TECHNICAL SCIENCES

A SURVEY ON CUBESAT STAR TRACKER DESIGNS

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Abstract

The rapid development of CubeSats has introduced new opportunities and challenges in space exploration, particularly in the realm of satellite attitude determination. Among the key technologies enabling precise attitude control is the star tracker, a sensor that uses star patterns to determine a satellite's orientation. This survey reviews the current state of star tracker design, specifically for CubeSats, covering both hardware and software components. It discusses critical elements such as optical assemblies, image sensors, and processing units, as well as algorithms used for star identification and attitude determination. The paper also compares commercial solutions with open-source, low-cost alternatives.

Keywords: nanosatellites, CubeSat, attitude determination, star tracker.

Introduction

In the dynamic realm of space exploration, the advent of nanosatellites, particularly CubeSats, has introduced a new era of cost-effective and accessible satellite missions [1]. These small spacecrafts (Figure 1), often characterized by their cubic shape and standardized form factors, have played a significant role in democratizing space research and encouraging creativity across a wide range of scientific fields. However, as the ambitions for nanosatellite missions keep growing, there is an increasing need for improved capabilities, especially with regard to accurate attitude determination and control.

Satellite attitude determination involves the accurate measurement of a spacecraft's orientation or attitude in space. The attitude of a satellite is defined by its position and orientation in three-dimensional space, typically described in terms of its roll, pitch, and yaw angles. Accurate knowledge of a satellite's attitude is crucial for its proper functioning, as it directly influences the pointing direction of onboard instruments, antennas, and solar panels. Various methods are employed in satellite attitude determination, ranging from sensor technologies like gyroscopes, accelerometers, and magnetometers to advanced techniques such as star trackers and optical sensors. These methods allow satellite operators and engineers to monitor and control the satellite's orientation, ensuring optimal performance in its intended mission, whether it involves Earth observation, communication, scientific research, or other space-based activities.

Figure 1 – PolyITAN-2 CubeSat

Star trackers (sensors), with their ability to provide high-precision orientation information by capturing and recognizing star patterns, have established themselves as indispensable components in larger satellite systems. However, adapting these systems for use in CubeSat nanosatellites presents a unique set of challenges and opportunities. This article aims to survey the existing body of knowledge in this area, examining the state-of-the-art technologies, identify key challenges, and unearth potential avenues for innovation.

Hardware design

The hardware design of most modern star trackers is quite similar. Paper [2] discusses various aspects related to the operation and performance of autonomous star trackers for spacecraft attitude determination. It explains how star sensors work, including algorithms for star detection, identification and centroiding. Key performance parameters like sensitivity, field of view, accuracy, noise equivalent angle, calibration, and catalog errors are analyzed in detail, with supporting simulations. Article also describes common methods to characterize star tracker accuracy using night sky observations or lab setups. To sum up, it provides a comprehensive tutorial on the functioning, error sources, and test & calibration of star tracker systems to determine spacecraft orientation.

The general structure of a modern star tracker hardware is shown in Figure 2. It typically consists of the following basic elements: stray light baffle, optical assembly, image sensor, processing unit and power supply.

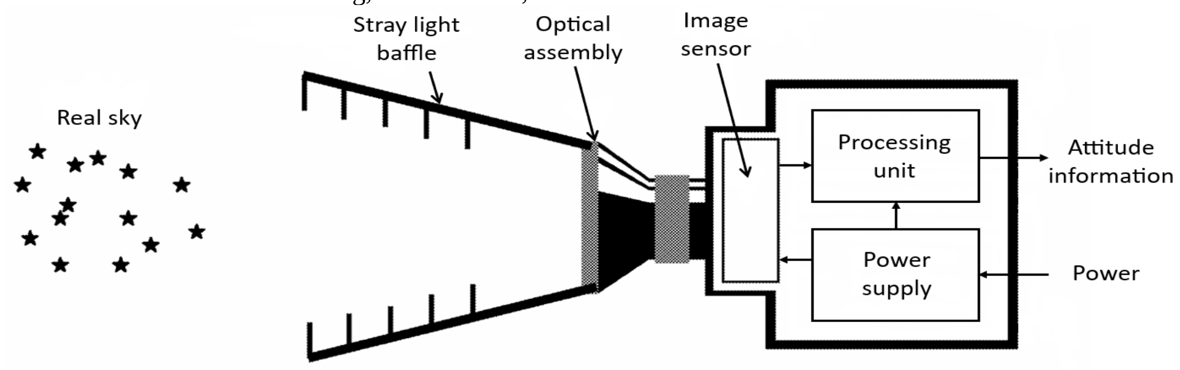


Figure 2 – General hardware structure of most modern star trackers

Stray light baffle is a tube that is placed in front of the lens to block out stray light from outside the star tracker's field of view. Stray light can come from the Sun, Earth, and other bright objects in the sky. It can interfere with the star tracker's ability to detect faint stars, which are essential for accurate attitude determination. The optical assembly is responsible for gathering light from stars. The specific type of optics used will depend on the desired field of view and resolution of the star tracker. A wider field of view will allow the star tracker to see more stars, but it will also reduce the resolution of the images, and vice versa.

Article [3] presents the optical design and stray light analysis of a star sensor for satellite attitude determination. The designed optical system is based on a 6-lens double Gauss system with a 60mm focal length and 14° x 14° field of view, optimized to be diffraction-limited in performance across the detector's 0.4-1μm wavelength range. Distortion is constrained below 0.03% to avoid star image displacement. Tolerance analysis shows that standard fabrication tolerances still yield satisfactory image quality, with RMS spot radius under 8 μm. Stray light rejection is analyzed by modeling a cylindrical baffle with six internal vanes. Point source transmittance (PST) simulations demonstrate that the baffle attenuates off-axis stray light by 10-11 times, effectively protecting the optical system from bright out-of-field sources that could saturate the detector or reduce image contrast. Overall, the paper discusses key optical and stray light considerations in designing a compact, diffraction-limited star sensor for precision satellite navigation and control.

Another crucial element is image sensor, a light-sensitive chip that captures the image of the stars. The number of pixels in the image sensor determines the resolution and field of view of the star tracker. Higher pixel counts allow more stars to be detected, enabling more accurate attitude determination. Quantum efficiency measures the sensor's ability to convert incoming photons into electrical signals, and higher quantum efficiency leads to better sensitivity and the ability to detect fainter stars. Larger pixel sizes generally result in higher sensitivity, but they also reduce the sensor's spatial resolution and field of view. Choosing the right image sensor with low noise, high sensitivity, and a wide dynamic range allows the star tracker to reliably detect and track stars, even in challenging lighting conditions.

The use of complementary metal-oxide-semiconductor (CMOS) Active Pixel Sensor (APS) imaging systems in star trackers for small satellites is discussed in [4]. CMOS APS sensors offer several advantages over traditional charge-coupled device (CCD) sensors, such as low power consumption, radiation hardness, simplified design, and on-chip integration. The researchers developed a prototype ground-based star camera using the STAR250 CMOS image sensor and evaluated its performance. They analyzed the sensor's sensitivity, noise model, and accuracy. Experimental results indicate that a CMOS APS-based star camera is a viable attitude sensor for small satellites, providing accurate star positioning through subpixel centroiding techniques. The researchers plan to further investigate the influence of APS sensor parameters, such as fill factor, on the star tracking accuracy. Overall, the paper demonstrates the potential of CMOS APS technology to replace traditional CCD sensors in small satellite star trackers.

Once an image has been captured, it must be processed by a processing unit to determine the attitude of the satellite. The processing unit is the brain of the star tracker. Typically, this is an ARM-based microprocessor running Linux with special software, but sometimes this unit may also include such unique features as an FPGA or a neural network accelerator. The computing power of the processing unit must be sufficient to ensure the required speed of algorithm execution. Also, something that almost no electronic device can do without is a power supply that receives energy from the satellite's main power bus and provides the necessary set of voltages to operate all the electronic components of the star tracker.

Software and algorithms

The entire process of determining attitude by a star tracker from the image of stars can be divided into three main steps: image processing, star pattern identification and attitude determination itself (Figure 3).

Firstly, raw images from the star tracker's image sensor are processed to identify stars. This might involve noise reduction, filtering, and techniques to enhance the visibility of stars. Then points of light (stars) are localized and isolated from the background data by thresholding the image. Once stars are identified, their centroids are computed to determine their precise locations within the image. Paper [5] investigates the performance of different centroiding algorithms used in astronomical adaptive optics systems under low light conditions. The researchers evaluated the centroid estimation error (CEE) of algorithms like Center of Gravity (CoG), Weighted CoG (WCoG), Iteratively Weighted CoG (IWCoG), and Intensity Weighted Centroiding (IWC) under different conditions, such as varying spot size, spot shift, and CCD sensor size. They found that maintaining a small spot size and using CoG or IWC methods performed best at low light levels, while IWCoG was more accurate at higher intensity levels.

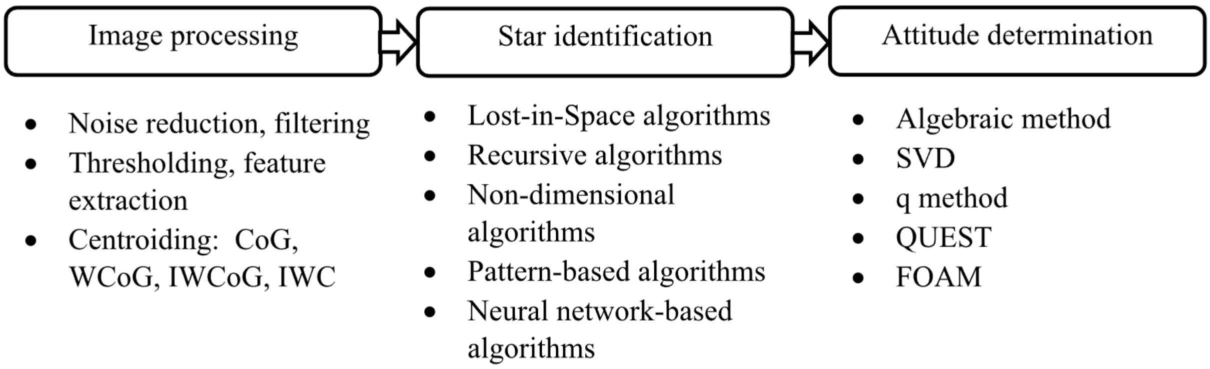


Figure 3 – Process of determining attitude by a star tracker

Secondly, the extracted features from the image are compared against a catalog containing information about known stars to identify the most likely matches for each detected star. In the article [6], Spratling et al. review the key developments in star identification algorithms over the past few decades, which are used in spacecraft attitude determination systems. It covers techniques for "lost-in-space" situations with no a priori attitude information, recursive methods when some attitude information is available, and non-dimensional methods that are robust to camera calibration errors. The algorithms are analyzed based on their feature extraction, database search efficiency, validation approach, and utilization of independent pattern features. The trend has been towards faster and more reliable techniques, with key innovations in the 1990s dramatically reducing the database search time. More recent work has focused on improving robustness to measurement errors and distortions. Notable advances include non-dimensional techniques invariant to camera calibration changes, as well as methods for rejecting non-stars during identification.

Finally, once the star patterns are recognized, the star tracker employs attitude determination algorithms to calculate the CubeSat's orientation in space. Article [7] compares several single-frame attitude determination methods for nanosatellites, including the algebraic method, Singular Value Decomposition (SVD), q method, Quaternion Estimator (QUEST), and Fast Optimal Attitude Matrix (FOAM). These methods use vector observations from sensors like magnetometers, Sun sensors and star trackers to estimate the satellite's orientation. Simulations using orbital parameters of the TIMED (Thermosphere, Ionosphere, Mesosphere Energetics & Dynamics) satellite show the SVD and q methods provide the most robust and accurate attitude solutions, while the QUEST method is the fastest. Overall, this research demonstrates the capabilities of different vector-observation based techniques for coarse 3-axis attitude determination of nanosatellites using common sensors, providing both accuracy and performance assessments to inform selection of the optimal approach.

Testing the performance of star trackers is another crucial aspect to consider. Article [8] describes the development of a software package to evaluate the performance of the star identification algorithm implemented in "StarSense". "StarSense" is a low-cost star tracker built from off-the-shelf components to determine satellite attitude in orbit. The software simulates and tests the centroiding, geometric voting, and quaternion estimator (QUEST) algorithms used in "StarSense" in terms of performance indicators like attitude accuracy, calculation time, memory usage, star catalog size, and sky coverage. The testing framework is fully parameterized so it can be applied to any star tracker system by changing hardware parameters like focal length, field of view, and distortion. The authors conclude that their software provides a robust, fast, and portable means to optimize star tracker algorithm performance across varying hardware setups.

Commercial designs

Let us move to the real examples of star tracker design. To begin with, there are a variety of commercial star sensors available on the market (Figure 4). Most of them have low power consumption, high accuracy and update rate, with some options small enough to be implemented on CubeSats. A comparison of their parameters is given in Table 1.

a) b) c)

Figure 4 – Commercial designs of star tracker:
Sagitta Star Tracker (a), AURIGA-CP (c), ST200 (b)

For example, Arcsec Space company offers their star tracking solution called Sagitta Star Tracker [9]. It has cross-boresight accuracy of 2 arcseconds and around boresight accuracy of 10 arcseconds. The star tracker can track stars up to magnitude 7, handling up to 64 stars simultaneously, with an update rate of 10 Hz and a field of view of 25.4°. Key features include star tracking and attitude determination, full image download capability, image histograms, a fast lost-in-space algorithm, and autonomous calibration.

Another example is AURIGA-CP [10], a star tracker optical head with software hosted in the spacecraft's on-board computer, specifically designed for small satellite missions. The product is guaranteed for a 10-year lifetime in Low Earth Orbit (LEO) and has been flight-proven since 2019 with the OneWeb megaconstellation. The optical head features a baffle for protection against direct Sun and Earth illumination, and up to three optical heads can be connected to the spacecraft's on-board computer via a SpaceWire interface. The centralized software is integrated into the spacecraft processor and can operate at frequencies up to 10 Hz, depending on host processor performance. It includes an embedded star catalog, algorithms, and software library inherited from Sodern's extensive experience. The low frequency spatial error is 9 arcseconds for XY axes and 51 arcseconds for the Z axis. The optical head operates on a 5V power supply. Its typical power consumption is 0.8W, with a maximum consumption of 1.1W.

Also worth mentioning is one of the most compact star sensors on the market, the ST200 [11], jointly developed by AAC Hyperion and Berlin Space Technologies. Despite its small size, it's also suitable for larger satellite platforms with additional interfaces and power supply ranges available. The ST200 offers high precision and performance, featuring a 5 Hz update rate, a low mass of 42 g and low power consumption of 600 mW. It provides an accuracy of 30 arcseconds for pitch and yaw, and 200 arcseconds for roll. The ST200 Star Trackers have been in use since 2015, flying on over 20 missions.

Table 1. Parameters of commercial star trackers

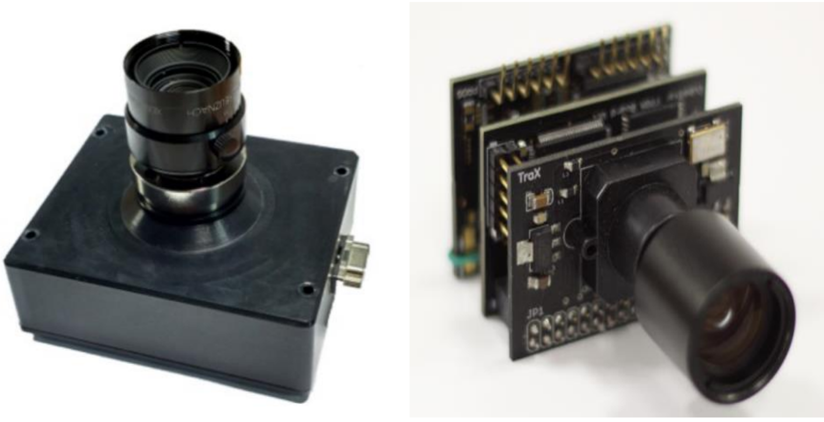
	Sagitta Star Tracker	AURIGA-CP	ST200
Company	Arcsec Space	Sodern	AAC Clyde Space
Accuracy	10 arcsec	9 arcsec	30 arcsec
Update rate	10 Hz	10 Hz	5 Hz
Power consumption	1500 mW	800 mW	600 mW
Dimensions	44 x 50 x 95 mm^3	66 x 59 x 94 mm^3	29 x 29 x 38,1 mm^3
Mass	270 g	225 g	42 g
Price	€35000	€50000	$25000

However, there are some drawbacks to using ready-made commercial solutions, the main one of which is their cost. Since such specialized devices like satellite star trackers are unique high-tech products, their price can reach tens of thousands of dollars. Disadvantages also include the difficulty of purchasing and receiving support for these products specifically in countries like Ukraine.

Open-source designs

Fortunately, there are several open-source projects and many scientific papers describing various implementations of star trackers developed at universities around the world (Figure 5). Some of them will be discussed below. A comparison of their parameters is given in Table 2.

Paper [12] presents the development of StarberrySense, a low-cost star sensor for small satellites based on a Raspberry Pi Zero controller and off-the-shelf components. The star sensor has a mass of 315g, power consumption under 1.25W, attitude accuracy of 30 arcseconds, and an update rate of 0.2 Hz in testing. It utilizes a region-growing algorithm for star detection in images and a geometric voting scheme paired with the QUEST algorithm for star identification and attitude determination. The sensor was subjected to thermal, vacuum, and vibration tests meeting CubeSat qualification standards. With a total cost under $1600, StarberrySense aims to provide an affordable high-precision attitude sensor option suitable for small satellite missions.



a) *b)*

Figure 5 – Open-source designs of star tracker: StarberrySense (a), CubeStar (b)

In the article [13], Gutierrez et al. introduced an ultra-low-cost open-source star sensor concept called "SPEL - Open Star Tracker" (SOST), developed using a Raspberry Pi computer and CMOS camera along with open-source astronomy software tools. The researchers proposed a new algorithm that involves stellar catalog segmentation and iterative matching to deal with the lost-in-space problem. Through ground and on-orbit testing, SOST demonstrated promising performance as an accessible, adaptable star tracking platform, providing 97.3% success rate and precision ranging from 0.5 to 4 arcminutes under 20 seconds processing time per image. Power consumption varied between 1.8- 2.4W depending on the operating mode. Environmental testing also validated SOST's feasibility and robustness to operate under orbital conditions for small satellite missions with tight cost budgets.

Article [14] describes the development of CubeStar, a nano star tracker designed specifically for CubeSats. It uses a commercial CMOS image sensor originally developed for the automotive industry along with custom star detection, centroiding, matching, and attitude determination algorithms running on an ARM processor. Key decisions in CubeStar's design included choosing a sensor sensitive enough to detect stars down to magnitude 5.5, and optics with a 42° circular field of view to ensure at least 3 stars are visible across 99.9% of the sky. The CubeStar engineering model consumes less than 500mW and achieved better than 0.01 degrees RMS accuracy during night sky testing while outputting attitude estimates at 1 Hz. Weighing less than 90g, the compact 3-PCB stack design meets CubeSat size constraints. It is scheduled to launch on the ZA-AeroSat CubeSat as part of the QB50 constellation to demonstrate its capabilities in orbit.

Table 2. Parameters of open-source star trackers

	StarberrySense	CubeStar	SOST
Accuracy	30 arcsec	36 arcsec	0.5 - 4 arcmin
Update rate	0.2 Hz	1 Hz	0.05 Hz
Power consumption	1250 mW	500 mW	1.8 - 2.4 W
Dimensions	98 x 75 x 69 mm^3	46 x 33 x 70 mm^3	
Mass	270 g	90 g	
Price	≈ $1600		

These examples confirm the feasibility of creating a low-cost star tracker that can determine orientation with high accuracy while being both small and power-efficient. However, there is a significant drawback common to all three solutions considered, namely the low refresh rate. The best result of 1 Hz is demonstrated by CubeStar [14], but this may not be enough for real-time attitude control, especially for orientation-sensitive applications such as Earth remote sensing. Therefore, one of the primary goals of future research will be to figure out ways to increase the speed of the star tracker. This can be done through software optimization and the use of hardware acceleration techniques.

Another interesting approach to increase star tracker update rate is described in research [15]. The main idea is to use an event camera for star tracking. Event cameras detect brightness changes asynchronously, outputting a stream of timestamped events that consumes less power and enables higher speed tracking compared to conventional cameras. The authors propose a processing pipeline to estimate absolute and relative rotation measurements between event images generated by integrating events over 40 ms time windows, enabling a potential 25 Hz attitude estimate update rate. Noisy measurements are optimized through new algorithms for rotation averaging and bundle adjustment. Across test sequences lasting 45 seconds with over 1000 event images each, the approach achieves less than 1 degree attitude estimation errors. The results demonstrate event cameras are a promising technology for spacecraft attitude determination via star tracking. However, modern event cameras still have relatively low resolution, which reduces accuracy compared to standard solutions (1 degree versus 0.01 degree). Also, prices on commercial event cameras are dramatically higher to conventional ones, limiting their usage in low-cost applications.

Conclusion

In conclusion, this review has surveyed the current state of knowledge on star tracker systems for nanosatellite attitude determination. Theoretical fundamentals, key performance parameters, algorithms, testing methodologies, and design approaches related to star trackers were examined. Key findings show that it is feasible to create a low-cost star tracker for CubeSats using off-the-shelf components and open-source software, as demonstrated by projects like StarberrySense, SOST, and CubeStar. These existing prototypes achieve arcminute-level attitude determination accuracy below $2000 in total system costs, but are limited to 0.2-1 Hz update rates. Therefore, ongoing research opportunities include boosting star tracker speed without dramatically raising the design cost. There could be both hardware and software methods, for example, choosing a more powerful processing unit, utilizing hardware acceleration, a neural network or FPGA for some image processing operations, using information from previous frames and other satellite sensors for faster star detection, etc. As small satellites continue advancing scientific and commercial space missions, developing accessible yet accurate star tracking technology remains an impactful area of research.

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