Research on the Construction Technology of INS Digital Prototype Based on Digital Twin

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Abstract. In response to the continuous advancement of digitalization and intelligence in equipment as mandated by the state, a digital twin-based inertial navigation digital prototype construction scheme has been designed. This scheme supports the realization of intelligent manufacturing, testing, evaluation, and operational assurance throughout the lifecycle of inertial navigation products. This paper decomposes the physical entities of the " three-autonomy " SINS and integrates component-level inertial navigation digital prototypes based on the principles of inertial navigation. The prototypes were integrated using heterogeneous models in simulation software. Pure navigation functionality verification was conducted on the prototypes. The results show that the errors in pure simulation of the inertial navigation digital prototypes constructed in this study are consistent with the physical navigation results of inertial navigation systems, providing a reference for the development of inertial navigation digital twin systems.

Keywords: Digital Twin; Digital Prototype; Inertial Technology.

1. Introduction

Inertial navigation systems are widely applied due to their high autonomy and strong concealment advantages. However, with the continuous advancement of equipment digitalization driven by changing international dynamics, there is a growing demand for INS to possess more sophisticated simulation technologies, scientific data management methods, and intelligent predictive health management capabilities throughout their entire lifecycle. Digital twin technology[1], known for optimizing the entire lifecycle tracking of equipment, has been extensively adopted in industry for digital transformation. Yet, its application in the field of INS remains relatively limited[2]. The lack of a comprehensive inertial digital twin system hinders the intelligent production level and cohesive simulation systems for INS, greatly affecting their iterative upgrades. The construction of digital twins is divided into two main parts: the establishment of the digital twin body and the integration of virtual and physical components[3]. This paper focuses on the construction of the digital twin body, specifically achieving the realization of digital prototypes[4]. These digital prototypes represent complete models of electromechanical products or subsystems on computers, maintaining the comprehensive characteristics of the objects being modeled. They enable performance monitoring across the entire lifecycle of inertial navigation systems, supporting their development, production, and operational assurance[5].

To address the current challenges faced by INS[6], such as the lack of adequate testing data representation methods, incomplete models across different stages, and poor alignment between simulation assessments and practical applications, this study leveraged the "three-autonomy " SINS (Self-Calibration, Self-Alignment, Self-Detection) [7]as a prototype. The goal was to construct a component-level digital prototype of the INS and integrate multiple heterogeneous models using GCAir software. The research involved conducting pure navigation simulations of the prototype. The simulation was designed to adhere closely to the operational norms of INS. The results demonstrated that the digital prototype of the INS, when subjected to pure simulation, exhibited errors consistent with actual navigation results. This effort provides a foundational reference for the subsequent development of inertial digital twin technology applications.

2. Research content

2.1 Scheme Design

2.1.1 Principle and composition of inertial navigation system

Accurately decomposing the INS structure is the foundation for constructing a high-fidelity inertial navigation digital prototype[8]. This paper focuses on the study of a digital prototype based on the " three-autonomy " SINS. The " three-autonomy " SINS, which can achieve self-calibration, self-alignment, and self-testing functions, has a wide range of application scenarios. Compared to conventional strapdown inertial systems, the " three-autonomy " SINS incorporates a significant number of electromechanical components. As a prototype for constructing, it effectively explores the technical route for improving the construction and application of INS prototypes. Its operational principle is illustrated in Figure 1.

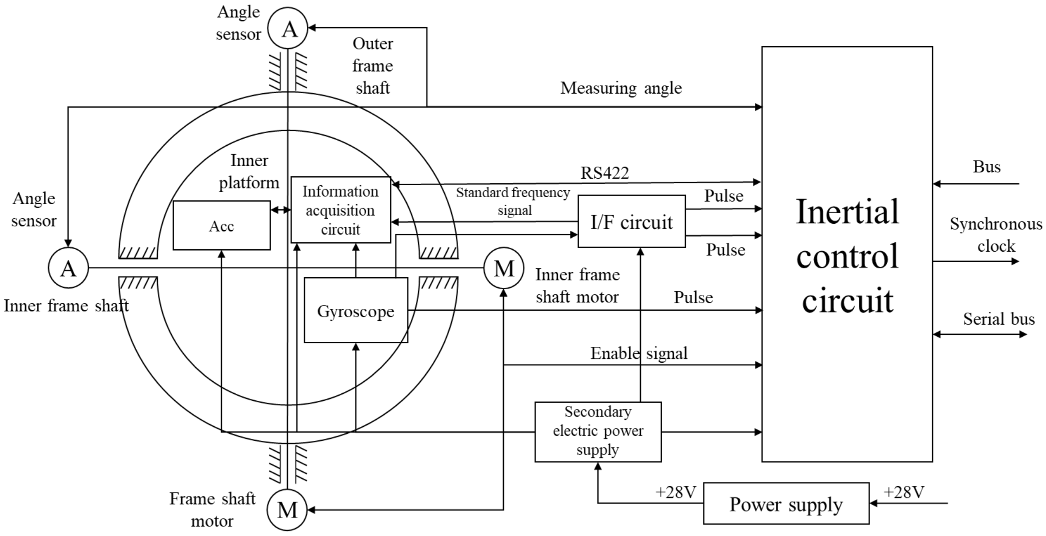
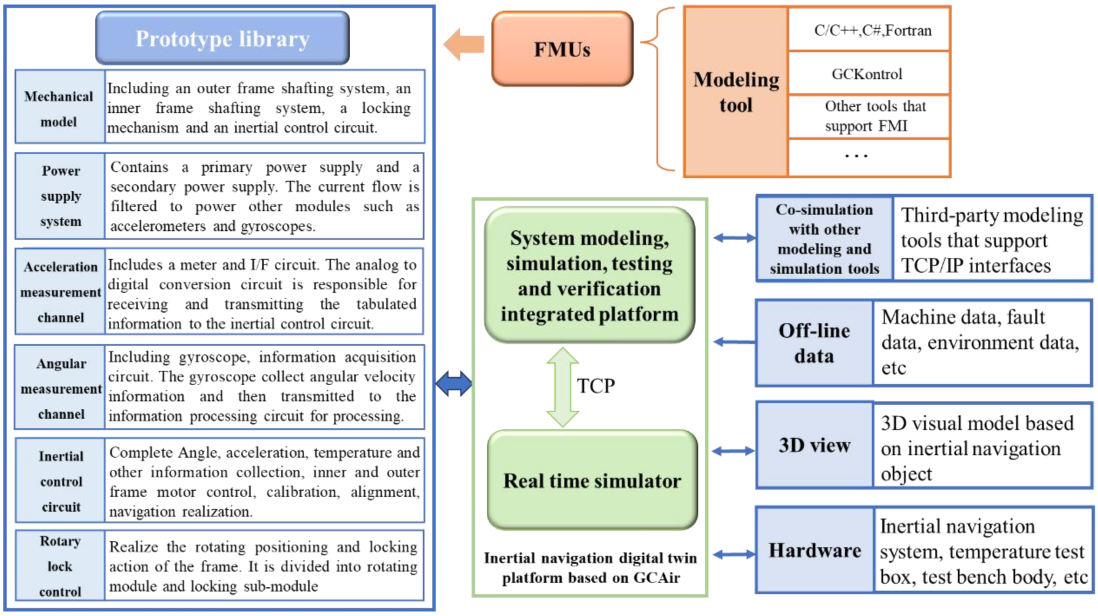


Fig. 1 Principle diagram of "three-autonomy" SINS

The " three-autonomy " SINS can be divided into angular velocity measurement channels, acceleration measurement channels, inertial group control circuits, power supply, and the servo control part for controlling the motion of the control framework. The digital prototype is built and integrated by constructing and connecting each module based on this prototype.

2.1.2 Overall technical architecture

Based on the decomposition of the " three-autonomy "SINS, achieving a comprehensive mapping of inertial navigation in the digital domain forms the basis for prototype development. INS are complex products integrating multiple structures, and integrating models from different software environments is a crucial task in digital prototype construction[9]. To achieve integration and coordinated testing of subsystem models developed in different software environments within the same environment, the author chose the domestic modeling and simulation testing development platform GCAir[10]. GCAir can collect and process large amounts of data in real-time. It supports integration and fusion of models created with various modeling tools (such as C/C++, Fortran) based on the FMI standard. It also facilitates integration of hardware devices under various bus protocols, aiding in the rapid construction of digital twins. The multi-source heterogeneous model integration scheme for inertial navigation based on the GCAir platform is illustrated in Figure 2.



Prototype library	
Mechanical model	Including an outer frame shafting system, an inner frame shafting system, a locking mechanism and an inertial control circuit.
Power supply system	Contains a primary power supply and a secondary power supply. The current flow is filtered to power other modules such as accelerometers and gyroscopes.
Acceleration measurement channel	Includes a meter and I/F circuit. The analog to digital conversion circuit is responsible for receiving and transmitting the tabulated information to the inertial control circuit.
Angular measurement channel	Including gyroscope, information acquisition circuit. The gyroscope collect angular velocity information and then transmitted to the information processing circuit for processing.
Inertial control circuit	Complete Angle, acceleration, temperature and other information collection, inner and outer frame motor control, calibration, alignment, navigation realization.
Rotary lock control	Realize the rotating positioning and locking action of the frame. It is divided into rotating module and locking sub-module

Fig. 2 Overall technical architecture for constructing inertial navigation digital prototype

Different disciplines utilize their respective modeling tools to form corresponding mechanical models, power supply systems, acceleration measurement channels, angular velocity measurement channels, inertial control circuits, and spin-lock control libraries within the SINS. This includes various Functional Mock-up Unit (FMU) models. Utilizing GCAir simulation software for multi-source heterogeneous model integration, along with loading offline data required for inertial unit operation, allows the complete construction of an inertial navigation digital prototype. Subsequently, connecting this prototype with hardware forms a complete inertial navigation digital twin system, which, when connected to a 3D visualization system, visually displays the prototype's operational status. Further elaboration on this aspect is unnecessary[11].

2.2 Model Construction.

2.2.1 Functional modeling

The inertial navigation digital prototype is a digital representation of the INS, following the same operational workflow. Unlike the physical system, the prototype cannot directly sense environmental factors such as acceleration, angular velocity, temperature, and other physical fields. Therefore, during the modeling process, these parameters must be inferred and provided. As a result, the operation of the digital prototype requires the input of IMU data. The functional block diagram of the inertial navigation digital prototype is shown in Figure 3.

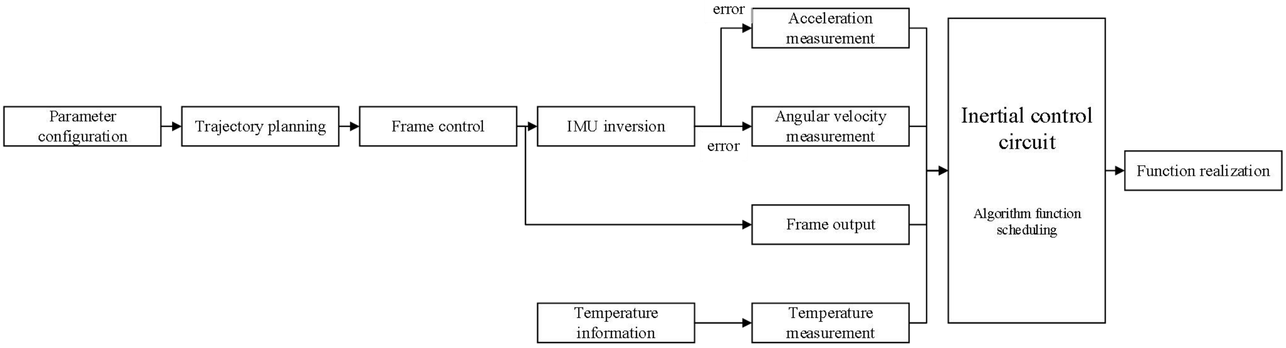


Fig. 3 Route chart of the digital prototype

In the process of operating the prototype, parameters are initially set to simulate the actual operation of the INS. This includes Earth parameters, inertial instrument error parameters, frame motion parameters, and other relevant factors. Next, trajectory planning is used to obtain motion information and parameters such as attitude, velocity, and position of the carrier. Different operational states of the inertial group, such as self-calibration, self-alignment, and rotation modulation, correspond to different frame rotation strategies. The motion of the carrier directly affects the base, and this motion information is transmitted to the prototype's IMU module through the frame system. The inversion algorithm module within the IMU then converts the base motion coupled with frame rotation into angular velocity and acceleration information relative to the inertial instrument installation axis of the platform. This information serves as input for the digital gyroscopes, accelerometers, and temperature sensors. The angular velocity measurement channel, acceleration measurement channel, and temperature measurement channel process the inertial instrument's sensitive axis angular velocity, acceleration, and temperature information obtained from the IMU inversion. Through a complete information processing flow, the digital inertial instrument provides measurement outputs, which serve as data sources for subsequent functionalities such as self-calibration, self-alignment, and navigation. The error input interface allows injection of temperature errors for environmental temperature simulation studies and can also simulate fault injections. The inertial control circuit is responsible for processing the measured data from the digital prototype's inertial instruments, frame angle data, and temperature measurements[12]. Depending on the functional requirements, it invokes different algorithm modules and frame control strategies to emulate the functionalities of the physical inertial system.

2.2.2 Model building

The system model of the digital inertial prototype supports multi-level nesting, enabling complex logical designs of subsystems and sub-subsystems. Within these subsystems, multiple FMU models are nested, and connections between subsystems and within subsystems can be achieved using ports and virtual buses. For instance, the core inertial sensor components of the inertial navigation system are integrated and encapsulated into an inertial measurement subsystem. This subsystem includes angular velocity measurement channels, acceleration measurement channels, and information processing circuits. The angular velocity measurement channel comprises gyroscopes and gyro information processing circuits, while the acceleration measurement channel includes accelerometers and analog-to-digital conversion circuits. The entire digital inertial prototype model, thus constructed, is illustrated in Figure 4.

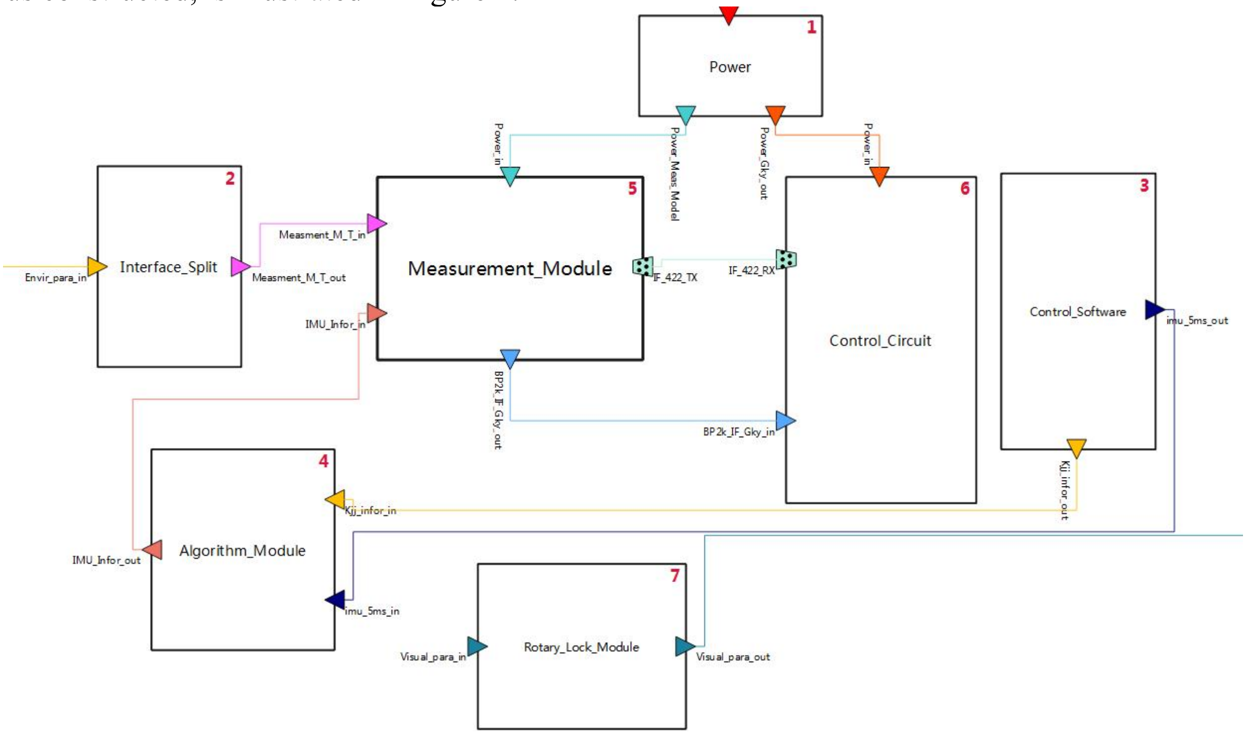


Fig. 4 Inertial navigation digital prototype

The prototype model is arranged from top to bottom and left to right as follows: Power Supply, Parameter Separation, Inertial Measurement Module, Inertial Control Circuit, Inertial Control Software, Algorithms, and Locking Section. Once the prototype starts operating, the power supply initiates by sending electrical signals to control startup. Pre-set operational parameters are sent from the parameter separation module to each internal component. The Inertial Measurement Module perceives and inversely calculates information such as angular velocity and acceleration. This data is then processed through information processing circuits and analog-to-digital converters to output signals such as pulses and reference frequencies to the Inertial Control Circuit and the algorithm section. These components control the prototype to perform functions such as frame rotation, calibration, and navigation of the inertial system. Compared to traditional simulations based on mathematical calculations, the digital inertial prototype maintains a complete workflow. Signals flow through different modules for various processing and transmission stages, adhering to operational principles consistent with physical inertial systems. It features a comprehensive data-driven structure, allowing for a more thorough representation of critical testing data, aiding in the establishment of various module models, and enhancing alignment with practical applications of inertial navigation.

The construction of inertial navigation digital prototypes should follow a modeling sequence from simple to complex, starting with broader granularity and gradually refining internal details, while expanding coupling factors. This approach enables the development path to progress from system-level, through component-level, to device-level. The focus of this paper lies specifically in the development of system-level digital prototypes for inertial navigation.

3 Simulation Verification

3.1 Initial data generation

The digital prototype cannot directly perceive physical fields like the inertial instruments in a physical inertial navigation system. It requires using IMU inversion algorithms to set motion trajectories, where attitude, velocity, and position navigation parameters derived from these trajectories are used to compute angular increments and velocity increments as the actual inputs for the digital prototype[13]. The IMU data generation process is shown in Figure 5

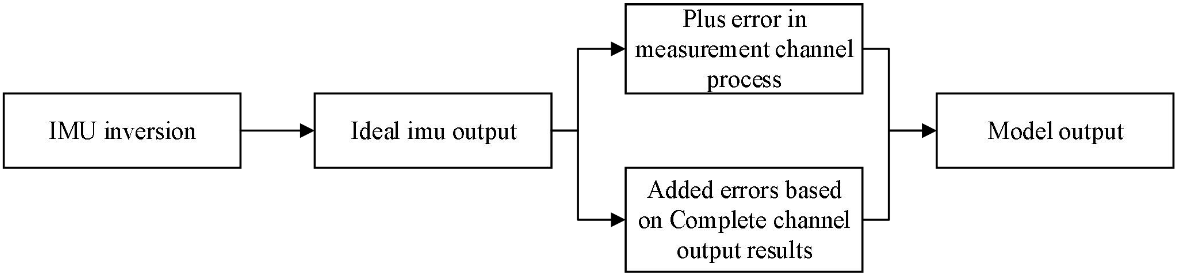


Fig. 5 IMU data generation flowchart

After obtaining ideal IMU outputs, this model supports error configuration for instruments in two forms: The first involves introducing errors during the measurement channel process. After the prototype starts, different modules exhibit their respective error characteristics, resulting in total output that represents the actual prototype output, aligning more closely with the operational conditions of the inertial system. The second form adds errors on top of the complete channel output, such as bias and scale factor errors, which constitute traditional error simulation. This paper has only conducted the second type of error setting for now. The trajectory setting is shown in Figure 6.

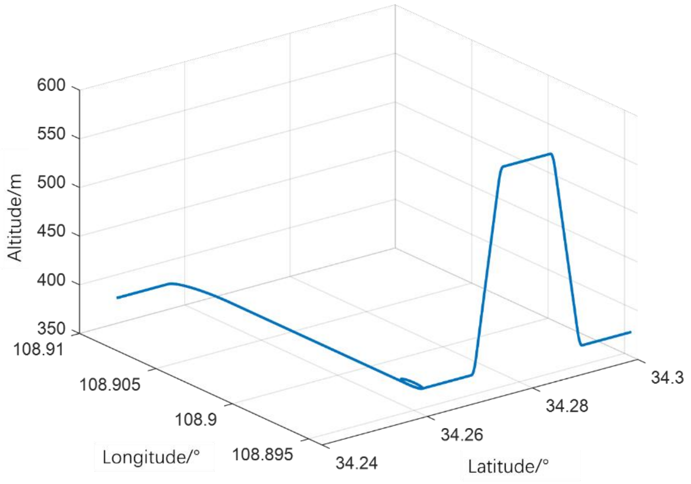


Fig. 6 3D image of simulation trajectory

Fig. 6 shows the 3D image of the simulation trajectory, The trajectory of the aircraft accelerated, went straight ahead at a constant speed, turned left 90° to the east, then turned north after 450° rotation, and reached the end after climbing and landing.

Based on the above trajectory inversion, IMU data are obtained is shown in Figure 7.

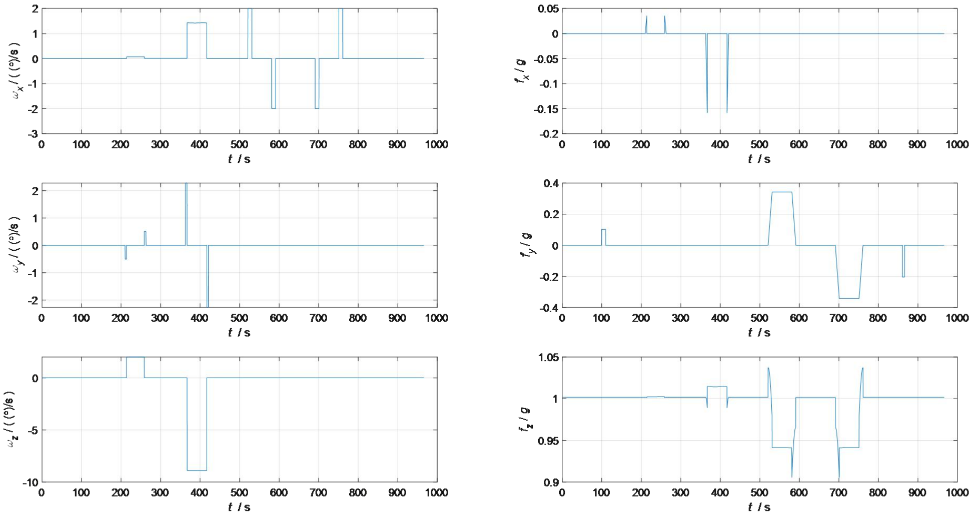


Fig. 7 IMU data curve

In the simulation process, in order to verify the effectiveness of the prototype operation, only common errors were set, and the error Settings of the accelerometer and gyroscope models were shown in Table 1.

Table 1. Inertial device error setting

Error	Gyroscope	Accelerometer
zero offset	$0.005\,^{\circ}/h$	$50\mu g$
random walk	$0.0003\,^{\circ}/\sqrt{h}$	$2\,\mu g/\sqrt{Hz}$

After the error shown in Table 1 in the prototype is given, the IMU data shown in Figure 7 is taken as input in Section 3.2 to conduct the simulation run of the digital prototype and perform functional verification of the digital prototype.

3.2 Navigation simulation

Using the data generated by simulation and the historical calibration process data of inertial group as input, the digital prototype simulation was run, and the constructed digital prototype was checked by simulation. The simulation output results and error curves of the INS digital prototype are shown in Figure 8 and Figure 9.

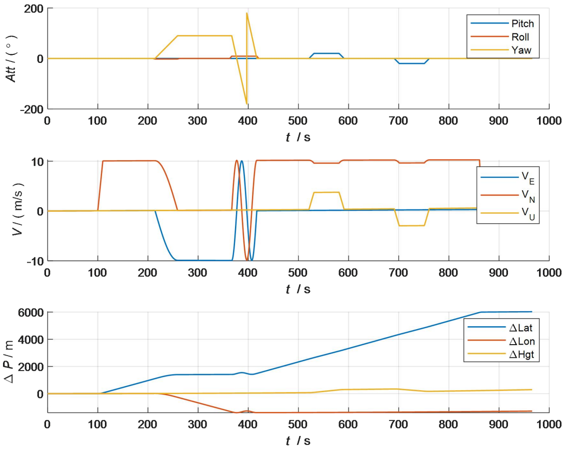


Fig. 8 Navigation result output curve

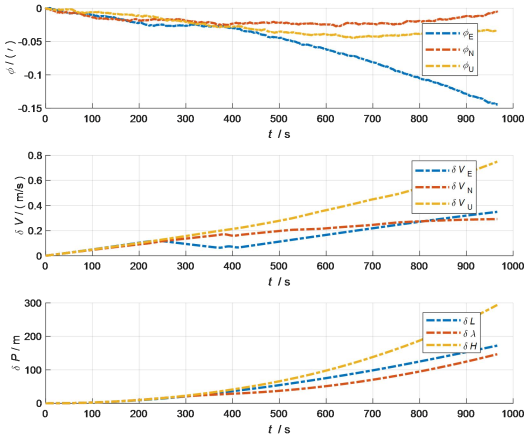


Fig 9 Navigation output error curve

The inertial instrument error in the digital prototype is shown in Table 1. The total simulation duration is 966s and the inertial navigation solution cycle is 0.01s. The navigation simulation results are shown in Figure 8. As can be seen from the output error curve shown in Figure 9, the attitude angle errors in the east, north and sky directions are -0.139′, -0.004′and -0.041′, respectively. The velocity errors were 0.38 m/s , 0.30 m/s and 0.68 m/s , respectively. The position errors are 146.8 m , 172.4 m and 293.9 m , respectively. The attitude, speed and position errors of the digital prototype are in line with the error requirements of the navigation algorithm. Therefore, it can be concluded that the models of the inertial navigation digital prototype are correct and the connections between them are correct.

4 Summary

This paper takes the "three- autonomy " SINS as a prototype and constructs a digital prototype in simulation software. The prototype includes modules such as power supply, gyroscope, accelerometer, inertial unit control circuit, information processing circuit, analog-to-digital conversion circuit, locking module, frame, and temperature measurement. Based on GCAir software, the model undergoes multi-source heterogeneous integration and conducts simulations including pure inertial navigation. This simulation conform to the operational conditions of physical inertial navigation systems, laying a foundation for subsequent research on inertial digital twin technology using inertial digital prototypes.

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