Research on moon surface positioning and navigation method based on stellar vector measurement

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Abstract. In response to the needs of positioning and navigation in lunar exploration projects such as manned landing on the moon, and the initial positioning of the lunar lander, this paper proposes a lunar positioning and navigation method based on stellar vector measurement and inclination information fusion, and demonstrates the correctness of the algorithm. A semi-physical simulation platform was built and the experimental method verified that the accuracy reached the positioning accuracy index of 30 arc seconds. Lunar surface positioning is different from ground positioning and cannot be positioned by satellites. This method solves the problems of low timeliness and low accuracy of ground measurement and control methods, greatly improving the timeliness and accuracy of lunar surface positioning, and has positive significance for lunar exploration projects.

1. Introduction

The moon is the closest celestial body to the earth, and the exploration of the moon has never stopped. With the further development of the manned lunar landing project, the demand for lunar surface navigation and lunar surface positioning is increasingly urgent, and the requirements for the accuracy of navigation and positioning are also increasing[1]. The control of the landing point of the lunar lander and the navigation requirements of the ascending section force the research of high-precision and high-reliability positioning and navigation methods to be put on the agenda[2]-[4]. At present, the main positioning methods of deep space probes are ground measurement and control and celestial navigation[4]-[6]. The ground measurement and control positioning technology is highly reliable, mainly including solar system radar technology, Doppler and radio and other ground measurement technologies; celestial navigation has strong autonomy and high accuracy, Mainly refers to the use of sun sensors and star sensors for navigation[7].

The traditional celestial navigation method can only output the posture quaternion information in the space inertial system, but not the geographic position information. The traditional ground positioning method mainly relies on GPS satellite navigation, but on the lunar surface cannot be located by similar methods, celestial navigation is the most reliable and accurate navigation method for positioning in the lunar surface. In this paper, by establishing the relationship between the lunar center inertial coordinate system, the lunar center lunar coordinate system, and the target point local coordinate system, the function of using star sensors and inclination sensors to complete the lunar surface fully autonomous positioning can be realized[8]-[10].
2. Definition of lunar navigation coordinate system

Refer to the ground positioning and navigation method, the lunar surface positioning and navigation need to establish the relationship between the lunar center inertial coordinate system, the lunar center fixed coordinate system, and the lunar target point coordinate system. The coordinate systems are separately introduced below.

2.1. Lunar center inertial coordinate system

The lunar center J2000 coordinate system is approximately as the lunar center inertial coordinate system, the origin of the lunar center J2000 coordinate system is defined as the lunar center of mass, and the reference plane is defined as the lunar equatorial plane[11]. The x-axis is defined as the direction from the moon’s center of mass to the moon’s zero meridian in the lunar equatorial plane at the time of J2000, the z-axis is perpendicular to the equatorial plane and points to the north pole of the moon, and the y-axis is perpendicular to the other two axes in the reference plane and constitutes a right-handed coordinate system.

2.2. The lunar center fixed coordinate system

The origin of the coordinate system is defined as the center of the moon, the reference plane is the equatorial plane of the moon, the x-axis is defined as in the reference plane, pointing from the origin to the starting meridian, the z-axis is perpendicular to the equatorial plane and points to the north pole of the moon, and the y-axis is in Cartesian coordinates. The system is perpendicular to the other two axes and constitutes a right-handed coordinate system. The Oxz half-plane of the lunar-fixed coordinate system is the starting meridian of the moon's longitude. From this half-plane to the east, it is recorded as the lunar center east longitude, and the west is recorded as the lunar center west longitude. This coordinate system rotates with the moon.

2.3. The lunar target point coordinate system

The coordinate system is fixed to the moon body, the origin is defined as the landing point or landing projection point, the x-axis points from the center of the moon to the landing point, the z-axis is in the local meridian and points to the north pole of the moon, and the y-axis forms a right-hand right angle with the other two axes. The coordinate system, which points to the local true east direction.

A schematic diagram of the coordinate system is shown in Figure 1.

![Diagram of lunar coordinate system](image)

**Figure 1 Definition map of lunar coordinate system**
3. Lunar surface positioning and navigation method based on inclination information

3.1. Conversion method of attitude information in different coordinate systems
Aiming at the problem that the star sensor cannot output position information autonomously to complete autonomous positioning, an autonomous navigation and positioning method on the moon surface based on the stellar vector is proposed, that is, by studying the lunar center inertial system, the lunar center fixed coordinate system, and the target point lunar level. For the coordinate system conversion relationship, it is necessary to analyze the conversion method of the attitude output by the star sensor in different coordinate systems.

3.1.1 Transformation of Lunar Center J2000 Coordinate System and Lunar Center Fixed Coordinate System
The orientation system time \( t_{DX} \) is converted to a time interval between the standard epoch J2000.0 and \( t_{DX} \), expressed in terms of the Julian century (36525 flat solar day), represented by the parameter \( T \):

\[
T = (t_{DX} - 20*3600)/36525/86400 + 3653/36525
\]

The pointing vector \( V_{J2000.0} (x_1, y_1, z_1) \) of the star sensor output in the J2000.0 lunar inertial coordinate system is converted to the Lunar Center Fixed Coordinate System. The conversion formula is as follows:

\[
V_{LCF} = (RM \cdot RS \cdot RN \cdot RP) \cdot (V_{J2000.0} - \omega_e \times R_{LCF})
\]

Among them:
- \( R_M \) is the pole shift rotation matrix, where the unit matrix is taken;
- \( R_S \) is the rotation matrix of the star;
- \( R_N \) is the nutation rotation matrix;
- \( R_P \) is the precession rotation matrix;
- \( R_{WGS84} \) is the carrier position under the Lunar Center Fixed Coordinate System.

Among them:

\[
\omega_e \times = R_p^T \cdot R_s^T \cdot \hat{R}_s \cdot R_M^T
\]

\[
\hat{R}_s = \begin{bmatrix}
-\sin \Theta & \cos \Theta & 0 \\
-\cos \Theta & -\sin \Theta & 0 \\
0 & 0 & 0
\end{bmatrix}
\]
\[ R_x = R_z(-z)R_y(\theta)R_z(-\zeta) \]
\[ = \begin{bmatrix} \cos(z)\cos(\theta)\cos(\zeta) - \sin(z)\sin(\zeta) & -\cos(z)\cos(\theta)\sin(\zeta) - \sin(z)\cos(\zeta) & -\cos(z)\sin(\theta) \\ \sin(z)\cos(\theta)\cos(\zeta) + \cos(z)\sin(\zeta) & -\sin(z)\cos(\theta)\sin(\zeta) + \cos(z)\cos(\zeta) & -\sin(z)\sin(\theta) \\ \sin(\theta)\cos(\zeta) & -\sin(\theta)\sin(\zeta) & \cos(\theta) \end{bmatrix} \] (5)

Where: the precession parameter \( z \), can be calculated by:
\[ \zeta = 2306''.2181T + 0''.301887T^2 + 0''.017927T^3 \] (6)
\[ z = 2306'' .2181T + 1''.094987T^2 + 0''.018207 T^3 \] (7)
\[ \theta = 2004''.3109T - 0''.42665T^2 - 0''.041533T^3 \] (8)
\[ R_x = R_y(-\varepsilon - \Delta \psi)R_z(-\Delta \psi')R_z(\varepsilon) \]
\[ = \begin{bmatrix} 1 & -\Delta \psi \cos \varepsilon & -\Delta \psi \sin \varepsilon \\ \Delta \psi \cos \varepsilon & 1 & -\Delta \varepsilon \\ \Delta \psi \sin \varepsilon & \Delta \varepsilon & 1 \end{bmatrix} \] (9)

Among them:
\[ \varepsilon = 23''.26'21'' .448 - 46''.8150T - 0''.00059T^2 + 0''.001813T^3 \]
\[ \Delta \Lambda = -17''.200\sin \Omega_m \]
\[ \Delta \varepsilon = 9''.202\cos \Omega_m \]
\[ \Omega_m = 125''.044555556 - 1934''.1361850* T_{J2} \]

3.1.2 Transformation between the lunar center fixed coordinate system and the target point lunar plane coordinate system

The vector (VYG) in the lunar center fixed coordinate system to the target point in the lunar plane coordinate system (MNU) can be expressed as:
\[ V_{MNU} = C_{LCF}^{MNU}(\lambda, 90 - \lambda, 90) \bullet V_{LCF} \] (10)
among them:
\[ C_{LCF}^{MNU}(\lambda, 90 - \lambda, 90) = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} \sin \varphi & 0 & -\cos \varphi \\ 0 & 1 & 0 \\ \cos \varphi & 0 & \sin \varphi \end{bmatrix} \bullet \begin{bmatrix} \cos \lambda & \sin \lambda & 0 \\ -\sin \lambda & \cos \lambda & 0 \\ 0 & 0 & 1 \end{bmatrix} \] (11)

3.2 Lunar surface positioning method based on inclination sensor

The goal of navigation and positioning is to obtain the position in the fixed coordinate system of the center of the moon. To calculate the position information, it is necessary to rely on the star sensor to obtain its attitude information in the center of the lunar J2000 inertial coordinate system, and the tilt sensor measures its position relative to the MNE target. The inclination angle of the coordinate system and the precise time.
Using a star sensor to complete astronomical positioning involves three steps:

1) Use the star sensor to output the attitude information of the star sensor in the inertial system;
2) Use the astronomical time information to solve the conversion relationship between the lunar center fixed coordinate system and the lunar center J2000 inertial coordinate system, and use the positioning information to obtain the conversion relationship between the horizon system and the earth system, and then obtain the relationship between the inertial system and the horizon system conversion relationship;
3) Use the conversion relationship between the inertial system and the horizon system to convert the determined posture to the horizon coordinate system, and then obtain the latitude and longitude information.

3.3. Multi-source lunar positioning method based on astronomical/inertial combination
This paper analyzes the error sources of the full link of the autonomous navigation system, and deeply studies the star vector observation model of the star sensor, the constant drift model of the tilt sensor, the system structure parameter model, the time synchronization error model, the lunar model, etc., and star observation through the field Tests are conducted to verify and identify the factors that have the greatest impact on the accuracy of the positioning and navigation system.

Figure 3 System principle block diagram

Figure 4 System principle block diagram

Figure 5 Schematic diagram of error source analysis
After analysis, the error sources of the lunar surface positioning method are divided into the following 4 categories:

1) Installation matrix error: the error of the installation matrix of the inclinometer and the star sensor and the error of the installation matrix of the star sensor and the inertial unit;

2) Instrument error: the error caused by the instrument itself such as star sensor and inclinometer;

3) Time reference error: time registration error of the output data of each component of the system;

4) Lunar oblateness and astronomical errors: the obliquity sensor measures the obliquity by sensing gravity, and the gravity direction is not pointed to the moon center due to the influence of the lunar oblateness. Calculating the transfer matrix from the J2000 system to the lunar fixed coordinate system requires correction of precession, nutation, and polar shift.

Through analysis and experiments, it can be judged that the accuracy of the tilt sensor is the factor that has the greatest impact on the accuracy of the system. Due to the advantages of small drift and high accuracy of the gyro in a short time, this paper proposes to use the tilt sensor to output initial tilt information and pass the system's own tilt angle. Methods such as zero calibration are used to obtain initial inclination information, and then use inertial recursion to maintain the output of high-precision inclination information.

It has been verified that the use of inertial units to output the tilt angle information effectively improves the accuracy of the tilt angle information and further improves the system accuracy.

4. Simulation analysis and verification

In the actual implementation process, a certain type of nano-star sensor, STM32 processor, Yongwei sensor inclinometer, GPS module connected to GPS antenna of BC20, and semi-physical simulation system were built in this project, and the principle verification test and accuracy verification were carried out on the ground test.

4.1. Uncorrected positioning results

Data fusion and latitude and longitude output are directly performed on the built simulation system, and the results are as follows:

![Figure 6 Uncorrected positioning results](image-url)
Initial result; no error correction has been made, at this time the latitude and longitude offset error is about 0.1~0.2°.

4.2. Experimental results after correcting the lunar oblateness
Experimental results after correcting the lunar oblateness are as follows:

![Figure 7 Experimental results after correcting the lunar oblateness](image)

After correcting the lunar oblateness error, the latitude offset error is reduced by about 0.05°.

4.3. Result after installation matrix error calibration
Result after installation matrix error calibration are as follows:

![Figure 8 Result after installation matrix error calibration](image)
Calibrate the relationship between the star sensor measurement system and the inclinometer measurement system, and correct the offset error. At this time, the offset error is close to zero.

4.4. Result of the positioning method by using inertia correction

Result of the positioning method by using inertia correction

![Figure 9 Result of the positioning method by using inertia correction](image)

After introducing the inertia correction, the high frequency error of the error is reduced by about 40%.

5. Conclusion

Based on the increasingly in-depth background of the lunar exploration project, this paper analyzes the conversion relationship between the lunar center inertial system, the lunar center fixed coordinate system, and the target lunar plane coordinate system for the positioning and navigation needs of the lunar lander, and proposes a star sensor, an inclination sensor, etc. The lunar surface positioning and navigation system with multi-device combination, and in view of the large instrument error of the inclination sensor, proposes a method to improve the accuracy of the system by using inertia. This paper verifies the positioning and navigation method and accuracy by building a semi-physical ground simulation platform, and verifies the correctness and accuracy of the lunar surface positioning and navigation method. The method in this paper can provide a new reference and basis for lunar surface exploration and lunar landing navigation, and has certain significance for lunar exploration projects and manned lunar landing projects.

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