve a target attitude determination accuracy of 1 deg. Each window is classified into 10 classes, which are used for the next step after classification into three groups: land, sea, and others.

### 4.2. Results and discussions

One successful example is introduced below. Figure 14 shows the result for the process of nadir vector determination. The algorithm successfully excluded an edge misdetection and derived accurate nadir vector parameters: $(\theta, \phi) = (-46.21, 23.01 \text{ deg})$ for the true value $(-46.12, 23.08 \text{ deg})$; hence, the error was $(0.09, 0.07 \text{ deg})$. The result of image recognition is shown in Fig. 15. The result of attitude determination around the nadir vector using this was $\psi = 23.2 \text{ deg}$ for the true value (i.e., 22.8 deg), and the error was $-0.39 \text{ deg}$.

However, it was not possible to perform the process successfully in some cases. In the principal failure case in the nadir vector determination step, only the shadow part of the Earth is in the FoV. Here, no edges are shown since the images obtained are completely black. In the image recognition and $\psi$ determination steps, the algorithm encountered two types of failure. One failure type is the case in which the FoV includes only sea, as shown in Fig. 16. This algorithm is based on land/sea arrangement; therefore, both land and sea must be visible. The other failure type, which is the most frequently occurring failure, is misclassification in the image recognition step. We tried to design the matching algorithm expecting a certain amount of robustness against defects, but the process is affected with several instances of misclassification. In particular, the clouds over the sea are misidentified as land, as shown in Fig. 17, and this often causes the failure of $\psi$ determination. The principal cause of this misdetection is likely to be the color bias of the monitor and camera. The image recognition accuracy can be increased by performing color calibration, or by training the neural network using actual images taken. Further improvement in accuracy is expected by collecting actual data during on-orbit demonstration.
Nine of the 23 cases, that is 39% of the cases passed all of the steps, which are shown in Fig. 18. Table 1 and Table 2 summarize the accuracy obtained and amount of time, respectively. Note the use of root mean square (RMS) and average (i.e., arithmetic mean). The execution time is about 5 s on average; thus, it is able to perform real-time processing at a rate of 0.2 Hz. The attitude determination accuracy in the $\theta$ and $\phi$ directions became much higher than 1 deg, and that in the $\psi$ direction also achieved 1 deg. Although the accuracy obtained is almost the same as that of coarse sun sensors and horizon sensors, our study excels at the point that the Earth sensor is able to determine three-axis attitude by itself. Another point that needs to be emphasized is that the hardware for this sensor can be shared with Earth observation instruments. Since this method realize 3-axis attitude determination without increasing the weight and volume, designing of micro-/nano-satellites will be significantly more flexible.

On the other hand, this method has some limitations as is obvious from the conditions of the experiment. It cannot be used at night because it uses visible light images. In the day-night boundary area, the third axis attitude determination accuracy is highly dependent on whether or not image recognition is successful. Actually, the image recognizer used in the experiment showed lower classification accuracy around the boundary areas. To improve the classification accuracy in the boundary area, the information of shooting position and time are required. For example, since the Earth’s edge and surface both need to imaged, it would be hard to use unless the satellite attitude is maintained to be local vertical/local horizontal (LVLH) or multiple Earth sensors are used. As a result of simulation assuming the same optical system as the experiment, 40% of the entire attitude captures no edges, and 44% cannot achieve an accuracy of 1 deg. In addition, both land and sea must be visible from the satellite for $\psi$ determination. In the simulation, 96% of the cases achieve an accuracy of 1 deg if both land and sea are detected at least 1%. However, 50% of the cases cannot detect enough land and sea, and in simulation including clouds, only 34% of the cases detect enough land and sea. These limitations are more severe for satellites in low-altitude orbits. For these reasons, it is expected to be used supplementarily, such as in combination with a rate sensor.

5. Conclusion

We proposed a three-axis attitude determination algorithm using an Earth sensor with an effective combination of geometric consideration and image identification technology. The results of the ground experiment showed that the algorithm successfully detected the three-axis attitude under certain conditions, and the accuracy was similar to that of a coarse sun sensor. Moreover, it was shown that it can be executed in real-time and on-board. The on-orbit demonstration experiment of this algorithm is being performed adequately. The results are currently being analyzed and will be reported.
in another paper soon. Although it has disadvantages such as being unavailable at night, it will be a powerful choice for attitude sensors used in micro-/nano-satellites.

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References

1) Nakaya, K., Konoue, K., Sawada, H., Ui, K., Okada, H., Miyashita, N., Iai, M., and Matunaga, S.: Tokyo Tech Cubesat: CUTE-I-design & Development of Flight Model and Future Plan, 21st International Communications Satellite Systems Conference and Exhibit, 2002, p. 2388.

2) Konoue, K., Sawada, H., Nakaya, K., Ui, K., Miyashita, N., Iai, M., Okada, H., Urabe, T., Yamaguchi, N., Kashiwa, M., Omagari, K., and Matunaga, S.: Development and Operation Reports of Pico-Satellite CUTE-I. IEICE Trans. Commun. B, J88-B (2005), pp. 49–57.

3) SpaceWorks Enterprises: 2018 Nano/Microsatellite Market Forecast, 2018, Available from: http://spaceworksforecast.com (accessed May 8, 2018).

4) Sasaki, K., Kikuya, Y., Koizumi, S., Masuda, Y., Shintani, Y., Tsunemitsu, T., Furuya, T., Iwasaki, Y., Takeuchi, Y., Watanabe, K., and Matunaga, S.: Variable Shape Attitude Control Demonstration with Microsat “Hibari,” 32nd Annual AIAA/USU Conference on Small Satellites, SSC18-WK1-05, Logan, U.S., 2018.

5) Pong, C. M.: On-Orbit Performance & Operation of the Attitude & Pointing Control Subsystems on ASTERIA, Proceedings of the AIAA/USU Conference on Small Satellites, Poster Session, Vol. 1, 2018.

6) Sekiguchi, T. and Shimizu, S.: A Study on Future Prospect of Optical Attitude Sensor, Proceedings of Space Sciences and Technology Conference, 2117, Niigata, Japan, 2017 (in Japanese).

7) Ozawa, T., Yatsu, Y., Yoshii, T., Mamiya, H., Kawai, N., Shimokawabe, T., and Matunaga, S.: Development of Low-cost and High-accuracy Star Tracker, Proceedings of Space Sciences and Technology Conference, 3310, Niigata, Japan, 2017 (in Japanese).

8) Shinmin, R., Priscal, C., Oyadomari, K., Attai, W., Wolfe, J., Gazulla, O. T., and Salas, A. G.: Using a Smartphone Camera for Nanosatellite Attitude Determination, Advanced Maui Optical and Space Surveillance Technologies Conference, E104, 2014.

9) Meller, D., Sripruetkiat, P., and Makovec, K.: Digital CMOS Cameras for Attitude Determination, 14th AIAA/USU Conference on Small Satellites, Logan, the U.S., SSC00-VII-1, 2000.

10) Sekiguchi, T., Yamamoto, T., and Iwamaru, Y.: Three-Axis Attitude Estimation Experiments Using CCD Earth Sensor, J. Space Technol. Sci., 20, 1 (2004), pp. 1.16–1.23.

11) Kouyama, T., Kanemura, A., Kato, S., Imamoglu, N., Fukushima, T., and Nakamura, R.: Satellite Attitude Determination and Map Projection Based on Robust Image Matching, Remote Sens., 9 (2017), p. 90.

12) Kanemura, A., Kouyama, T., Kato, S., Imamoglu, N., Fukushima, T., and Nakamura, R.: Turning a Two-dimensional Image Sensor to an Attitude Sensor: Image Matching for Determining Satellite Attitudes, Geoscience and Remote Sensing Symposium (IGARSS), 2017 IEEE International, IEEE, 2017, pp. 2748–2751.

13) Chen, L., Yang, Z., Ma, J., and Luo, Z.: Driving Scene Perception Network: Real-time Joint Detection, Depth Estimation and Semantic Segmentation, 2018 IEEE Winter Conference on Applications of Computer Vision (WACV), IEEE, 2018, pp. 1283–1291.

14) Siam, M., Gamal, M., Abdel-Razek, M., Yogamani, S., Jagersand, M., Zhang, H.: A Comparative Study of Real-time Semantic Segmentation for Autonomous Driving, Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition Workshops, 2018, pp. 587–597.

15) Kikuya, Y., Sasaki, K., Koizumi, S., Masuda, Y., Ozawa, T., Shintani, Y., Yatsu, Y., and Matunaga, S.: Development of Low-cost and High Performance Attitude Sensor Applying Neural-network Image Recognition Technology, i-SAIRAS, 2C2, Madrid, Spain, 2018.

16) Iwasaki, Y., Kikuya, Y., Sasaki, K., Ozawa, T., Shintani, Y., Masuda, Y., Watanabe, K., Mamiya, H., Ando, H., Nakashima, T., Yatsu, Y., and Matunaga, S.: Development and Initial On-orbit Performance of Multi-Functional Attitude Sensor using Image Recognition, 33rd Annual AIAA/USU Conference on Small Satellites, SSC19-XII-04, Logan, U.S., 2019.

17) Kanatani, K.: Geometric Computation for Machine Vision, The Oxford Engineering Science Series, No. 37, Clarendon Press, Oxford University Press, New York, 1993, pp. 15–20.

18) Fischler, M. A. and Bolles, R. C.: Random Sample Consensus: a Paradigm for Model Fitting with Applications to Image Analysis and Automated Cartography, Commun. ACM, 24, 6 (1981), pp. 381–395.

19) Ohta, K., Koske, T., Yatsu, Y., and Matunaga, S.: On-board Satellite Imagery Classification using Convolutional Neural Networks, 1st International Symposium on Space Technology and Science, 2017-n-10, Matsuyama, Japan, 2017.

20) Koizumi, S., Kikuya, Y., Sasaki, K., Masuda, Y., Iwasaki, Y., Watanabe, K., Yatsu, Y., and Matunaga, S.: Development of Attitude Sensor using Deep Learning, 32nd Annual AIAA/USU Conference on Small Satellites, SSC18-WK7-01, Logan, U.S., 2018.

21) Yatsu, Y., Watanabe, K., Kikuya, Y., Kawai, N., and Matunaga, S.: In Orbit Demonstration of Raspberry Pi as a High-performance Mission OBC, 334th Annual AIAA/USU Conference on Small Satellites, SSC20-XI-04, Logan, U.S., 2020.

22) Autodesk Inc.: Maya, 2018, Available from: https://www.autodesk.co.jp/products/maya/overview (accessed February 18, 2018).

23) Przyborski, P.: NASA Visible Earth: April, Blue Marble Next Generation, 2004, Available from: https://visibleearth.nasa.gov/ (accessed January 30, 2018).

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