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# Challenges to overcome limitations of human centric practices in celestial navigation at sea

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**Abstract**--Celestial navigation for position-fixing ships at sea has been practised for over two centuries, and the fundamental principles are the same even today. However, the mariner's interest has gradually eroded in practising celestial navigation at sea with the proliferation of satellite-based systems with better positional accuracy. The primary cause for neglecting celestial navigation at sea is limited dependence on manual observation of heavenly bodies. Computational celestial navigation methods have achieved near real-time calculation with advanced software. However, the accuracy of the computed position depends on the feed of manually observed altitude of celestial bodies. To revive the time-tested and proven celestial navigation at sea, this paper analyses the challenges of overcoming this human-centric observation. The paper explores ways and means to improve positional accuracy by advanced technology for auto-observation of celestial bodies to wean off these observational errors. Further, the article thrives to achieve an autonomous celestial navigation system enabling it as an alternate tool for position fixing at sea by focusing on the sole integration of automated observation devices with advanced algorithms-based software processing to augment positional accuracy apart from achieving instant determination of a ship's position at sea.

**Keywords**--celestial navigation, celestial body observation, technology advancement, optical sensor, autonomous system.

**Introduction**

The Celestial Navigation for position fixing ships at sea has been practised for over two centuries, and the fundamental principles are the same even today. However, the mariner's interest has gradually eroded in practising celestial navigation at sea with the proliferation of satellite-based position fixing systems. When analysing the primary cause for the neglect of celestial navigation,

limitations due to manual observation stand out, among other reasons. Computational methods for celestial navigation position fixing have recently progressed in achieving near real-time calculation with advanced software. However, the accuracy of the computed position depends on the feed of manually observed altitude of celestial bodies. To revive the time-tested and proven celestial navigation at sea, this paper analyses the challenges to overcoming human-centric observation of celestial bodies and explores ways and means to improve positional accuracy.

## **Methods**

The study method includes an analysis of limitations experienced in celestial navigation position fixing compared with satellite-based position methods. In particular, errors caused by human-centric observation are practised in the celestial navigation procedure at sea. The method of analysis further includes the factors necessitating the celestial navigation to be a standalone positioning system at sea and how to reap benefits from vital technological advancement today to revive the traditional celestial navigation system.

## **Limitations in Position Fixing by Celestial Navigation at Sea**

Celestial navigation at sea has many advantages as it is a time-tested independent positioning system. However, compared with the current satellite-based position fixing systems, it suffers comparable limitations like observational limitations, position accuracy, and computation procedure. Notably, observational limitations are its dependence on fair weather, limited altitude window, the necessity of twilight conditions, dependency on the sextant instrument and manual observation of celestial bodies. Limitations in the observation of heavenly bodies can be clubbed broadly into two main aspects, namely:

- Manual (Human-centric) Observation and
- Environmental Restriction

Here, the second aspect, 'environmental restrictions', is predominantly due to dependency on sighting the celestial bodies due to a restricted time window for observation. These restrictions are due to inclement weather, the ability to sight stars and planets only during twilight periods and the inability to use celestial bodies during monsoon periods. This environmental impediment needs further research and deliberation to overcome. Meanwhile, this paper focuses on challenges to overcoming the limitation of human-centric observation with advanced technology tools to enhance position accuracy during fair weather conditions.

## **Analysis of Limitations of Human Centric Factors in Celestial Navigation**

A comparative Study on existing practices, wherein the manual observation of celestial bodies in Celestial Navigation with Satellite-based Navigation is highlighted in Table 1. Advanced technology tools for observation and computation could overcome these contributory factors to improve the Celestial

Navigation practices at sea. This paper explores similar tools clubbed with an ideal electro-optical system as an automatic observation tool. Avoidance of human-centric observation of celestial bodies to negate error creeping in can enhance the ship's position accuracy based on the celestial navigation principles (Spitzer, Cary R, 2007).

### **Imperatives for Celestial Navigation as a Standalone system at sea**

Mariners have used the Global Positioning System (GPS) as the primary system for navigation since the early 1990s. GPS is considered more cost-effective and more accurate than a celestial navigation system. However, Satellite systems are prone to security threats like computer malware, electromagnetic pulse attacks and jamming (Peterson, 2016) and denial of GPS use unexpectedly with misuse of advanced technology for disruption. GPS is operated by the US Navy and allows merchant vessels of all countries to use it. As witnessed during recent development, US agencies can tweak GPS accuracy or introduce positional errors, if desired, during conflicts/wars, international sanctions, or political imbroglio. Another drawback with satellites is that they can be damaged or disabled during Sunspot activity. This vulnerability of GPS necessitates the backup system for marine navigation, which is standalone, fool-proof and highly accurate for position fixing at sea.

### **Inertial Navigation System (INS)**

An Inertial Navigation System (INS) is an alternative to GPS / Satellite navigation systems, capable of accurately maintaining the ship's dead reckoning. Still, the position's accuracy is not guaranteed for extended periods (Athena Navy, par 6). Further, INS needs regular alignment with an external reference system, the GPS. This reference system could be changed to a reliable standalone celestial navigation system with an envisaged advanced technology tool, as proposed in the paper. Integrating celestial navigation and inertial navigation systems is not a novel concept and has been existing, but with manual feed. Celestial navigation may not be feasible during a cloudy day; however, INS is regarded as an "excellent bad-weather flywheel" (Kaplan, par 4).

Table 1

Contributory Factors towards less reliability and accuracy in Celestial Navigation at sea in comparison with the Satellite Navigation

Contributory Factors	Position Fixing by Celestial Navigation at Sea	Position Fixing by Satellite Navigation at Sea
Average Accuracy of Fix	1 to 1.5 NM (1850 to 2750 m)	100-300 m
Needed Input Parameters		
Altitude / Azimuth of Celestial Body & Time	3 or 4 number of celestial bodies	Nil
Availability of Satellite	Nil	Ephemeris data of 3 or 4 number satellites
Errors in accuracy caused by		
Instrument error	Yes	Nil
Manual observation	Improper observation of	Automatic

error	Celestial body manually Unclear UL/LL of the Celestial body or Horizon	
Inaccurate reading of Altitude from Sextant	Yes. Induces errors in position accuracy	Nil
Refraction Error	Position Accuracy error	Nil
Height of Eye / Dip Error	Position Accuracy error	Nil
Parallax error	Position Accuracy error	Nil
Manual Sight reduction of azimuth	Position Accuracy error	Nil
<b>Suitability Factors</b>		
Single CB observation	Yes	No
Weather dependence	A restricted time window for observation of celestial body	No
Suitability for Coastal & Ocean Passage	Accuracy and Time Lag do not suit coastal passage	Reliable for both passages
Autonomous	Yes, it does not depends on external inputs	It depends on Satellite Signals
Reliability	60%	95%
Time Lag	Yes	Instantaneous Fix

## Results and Discussion

The result of the analysis paves the way for introducing modern concepts and tools of advanced technology into the celestial navigation practices at sea to make it a robust navigation system with better accuracy in position fixing.

### Celestial Navigation as an Autonomous System

Modern Concepts for Marine Navigation. With advanced technology in scientific/industrial applications, it is highly possible to select tools/devices to observe the celestial bodies automatically and select suitable algorithm-based software to compute the accurate position of a ship at sea. It involves the following vital steps:

- Identification of Celestial Body
- Determining Coordinates of Celestial Body (Azimuth / Altitude)
- Algorithm/software to compute the ship's position

### Identification of Celestial Body

The main ingredient of accurate celestial position fixing is the identification of celestial bodies to be observed, especially stars and planets. The traditional identification procedure is highly reliable, but when coupled with automated software-based identification techniques, the observation becomes much more straightforward, and position accuracy enhances. Modern software-based applications like Google sky, Sky Safari, Star Tracker, and Skyview work on iOS and Android to show 88 constellations of stars, over 8000 sky objects, the Sun,

Moon and Planets in real-time. These Apps use a 3D compass in AR (Augmented Reality) mode that indicates the position of sky objects searched for, like a mobile planetarium (Brown, 2022). Further, Star Tracker has a graphics feature for the 12 zodiac signs to enhance constellations. Its part will tell us all upcoming astronomical events and celestial bodies visible at our location, as shown in Figure 1, with the approximate position, date & time set. Most of these applications are freely available for commercial use. Conjoining these technologically advanced applications along with one of the many existing star identification algorithms based on current star catalogues will undoubtedly result in accurately identifying celestial bodies. The full-sky autonomous star identification algorithm is one of them, and it intends to solve the "lost-in-space" problem for spacecraft attitude determination (Jiangbo, 2019). When these advanced technology tools are used for autonomous identification of celestial bodies in celestial navigation at sea, it will highly reduce human-centric observation errors and enhance position accuracy.

### **Camera Sensor**

Prevention of human observational error refines the positional accuracy of celestial navigation. Moreover, it could achieve by introducing automatic observation using the commercially available advanced technological tool. The advanced camera (used in star trackers of spacecraft) for auto-observation of celestial bodies can replace the sextant under a controlled environment, including computer guidance for using select heavenly bodies. An advanced camera must meet ergonomic conditions for a stabilised mounting to prevent the ship's roll, pitch and yaw motions while housing it at a known height atop the ship bridge.

### **Active Pixel Sensor (APS)**

Patterns of stars, a single star, or the Sun's position in the celestial sphere give us a point of reference and are very useful for navigation. Present generation star trackers, used in spacecraft, transfer the entire star image from the camera to the computer's microprocessor for processing the whole picture. Two types of star cameras are used in modern star trackers: the Charge-Coupled Device (CCD) sensor and the Active Pixel Sensor (APS). As against the traditional CCD technology, the APS is a new compact imaging device with an array of photo sensors and a higher dynamic range (Liebe, Dennison, Hancock, Stirbl, & Pain, 1998). A miniaturised camera with an Active Pixel Sensor (APS) is used in a Wide Field of View (WFOV) to recognise star patterns. APS is a new compact imaging device with an array of photosensors. APS uses only a fraction of the power used by standard / traditional Charged Coupled Device (CCD), enabling a significant reduction in the energy, size, weight and cost of imaging and spectroscopy instruments (Peng Zhang, 2014). As a result, the WFOV camera can observe a wider field and take pictures of the star patterns in its view. The star camera's sensor can track both bright and faint celestial bodies in its field of view and prevent extremely bright bodies when programmed, such as the Moon or the Sun, from spilling over into the pixels of captured stars. Using an advanced image algorithm, the captured images compared to a star catalogue stored in the onboard computer memory can achieve the desired result.

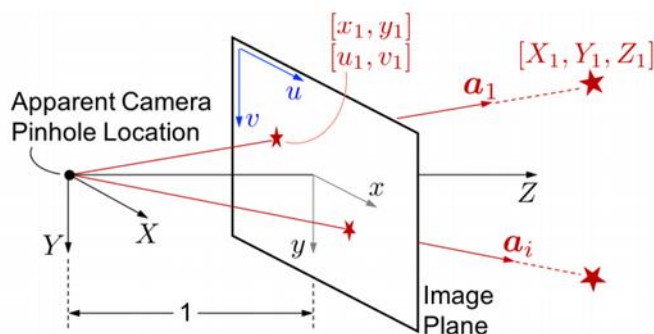


Figure 1. Illustration of Star Tracker App Screen for identification in real-time of stars in the constellation – Tech Services & Software, CNET (Brown, 2022)<sup>[5]</sup>

### Projective Camera

The pinhole camera model describes an ideal projective camera, as shown in Figure 2. Here, the camera's z-axis is along the optical axis going out of the camera and the location  $x$  piercing the star image plane (in front of the camera's optical centre) is worked out using projective geometry. Its coordinates are found using focal length normalised coordinates (homogeneous coordinates of the projective space), which is feasible with the projective camera image. A specific algorithm autonomously recognises it. Images of star fields collected by a projective camera are instrumental in star identification as it provides a comprehensive and systematic framework for invariant-based star identification (CRASSIDIS, 2021).



Figure 2. Illustration of the camera frame, an image plane at unit depth and Star projection geometry with the pinhole camera model. Source: (CRASSIDIS, 2021)

Digital images of stars collected by projective cameras contain valuable information for application in many fields, including celestial navigation. Star patterns, also known as asterism, use only the pixel coordinates of the stars in an image to identify each star's position. It describes the pattern geometry that

remains unchanged under the action of a projective camera at an unknown location of the camera. It is achieved by computing algebraic quantities of different numerical values for each star pattern (asterism). The collection of these algebraic quantities, called simply invariants, are used to construct asterism descriptors in a projective camera-based identification process. Invariant asterism descriptors are the mathematical construct of practical star identification algorithms.

### **Identification Algorithm**

Numerous star identification algorithms are used in spacecraft to position themselves in space using a star camera (star sensor) orientation determination applications. For a star pattern (asterism) to be recognisable in a single image, there must be some attribute of the pattern that is always recoverable from only its appearance in the image. These algorithms use attributes related to geometric or photometric properties of the asterism (star pattern) to recognise. More importantly, the algorithm used in the projective camera can identify the asterism with the pattern geometry, using only the pixel coordinates of the stars in an image alone. It helps recognise star patterns (i.e., asterisms) for a wide array of different imaging systems. These asterisms made star identification possible from most current star catalogues (LEEUVEN, 2007). These advanced algorithms and the projective camera, used as a star sensor in spacecraft, could be explored for use onboard ships for celestial navigation applications with suitable modification to the technology involved. When processed by this advanced algorithm with the star catalogue in ship-based computer processing, the captured digital image can facilitate the identification and obtain of the star's coordinates, altitude/zenith distance and azimuth.

### **Determination of Celestial Body Coordinates (Azimuth / Altitude)**

As per principles of celestial navigation at sea, the altitude and azimuth of a celestial body are used for position finding of a ship at sea. Altitude above the horizon and the Azimuth angle from the true North are coordinates of a celestial body in the celestial horizon system, as shown in Figure 3. The body's altitude (star, planet, moon or Sun) for the visible horizon is obtained based on the sextant angle from the ship. This sextant altitude is then corrected to true altitude concerning the celestial horizon. The celestial horizon; is an imaginary great circle in the celestial sphere at 90 degrees from the observer's (ship's) zenith and nadir. True altitude thus obtained is for finding the zenith distance (angular distance from the observer's zenith to the celestial body) at that instant of measuring its altitude. Depending on the celestial navigation position fixing method, Intercept, Longitude by Chronometer, Meridian Passage, and Polaris method used, the parameters of the observed celestial body, like zenith distance, azimuth, and declination of the body, could be used to compute the position.

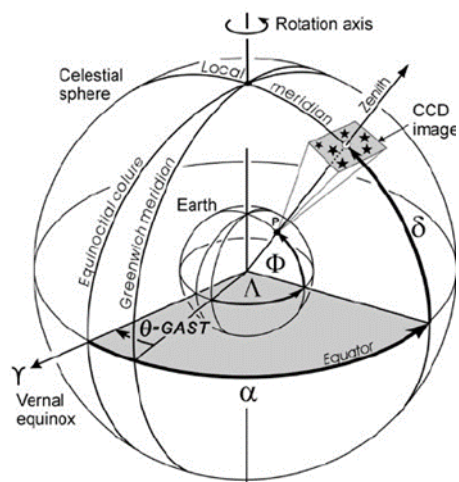


Figure 3. Altitude-Azimuth system coordinates and specifies the position of an object in terms of two angles – the altitude above the horizon and the azimuth, which is the angle clockwise from the true North

Notably, the visible horizon of an observer (ship at sea) plays a vital role in determining the altitude of the observed celestial body. From the altitude, the zenith distance of the celestial body is computed, as both angles complement each other to find the ship's position. The zenith of an observer (vessel) is an imaginary point directly above a particular location on the imaginary celestial sphere. It is a vertical straight line overhead an observer from the Centre of the Earth (Centre of the celestial sphere). Celestial position fixing methods use either this true altitude angle for the celestial horizon or the true zenith angular distance. As altitude angle is measured for the visible horizon in manual observation, the manual observation and reference of the visible horizon could be done away with direct measurement of the zenith angular distance of a celestial body by an automated observational device.

### Digital Zenith Camera

Geodetic astronomy is the only discipline that provides methods for directly observing the direction of the plumb line (vertical line) (Hirt C. R., 2004). With the advancement of technology, a significant change has occurred in geodetic astronomy. Digital zenith camera systems based on digital imaging sensors (CCD) with an improved degree of automation and efficiency are used to accurately observe the direction of the plumb line, as shown in Figure 4 and its vertical deflection. The principle of this new digital zenith camera system (DZCS) and its data processing is similar to the projective camera and its reduction of astrometric data. Most modern star catalogues describe a star's direction by a pair of angles known as Declination and Right ascension (R.A.) in the Celestial Reference Frame (Feissel, 1998). In the DZCS, the direction of the plumb line ( $\Phi$ ,  $\Lambda$ ) is obtained utilising direct measurements of celestial bodies, primarily stars, taking into equatorial coordinates Right Ascension and Declination of celestial bodies

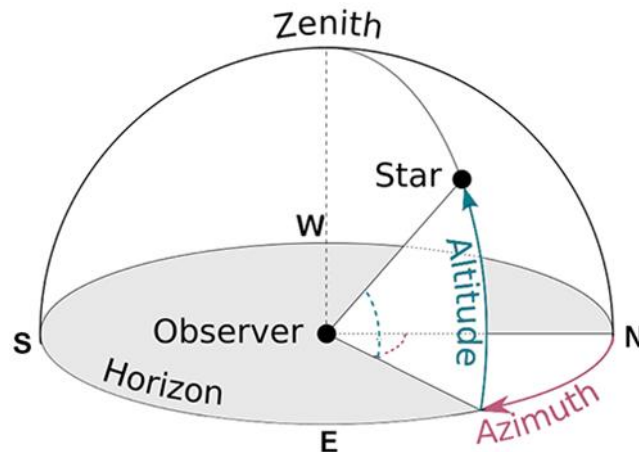


Figure 4. Digital Zenith Camera System – Direction of Plumb line. Source: (Hirt C. R., 2004)

The software package used in geodetic astronomy is the Automatic Real-time Image Processing System for Geodetic Astronomy (AURIGA) for processing DZCS measurement (Hirt C. R., 2004). This software extracts stars from the image data, accesses star catalogue data, performs a precise astrometric data reduction and computes required corrections yielding astronomical coordinates  $\Phi$ ,  $\Lambda$  of the camera. The AURIGA data processing usually takes some seconds per single solution, thus enabling real-time determination of vertical deflection data and the highly accurate determination of the geometry of the gravity field along profiles for validation purposes. One can use this technique and software processing to determine an observer's zenith (ship at sea) and zenith distance, which is a complimentary angle of the altitude of celestial bodies.

### **Azimuth Method**

Position computation is achieved by the intercept method in the traditional celestial position fixing of a ship at sea. The intercept method uses altitudes of stars and planets, ideally visible during the twilight periods. However, it is highly feasible to identify the azimuth of each star at an instant of time to the true North. The azimuth is the angle between the observer's celestial meridian and the great circle passing through a celestial body. Azimuth angle could be measured throughout stars/planets visibility in the night azimuth angle of the Sun during the daylight hours, unlike altitude measurement, which depends on the window of twilight periods (Nguyen, 2017). The azimuth angle between great circles of three celestial bodies from an observer's (ship) position is shown in Figure 5.

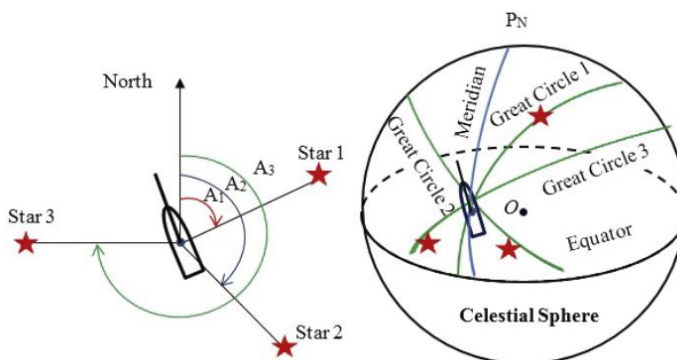


Figure 5. The Great Circle Azimuth of Celestial Bodies from a ship's Position (Meridian). Source: (Nguyen, 2017)

When an observer measures a celestial body's azimuth, he finds an angle between his meridian (great circle from True North to Observer) and the star's great circle. As known, the light transmits from any celestial body (including stars) to the observer's eyes by the shortest arc described by a great circle. That is to say, in the celestial sphere, two great circles create the azimuth angle, the first one being the meridian arc of the observer from the ship's position and the one being a great circle that goes through the celestial body and the ship's position. The arc of the great circle, which goes through the ship's position and the celestial body, is also known as the Circle of Position (COP), which determines the ship's position (Earle, 2005).

The azimuths of three celestial bodies are shown in Figure 5. The azimuth can be computed by the spherical trigonometric formula for the celestial sphere when the altitude of the celestial body is known, by

$$Z = \cos^{-1}[(\sin(\text{declination}) - \sin(\text{Latitude}) \times \sin(\text{Hc})) / (\cos(\text{Latitude}) \times \cos(\text{Hc}))] \dots (1)$$

The azimuth can be computed when Hour Angles and Declination of the Celestial body are known, by

$$Z = \tan^{-1}\left(\frac{\sin \text{LHA}}{(\cos L \tan d) - (\sin L \cos \text{LHA})}\right) \dots (2)$$

{L is the Latitude of Observer, and D is the declination of the observed celestial body at that instant. LHA is the Local Hour Angle is the angle between the meridian of the celestial body and the observer's meridian, LHA = GHA (of the celestial body) - Longitude (of the observer)}

The azimuth can also be computed when assumed Latitude, precise Declination and Hour Angle are known, by

$$Z = \cos^{-1} [(\sin \varphi_2 - (\sin \varphi_1 \cos \delta)) / (\cos \varphi_1 \sin \delta)] \dots (3)$$

This Azimuth method of position finding could be used to determine the ship's position by Sun during the day and by stars & planets during the night with reasonable accuracy and effectiveness. Thus, if a celestial body's azimuth is observed with reliable accuracy using a technologically advanced optical device instead of the current practice of human observation, the position fixing by celestial navigation at sea becomes highly reliable and accurate.

### **Algorithm/software to compute the ship's position**

Many advanced computer-based algorithms/software are currently available to compute a ship's position coordinates based on celestial bodies' altitude and azimuth. These algorithms are adaptively robust maritime celestial navigation algorithms in which each observation value is given an equivalent weight according to the robust estimation theory and the dynamic balance between astronomical observation and prediction values of ship motion by applying adaptive factors (Li, 2022). As proposed in this paper, it is possible to interface the auto-feed coordinates of observed celestial bodies from a remote observation device with this advanced computing software. This arrangement will make it free from human-centric observation to a great extent, thus achieving error elimination in observation and accuracy improvement of the ship's position.

### **Autonomous Celestial Navigation Sensor**

Stars and other celestial bodies were extensively used for safe navigation at sea for centuries, except it lacks positional accuracy owing to inherent limitations. The main contributory factors of inaccurate position based on celestial navigation principle are the human-induced error in observation and time window restriction. Exciting research exists on the Stellar Positioning System (SPS) (Julie J. Parish, 2010), which recognises the celestial bodies from an image without the aid of a human and independently looks up their inertial positions in a star catalogue. Advancement in technology and the development of modern software-based processors in the computer system has catapulted the performance and accuracy of the electro-optical system, including optical camera sensors used in various applications. Star sensors, and cameras, have advanced technologically as satellite-based applications demanded refinement over a while in their size, weight and other parameters apart from furthering the accuracy in performance onboard the spacecraft. However, Star identification was predominantly for altitude determination, used for other applications in spacecraft and onboard other crafts.

Notable fields of application include Star Gyros (Benjamin B, 2009), where the images of star cameras are used to estimate the spacecraft's angular velocity. Image interpretation with bearing determination of the observed celestial bodies like Sun, Moon, Planets or Stars have the best potential to arrive at an autonomous celestial navigation device for use onboard ships. Likely, the advantage of technological advancement in the electro-optical system and modern camera device and the development of cutting-edge algorithms could blend with principles of celestial navigation. Applying advanced technology in optical sensors to observe stars & other heavenly bodies and suitable algorithm-based software

can provide an autonomous celestial navigation sensor. It can enhance the accuracy of celestial navigation position fixing onboard ships apart from eliminating a few existing limitations described earlier in the paper.

## **Conclusion**

The application of advanced technology tools in industrial fields has improved efficiency. Technically, automated tools like artificial intelligence and robotic technology are available to take on human-less tasks. Similar tools clubbed with an ideal optical instrument could be made available to observe celestial bodies to negate creeping in human error in observation apart from improving celestial navigation position fixing accuracy. This paper analysed means modern concept for transforming celestial navigation as an autonomous system for marine navigation at sea. It includes using zenith distance (compensatory angle of altitude) and azimuth (true bearing) of the celestial bodies, Sun, Moon, Planets and navigable stars to find position based on the celestial navigation principle. Further, the paper analysed the concept of an advanced algorithm for computation, thus eliminating human elements in all stages of position-fixing techniques. This paper examined the algorithms used in star identification and autonomous recognition of asterism in a digital image of star fields obtained by the projective camera. Further theoretical analysis and simulation of such methods can validate the effectiveness of a star sensor camera for use onboard ships to arrive at an autonomous celestial navigation sensor. Thus, it would enhance the accuracy of celestial navigation position fixing and achieve automation of celestial navigation at sea.

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