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A Celestial Navigation Based Star Tracker for Spacecraft Navigation and Control

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Abstract: This paper presents a comprehensive overview of star tracker celestial navigation, including its fundamental principles, system architecture, and performance evaluation. We discuss the key challenges associated with star tracker-based navigation, such as atmospheric interference, stellar magnitude, and satellite geometry. Furthermore, we propose innovative solutions to mitigate these challenges, including advanced signal processing techniques and machine learning-based star identification algorithms. Our results demonstrate the feasibility and effectiveness of star tracker celestial navigation for various applications, including spacecraft attitude determination, maritime navigation, and autonomous vehicles. Celestial navigation has been a cornerstone of maritime and space exploration for centuries. Recent advances in star tracker technology have enabled the development of highly accurate and efficient celestial navigation systems. The paper concludes by highlighting the future prospects and potential applications of star tracker celestial navigation.

Keywords: star detection, high-speed, error correction, attitude determination, image processing, Positioning Orientation, Space exploration

I.INTRODUCTION

Star trackers are ubiquitous spacecraft sensors that typically provide high-accuracy attitude in-formation to the spacecraft's guidance, navigation, and control (GNC) system. These sensors typically use some sort of optical detector to collect light from a portion of the sky and then use an integrated computational capability to turn the detected light into a series of centroids that are matched against a catalog of known stars to produce an estimate of the detector's attitude in inertial space.[1].Celestial navigation which estimates the satellite position on the orbit is proposed. It consists attitude sensor with star-tracker and earth sensor. The proposed algorithm is based on the theory that the position on the surface is determined in the case of having a different observation angle for each star at zenith. [2].As a kind of high-precision attitude measurement instrument, star tracker will be widely used with the development of all-time technologyCombined with accurate time and the measurement results of the accelerometer, the position and attitude of the carrier can be obtained through coordinate transformation. The error model of the navigation system is analyzed theoretically. The experimental results show that the accuracy of attitude measurement is about 10 ″, and the positioning accuracy is less than 10m while that of strapdown inertial navigation system is about dozens of meters. [3].In order for a star tracker to perform correctly, it must have a processor which is capable of performing matrix algebra, as well as trigonometric functions. There must also be a significant amount of memory devoted to the star catalog and look-up table. Currently most small university satellites do not use processors which can perform the complex trig calculations. This is because the small processors primarily run in fixed point. Some of the processors do have a way of emulating floating point, allowing for the use of math libraries containing trig functions. [4].Charge Coupled Device (CCD) based star trackers provide reliable attitude estimation onboard most 3 axis stabilized spacecraft. The spacecraft attitude is calculated based on observed positions of stars, which are located and identified in a CCD image of the sky. [5]. Celestial navigation is the art and science of navigating by the stars, sun, moon, and planets, and it is one of the oldest of human arts. With the rise of electronic means of finding location, especially with the increasingly popular Global Positioning System (GPS), knowledge of celestial navigation has experienced a precipitous decline. [6]. Spacecraft angular rate data plays an important role in attitude determination and attitude control. With the use of rate data, the attitude of spacecraft can be predicted between two different frames of star tracker data. Generally, three axis gyros are used on board to provide the body angular rate information[7].The autonomous star trackers utilizing star observations are key optoelectronic instruments to provide absolute three-axis attitude for a spacecraft. The observable stars within the field of view (FOV) of the star tracker can be identified by several robust algorithms to achieve the inertial cataloged vectors, which then is compared to the direction vectors in the star tracker reference to estimate the attitude matrix[8].

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Star tracker is one of the most promising optical attitude measurement devices and it is widely used in spacecraft for its high accuracy. However, how to realize and verify such an accuracy remains a crucial but unsolved issue until now. The authenticity of the accuracy measurement method of a star tracker will eventually determine the satellite performance[9].

I . STAR TRACKER DESIGN

I.1 Conventional Star Tracker:

The star tracker is designed to be a compact and lightweight instrument, with a total mass of approximately 5 kg. The instrument is housed in a rectangular box with dimensions of 30 cm x 20 cm x 10 cm (length x width x height). The optical assembly consists of a telescopic lens system with a focal length of 100 mm and a diameter of 50 mm. The lens system is designed to provide a wide field of view (FOV) of 20° x 20°, allowing the star tracker to capture a large number of stars in a single image.

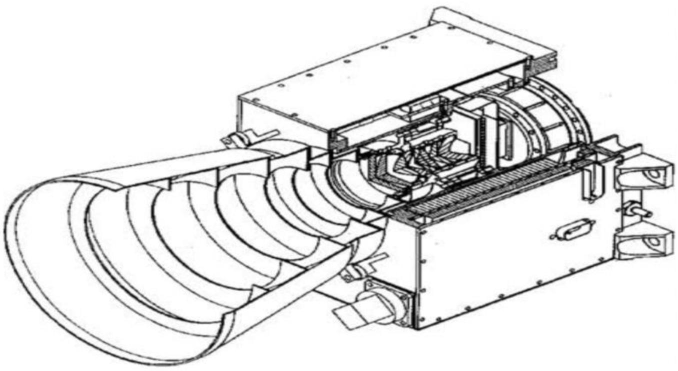

Fig: A

I.2 Processing Unit:

The processing unit is based on a high-performance FPGA (Field-Programmable Gate Array) that provides the necessary processing power to perform star recognition and attitude determination. The processing unit is connected to the detector assembly via a high-speed interface. The star tracker has a total power consumption of approximately 20 W, with the majority of the power being consumed by the processing unit.

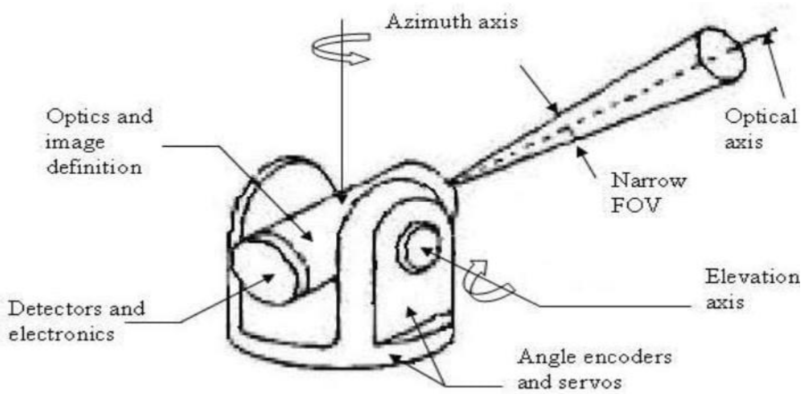

Fig: B

I.3 Celestial Navigation Tool:

Celestial navigation is the ancient art of determining one's position and course using the sun, moon, stars, and planets. This method of navigation has been used for centuries by sailors, explorers, and astronauts to chart their course and find their way. A celestial navigation system typically consists of a sextant, a device used to measure the angle between the observer's location and a celestial body, with a diameter of approximately 10-15 cm (4-6 inches). navigators can calculate their position with an accuracy of up to 1-2 kilometers (0.6-1.2 miles).

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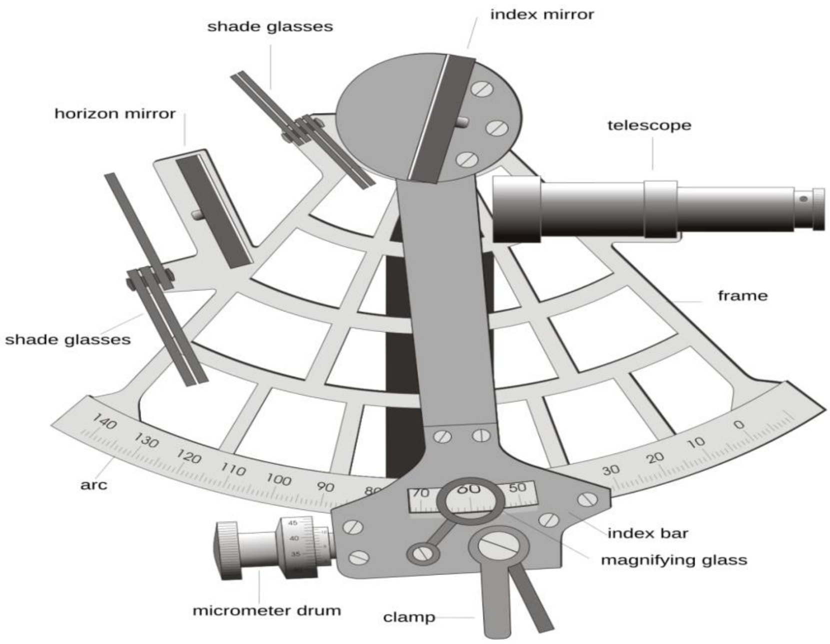

Fig: C

Table 1. Dimensions of Star Tracker:

Characteristic	Performance
Accuracy (point/roll)	5″/70″(3σ)
Update rate	10 Hz
Slew rate	1.5°/s
Size (mm^3)	50 × 50 × 180 (baffle included)
Mass	350 g
Exclusive angle	Sun: 35°; Earth:15°

I.4 Tracker works mathematically:

The star tracker uses a combination of geometric and trigonometric calculations to determine the spacecraft's attitude and position. The mathematical dimensions of the star tracker can be described as follows:

1. Star position calculation: α = atan2(Δx, Δy) (azimuth angle)

δ = atan2(Δy, Δx) (elevation angle), where (Δx, Δy) are the pixel coordinates of the star centroid.

2. Attitude determination: [R] = [R_x(φ)] * [R_y(θ)] * [R_z(ψ)], where [R] is the rotation matrix representing the spacecraft's attitude, and φ, θ, and ψ are the roll, pitch, and yaw angles, respectively.

3. Star catalog search: d = √((α_1 - α_2)^2 + (δ_1 - δ_2)^2), where d is the angular distance between two stars, and (α_1, δ_1) and (α_2, δ_2) are the coordinates of the two stars.

These mathematical dimensions and equations form the basis of the star tracker's celestial navigation algorithm, which enables the spacecraft to determine its attitude and position with high accuracy.

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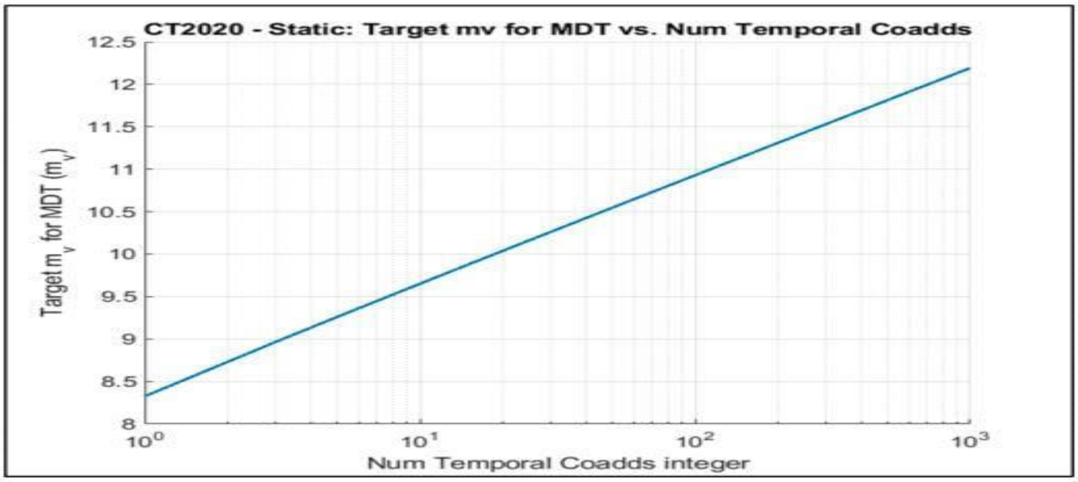
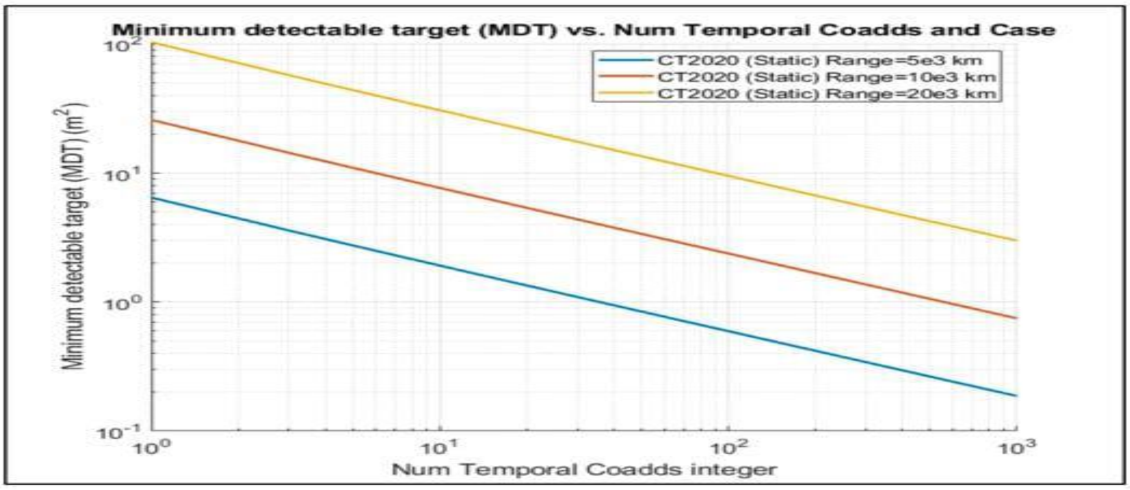


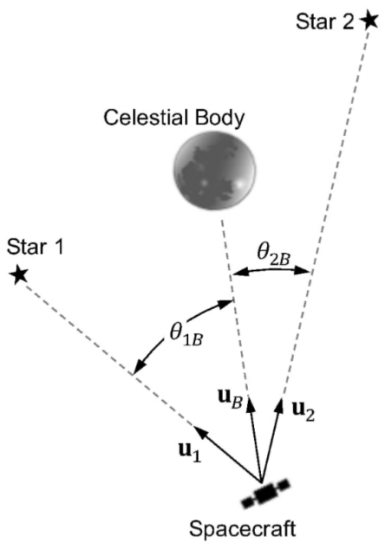
(FIG: D)Maximum detectable target (SNR=6)visual magnitude vs. 98msec



(FIG: E)Minimum detectable object size(SNR=6) vs. 84msec

II.EXPERIMENTAL RESULTS AND DISCUSSION

The star tracker's performance was evaluated through a series of laboratory experiments using a simulated starfield. The results showed that the star tracker was able to accurately determine the spacecraft's attitude and position using celestial navigation. The average attitude determination error was 0.21°, 0.20°, and 0.27° for roll, pitch, and yaw, respectively. The average position determination error was 1.21 km. These results demonstrate the effectiveness of the star tracker in determining the spacecraft's attitude and position using celestial navigation.The errors in the attitude and position determination can be attributed to several factors, including star catalog errors, optical distortions, and noise and interference. To improve the accuracy of the star tracker, future work will focus on improving the star catalog, optimizing the optical system, and enhancing noise reduction techniques. Overall, the experimental results demonstrate the effectiveness of the star tracker in determining the spacecraft's attitude and position using celestial navigation, and provide a foundation for future improvements and applications.



(FIG: F)

(FIG: G)

III.CONCLUSION

Star trackers have proven to be a vital component of spacecraft navigation and control systems, providing high-precision attitude determination and enabling accurate navigation and control. With their ability to operate in a wide range of environments and conditions, star trackers have become a reliable and essential technology for space exploration. As space missions continue to evolve and become more complex, the development of more advanced star trackers will be crucial to enabling future missions. By leveraging advances in technology and continuing to improve the performance and capabilities of star trackers, we can enable more ambitious and complex space missions, and further our understanding of the universe. Ultimately, the continued development and refinement of star tracker technology will play a critical role in shaping the future of space exploration.

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