2025 21st IEEE International Colloquium on Signal Processing & Its Applications (CSPA), 7-8 February 2025, Pulau Pinang, Malaysia

Review Paper on Centroiding Algorithm for Lunar Navigation

1st Anis Hannani Razaman
Department of Electrical and Computer Engineering.
International Islamic University Malaysia
Kuala Lumpur, Malaysia
anishannani.r@live.iium.edu.my

2nd Yasser Asrul Ahmad
Department of Electrical and Computer Engineering
International Islamic University Malaysia
Kuala Lumpur, Malaysia
yasser@iium.edu.my

3rd Othman Omran Khalifa
Department of Electrical and Computer Engineering
International Islamic University Malaysia
Kuala Lumpur, Malaysia
khalifa@iium.edu.my

4th Norazlina Saidin
Department of Electrical and Computer Engineering
International Islamic University Malaysia
Kuala Lumpur, Malaysia
norazlina@iium.edu.my

5th Amelia Wong Azman
Department of Electrical and Computer Engineering
International Islamic University Malaysia
Kuala Lumpur, Malaysia
amy@iium.edu.my

2025 21st IEEE International Colloquium on Signal Processing & Its Applications (CSPA) | 979-8-3315-2219-3/25/$31.00 ©2025 IEEE | DOI: 10.1109/CSPA64953.2025.10933304

***Abstract*— This paper reviews on potential algorithms for navigation on the moon's surface, focusing on centroiding algorithms in star sensors or trackers. Accurate positioning is crucial for lunar missions since there's no Global Positioning System (GPS), and navigation depends on pre-installed maps and sensors like Light Detection and Ranging (LiDAR) and star trackers. Star sensors or trackers are ideal for these missions due to their high accuracy. However, the moon's environment adds challenges, like interference from bright reflections and noise from radiation. This paper reviews different star-sensing methods, comparing CMOS and CCD sensors, and assesses their algorithms for their effectiveness in lunar mission. The research gap which are the strengths and weaknesses of these methods were discussed and identify areas for improvement. By addressing these gaps, this study aims to contribute to the development of more robust and accurate centroiding algorithms, advancing lunar navigation technologies for future exploration missions.**

Keywords*—*Lunar navigation, CMOS, Star Sensor, Centroiding Algorithm, Image Extraction

I. INTRODUCTION

Attitude determination is a critical aspect of spacecraft navigation, and star cameras, also known as star trackers, have become crucial for this purpose. Stars are good reference points for determining spacecraft attitudes in space missions due to their fixed positions relative to the Earth and the sun [1]. Unlike other celestial references such as Earth, the sun, or the moon, stars provide a more stable and accurate foundation for orientation calculations. Star sensors, a key component of star trackers, offer several advantages including high precision, low power consumption, and lightweight construction [2]. In space missions, particularly on the lunar surface, the absence of day-night cycles and atmospheric interference makes star centroiding a viable navigation method. However, navigating on the moon lacks GPS, relying instead on preinstalled terrain mapping and onboard sensors like LiDAR and cameras [3]. This method lacks precision but parallels how geostationary satellites use stars for navigation, benefiting from the moon's obstructed star visibility.

Lunar star trackers also face the problem of bright spots, like solar reflections off the Moon's surface, which can interfere with accurate centroiding. The lack of atmosphere means that cosmic and solar radiation can cause extra noise in the images. Therefore, the main challenge in developing navigation systems for the Moon is creating centroiding algorithms that can handle these unique conditions and work within the Moon's limited power resources. This research aims to create a centroiding algorithm that can handle the noise from the lunar surface and work for long periods without losing accuracy. The focus is on improving the precision and robustness of these algorithms under lunar conditions, and the research will not address hardware resilience or other sensor types beyond star sensors used for lunar missions.

This paper is organized as follows; Part II reviews existing research on star sensors and centroiding algorithms, with a comparison of different methods used in space missions. Part III discusses key components including sensor technologies, image extraction methods, and the challenges of star centroiding in the lunar environment. Part IV concludes the findings from the research and suggests directions for improving centroiding algorithms for lunar missions.

II. RELATED WORKS

A. Sensor Technologies for Star Trackers

In lunar missions, star trackers, as shown in Figure 1, are crucial for navigation as they identify star positions to help orient the spacecraft. These systems have a complex structure designed to capture clear star images, even under challenging conditions with noise and stray light that can blur star maps. As noted in [4], star trackers provide greater accuracy than other attitude sensors like magnetometers, gyroscopes, sun sensors, and earth horizon sensors. Two main types of imaging sensors are typically considered for star trackers: complementary metal-oxide semiconductor (CMOS) and charge-coupled device (CCD) [5]. Active Pixel Sensor (APS) CMOS technology is especially suited for space missions, as it offers high integration, better resistance to radiation, lower power use, and lower cost compared to CCDs, making it ideal for power-constrained lunar missions [6].

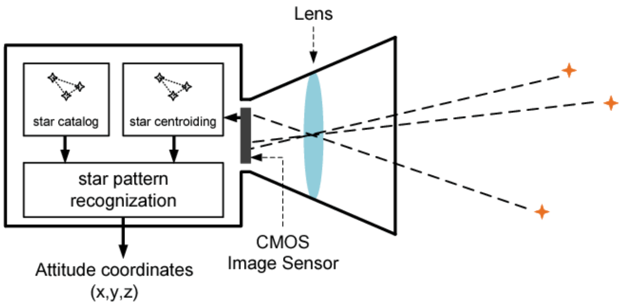

Figure 1: Typical star tracker configuration [4]

The CMOS image sensor captures an image of the stars. The centre points of the stars are identified and calculated to form a star pattern. Then, the recognition algorithm matches this pattern with a star catalogue to determine the spacecraft's orientation.

This paper [2] studies the radiation effect of star sensors specifically because many studies have already been done related on the radiation effect of CCD/CMOS. In this experiment, a CCD image sensor used in star sensors is subjected to proton radiation to assess its performance under radiation exposure. The methodology involves irradiating the sensor with 3.0 MeV protons across a range of fluences, up to 7.36 x 10^10 p/cm², simulating cumulative space radiation damage. The experiment has also been done with a CMOS image sensor. As radiation fluence increases, the clarity of star images declines, with stars appearing progressively blurred and dark noise becoming more prominent. Both experiments brought to the conclusion that although CCD sensor can output images, the increasing of the noise caused the dark signal increases dramatically. Therefore, the accuracy of parameter calculation also decreases. For CMOS image sensor proton radiation experiment, the imaging performance is decreased but the mean square error of the star centroid is no obvious dependence on the proton radiation. This comparison of CMOS and CCD shows CMOS as the better choice, especially given the power and durability demands on the moon's surface.

B. Star Image Extraction Algorithm

Accurate star image extraction is essential for precise attitude measurements, as it directly affects the centroiding calculation used to identify the star positions for navigation [7]. One key component of image extraction is thresholding, a technique that helps distinguish stars from background noise by setting intensity limits. Another technique is Binary Large Object (BLOB) detection, which identifies "blobs" or star-like objects in an image. BLOB detection works by defining a response function that counts intensity changes along the edges of each detected star (or BLOB), allowing it to identify star shapes and sizes accurately [8]. This approach helps separate stars from noise and background, contributing to the algorithm's overall accuracy.

This paper [9] presents a study on the performance of seven algorithms to detect the star image which are the Bernsen method, Otsu method, Tsai method, Niblack method, Kittler Illingworth, iterative thresholding and improved iterative on three images with ten different scenarios. The performance of the tested algorithms is defined by the amount of true detection number (TDN) and false detection number (FDN). The FDN defines the number of star pixels misinterpreted as background or background misinterpreted as star pixels, meanwhile the TDN defines as the number of real stars detected. The highest TDN indicates that the algorithm performs the best. The Bernsen method, with the highest TDN, calculates a threshold value for each pixel based on the contrast within its local area instead of applying a single, global threshold across the entire image. The Bernsen threshold value T is calculated as follows:

$$T(x,y) = \frac{C(x,y)_{max} + C(x,y)_{min}}{2} \tag{1}$$

Although the Bernsen's method gives good results with the greatest number of TDN, the performance decreased as the image size increased and contained three or four types of noise.

An image extraction algorithm based on YOLOv5 has been proposed in [1] to enhance the efficiency of star detection in star trackers. Based on the flowchart in Figure 2, the algorithm procedures to extract the star images are as follows. The original star maps are too large and very slow to process so it is divided into 2x2 sub-images. Sub-maps are then fed into the trained YOLOv5 network to detect the star images so the region of stars can be predicted. The centroiding algorithm is applied to calculate the coordinates based on the predicted region. According to the relationships between the sub-maps and the original star maps, the star images coordinates in the original star are obtained.

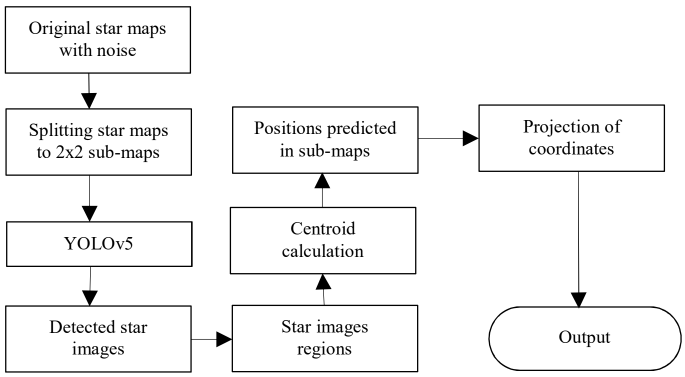

Figure 2: Flow chart of image extraction algorithm [1]

C. Star Centroiding Algorithm

A star centroiding measurement in star trackers using CMOS image sensor also has been discussed in [4]. The detector for this work is using a capacitive transimpedance amplifier (CTIA) to improve sensitivity to low-level starlight. As shown in Figure 3, the lens point spread function (PSF) will cause the star energy to spread over several adjacent pixels and form a star spot. The 5x5 region- of-interest (ROI) pixel responses are highlighted and the star centroiding can be calculated by using center-of-mass in equation (2), where S_{ij} is the signal magnitude (intensity) at pixel (*i,j*) in the region or interest. x_i and y_i are the *x* and *y* coordinates of S_{ij} pixel.

$$x_c = \sum_{i,j} x_{ij} S_{ij} \Big/ \sum_{i,j} S_{ij}$$
$$y_c = \sum_{i,j} y_{ij} S_{ij} \Big/ \sum_{i,j} S_{ij} \qquad (2)$$

As shown in Figure 4, the orbital move of the satellite causes the star spot to move in the opposite direction on the focal plane. Extended integration time might improve SNR by capturing more light from faint stars. However, in dynamic orbital conditions, this leads to systematic errors such as the “tail effect” due to star movement on the focal plane.

To solve this problem, the high sensitivity pixel, the capacitive transimpedance amplifier (CTIA) pixel, is applied to the system. The separate capacitor in a CTIA pixel enhances the sensor’s ability to capture dull objects, like faint stars, by amplifying weak signals without needing much light. After the pixel operations and implementation were performed, the centroiding test took place in a dark room. Three circular spots with the same distance are representing a star pattern, projected from an LCD screen. Applying the centroiding algorithm in equation (2), the respective centroids can be calculated. 100 frames were captured and for each frame, the relative distance error was also being calculated. Centroiding accuracy improves as centroiding gain increases, meaning a higher gain boost the signal-to-noise ratio (SNR) in the star area, resulting in better accuracy in locating the centre of the star. As shown in the graph from Figure 5, the ⅔ signal swing which is considered as a high background level still can achieve good centroiding accuracy at higher centroiding gain.

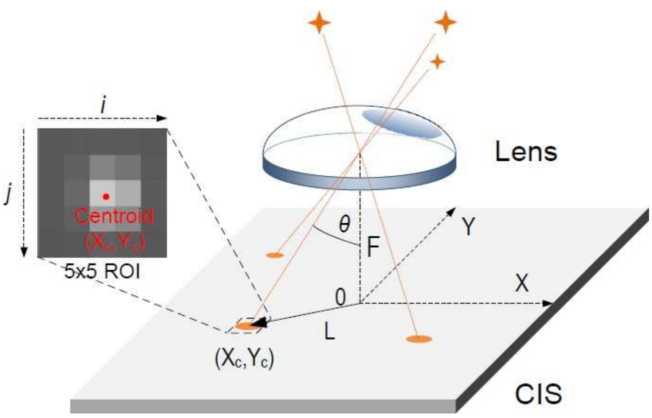

Figure 3: Star sensor maps onto focal plane [4]

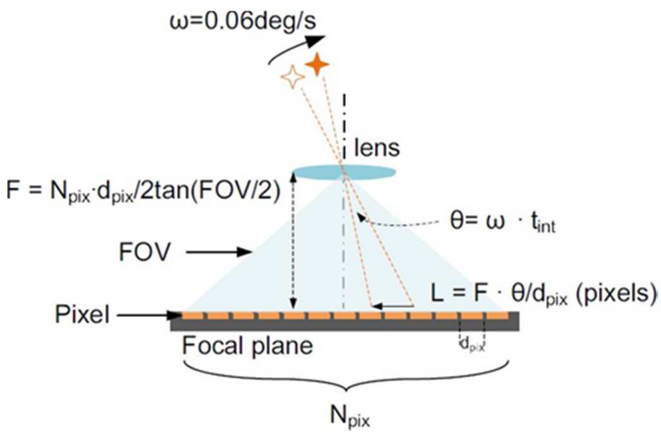

Figure 4: Dynamic condition of orbiting satellite [4]

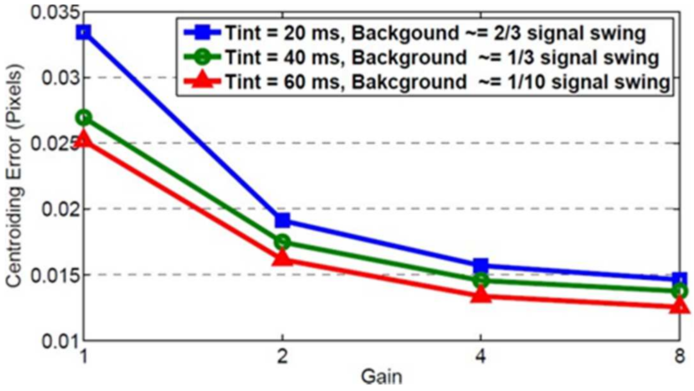

Figure 5: Measure relative distance error [4]

Achieving high accuracy in designating the centroids of star images on the sensor array is essential, as it directly impacts the accuracy of attitude estimation. The Sieve Search Centroiding Algorithm (SSA), introduced in [10], enhances accuracy star centroid detection by dividing the region of interest (ROI) into smaller sub-squares, processing gray-scale accumulations within them to locate star centroids. The flowchart for centroiding using SSA is shown in Figure 6.

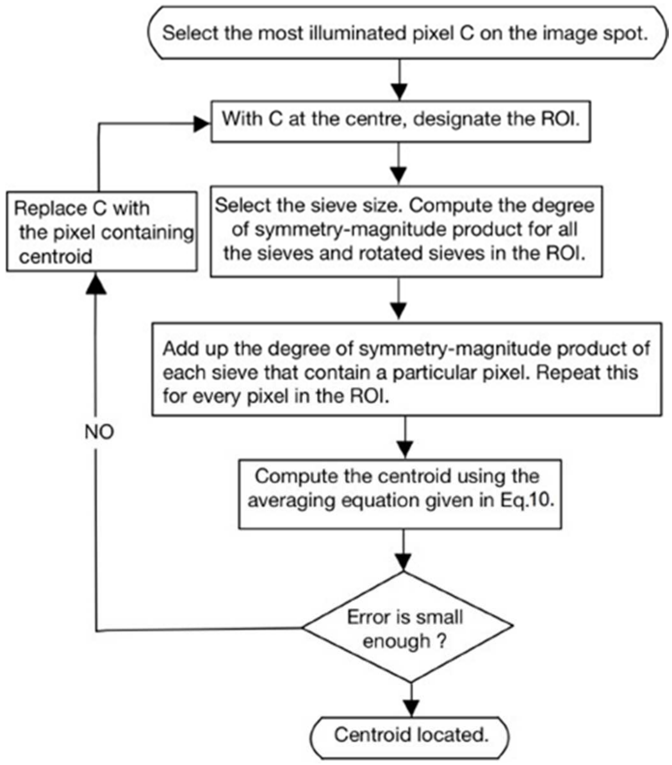

Figure 6: Flow chart of centroiding using SSA

To compare the performance of the proposed algorithm, the simulation of STAR1000 APS CMOS array was used as a testbed. Star images with different brightness, spread radius, noise level, and centroid location were used for the testing. SSA offers a balance between speed and precision, comparable to gray-scale methods like Center of Mass (COM) and Intensity-Weighted Center of Gravity (IWCOG), but with robustness closer to fitting algorithms such as Gaussian-Based Fitting (GBF). SSA’s simplicity and efficiency make it ideal for real-time star centroiding.

D. Non-Stellar Image Elimination

The non-stellar objects in space such as planets, asteroids, comets or even artificial satellites or spacecraft might potentially affect the stellar image quality. Paper [7] suggested an approach to eliminate the big bright spot non-stellar images by first segmenting the stellar image using iterative thresholding, then performing the star centroid calculation. By using the centre of gravity (CoG) algorithm from equation (2), the star centre coordinates can be extracted.

The proposed method for determining the star's centre involves first identifying the coordinates of the maximum value (the brightest point) of the star object. If the object has only one maximum value, that pixel is directly taken as the star's centroid. However, if there are multiple maximum values, a 5x5 window is set around each bright spot, and the brightness within each window is summed. The coordinates with the highest summed brightness value are then selected as the centroid of the star. Finally, the centre coordinates are calculated using the equation [7] below:

$$(x_c, y_c) = max(StarObject) \tag{3}$$

Next, the stars' centroid coordinates from the proposed algorithms are compared with centroid coordinates of the star generated in the stellar data file. The performance will be assessed with five parameters: resolution, magnitude, field of view, defocus level, and noise. From the test, it can be concluded that a large stellar image resolution, a higher magnitude, a higher FOV can increase the amount of star appeared but can affect the algorithm's capability due to the increasing of the processing time. A high defocusing level and noise can badly influence the star image quality and attitude calculation. The proposed algorithms' ability to identify stars that are heavily impacted by sunlight is constrained.

III. DISCUSSION

The discussion section serves to consolidate and summarize the related works reviewed in this paper, highlighting key methodologies, findings, and limitations of existing centroiding algorithms for lunar navigation. To provide a clear and concise comparison, the information has been organized into a tabular format, as shown in Table 1. The table includes the approach and methods of each paper as well as the contributions and limitations of the results. This approach allows for an easy overview for us to identify the research gap of the existing works.

TABLE 1: TABLE OF COMPARISON

Paper	Approach	Contributions	Limitations
Anti-noise Star Image Extraction Algorithm for Star Tracker Based on YOLOv5, 2023[1]	Uses a series of YOLO networks to improve the ability of the star trackers to detect images.	Nearly all the star images can be detected with an average error of centroids about 0.5 pixels.	Needs a lot of labelled star images for training, and it may struggle with noise and distortions specific to the lunar environment.
Study the performance of star sensor influenced by space radiation damage of image sensor, 2019 [2]	CCD and CMOS image sensor used in star sensors is subjected to proton radiation to assess its performance under radiation exposure.	Comparison between CCD and CMOS shows CMOS as the better choice in term of power and durability demands on the moon's surface	CCD sensor can output images but the increasing of the noise caused the dark signal increases dramatically.
A Global-Shutter Centroiding Measurement CMOS Image Sensor, 2014 [4]	Uses CTIA pixel and column-level signal processing, proposes a focal-plane algorithm to achieve high SNR in star regions.	The relative centroiding performance is more than 1% higher compared to a commercial image sensor.	Have major noise sources in the CTIA pixel including OTA noise, readout noise and reset noise.
Non-Stellar Big Bright Object Elimination and Star Centroid Extraction Algorithms, 2024 [7]	The segmentation of stellar images using iterative thresholding, elimination of non-stellar bright objects and star centroids calculation.	Even in the presence of noise, the suggested algorithms are able to locate the centre of the star.	The suggested algorithms' ability to identify stars that are heavily impacted by sunlight is constrained.
A Comparative Study of Star Detection Methods for a Satellite-Onboard Star Tracker, 2019[9]	Study on the detection performance of seven algorithms on three-star images with ten different scenarios.	We found that Bernsen's method gives good result with TDN of 10/10 images containing a right star detection.	The performance decrease as the image size gets larger and contains three of four types of noise.

Sieve Search Centroiding Algorithm for Star Sensors, 2023 [10]	Divides the region of interest into smaller sub-squares, analysing the intensity distributions to locate the centroid of a star image.	Improve accuracy over a simple method; centre-of-mass (COM) while being faster than more complex fitting algorithms.	Sensitivity to noise and parameter variations.

In summary, while current technologies and algorithms have made progress, there are still big challenges in adapting them for lunar missions. We need better solutions that can handle noise, work well with limited data, and perform reliably under the moon's tough conditions.

IV. CONCLUSION

In this review, we looked at the progress and challenges in using star trackers and centroiding algorithms for navigation on the lunar surface. Although improvements in sensor technology and image extraction methods have been made, the unique conditions on the moon still face many difficulties. Issues like noise from cosmic radiation, reflections from the terrain, and limited power and resources reduce the accuracy and reliability of current systems. To address these challenges, a few recommendations can be made. First, there is a need to develop algorithms that can handle noise effectively. The lunar environment creates many disturbances, such as reflections from bright terrain and radiation effects. Future research should focus on improving algorithms to filter out these interferences, ensuring accurate results even in harsh conditions. Combining traditional methods with newer AI techniques could also help improve performance. Second, creating a specialized dataset of star images for lunar conditions is important. Many algorithms, such as those based on YOLOv5, need large amounts of labelled data for training. Existing datasets often do not include the specific challenges found on the moon, such as brightness variations and noise. Building a dataset that reflects these conditions; using either simulations or real mission data, would improve the accuracy of these algorithms. Lastly, algorithms should be designed to work efficiently with the limited resources available on lunar missions. Since power and computational capacity are limited, it's crucial to create lightweight and energy-efficient solutions. For example, using global-shutter CMOS sensors and simpler centroiding methods can help balance precision with resource usage. This step is important for making these systems reliable and practical for long-term use.

In conclusion, while current star trackers and centroiding algorithms are effective in many cases, they need to be adapted to meet the specific demands of lunar missions. By focusing on noise-resistant algorithms, better datasets, and resource-efficient designs, future research can help improve navigation systems for the moon. These improvements will not only make missions more accurate but also ensure they run smoothly and efficiently.

ACKNOWLEDGEMENTS

This research project is funded by the International Islamic University Fundamental Research Grant Scheme (FRGS) code number FRGS/1/2024/TK07/UIAM/02/1. Some of the work in this project are also partly funded by the IIUM grant ID SPI24-224-0224.

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