ISSN: 2414-1895 DOI: 10.6919/ICJE.202502_11(2).0001

An Overview of the Current Research Status of Gyro-Free Inertial Measurement Technology

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Abstract

Gyro-free inertial measurement technology utilizes an array of accelerometers to replace traditional gyroscopes for measuring the attitude of a carrier. By synthesizing existing literature, this paper summarizes the research on gyro-free strapdown inertial measurement technology. It conducts comparative analysis on two aspects: different accelerometer configurations and algorithms for calculating angular velocity. The advantages and disadvantages of corresponding configurations and solution methods are summarized. Finally, future research directions are discussed.

Keywords

Gyro-Free Inertial Measurement; Accelerometer Configuration; Angular Velocity.

1. Introduction

The concept of utilizing only linear accelerometers to measure the angular velocity of a carrier was first proposed by Victor B. Corey in 1962[1]. Following this proposal, extensive research on gyro-free inertial measurement technology has been conducted both domestically and internationally. In recent years, with rapid advancements in microelectronics and sensor technologies, gyro-free inertial measurement units (IMUs) have garnered significant attention due to their low cost, miniaturization, and high reliability. Gyro-free IMUs achieve precise measurements of the carrier's motion state by using an array of accelerometers to measure acceleration and indirectly calculating angular velocity through mathematical models. This technology finds widespread application in aerospace, military equipment, autonomous driving, robotics navigation, wearable devices, and many other fields.

Traditional gyroscopes, due to their high cost and susceptibility to damage, limit their applicability in certain domains. Therefore, gyro-free IMUs present an attractive alternative, especially in high-overload environments where they offer more stable and reliable measurement results. This paper provides a comprehensive review of the research progress in gyro-free inertial measurement technology, focusing on accelerometer configurations and angular velocity calculation algorithms. Additionally, it discusses future development directions, aiming to provide valuable references for researchers and technical developers in military equipment, aerospace, and related fields.

2. Accelerometer Configurations

The gyro-free inertial measurement unit (GFSINS) measures specific force by deploying multiple accelerometers at different positions on the carrier and establishes a system measurement equation based on the relationship between these measurements and the carrier's motion parameters. By solving this equation, one can obtain the carrier's motion parameters, such as position, velocity, and attitude. In gyro-free IMUs, the core focus is on optimizing the layout and configuration of the accelerometers to minimize the impact of measurement errors and assembly errors on the accuracy of motion parameter solutions. Thus, researchers are dedicated to exploring and optimizing accelerometer configurations to enhance solution accuracy. This section will outline the current research status of various configuration schemes, highlighting their advantages and disadvantages for reference in subsequent studies.

2.1 Six-Accelerometer Configuration

In 1967, Alfred R. Schuler theoretically proved that only linear accelerometers could be used to measure the angular velocity of a carrier and proposed three feasible six-accelerometer configurations based on this theory [2]. In 1991, Marcelo C. Algrain derived the theoretical output equations of linear accelerometers through rigid body dynamics, proposing that at least six accelerometers were needed to fully solve the carrier's motion parameters [3].

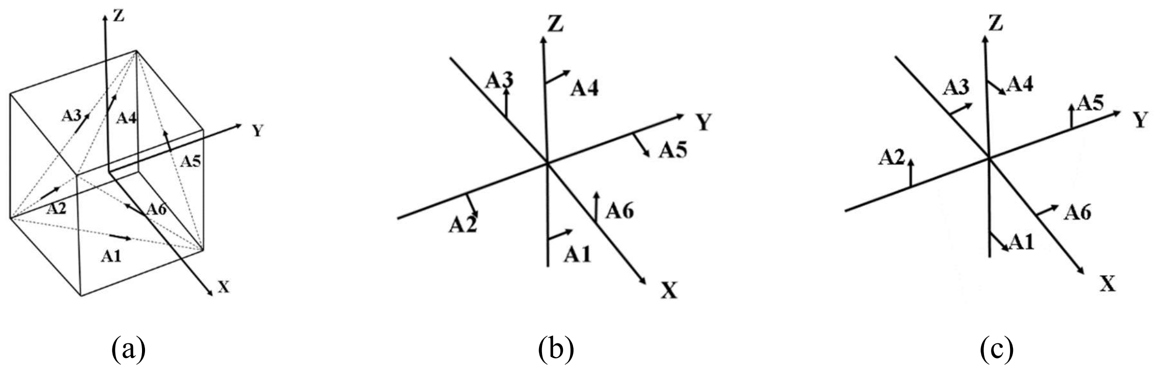

Fig. 1 Six-Accelerometer Configuration

In 1994, Chen proposed a six-accelerometer configuration (as shown in Fig. 1a) that, with the minimum number of accelerometers, achieved a stable mechanization equation similar to the most recent nine-accelerometer scheme. This configuration can calculate the carrier's rotational acceleration, and integrating directly yields the angular velocity. This novel design can integrate with other sensors with complementary characteristics to enhance performance in navigation applications [4].

In 2001, Tan developed basic solution algorithms based on Chen's six-accelerometer configuration from 1994, establishing state equations for solving angular velocity and output equations for calculating linear acceleration, and provided sufficient conditions for determining the feasibility of the configuration [5]. In 2002, Lee improved the method for solving angular velocity in the previously designed six-accelerometer configuration, proposing an innovative estimation method that resolved the divergence issue in full-accelerometer inertial navigation systems (INS) based on recursive least squares [6]. Tsai defined EcoIMU in 2010, which uses a pair of triaxial accelerometers as an inertial measurement unit, and demonstrated its feasibility through experiments in the form of a wearable sensor system [7].

Professor Shi proposed two six-accelerometer configurations that differ from previous ones, which are suitable for missile-like cylindrical carriers, installed along the axis of the projectile (as shown in Fig. 1b and c). These configurations were compared and analyzed [8].

2.2 Nine-Accelerometer Configuration

In 1975, A.J. Padgaonkar summarized the reasons for the failure of six-accelerometer configurations and designed a nine-accelerometer configuration (as shown in Fig. 2a), validating its stability through turntable tests. However, while it was less sensitive to small errors in the data, it could not resolve sign ambiguity issues when errors were present [9].

In 1997, Ma designed a nine-accelerometer configuration scheme for the first time and compensated for errors in the calculated values of carrier angular acceleration and angular velocity by estimating

ISSN: 2414-1895 DOI: 10.6919/ICJE.202502_11(2).0001

system errors before launch [10]. However, this scheme also had difficulties in accelerometer installation and produced large installation errors, making it difficult to engineer. Wang designed a nine-accelerometer configuration (as shown in Fig. 2b) in 2007, solving for angular acceleration and the square of angular velocity. By taking the square root of the square terms and combining them with the integral term of angular acceleration to determine the sign, simulations showed that this configuration suppressed the divergence of angular velocity calculation errors [11]. This approach requires installing three accelerometers at the center of mass, with high requirements for the size and machining accuracy of the accelerometers. Xiao proposed a new algorithm to eliminate calculation errors caused by sensor volume by addressing the challenge of installing multiple accelerometers at the same point [12].

(a) (b)

Fig. 2 Nine-Accelerometer Configuration

2.3 Twelve-Accelerometer Configuration

In 2006, Buhmann proposed dividing twelve accelerometers into four groups, with each group's triaxial accelerometers installed at a vertex of a cube, and the sensitive directions aligned with one edge of the cube (as shown in Fig. 3a). Compared to previous methods, this configuration only required simple matrix multiplication to solve for motion parameters, reducing computational load. Additionally, using Kalman filtering, the twelve-accelerometer array data was fused with GPS data, showing significant improvement in position and direction standard deviation compared to single GPS data [13].

In 2007, Parsa improved the above configuration by dispersing the twelve accelerometers across the faces of the cube, with two accelerometers per face (as shown in Fig. 3b). By measuring gravity acceleration on multiple known directions, the orientation installation error of each sensor could be determined for subsequent calibration [14]. Wang added another set of six accelerometers that could be independently solved to create a twelve-accelerometer configuration based on J.H. Chen's classic six-accelerometer configuration. This combined solution avoided error accumulation and increased redundancy for solving the angular velocity of the projectile, but had issues with sign misjudgment when calculation results approached zero [15].

Mu designed a configuration suitable for cylindrical structures based on the geometric characteristics and motion of the projectile, placing twelve accelerometers at the edges of the top and bottom surfaces of the cylinder (as shown in Fig. 3c). This method increased the redundancy of the test system, allowing the system to continue operating and maintaining measurement accuracy even if one or two sensors failed, enhancing the stability and reliability of the test system, although it required high positional accuracy and posed challenges in installation [16].

Zhang proposed a typical twelve-accelerometer array (as shown in Fig. 3d), solving for angular acceleration, the square of angular velocity, and cross terms of angular velocity through linear operations [17]. Cai improved this configuration by extending the distance between individual triaxial accelerometers, making the configuration more suitable for cylindrical rotating projectiles [18].

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Yang addressed the difficulty of installing the cubic configuration in 2011, proposing a planar twelve-accelerometer configuration distributed along a circular pattern within a flat baseplate. By introducing adaptive strong tracking Kalman filters into acceleration estimation, error divergence was suppressed, reducing installation errors and achieving higher precision in carrier angular velocity [19].

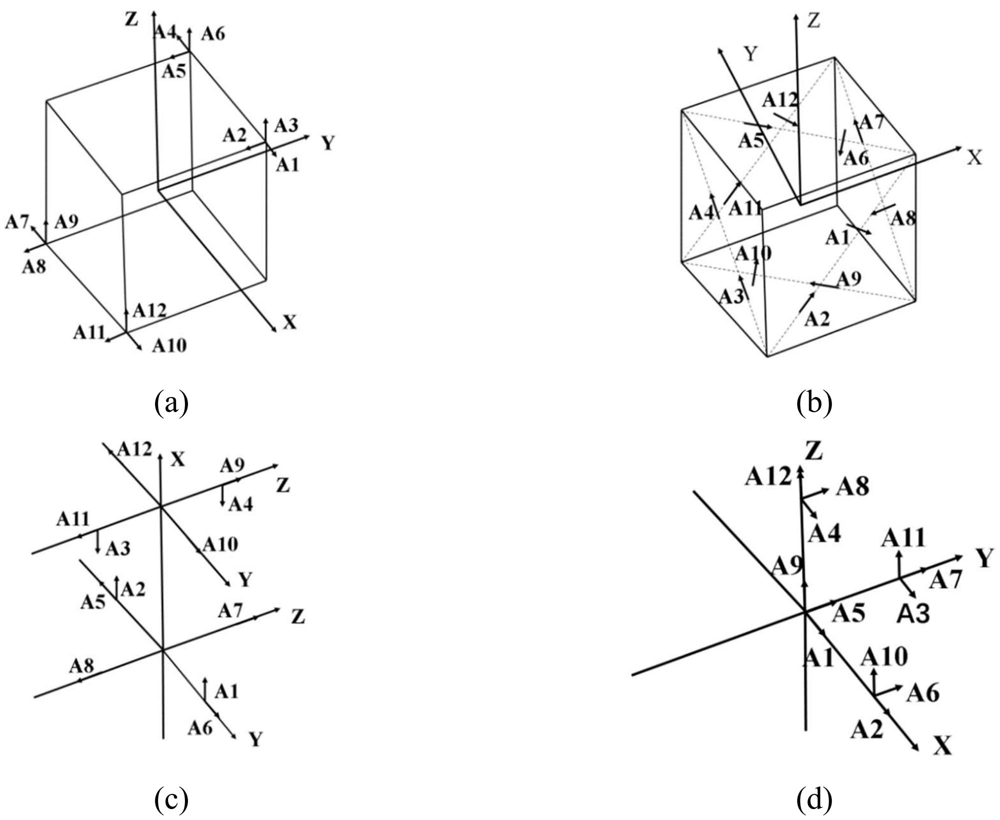


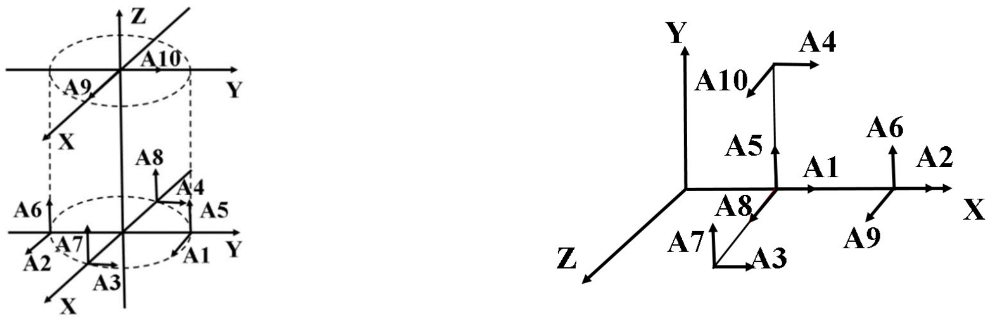
Fig. 3 Twelve-Accelerometer Configuration

2.4 Other Configurations

In 2010, Liu, inspired by Mu's cylindrical ten-accelerometer configuration, designed a ten-accelerometer configuration suitable for slender rotating projectiles. Ten accelerometers were distributed on the upper and lower bases of the cylinder (as shown in Fig. 4a). If any accelerometer failed, the system could be reconfigured to ensure normal operation and maintain measurement accuracy [20].

In 1999, Xiong proposed a ten-accelerometer configuration for ballistic correction fuzes (as shown in Fig. 4b), mainly applicable to rocket launchers or tube artillery. Using this configuration significantly improved the accuracy of navigation information and reduced the calculation error of projectile angular velocity by applying relevant filtering techniques, enhancing the precision of shells [21].

In summary, current research on GFSINS configurations primarily focuses on six-accelerometer, nine-accelerometer, and twelve-accelerometer configurations. Six-accelerometer configurations achieve minimization of measurement and assembly errors through optimized layouts and configurations, but their solution accuracy may be limited on complex carriers. Nine-accelerometer configurations improve system stability and resistance to small errors, but pose installation challenges and are less favorable for large-scale engineering applications. Twelve-accelerometer configurations enhance system stability and reliability through increased redundancy but require higher installation precision and position requirements and involve higher computational complexity. Therefore, selecting an appropriate configuration should consider factors such as the shape of the carrier, application scenarios, and computational resources comprehensively.



(a) (b)

Fig. 4 Other Configurations

3. Angular Velocity Calculation Algorithms

Enhancing the accuracy of angular velocity calculations is the core and challenge of research on GFSINS. In GFSINS, accelerometers produce differences between actual outputs and theoretical values due to various measurement errors and installation deviations. These discrepancies further affect the accuracy of angular velocities calculated from accelerometer data. Given the inherent difficulties in eliminating these errors from accelerometers, the primary objective of developing angular velocity calculation algorithms is to strengthen the algorithm's resistance to these errors, thereby minimizing their negative impact on angular velocity precision. In the absence of traditional gyroscopes, the available angular velocity-related information in an inertial measurement unit includes: angular accelerations along three axes, squared terms of three-axis angular velocities, and cross-product terms, totaling nine parameters. Consequently, all current research schemes on angular velocity calculations revolve around these nine or some angular velocity-related parameters, aiming to enhance the accuracy of angular velocity calculations through optimized algorithms.

To improve the solution accuracy of gyro-free inertial testing technology, Orlando V established a noise state model of the system and utilized Kalman filtering to correct satellite attitude errors in 1986 [22]. In 1995, Ma studied two angular velocity calculation methods in a nine-accelerometer scheme, deriving angular velocity cross-product terms and angular accelerations from sensor output equations. The first method directly integrated angular accelerations to obtain angular velocities, while the second method obtained the absolute value of angular velocities from the product terms and then determined the angular velocity signs using the first method[23]. Zhao linked these two methods by employing a least-squares filter estimation approach to estimate the differences and compensate for errors, showing that this method suppresses the growth rate of errors[24]. Zhao further applied a least-squares filter approach to bound filter the angular velocities calculated by the aforementioned two methods, demonstrating that the estimated angular velocities did not diverge over time and achieved high precision [25].

Zhang et al. used the principle of weighted average algorithms to fuse and compensate for errors in different angular velocities calculated by integration, square root extraction, and iterative methods in GFSINS. Three-dimensional turntable tests showed that the angular velocities obtained through data fusion had higher precision than those from single algorithms [17]. Cao et al. developed an angular velocity calculation model for a twelve-accelerometer configuration suitable for high-spin projectiles, accounting for installation errors. They employed nonlinear least-squares methods to solve the nonlinear mathematical model containing installation errors, using damped Gauss-Newton methods to find optimal solutions. Simulation results indicated that angular velocity precision was significantly higher than traditional calculation methods [26]. In 2003, Ding designed a Kalman filter to estimate line speed, displacement, angular velocity, and angles from linear accelerations and angular accelerations derived from a nine-accelerometer configuration. Simulation results showed that the error amplitudes of these parameters were notably reduced [27]. Wang designed an independent

Kalman filter for angular velocity calculations in a twelve-accelerometer configuration [28]. Cheng designed an extended Kalman filter algorithm using Singer tracking models to estimate angles and angular velocities. This method's advantage is its high computational efficiency, making it suitable for various attitude motion modes [29]. Zhao et al. proposed an auxiliary algorithm for attitude and angular velocity in an existing nine-accelerometer configuration, combining the strengths of open and integration methods to completely eliminate symbol judgment errors and improve system solution precision [30]. Xiao proposed a new algorithm to eliminate calculation errors from multiple accelerometers installed at the same point by addressing the challenge of sensor volume [12].

Zhao et al. constructed an extended Kalman filter to calculate attitude angular velocities, verifying its feasibility through simulations [31]. Besides Kalman filtering, Liu built an H∞ filter, applying it to existing ballistic data and comparing results with those from integration, square root extraction, and Kalman filtering methods. Results indicated that this method offered high solution precision[32]. Based on various angular velocity algorithms, data fusion theories have been extensively applied in GFSINS angular velocity calculations. Wang proposed a data fusion method based on hypothesis testing theory to calculate angular velocities, suppressing calculation errors and improving navigation precision by an order of magnitude [33].Liu designed extended Kalman filter and unscented Kalman filter algorithms to estimate carrier motion parameters for four different twelve-accelerometer configurations. Results showed that both algorithms could reduce the impact of configuration schemes on solution precision [34].

Angular velocity calculation methods primarily handle the nine parameters related to angular accelerations along three axes, squared terms of three-axis angular velocities, and cross-product terms, as well as data fusion. Current methods often rely on specific scenario assumptions, limiting their applicability across different scenarios. Each method has distinct advantages and disadvantages. Open methods are straightforward but cannot directly determine symbols for certain configurations and exhibit larger errors at low speeds. Differential methods extract angular acceleration information from acceleration signals but are sensitive to noise and prone to cumulative errors. Integration methods are intuitive and easy to implement but suffer from cumulative errors under noise and error influences. Weighted average methods enhance precision through data fusion but involve complex weight allocation and improper distribution can lead to errors. Hypothesis testing methods effectively identify outliers and improve result reliability but are complex to implement and require more computational resources. Kalman filters are suitable for linear systems with rigorous theory but are limited to linear systems. Extended Kalman filters are applicable to nonlinear systems but can introduce significant errors during linearization. Unscented Kalman filters do not require linearization and are suitable for highly nonlinear systems but have higher computational complexity.

4. Summary and Future Prospects

This paper reviews the current research status of accelerometer configurations and angular velocity calculation algorithms in gyro-free inertial measurement technology. Through the study of six-, nine-, and twelve-accelerometer configurations, we detailed the characteristics, advantages, and existing issues of each configuration.

(1) Six-Accelerometer Configuration: By optimizing the layout and configuration of accelerometers, this configuration can minimize measurement and assembly errors, making it suitable for various carriers. However, its solution accuracy may be limited in some complex carriers.

(2) Nine-Accelerometer Configuration: This configuration enhances system stability and robustness against small errors but faces challenges in installation and large-scale engineering applications.

(3) Twelve-Accelerometer Configuration: This configuration increases system stability and reliability through redundancy but requires higher installation precision and position requirements and involves higher computational complexity.

Additionally, this paper summarizes several angular velocity calculation algorithms, including open methods, differential methods, integration methods, weighted average methods, hypothesis testing methods, Kalman filters, extended Kalman filters, and unscented Kalman filters. Each algorithm has unique advantages and disadvantages, requiring selection and optimization based on specific scene demands and system characteristics.

Despite significant progress in gyro-free inertial measurement technology, numerous challenges remain, particularly in enhancing solution accuracy, robustness, and real-time performance. Future research directions should focus on the following areas:

(1) Novel Configuration Designs: Explore more innovative accelerometer configurations, especially for complex carriers. For example, design more flexible and robust configurations to meet diverse application needs.

(2) Algorithm Optimization: Develop more efficient angular velocity calculation algorithms to reduce computational load and improve real-time performance. For instance, optimize parameters in Kalman filters and unscented Kalman filters to enhance filtering accuracy and robustness.

(3) Error Compensation: Investigate effective ways to handle installation errors and other external disturbances to improve system robustness. For example, use adaptive filtering algorithms and sensor fusion techniques to mitigate the impact of system errors.

(4) Data Fusion: Utilize data fusion techniques to integrate external information sources such as magnetometers and GPS to further enhance navigation accuracy. For example, employ multi-sensor fusion and data fusion algorithms to improve overall system precision and reliability.

(5) Engineering Applications: Strengthen research on the practical engineering applications of gyro-free inertial measurement technology, promoting its widespread use in aerospace, autonomous driving, robotic navigation, and other fields.

Through in-depth exploration of these research directions, gyro-free inertial measurement technology is expected to achieve higher precision and better robustness, further advancing the development and application of related fields.

Acknowledgments

This research was funded by the Postgraduate Research & Practice Innovation Program of Jiangsu Province (SJCX23_0116).

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