# Image-based attitude determination for small satellites using low-cost vision sensor



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# *Image-based attitude determination for small satellites using low-cost vision sensor*


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***Abstract*— The robust attitude determination system is an important component of many satellite missions. However, most of the small satellites operate without redundant attitude sensors and are therefore highly vulnerable to the failure of such sensors. It is common for small satellites to carry an imagery sensor as its primary payload. However, a majority of these sensors are only used for earth observation and scientific missions. This paper presents an approach to the vision-based attitude propagator concept for low-cost small satellite attitude determination and control system (ADCS). The proposed attitude determination system is a vision-based attitude propagator that is capable of propagating a satellite's attitude by tracking the motion of the visual features in an imager's field of view. The system described in this paper, implemented using a low power onboard computer, inexpensive monocular CMOS camera and MEMS-based inertial sensors, to increase the accuracy and robustness of attitude estimation algorithm to minimize different drift sources affecting visual position, attitude, and scale drift.**



***Keywords—vision-based sensor, image processing, small satellites, attitude determination***


## I. Introduction

Since year 2000, a miniature sized spacecraft technology revolutionized the small satellite industry. First started as educational tools the small satellites has been shown to be capable of accomplish a sophisticated missions and scientific experiments [1][2][3]. However, due to small satellite's low available volume, power and other constraints are limit the range of possible applications. Majority of these limitations effect on earth observation technologies and attitude determination and control systems. Achieving accurate and robust attitude determination and control system in small form factor is challenging and complete attitude knowledge in inertial space require a combination of multi sensors due to maintain attitude estimation in eclipse and sunlit sides [4]. Nowadays, most spacecraft missions use high performing star trackers for 3-axis attitude determination system to meet their mission requirements. However, these star trackers are not suitable for small satellites due to its volume and power constraints. Small satellites are often used miniaturized sun sensors and magnetometers to achieve required attitude knowledge. However, these sensors have several limitations: sun sensors cannot generate the sun vector during in eclipse, while magnetometers cannot provide accurate attitude knowledge due to the constantly changing Earth magnetic field. To overcome these limitations, vision-based attitude estimation approaches have been developed. Considering that many small satellites carry an imagery sensor for earth observation or other scientific mission purposes. On other hand, Earth horizon curvature and visual features in an imager's field of view provides a valuable attitude references for attitude estimation. Detection of a reliable world references in an imager's field of view can provide absolute measurement with a relatively constant level of accuracy. Also, this information may be redundant to provide fault-tolerance and can be used to increase accuracy of inertial measurement systems, or may be replace another attitude estimation system to reduce cost, size and power consumption. In this paper, we propose vision-based attitude propagator that combines roll and pitch angles estimation from Earth horizon curvature using image processing algorithm and inertial gyro data in Unscented Kalman Filter framework. Using the advantages of Earth horizon curvature, the roll and pitch angles are estimated by horizontal and vertical movement of Earth center in relation to the centre of imagery sensor. In this work, we focused on pitch and roll angle estimation based on Earth horizon curvature and aim at developing robust and accurate vision-based attitude determination algorithm. This paper is organized as follows. Section 2, related work is discussed. Section 3 describes the relationship between attitude, earth horizon curvature and coordinate systems. Image processing algorithm is presented in Section 4. The evaluation results of our purposed approach obtained by simulation and experiments are shown in Section 5.

## II. Related Work

Research on Earth horizon-based attitude determination system using CMOS camera is not a new idea [5][6]. Using the advantage of Earth horizon curvature in imager's field of view to estimate spacecraft's nadir vector parameter has been one main focus. Other related research is using CMOS camera as Star tracker sensor to estimate spacecraft's relative motion in 3 degrees of freedom [7]. In [8][9][10] the authors proposed an various image-based methods for remote sensing satellite's attitude determination and control system in order to derive attitude knowledge from tracked features in imager's field of view. In Earth horizon curvature-based methods, when the horizon is visible in imager's field of view, it can provide an absolute attitude knowledge from captured images. Main advantage of using CMOS camera as motion sensor is efficient, fuse with other sensors to refine the attitude accuracy and relatively inexpensive approach in terms of achieve more accurate attitude determination system for small satellites. Our approach in this paper is also based on Earth horizon curvature detection using image processing algorithm to estimate satellite's critical roll, pitch and nadir parameters then fuse with the IMU gyro measurement.

## III. ATTITUDE FROM EARTH HORIZON IMAGE

This section presents a geometric relationship between orientation of vision sensor and Earth horizon curvature as viewed from satellite. Attitude of the spacecraft is the rotation from Earth Centered Inertial frame to the satellite body-fixed coordinate frame. In this work, we assume that vision sensor is rigidly attached to the spacecraft structure and z-axis of satellite body-fixed coordinate frame is defined to be the optical axes of the vision sensor and lies in same plane as the z-axis of camera frame. Earth's portion viewed from space in imager's field of view depends on vision sensor's parameters and altitude of spacecraft. Fig. 1, Fig. 2 and Fig. 3 show the illustrations of the relationship between image plane, satellite attitude and coordinate systems. Most small satellites launched in Low Earth Orbit (LEO), often used small and low-cost CMOS camera for its defined mission. These vision sensors have fixed lenses, focal length and field of view.

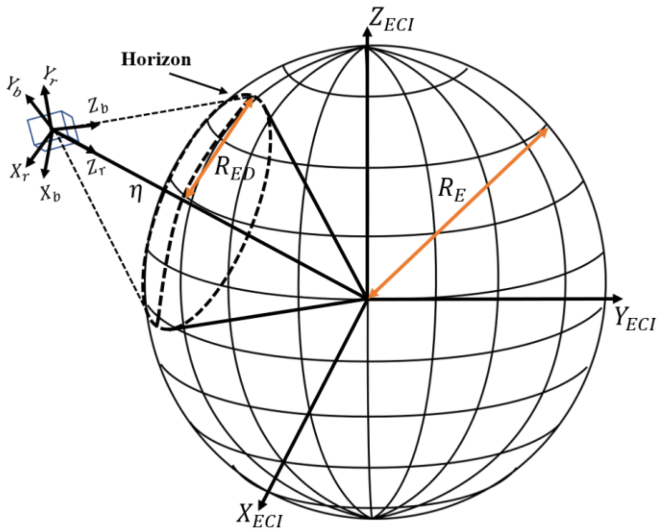


Fig. 1. Definition of coordinate systems.

It is important to note that the higher altitude, the bigger Earth's portion appears in the imager's field view and bigger its radius. Fig. 4 shows a plot of the ratio of radius of Earth horizon in imager's field of view and actual Earth radius as a function of altitude in range of interest according to simulation of camera with fixed FOV. Fig. 5 shows a plot of the ratio of candidate image plane area in imager's field of view and area of full-sized Earth in image plane as function of satellite altitude according to simulation of camera with fixed FOV.

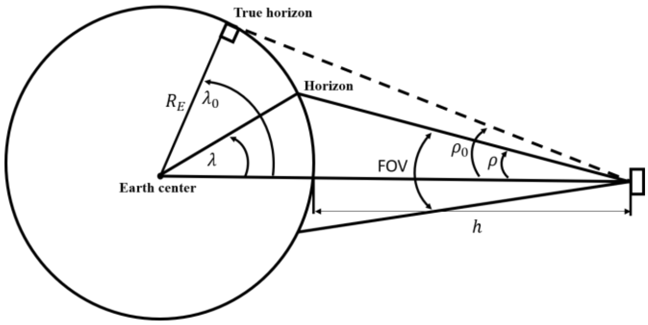


Fig. 2. Portion of the Earth viewed and seen by spacecraft.

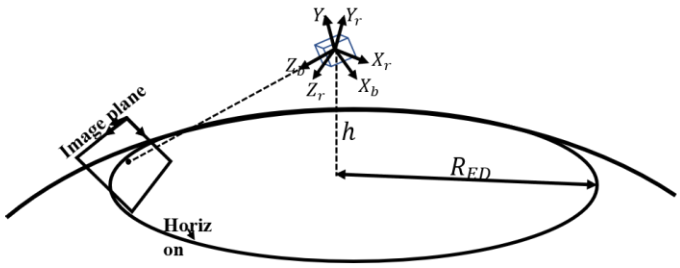


Fig. 3. The relationship between image plane and satellite attitude.

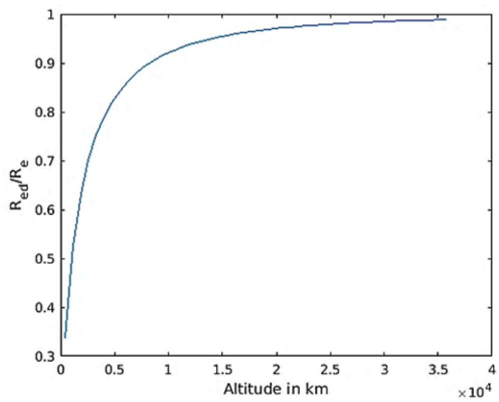


Fig. 4. Ratio of radius of Earth horizon in imager's field of view and actual radius of Earth as function of satellite altitude.

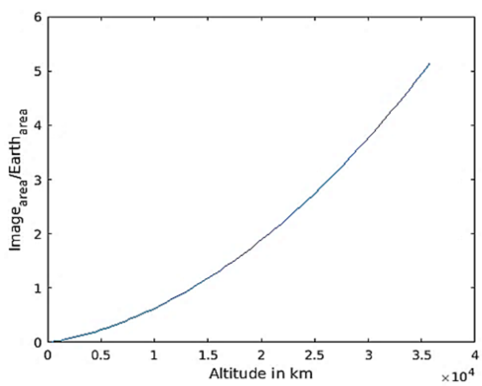


Fig. 5. Ratio of candidate image plane area in imager's field of view and area of full-sized Earth in image plane as function of satellite altitude.

## IV. Image Processing Algorithm

An outline of the proposed algorithm is shown in Fig. 6. The first step in algorithm is the reads images from vision sensor and apply low pass filter in order to minimize noise in measurements. Morphological smoothing filter and thresholding is then performed on image. Edge estimation algorithm scans the entire image to detect the position of Earth horizon curvature edge. Once contour search algorithm performed, the Least-square Circle fitting algorithm is used to estimate candidate radius and position of Earth center in image plane. From these computed values, the algorithm estimates the pitch and roll parameters as follows:

$$\theta = tan^{-1}\left(\frac{L - R_e}{Focal\, lenght}\right) \tag{1}$$

$$\varphi = tan^{-1}\left(\frac{c_x}{c_y}\right) \tag{2}$$

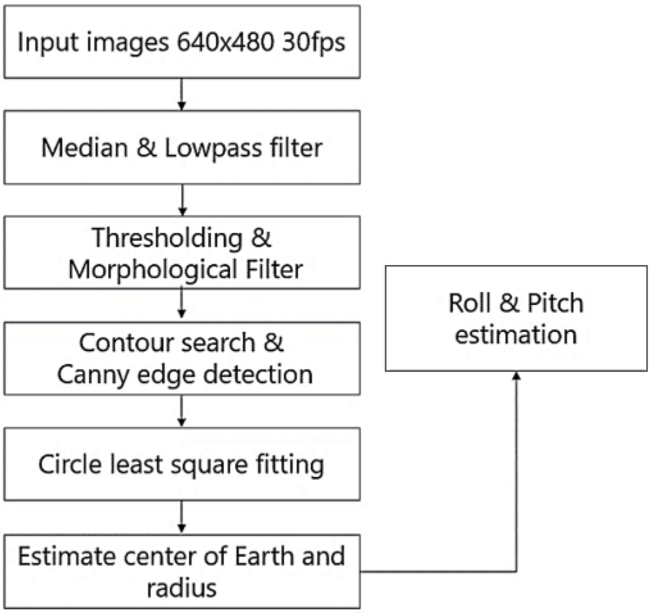


Fig. 6. Image processing algorithm for the Earth horizon estimation.

## V. Experimental Results

In order to verify the robustness of proposed approach, we applied our algorithm to satellite captured images with actual roll and pitch changes. By projecting imagery data into the scene, we estimated the attitude of the prototype setup by the vision-based method. However, lacking the attitude data information of the corresponding HDEV payload's imagery data, we made the experiment by using a high-precision one axis rate table. Results of attitude estimation experiments are shown in Fig. 7, Fig. 8, Fig. 9, Fig. 10 and Table 1.

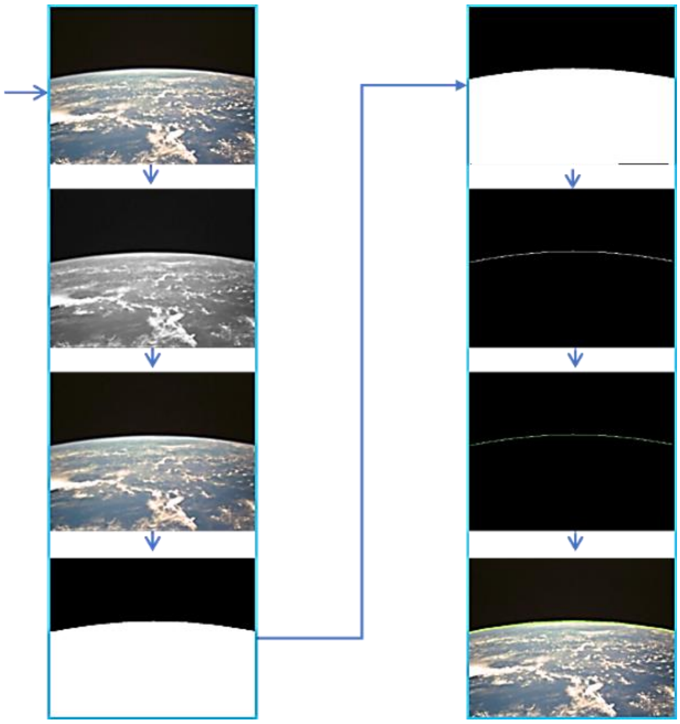

Fig. 7. Image processing algorithm's output corresponding to each steps of the proposed algorithm.

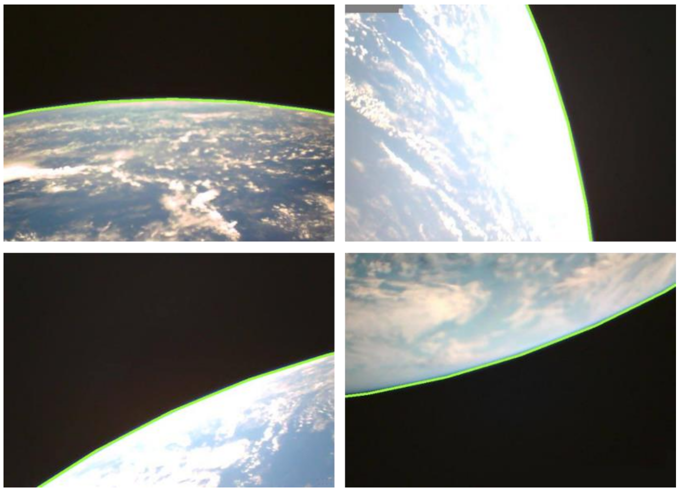

Fig. 8. Earth horizon detected in sample images during pitch and roll estimation.

TABLE I. Summary of Estimation Errors Relative to Ground Truth.

| Angles | Average Error | Maximum Error |
|---|---|---|
| Pitch | ±0.37 degrees | ±1.48 degrees |
| Roll | ±0.67 degrees | ±1.49 degrees |

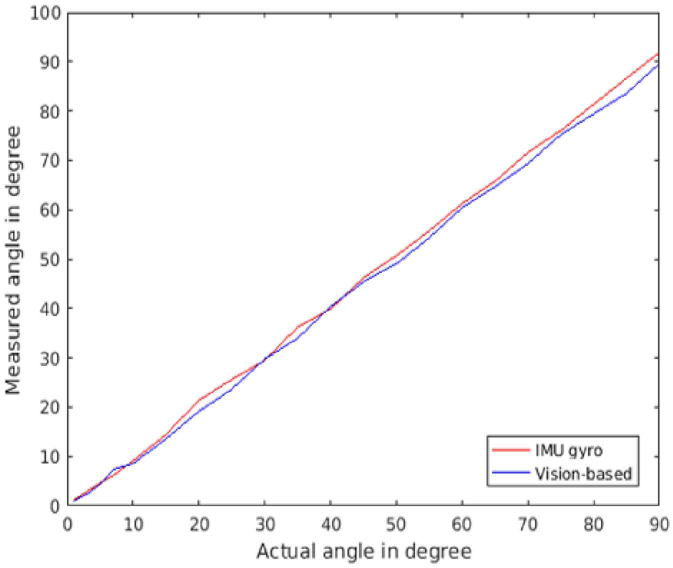


Fig. 9. Vision-based approach and MEMS gyro measurement comparison result of the pitch angle experiment.

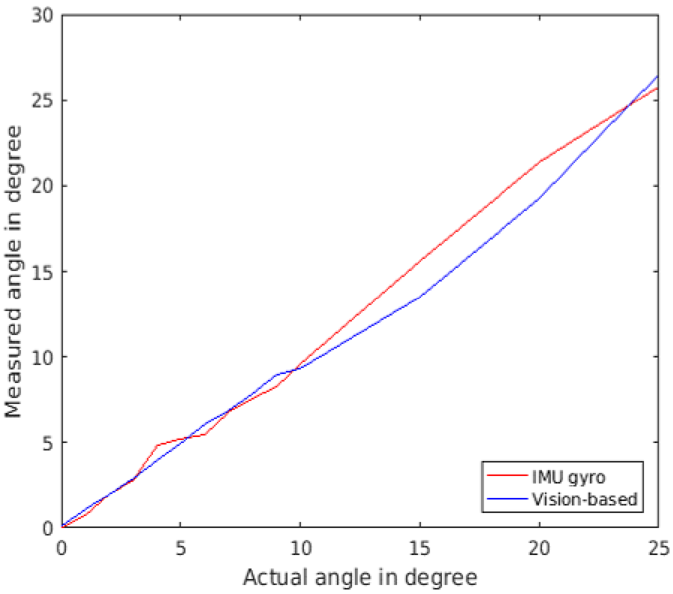


Fig. 10. Vision-based approach and MEMS gyro measurement comparison result of the roll angle experiment.

## VI. CONCLUSIONS

In this paper, we were interested in problem of roll and pitch angles estimation of small satellites with vision sensor. We evaluated our approach using precise rotary table and MEMS gyro sensor to compare the measurement accuracy. The algorithm is based on detecting Earth horizon curvature in imager's field of view. The vision-based method employed the satellite's nadir pointing camera as the attitude sensor and the satellite's attitude information derived from captured sequential images based on Earth-observation geometrical constraints and image processing techniques. Our approach also can be integrated with other attitude sensors such as star tracker, sun sensors, and magnetometers in the filter framework to improve attitude estimation capability in different cases.

## REFERENCES


[1] D. Del Corso, C. Passerone, L. Reyneri, C. Sansoe, S. Speretta and M. Tranchero, "Design of a university nano-satellite: The PiCPoT case," IEEE Transactions on Aerospace and Electronic Systems, 47, (3), 2011.

[2] C. Underwood, S. Pellegrino, V.J. Lappas, C.P. Bridges, and J. Baker, "Using cubesat/micro-satellite technology to demonstrate the autonomous assembly of a reconfigurable space telescope (AAReST)," Acta Astronautica, vol. 114, pp. 112–122, 2015.0

[3] T. N. Woods, A. Caspi, P. C. Chamberlin, A. Jones, R. Kohnert, J. P. Mason, C. Moore, S. Palo, C. Rouleau, S. C. Solomon, J. Machl and R. Viereck, "New Solar Irradiance Measurements from the Miniature X-ray Solar Spectrometer CubeSat," The Astrophysical Journal Letters, 835, 122, 2016.

[4] J.R. Wertz, Spacecraft attitude determination and control, Springer Science & Business Media, 1978.

[5] D. Meller, P. Sripruetkiat, and K. Makovec "Digital CMOS Cameras for Attitude Determination," Proceedings of the 14th AIAA/USU Conference on Small Satellites, pp. 1–12, August 2000.

[6] D. Bahar, M.M. Effandi, M. Hassan, N. Hamzah, A. Arshad, X. Farr, L. Visagie and W. Steyn. "Modular CMOS Horizon Sensor for Small Satellite Attitude Determination and Control Subsystem," 2006.

[7] S.A. Rawashdeh, and J.E Lumpp, "Image-based attitude propagation for small satellites using RANSAC," Aerospace and Electronic Systems, IEEE Transactions on, vol. 50, (3), pp. 1864–1875, 2014.

[8] A. Bevilacqua, A. Gherardi, and L. Carozza, "A vision-based approach for high accuracy assessment of satellite attitude," In Computer Vision Workshops (ICCV Workshops), IEEE 12th International Conference on, pp. 743-750, 2009.

[9] A. Zdešar, G. Klančar, G. Mušič, D. Matko, and I. Škrjanc, "Design of the image-based satellite attitude control algorithm," XXIV International Conference on Information, Communication and Automation Technologies (ICAT), pp. 1–8, 2013.

[10] D. Amartuvshin, K. Asami, "Visual-Inertial attitude propagation for small satellite using Unscented Kalman filter," 4th IAA Conference on Dynamics and Control of Space Systems (DYCOSS), pp. 1–13, 2018.