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Internal Navigational System in Aircraft

Repülőgépek belső navigációs rendszere

Amina Bagoudinova*, Guyen Ganbat *, Arnold Őszi, PhD.*
* Óbuda University, Faculty of Mechanical and Safety Engineering, Budapest, Hungary
abagoudinova@mail.ru, guyen.ganbat@gmail.com, oszi.arnold@bgk.uni-obuda.hu

***Abstract* — Inertial navigation systems (INSs) are essential for modern aircraft, enabling accurate determination of position, attitude, and velocity without external references. This paper reviews the operational principles of INS, emphasizing the integration of gyroscope and accelerometer data, data flow within the system, and the importance of platform stabilization and alignment procedures. Key sources of error—such as sensor noise and platform instability—are identified, along with current strategies for error compensation and calibration. The evolution towards Inertial Reference Systems (IRS) is also discussed. By summarizing both theoretical foundations and practical considerations, this paper supports the development and maintenance of reliable INS solutions for aviation.**

Keywords: inertial navigation system (INS), aircraft navigation, attitude and heading reference systems (AHRS), sensor fusion, error mitigation.

***Összefoglalás* — A belső navigációs rendszerek (Internal Navigation System, INS) nélkülözhetetlenek a modern repülőgépek számára, mivel külső referenciák nélkül is pontos pozíció-, attitűd- és sebességmeghatározást tesznek lehetővé. A cikk áttekinti az INS-ek működési elveit, kiemelve a giroszkóp- és gyorsulásmérő-adatok integrációját, az adatáramlás fő szakaszait, valamint a platform stabilizálásának és igazításának szerepét. Azonosítjuk a legfontosabb hibaforrásokat – például az érzékelőzajt és a platform instabilitását –, továbbá bemutatjuk a korszerű hibakompenzációs és kalibrációs eljárásokat. Kitérünk az INS rendszerek fejlődésére és az IRS-ek (inerciális referencia-rendszerek) irányába mutató tendenciákra is. A tanulmány célja a megbízható navigációs rendszerek fejlesztésének támogatása az elméleti és gyakorlati szempontok bemutatásával.**

Kulcsszavak: belső navigációs rendszer (INS), repülőgép navigáció, helyzet- és irányreferencia-rendszerek (AHRS), szenzorfúzió, hibacsökkentés.

1 INTRODUCTION

Inertial navigation systems (INSs) have become indispensable for modern navigation applications, providing precise positioning and attitude information even in the absence of external references. In the realm of aviation, INSs are essential components of aircraft navigation systems, enabling pilots to navigate accurately, safely, and efficiently [1].

INS typically consists of three main components: gyroscopes, accelerometers, and a central processing unit (CPU) (Fig. 1). Gyroscopes measure angular rates, enabling the INS to determine the aircraft's orientation. Accelerometers measure linear acceleration, which is used to compute the velocity and position of the aircraft. The CPU integrates sensor data, applies navigation models, and generates navigation outputs

Fig.1. Inertial Navigation System (INS)

The accuracy of an INS is primarily determined by the performance of its sensors and the implementation of error mitigation strategies. Sensor noise, platform instability, and modeling errors can significantly degrade INS performance. To address these challenges, advanced INS designs incorporate sensor fusion techniques, that combine data from multiple sensors to improve accuracy and robustness.

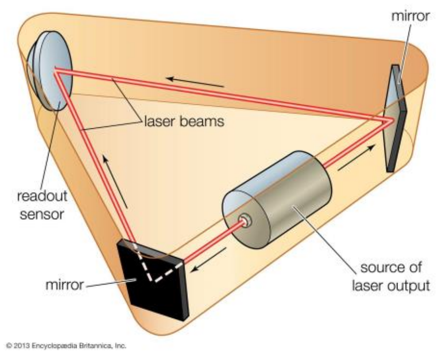

Fig.2. Gyroscope

Gyroscopes (Fig. 2) are critical components of INSs, as they measure angular rates and form the basis for determining aircraft orientation [2]. The most common type of gyroscope in INSs is the ring laser gyroscope (RLG), which utilizes the Sagnac effect to measure angular displacement. RLGs offer high precision and stability, making them well-suited to demanding navigation applications.

Fig.3. Accelerometer

Accelerometers (Fig. 3) are the other key sensors in INSs. MEMS (micro-electromechanical system) accelerometers are widely used in INSs due to their small size, low cost, and reliable performance.

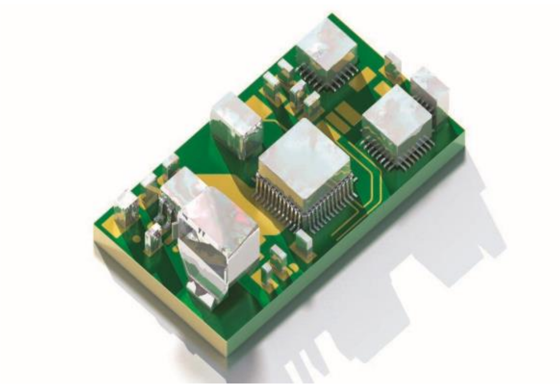

Fig.4. Attitude and heading reference system (AHRS)

An attitude and heading reference system (AHRS) (Fig. 4) is a specialized type of INS that combines gyroscopes and accelerometers to determine the aircraft's attitude (orientation) and heading (direction). AHRSs are often used as backup systems for INSs or as standalone navigation systems for cost-sensitive applications.

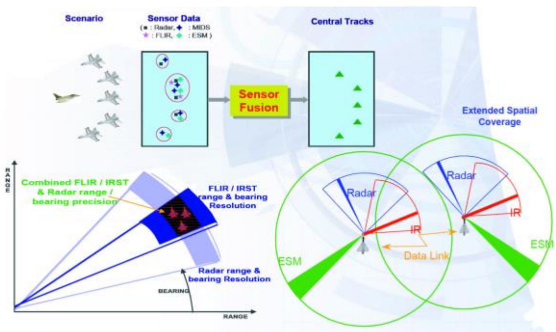

Fig.5. Sensor fusion

Sensor fusion techniques (Fig. 5)) combine data from multiple sensors to improve the accuracy and robustness of navigation systems.

Error mitigation is essential for maintaining INS accuracy. These strategies include techniques such as:

- Data averaging: Averaging multiple sensor readings can reduce the impact of sensor noise;
- Calibration: Regular calibration of sensors can help to compensate for sensor drift;
- Model updates: The INS's navigation models can be updated periodically using external references, such as GPS, to improve accuracy.

2 PRINCIPLE OF OPERATION

An INS operates based on the fundamental laws of motion. Gyroscopes measure angular rates, while accelerometers measure linear accelerations. The INS integrates these measurements over time to determine the position, attitude, and velocity of the aircraft [2].

Attitude is described by three Euler angles: roll, pitch, and yaw. Roll denotese rotation of the aircraft about its longitudinal axis, pitch is the rotation about its lateral axis, and yaw is the rotation about its vertical axis. The INS's velocity is represented by three components: north, east, and down.

Position is determined by integrating its velocity over time. However, this process can lead to errors due to sensor noise, platform instability, and modeling inaccuracies. To mitigate these, the INS employs a variety of techniques, such as sensor fusion and Kalman filtering [7].

2.1 Data Flow

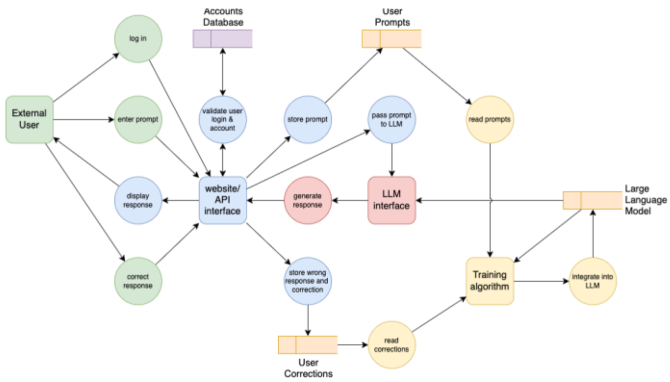

Fig.6. Data flow of INS

The data flow in an INS (Fig. 6) typically follows a three-stage process [4]:

- Sensor data acquisition: Collecting angular rates and linear accelerations from the gyroscopes and accelerometers, respectively.
- Attitude determination: Integration of angular rates to determine the aircraft's orientation.

- Position and velocity estimation: Integration of accelerometer data and application of a velocity model to obtain position and velocity estimates.

The central processing unit (CPU) is responsible for coordinating all aspects of the data flow. The CPU also implements error mitigation strategies to ensure accurate estimation of position, attitude, and velocity.

2.2 Platform Stabilization

Platform stabilization is essential for INS accuracy [3]. The INS platform must be isolated from external disturbances such as vibration and acceleration, to ensure accurate sensor measurements. This is typically achieved using of gimbals and dampers.

2.3 Alignment

Alignment is the process of initializing the INS by setting its reference frame to match the actual orientation of the aircraft. This is typically done using external references, such as GPS or magnetic heading.

2.4 Operation

Once the INS is aligned, operation can begin. The position, attitude, and velocity estimates, computed by INS, are then used for navigation and guidance, including providing heading information to autopilots and controlling the aircraft's flight path.

2.5 Errors

INS errors can arise from a variety of sources, among which are [7]:

- Sensor noise,
- Platform instability,
- Model inaccuracies.

These errors can degrade INS accuracy and must be considered in the design and implementation of INSs.

Error mitigation strategies can reduce the impact of INS errors. These strategies include:

- Sensor fusion,
- Calibration,
- Model updates.

By implementing error mitigation strategies, INSs can achieve high levels of accuracy and reliability.

3 Data Flow

3.1 Sensor Data Collection

The process begins with the collection of sensor data from various sources, primarily gyroscopes and accelerometers. Gyroscopes measure angular rates, providing information on the aircraft's rotation around its three axes: roll, pitch, and yaw, and accelerometers quantify linear accelerations along three axes: north, east, and down, reflecting the aircraft's movement relative to the Earth's surface [2].

3.2 Data Processing and Integration

The acquired sensor data undergo rigorous processing and integration to extract meaningful information. Gyroscope data are integrated over time to determine the aircraft's orientation relative to inertial space. This attitude information is crucial for correctly interpreting accelerometer readings. Accelerometer data are combined with attitude information and applied to a velocity model to estimate the aircraft's velocity and position.

3.3 Sensor Fusion and Kalman Filtering

The INS utilizes a technique known as sensor fusion to combine data from multiple sensors, including gyroscopes and accelerometers. This fusion process ensures that the INS receives the most accurate and comprehensive information for navigation computations. Kalman filtering is a mathematical algorithm employed to refine navigation estimates by considering prior knowledge and sensor data. It effectively mitigates the effects of sensor noise and errors.

3.4 Central Processing Unit (CPU)

The central processing unit (CPU) plays a pivotal role in coordinating the data flow, as well as managing sensor data acquisition, processing, and integration. The CPU also implements error mitigation strategies and applies Kalman filtering to enhance the accuracy of the INS.

3.5 Navigation Information Delivery

The culmination of the data flow process is the delivery of precise navigation information to the aircraft's autopilot and other systems. The INS provides the aircraft with its position, attitude, and velocity infomration, which are essential for navigation, guidance, and control. The autopilot relies on this information to maintain the aircraft's flight path, while other systems, such as flight management computers and terrain awareness and warning systems (TAWS), also utilize the INS navigation data.

4 Platform Stabilization

Platform stabilization is a critical aspect of inertial navigation systems (INS), as it ensures the accurate measurement of angular rates and linear accelerations. The INS platform houses sensitive gyroscopes and accelerometers, that require a stable platform to function effectively. Without proper stabilization, the platform is subject to disturbances and vibrations, causing errors in the sensor readings. These errors accumulate over time, leading to significant inaccuracies in the INS navigation calculations.

To mitigate these errors, INSs incorporate sophisticated stabilization mechanisms, typically involving gimbals. Gimbals are highly precise mechanisms that isolate the sensor platform from external disturbances, enabling it to maintain a fixed orientation relative to inertial space. This isolation prevents the platform from being influenced by vibrations, motion, and other external forces, thus ensuring the accuracy of sensor readings.

There are two primary types of gimbal systems employed in INSs: strapdown and gimballed.

Strapdown systems utilize electronic gyroscopes to compensate for platform motion, thereby effectively eliminating the need for physical gimbals. This approach simplifies the INS design and reduces weight, but it relies on the accuracy of the electronic gyroscopes. Gimballed systems, on the other hand, physically isolate the sensor platform using mechanical gimbals, providing a more robust and reliable stabilization method.

The importance of platform stabilization in INSs cannot be overstated [3]. Without proper stabilization, the INS would quickly accumulate errors, rendering it ineffective for accurate navigation. The accumulation of errors would result in significant discrepancies between the INS navigation estimates and the aircraft's actual position and orientation. This may lead to navigation errors, deviation from flight paths, and potential safety hazards.

Therefore, platform stabilization is an essential component of any INS. It ensures the accuracy of sensor readings, enabling the INS to provide reliable and precise navigation information for aircraft operation, even under challenging environmental and flight conditions.

5 Alignment

Alignment is a crucial step in the initialization of an inertial navigation system (INS), ensuring that the reference frame of the system is properly aligned with the Earth's reference frame.

This alignment is essential for accurate navigation, as it allows the INS to:

- Determine the aircraft's absolute position: Without proper alignment, the INS would have no reference point to measure the aircraft's movement relative to Earth.
- Correct for gyroscope bias: Gyroscopes gradually drift over time, accumulating errors that can significantly impact navigation accuracy. Proper alignment calibrates the gyroscope bias, minimizing its impact on navigation.
- Ensure consistent heading: The INS relies on the gyroscopes to measure the aircraft's heading. Without proper alignment, the heading estimates drift, making it difficult to maintain a consistent flight path.

5.1 Primary methods for aligning an INS

Two primary methods are used for aligning an INS:

- Pre-alignment: Pre-alignment involves setting up the INS at a ground station with known coordinates and orientation. The INS collects sensor data and compares it to the known reference frame. This process allows the INS to calibrate its sensors and initialize its internal navigation model.
- In-flight alignment: In-flight alignment is used when pre-alignment is not feasible, such as during takeoff or landing. This method involves using external references, such as global navigation satellite system (GNSS) signals or magnetic fields, to align the INS reference frame with the Earth's reference frame.

The accuracy of alignment is critical for precise navigation. If the INS is not properly aligned, it accumulates errors over time, leading to inaccurate position and heading estimates. These errors can be significant, especially during long-duration flights.

5.2 Techniques to ensure the accuracy of alignment

To ensure the accuracy of alignment, a variety of techniques are employed, including [5]:

- Careful sensor selection: Using high-quality sensors and minimizing sensor noise improves the accuracy of alignment.
- Rigorous calibration: Calibrating the sensors before and after alignment further enhances accuracy.
- Repeated alignment: Aligning the INS periodically, such as after significant maneuvers or changes in the environment, can maintain accuracy over time.

In summary, alignment is an essential part of INS operation, ensuring that the system provides accurate and precise navigation information. By carefully aligning the INS and using appropriate techniques, aircraft can navigate safely and efficiently, even in challenging environments.

6 Section Headings Operation

6.1 INS Operation During Different Flight Phases

The operation of an inertial navigation system (INS) varies throughout the phases of flight. During takeoff, the INS relies primarily on stored pre-alignment data to determine the initial position and orientation of the aircraft. Once airborne, the INS continuously updates its position and velocity estimates using its internal navigation model and sensor data from gyroscopes and accelerometers.

During cruise, the INS operates independently, providing accurate navigation information for the autopilot to maintain the aircraft's flight path and altitude. The INS continues to integrate sensor data to refine its position and velocity estimates, ensuring precise navigation even over extended periods.

Approach and landing require greater accuracy, as the aircraft transitions to lower altitudes and higher speeds. In these phases, the INS may integrate external navigation data from global navigation satellite systems (GNSS) to enhance its accuracy and reduce reliance on accumulated errors. The INS then provides this refined navigation information to the autopilot to guide the aircraft safely totouchdown [6].

6.2 Integration with Other Navigation Systems

The integration of INSs with other navigation systems, such as GNSS, has become increasingly common in modern aircraft [4]. GNSS provides absolute position information based on signals from satellites, whereas the INS provides continuous position updates even in the absence of GNSS data. This combination of systems significantly improves the accuracy and reliability of navigation, particularly during critical phases of flight.

GNSS data can also be used to periodically update the INS reference frame, thereby minimizing the accumulation of errors over time. This integration enables the INS to maintain high accuracy even during long-duration flights without external reference signals.

6.3 Adaptation to Aircraft Dynamics and Environmental Conditions

The INS continuously adapts to changes in aircraft dynamics and environmental conditions to maintain accurate navigation. The internal navigation model of the INS takes into account factors such as aircraft acceleration, airspeed, and changes in the Earth's magnetic field. This adaptation ensures that the INS calculations remain accurate even as the aircraft's environment and conditions change.

For instance, the INS can compensate for changes in airspeed by adjusting its estimates of ground speed and position. Similarly, the INS can adapt to changes in the magnetic field of the Earth by incorporating updated magnetic field data into its navigation model.

This adaptability is crucial for ensuring the INS accuracy in challenging environments, such as during high-speed maneuvers or in areas with strong magnetic interference. By continuously adapting to changing conditions, the INS can provide reliable navigation information even under demanding flight scenarios.

7 Errors

7.1 Common Errors in INS

Despite their sophisticated design and advanced technology, INSs are susceptible to errors that can degrade their accuracy and performance [8]. These errors can arise from various sources, including:

- Sensor drift: Gyroscopes and accelerometers, the primary sensors used in INSs, are prone to drift over time. This drift causes the sensors to gradually deviate from their true readings, leading to errors in the INS navigation.
- Calibration inaccuracies: Imperfect calibration of sensors can introduce errors in the INS measurements. Deviations from the calibrated values can accumulate over time, further degrading the INS accuracy.
- External disturbances: External factors such as vibrations, temperature fluctuations, and magnetic interference can affect the readings of gyroscopes and accelerometers, introducing errors into INS calculations.

7.2 Sources of Error

The accumulation of errors over time presents a significant challenge for INSs [7]. These errors can become substantial, especially during long-duration flights or in challenging environments. To mitigate these errors, INSs employ various techniques, including:

- Sensor Fusion: Combining data from multiple sensors, such as gyroscopes, accelerometers, and magnetometers, helps compensate for individual sensor errors.
- Kalman Filtering: Kalman filtering is a mathematical algorithm that continuously updates the INS's navigation estimates based on sensor data and prior knowledge. This technique refines INS estimates and reduces the impact of errors.
- Regular Alignment: Aligning the INS periodically ensures that its reference frame remains accurate and that the effects of sensor drift are minimized.
- External References: Integrating INS with external navigation systems, such as GNSS, provides accurate position updates and reduces reliance on accumulated errors.

7.3 Mitigating and Correcting Errors

By employing these techniques, INSs can effectively mitigate and correct errors, maintaining high accuracy and reliability for navigation applications [7]. However, it is important to note that no navigation system is entirely immune to errors. Continuous monitoring and maintenance of INSs are essential to ensure their performance and safety.

8 Case Studies

INSs are widely used in civil aviation, particularly in commercial aircraft [7]. They play a crucial role in navigation, providing accurate position, attitude, and velocity information for various aircraft systems, including autopilots, flight management computers, and terrain awareness and warning systems (TAWS).

8.1 Case Study 1: Precession Error Compensation

Precession error is a common challenge in INSs, caused by the gradual rotation of the gyroscope axis due to external forces. In commercial aircraft, this error can accumulate over time, leading to significant inaccuracies in navigation calculations. To address this issue, commercial aircraft typically employ dual-gyroscope systems with cross-coupling compensation. This technique involves using two gyroscopes mounted in perpendicular directions, to cancel out the effects of precession error.

8.2 Case Study 2: INS Integration with GNSS

INSs are often integrated with GNSS receivers to enhance navigation accuracy and reliability. GNSS data provides absolute position information, while the INS provides continuous position updates even in the absence of GNSS signals. This combination is particularly valuable during approach and landing phases when high precision is critical. By integrating INS and GNSS data, aircraft can maintain accurate navigation even during periods of signal loss or interference [9].

8.3 INS in Military Aviation

INSs are also extensively used in military aviation, where they play a vital role in navigation, targeting, and weapon delivery. Their ability to operate without external references makes them particularly valuable in combat scenarios where GPS signals may be disrupted or unavailable [1].

8.4 Case Study 3: INS in Helicopters

In helicopters, INSs are essential for maintaining accurate heading and attitude control, particularly during hover and low-speed maneuvers. They enable the pilot to maintain a stable flight path and perform precise maneuvers, even in challenging environments.

8.5 Case Study 4: INS in Unmanned Aerial Vehicles (UAVs)

In UAVs, INSs are critical for autonomous navigation and flight control. They provide the UAV with the necessary information to navigate to its destination, avoid obstacles, and perform maneuvers as programmed [5].

8.6 Challenges in Practical Implementations

Despite their advantages, INSs also face challenges in practical implementations. These challenges include:

- Cost: INSs are relatively expensive compared to other navigation systems, such as magnetic compasses or air data computers. This can limit their use in smaller aircraft or in applications where cost is a major concern [2].
- Complexity: INSs are complex and require specialized expertise for installation, maintenance, and calibration. This can pose challenges for operators lacking the necessary technical resources [2].
- Calibration and maintenance: INSs require regular calibration and maintenance to ensure their accuracy and reliability. This can be costly and time-consuming, especially in remote or challenging environments [2].
- External Dependence: INSs rely on external references, such as GNSS, for absolute position updates. In the absence of these references, INS accuracy will degrade over time [1].

8.7 Case Study 5: INS in Harsh Environments

INSs are particularly challenging to operate in harsh environments, such as combat zones or high-altitude flights. In these environments, they are susceptible to damage from external forces, such as shock, vibration, and extreme temperatures.

To address these challenges, INSs are typically hardened to withstand harsh environments. This may involve using ruggedized components, employing redundancy, and implementing advanced error detection and correction techniques.

9 Conclusion

Inertial navigation systems (INS) play a critical role in navigation, providing accurate position, attitude, and velocity information for various applications. Understanding the principles of INS operation, data flow, platform stabilization, alignment, errors and their mitigation strategies is essential for designing, implementing, and maintaining reliable INSs for aircraft operation [8].

Key takeaways:

- INSs rely on gyroscopes and accelerometers to measure angular rates and linear accelerations, respectively.
- The data flow of an INS typically involves three stages: sensor data acquisition, data processing and integration, and navigation information delivery.
- Platform stabilization is crucial for INS accuracy, ensuring isolation from external disturbances. Gimbals and dampers are common stabilization mechanisms.
- Alignment is essential for initializing the INS reference frame and compensating for gyroscope bias. Pre-alignment and in-flight alignment are common methods.
- INS errors can arise from sensor drift, calibration inaccuracies, and external disturbances. Sensor fusion, Kalman filtering, regular alignment, and external references help mitigate these errors.
- INSs are widely used in civil aviation, military aviation, helicopters, UAVs, and other applications.
- Practical challenges of INSs include cost, complexity, calibration and maintenance requirements, and external dependence.
- INSs are particularly challenging to operate in harsh environments, and hardening techniques are employed to address these challenges.

INS provides valuable navigation information for accurate positioning, attitude control, and flight guidance.

By understanding the fundamentals of INS operation, data flow, error mitigation, and practical implementation, stakeholders can effectively incorporate INSs into their applications for safe and reliable navigation.

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