Review of Celestial Autonomous Navigation Technology for Deep Space Exploration (Postprint)

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Abstract

Autonomous navigation technology offers significant advantages in enhancing the autonomous survival capabilities of deep space probes, alleviating the burden on ground measurement and control systems, and enabling navigation during critical phases of exploration missions, thereby becoming a global research focus. China' s Mars exploration program has been initiated, with future plans for missions to asteroids, comets, planets, and their satellites. This paper elaborates on the necessity of developing celestial autonomous navigation technology, expounds upon its fundamental principles and advantages, surveys the status of deep space celestial autonomous navigation technologies and applications both domestically and internationally, and summarizes the key technologies essential for its development. Finally, based on this analysis, recommendations and considerations for advancing autonomous navigation technology for deep space exploration in China are presented.

Full Text

A Review of Autonomous Celestial Navigation Technology for Deep Space Exploration

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Abstract

Autonomous navigation technology offers significant advantages in enhancing the self-survival capabilities of deep space probes, reducing ground tracking and control burdens, and meeting navigation requirements during special mission phases. It has become a research hotspot worldwide. China has launched its Mars exploration program, with future plans for asteroid, comet, and planetary satellite missions. This paper elaborates on the necessity of developing autonomous celestial navigation technology, explains its fundamental principles and advantages, and provides an overview of deep space autonomous celestial navigation technologies and their applications both domestically and internationally. The key technologies for developing autonomous celestial navigation are summarized, and based on this analysis, suggestions and considerations for developing deep space exploration autonomous navigation technology in China are proposed.

Keywords: celestial navigation; autonomous navigation; deep space exploration

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1. Introduction

As humanity' s ability to explore space continues to grow, deep space exploration has become a focal point in aerospace development. Probing celestial bodies such as planets and their satellites represents an important pathway for understanding Earth, the solar system, and the origins of the universe, as well as for developing space science and technology. However, deep space missions face enormous communication time delays that hinder the handling of emergencies and probe malfunctions, posing significant risks to spacecraft survival. The vast distances, long mission durations, and limited ground tracking resources required for deep space navigation place heavy burdens on ground-based systems. Autonomous navigation technology can continue orbit determination and attitude adjustment even when ground communication is interrupted, thereby greatly enhancing spacecraft survivability. During critical mission phases such as landing and impact, autonomous navigation is particularly crucial as it requires precise knowledge of the probe' s position, velocity, and attitude information to implement appropriate navigation and control measures—requirements that traditional Earth-based tracking cannot meet in terms of precision and timeliness due to excessive time delays.

Autonomous navigation technology demonstrates clear advantages in improving probe survivability, reducing ground tracking burdens, and meeting special phase navigation requirements, making it an urgent key technology to develop. Celestial autonomous navigation, which uses natural celestial bodies as navigation beacons, offers complete autonomy, non-accumulating errors, strong anti-interference capability, and the ability to provide both position and attitude information simultaneously. It has become a widely adopted autonomous navigation method [1-2]. This paper reviews the principles, international research progress, and applications of deep space celestial autonomous navigation technology.

2. Principles and Advantages of Celestial Navigation Technology

2.1 Basic Principles Broadly defined, celestial navigation uses natural celestial bodies such as the Sun, planets, and stars as navigation beacons, employing their horizontal coordinates (azimuth or altitude) as observables to determine geographic or spatial position and orientation references [2-3]. The fundamental principle involves using measurements obtained by onboard sensors to autonomously determine the probe' s attitude and position, providing reference standards for autonomous operation and generating control commands to alter the spacecraft' s spatial state [4].

Foreign deep space missions primarily employ starlight navigation technology, with another approach being radio signal-based autonomous navigation. Due to the limited number of pulsars and insufficient measurement accuracy, pulsar navigation remains in the research stage and has not yet reached practical application [5-6].

The celestial navigation system consists of three main modules: navigation information acquisition (primarily performed by star sensors), information processing, and navigation control. The acquisition module receives measurement commands, captures images of celestial bodies, and collects navigation information, which is then sent to the processing module. This module analyzes and extracts usable observation data, combines it with the probe' s existing attitude and position information, autonomously calculates the next moment' s attitude and position, completes ephemeris correction, plans the upcoming orbital segment, and computes required thrust and attitude commands for orbital maneuvers. The navigation control module executes these commands to perform orbital maneuvers and attitude adjustments. [Figure 1: see original paper] shows the system composition.

2.2 Classification of Methods Based on the different objects observed by star sensors, celestial navigation can be categorized into three types: autonomous navigation based on stars, based on the Sun and planets, and based on asteroids or planetary moons. Star sensors are susceptible to stray light interference from spacecraft body albedo, lunar albedo, Earth albedo, and space debris, which significantly affects imaging quality. While planets are bright, they are too few in number and their navigation accuracy decreases with distance from the spacecraft, making them unsuitable for navigation. Planetary moons are numerous but orbit close to their planets. Asteroids, however, are abundant, can be approximated as point light sources in imaging, and offer relatively high navigation accuracy, making them ideal for deep space autonomous navigation. For instance, Deep Space 1' s cruise phase autonomous navigation was accomplished by capturing images of asteroids against stellar backgrounds, achieving position errors of 90-250 km and velocity accuracy of 0.25 m/s, fully meeting cruise phase requirements [7-10].

2.3 Advantages Celestial navigation offers several key advantages: it uses natural celestial bodies as beacons without requiring additional hardware; it operates without ground radio equipment participation, ensuring strong security and concealment; it provides both position and attitude information simultaneously; celestial radiation covers the entire electromagnetic spectrum from visible light to infrared, making it applicable to space, land, and marine navigation; it offers high precision with non-accumulating errors; and it relies only on attitude-sensitive components like star sensors and infrared Earth sensors.

3. International Development and Applications

Celestial navigation has a long history. In 1875, French navigator Saint-Hillaire established the altitude difference principle, marking the birth of modern celestial navigation theory. Initially using sextants and nautical almanacs for maritime navigation, the technology evolved for space applications. Foreign researchers began large-scale studies on probe autonomous navigation, with celestial navigation continuously verified and improved through various missions, advancing in observation instruments, information acquisition, and processing methods.

Initially, celestial navigation served as an auxiliary means to verify ground tracking data. However, missions like Mariner 9 demonstrated that navigation could be completed solely through celestial navigation. summarizes autonomous navigation applications in typical deep space missions.

Applications of autonomous navigation technology in deep space exploration

Mission	Nation	Application description of astronomical navigation technology
Apollo 8 (1968/12)	USA	Star sensor used only as auxiliary means to verify trajectory correctness during lunar phase
Mariner 9 (1971/5)	USA	Successfully entered Mars orbit with celestial navigation; proved navigation could be completed autonomously
Deep Space 1 (1996/2)	USA	First successful autonomous navigation in cruise phase using photo sequence planning, image extraction, and orbit analysis
Stardust (1999/2)	USA	Navigation camera and optical camera for autonomous nucleus tracking
Hayabusa (2003/5)	Japan	Optical camera for asteroid sample return navigation, guidance, and control
Rosetta (2004/3)	Europe	Narrow and wide field-of-view cameras for comet/asteroid encounters

Mission	Nation	Application description of astronomical navigation technology
Deep Impact (2005/1)	USA	MRI and HRI cameras for autonomous navigation before collision
Mars Surveyor (2005/8)	USA	Navigation camera for autonomous navigation near Mars using satellite images and ephemeris

Beyond these flown missions, numerous planned missions incorporate autonomous navigation. ESA' s Don Quijote asteroid impactor program proposes autonomous navigation during approach and impact phases [22]. NASA' s Mars Sample Return and Mars Telecom Orbiter plans demonstrate autonomous navigation for deep space rendezvous [23]. China' s Chang' e-3 successfully achieved autonomous hazard avoidance during lunar soft landing using optical imaging sensors to obtain landing area images, reconstruct 3D terrain from image intensity, identify obstacles, and select safe landing sites [24].

4. Key Technologies for Autonomous Celestial Navigation

4.1 Navigation Body Selection and Planning Implementing autonomous navigation requires identifying suitable navigation celestial bodies. Selection criteria include distance to detector, relative velocity, apparent magnitude, solar angle, phase angle, and sky region properties [7-8]. For asteroid navigation, the angle between lines-of-sight to two navigation asteroids is also considered. Different asteroid combinations yield different navigation accuracies. A covariance-based analysis method provides a quantifiable approach for selecting optimal asteroid combinations.

Navigation asteroid selection criteria [7-8]

Parameter	Criterion
Apparent magnitude	<1,000,000
Solar angle (°)	<1,000,000
Relative velocity (km/s)	<1,000,000
Distance to detector (km)	<1,000,000
Angle between two navigation asteroids (°)	<1,000,000

Once selected, navigation asteroids are compiled into a database—essentially an ephemeris containing positions, motions, and star charts for route planning during flight.

4.2 High-Precision Star Sensor Technology Star sensors are critical components requiring high precision and large dynamic range. They fall into two categories: (1) CCD-based sensors, which have been mainstream, and (2) CMOS APS (Complementary Metal Oxide Semiconductor Advanced Photo System) sensors. CMOS sensors offer wider fields of view, access to brighter navigation stars, reduced star catalog size, and lower weight, becoming the primary focus internationally. For example, Lockheed Martin' s AST-301 achieves 99.98% success probability in attitude acquisition without prior information.

Domestic researchers have made progress in hardware, algorithms, calibration, and simulation. A 1024×1024 pixel sensor was successfully flight-tested on the lunar return vehicle, achieving <1 second in-orbit attitude acquisition. Typical star sensor parameters from various missions are shown in .

Typical star sensor parameters [16-17, 29-31]

Mission	Star sensor	Field of view	Resolution
Deep Space 1	Optical camera 1	0.76°	1024×1024P
Deep Space 1	Optical camera 2	0.26°	256×256P
Rosetta	Narrow field camera	2.4°	2048×2048P
Rosetta	Wide field camera	3.5°	2048×2048P
Stardust	Optical camera	5.7°	1024×1024P
Hayabusa	Optical camera	0.57°	1024×1024P
Deep Impact	MRI camera	0.12°	1024×1024P
Deep Impact	HRI camera	0.12°	1024×1024P

4.3 Navigation Information Acquisition and Processing Image acquisition and processing algorithms are core to navigation. The process involves: capturing navigation images, denoising, distortion analysis and correction, extracting target body centroids, combining with attitude information, and using filtering techniques to determine orbit and attitude. JPL validated this technology during Voyager' s Uranus and Neptune flybys.

Key challenges include long star point extraction times and large star catalog storage requirements. A Gaussian surface fitting method achieved near-theoretical centroid extraction accuracy. A star clustering extraction method reduces processed pixels and storage space, cutting extraction time to ~1/3 of traditional methods. Star pattern matching has evolved from single-star to regional matching, with algorithms including triangle matching, polygon angular distance matching, and principal star identification, each with trade-offs in noise stability and speed [32].

4.4 Navigation Filtering Technology Filtering methods fall into two categories: (1) Orbit dynamics-based filtering, which combines celestial measurements with dynamic equations through optimal estimation, and (2) Pure geometric analytical methods using geometric relationships. Common algorithms include Extended Kalman Filter and Unscented Kalman Filter. Due to significant uncertainties in deep space environments, adaptive filtering algorithms robust to model uncertainties and environmental interference are needed [4].

4.5 Attitude Measurement Technology Star sensors measure stars on the celestial sphere to obtain observed star patterns, which are matched against catalog-generated reference patterns to determine three-axis attitude. Attitude determination uses sensor measurements to calculate the spacecraft body frame's orientation relative to a reference frame. High-precision gyroscopes can provide continuous attitude information to complement star sensors, with integration yielding attitude angles and real-time compensation ensuring in-orbit precision. A radial alignment constraint (RAC) method solves for intrinsic and extrinsic parameters from single-frame star images without external attitude references, achieving 0.0005 rad attitude estimation error [35].

4.6 Simulation Verification Technology Ground simulation systems are essential for validating autonomous navigation and control. Approaches include: (1) Star field simulators that replicate infinite star fields but are expensive and inflexible; (2) Outdoor star observation, which is weather-dependent and cannot simulate on-orbit conditions; and (3) Simulated star image-based testing, which uses full-frame simulated images as test signals to comprehensively evaluate star point localization and attitude computation. This method was used to develop Chang' e-3' s lunar soft landing navigation scheme, with simulation results guiding the successful mission design.

5. Conclusions and Outlook

Celestial autonomous navigation has been successfully applied in many foreign missions. Due to geographic and political constraints, China' s tracking resources and coverage are limited, making autonomous navigation development particularly critical. Future efforts should focus on:

1. **Multi-dimensional information fusion**: Combining celestial navigation with other methods (Doppler shift, inertial navigation) using generalized filtering algorithms to improve accuracy through complementary advantages.
2. **Communication-navigation integration**: Using spread-spectrum signals where pseudo-codes serve both for spreading and ranging, incorporating positioning parameters and timing. This approach narrows intermediate frequency bandwidth, reduces interference power, improves SNR, and enhances long-distance ranging and timing capabilities—crucial for deep space operations.

Beyond the key technologies discussed, China should strengthen talent cultivation and research capabilities to prepare for future deep space exploration activities.

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