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Research of Strapdown Integrated Navigation System Based on Rotation Control Technology

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ABSTRACT

To realize high-precision Single-axial Rotating FOG-SINS, a low-power, low-cost, middle-precision rotating control mechanism design for single-axial rotating navigation system is put forward. Through theory analysis, design and experimental verification, the rotating control mechanism has good control precision and high reliability, which meets the demands for developing middle & high-precision FOG-SINS.

1. Introduction

Nowadays, foreign high-precision FOG-SINS is gradually replacing the expensive ESG inertial navigation system to provide ships with high-precision, low-cost and long-endurance inertial navigation system. In order to improve the accuracy of SINS based on the existing FOG, it is imperative to adopt the rotary modulation technology of error self-compensation.

At present, the continuous rotation alignment has become an effective technical means to achieve high-precision of FOG inertial navigation system. The technology of the continuous rotation scheme using single-axial rotating FOG-SINS is realized by the regular movement of the inertial measurement unit (IMU) of FOG around the rotation axis. By modulating the error of the inertial device in the rotation period, the drift error is compensated, and the growth of the error with time is controlled, so as to greatly improve the alignment accuracy and convergence speed of the system. Therefore, the technology has become one of the highlights of engineering application research.

2. Principle and Design Scheme

The single-axial rotating modulation technology of inertial navigation system is to install IMU on the single-axial rotation mechanism, which drives the IMU to rotate around the axis according to the set rule. The rotation axis

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of the platform is perpendicular to the horizontal plane of the carrier. Under the normal reciprocating rotation control mode, the rotary mechanism drives the IMU to move from 0° to 360° of the optical code disk at a set rate, and then move from 360° to 0° for reciprocating rotation, based on the range value of the uniaxial angle measuring device [1,2].

Heading uncoupled reciprocating rotation mode is the superposition of heading tracking motion and reciprocating rotation motion. Assuming that the carrier is stationary, IMU will rotate according to the set rule. However, in practice, the carrier is always in various motions, and the angular motion of the carrier is coupled with the rotation of IMU. Under the influence of the carrier's heading motion, for the navigation system, IMU does not rotate according to the ideally set scheme, affecting the rotation modulation. In the navigation system, the equivalent gyro drift is related to the carrier's heading angle amplitude, angular frequency, the occurrence time of the carrier's heading, the time of heading angular motion and the rotation time of IMU relative to the carrier [3,4]. Due to the heading motion of the carrier, the motion of IMU in the navigation system is irregular. Within a rotation cycle, the error integral is not zero. That is, the course motion of the carrier offsets the modulation effect of IMU rotation. If the angle of the carrier's heading motion is always the same as the IMU's rotation angle relative to the carrier, and the direction is opposite, then the measurement error in the navigation system does not change, and the carrier's heading motion completely offsets the effect of rotation modulation. Ideally, using the calculated carrier's posture data and the set rotation modulation law to drive the IMU to rotate relative to the carrier can effectively eliminate the influence of the carrier's heading motion, and isolate the system from the carrier's heading motion, so that the IMU can rotate regularly relative to the navigation system. The positional relation between INS and IMU is shown in Figure 1 [5].

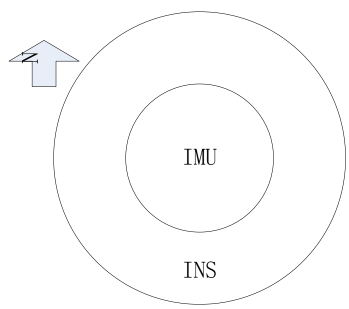

Figure 1. Positional relation between INS and IMU.

Heading uncoupled reciprocating rotation mode takes the geographical coordinate system as the benchmark and the demodulated initial heading angle as the zero position. According to the demodulated heading angle and angular velocity, it can reciprocate at a constant speed between 0° and 360°. The ideal situation is that no matter how the heading of the carrier (INS) changes, the rotating mechanism will rotate back and forth at a uniform speed around the reference angle of the geographic coordinate system [6-9].

The working principle of the rotating mechanism is as follows: The inertial measurement unit in the inertial navigation system is placed on the rotating mechanism, the DC motor drives the rotating mechanism to rotate through the gearbox and belt bearing, and the angular position is uploaded through the angle measuring device. The rotating mechanism returns to the zero position and waits for the command sent by the guidance computer. The rotating mechanism drives the inertial measurement unit to rotate at the set speed and rotation mode, or receives the position command sent by the guidance computer, turning to the required position at a fixed rate and stabilize at that position. At the same time, the real-time information of the rotating mechanism is transmitted to the external guidance computer through the serial port [10-12].

The rotation mechanism mainly realizes two functions: one is to receive the rate command sent by the guidance computer and rotate at the set rate and rotation mode; the second is to receive the position command sent by the guidance computer, turn to the required position at a fixed rate, and stabilize at this position. In addition, the rotating mechanism must also have the functions of power-on self-test and patrol inspection during operation, and send the results to the INS through the status word. If "stall" and other non hardware damage faults are found during the operation of the rotating mechanism, under the condition that the processor of the rotary control circuit can communicate with the inertial navigation system normally, the rotating mechanism shall be able to reset after the INS sends the reset command, and the control program shall be restarted [13-15].

The design scheme of the rotating mechanism considers the actual working requirements of the system, and integrates the sensor, processor and controller into a mechanical structure. The rotating mechanism is mainly composed of rotary control circuit, rotating control software, uniaxial angle measuring device, DC motor and other sub components. The composition and relationship of the rotating mechanism are shown in Figure 2. In the system, the rotary control circuit and its software collect the angle measurement information, realize the velocity driven by the motor, and communicate with the inertial navigation system. The guidance computer sends the same

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synchronization signal to the rotary control circuit and the angle measuring device, and the rotary control circuit and the guidance computer simultaneously receive the angle measuring data sent by the angle measuring device. The small DC motor is responsible for the implementation of rotation function.

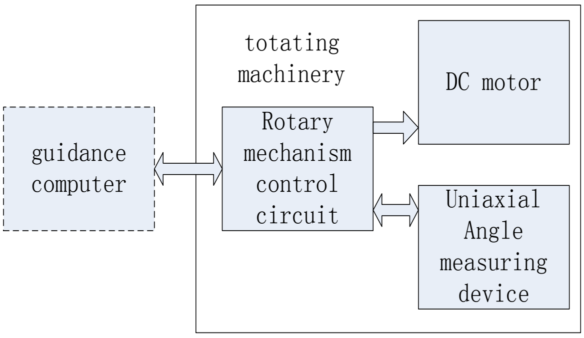

Figure 2. Rotary mechanism system.

3. Hardware Design

3.1 Design of Control Circuit

The rotary control circuit is responsible for collecting angle measurement information, driving the motor, communicating with the inertial navigation system, receiving instructions and sending data and status. The rotary control circuit obtains the accurate information of the angle measuring device at a fixed time. The control system drives the DC motor through the D/A converter and OP Amp, and uses it to form a complete motion control system with the processor, motor and angle measuring device. The 3D diagram of the rotary control circuit is shown in Figure 3.

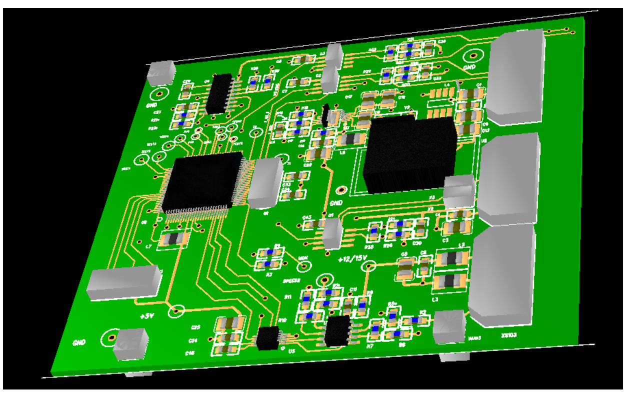

Figure 3. The 3D diagram of the rotary control circuit.

3.2 Selection of Uniaxial Angle Measuring Device

The uniaxial angle measuring device is mainly used in the angle measuring system of rotary mechanism. The rotary mechanism controls the movement of IMU according to the output angle signal of uniaxial angle measuring device, including angular position control and angular speed control. The rotary mechanism adopts the uniaxial angle measuring device of Changchun Institute of Optics, Fine Mechanicsand Physics, with a resolution better than 2.5”; response delay of synchronous signal shall not be greater than 5 μs; data output is less than 100 μs; power consumption is not greater than 1 W; the maximum allowable mechanical speed shall not be less than 20 rpm [16].

The working mode of the uniaxial angle measuring device is shown in Figure 4. The angle measuring device responds to the falling edge of the synchronization signal in an interrupt manner, triggers angle sampling, and then outputs angle data. From receiving the synchronization signal to completing the data output, it is less than 100 μs.

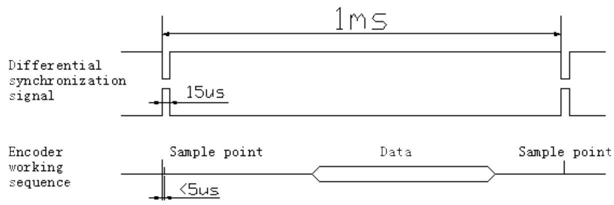

Figure 4. The working mode of the uniaxial angle measuring device.

The uniaxial angle measuring device sends the same synchronization signal to the rotary control circuit and the angle measuring device through the guidance computer, and the rotary control circuit and the guidance computer simultaneously receive the angle measuring data sent by the angle measuring device, as shown in Figure 5. The navigation software enters the 1 ms timing interrupt program. When the gyro is gated, the synchronization signal will be sent, and the maximum sampling delay after the angle measuring device receives the synchronization signal is 5 μs.

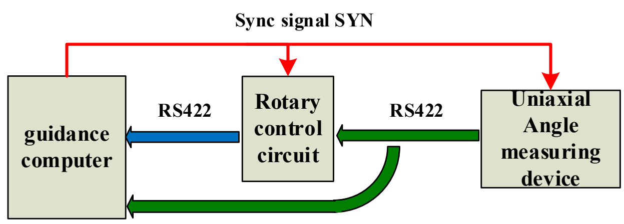

Figure 5. Diagram of data synchronization of rotary mechanism.

The conversion between digital quantity and arcsec of uniaxial angle measuring device is as follows:

$$1LSB = \frac{360^{(\circ)} \bullet 3600^{('')}}{2^{21}(=2097152)} \approx 0.618^{('')} \tag{1}$$

The digital quantity of uniaxial angle measuring device represented by 1 minute of arc is:

$$1^{(')} = \frac{2^{21}}{360^{(°)} \bullet 60^{(')}} \approx 97.09LSB \quad (2)$$

In the process of rotation, assuming that the angular velocity is 5, the angular error caused by the 5 ms software delay is:

$$\Delta\theta 1 = V_{速度} \bullet t_{时间} = \frac{5\,(°/s) \bullet 3600^{('')}}{1^{(°)} \bullet 1000S} \bullet 5ms = 90^{('')} \quad (3)$$

This formula indicates that the regulating accuracy is $90^{('')}$.

3.3 Selection of Motor

Measure and calculate the driving torque required by the 4.5 kg rotator, and the required torque is as follows:

3.3.1 Torque Required to Overcome Friction Torque

Friction torque includes the friction torque of uniaxial angle measuring device bearing, torque motor bearing and torque motor brush, the influence of lubricating grease on bearing friction torque, and the load increased by assembly error. The friction torque of the uniaxial angle measuring device is measured by hanging weights. The weight is 0.104 kg, and the arm of force is about 12.5 mm. The result is:

0.104×9.8×0.0125 = 0.01225Nm (P = mgL) (4)

The total friction torque of the motor, with a starting voltage of 0.6 V, is estimated as:

(0.7 ~ 0.8)×0.6/24 = (0.0175 ~ 0.02)Nm (5)

Therefore, under normal temperature, the friction torque of the rotary mechanism is about 0.03 Nm. Considering the increase of friction torque at low temperature, the friction torque is taken as 0.1 Nm.

3.3.2 Torque Required for Acceleration of Rotary Mechanism

The maximum load generated by moment of inertia occurs at the end of commutation acceleration. At this time, according to the system requirements, the maximum angular speed of the rotary mechanism reaches 100 °/s (17 rpm), and the required torque is:

$T_{j1} = Jd\omega_1/dt = 0.01969×100/57.3=0.034Nm$ (6)

3.3.3 Torque Required by Tracking Carrier Accelerative Rotation

According to the test data of a certain type of inertial navigation system, the instantaneous angular acceleration is not greater than 1500 $°/s^2$, so the torque to ensure the smooth rotation of the rotary mechanism is

$T_{j2} = Jd\omega_2/dt = 0.01969×1500/57.3=0.515Nm$ (7)

3.3.4 Torque Generated by Off-centre Rotating Part under Impact (15 g/11 ms)

According to the recalculation results, the eccentric distance of the rotating part is 0.23 mm, and the weight of the rotating body is 4.6 kg. Considering that the mechanism is amplified by 1.8 times, the actual acceleration reaches 27 g. Therefore, the torque generated by off-centre rotating part under impact is:

$T_p = Mal = 4.6×27×9.8×0.23×10^{-3} = 0.28Nm$ (8)

To sum up, the torque that the motor needs to provide under extreme conditions is the resultant force of the above torque, that is:

T = 0.1+0.034+0.515+0.28 = 0.929Nm (9)

Considering that the probability of extreme conditions (e.g., carrier is 1500 $°/s^2$) is small, we balance the weight of the rotating body to reduce the eccentricity and 50% torque generated by shock, based on 50% of the extreme conditions, so the torque to be provided by the motor is:

T = 0.1+0.034+0.2575+0.15 = 0.54Nm (10)

3.3.5 Calculation of Transmission between Uniaxial Angle Measuring Device and Motor

The relationship between the speed of the uniaxial angle measuring device and the voltage that controls the speed of the motor is as follows:

$$Vt\arg et = K \bullet N \quad (11)$$

where, $Vt\arg et$ is the voltage controlling motor speed (V); K is the speed scale factor formed by the combined action of motor gearbox and gear; N is the speed of optical code disk (rpm).

The conversion relationship between rpm and 0.00001 (°)/s is

$$N \bullet 360^{°} / 60S = \omega / 10^5 (°) / S \quad (12)$$

where, ω is the angular velocity of the uniaxial angle measuring device (0.00001 (°)/s). 1 rpm = 6 (°)/s.

4. Software Design

4.1 Software Functions of Rotary Mechanism

The rotary mechanism takes the one-chip computer as the control system, so its function is realized through the design of the rotary control software, including:

1) Initialization of registers and variables of one-chip computer;

2) Communicate with the guidance computer, receive

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control commands and feed back the status of the rotary mechanism;

3) Generate the synchronization signal of the uniaxial angle measuring device and receive its output angle signal;

4) Control the motor to realize the motion control command sent by the guidance computer;

5) The corresponding protection function of the rotary mechanism.

The internal interface control flow of main software components is shown in Figure 6.

The software process mainly includes:

1) Realize the initialization of the central processing unit;

2) Carry out self inspection activities for the rotary mechanism;

3) Interpret navigation commands circularly and execute corresponding actions;

4) Respond to CPU timing interrupt and external interrupt requests at any time.

The guidance computer sends various navigation commands to the rotary mechanism. The conditions for these commands are:

1) When the rotary mechanism works abnormally and needs to be corrected, an external command is sent to reset;

2) When the rotary mechanism is needed to work normally, an external command is sent to control the reciprocating rotation;

3) When the rotary mechanism needs to be stationary at a certain angle, the external sends the absolute position control command;

4) When the rotary mechanism needs to rotate at the specified speed, the external sends the speed control command;

5) When the rotary mechanism needs to rotate relative to a fixed angle and is stationary at another relevant angle, the external sends the relative position control command;

6) When the rotary mechanism needs to rotate continuously for multiple cycles in one direction according to the requirements of INS, the external sends an online calibration control command;

7) When the rotary mechanism needs to rotate to the specified angle at one time according to the requirements of INS, the external sends the initial calibration control command;

8) When the rotary mechanism needs to track the course and speed changes outside the carrier in real time to realize the reciprocating rotation relative to the geographical coordinate system, the external sends the course decoupling reciprocating rotation control command.

At any time in the above process, the rotary mechanism responds to different interrupt sources and saves new commands. After the action of the previous command is completed, execute the action of the latest command.

Various interrupt sources are as follows:

Interrupt source (1 = the highest priority) REST: reset interrupt;

Interrupt source (2 = high priority) INT0: external synchronization signal request interrupt;

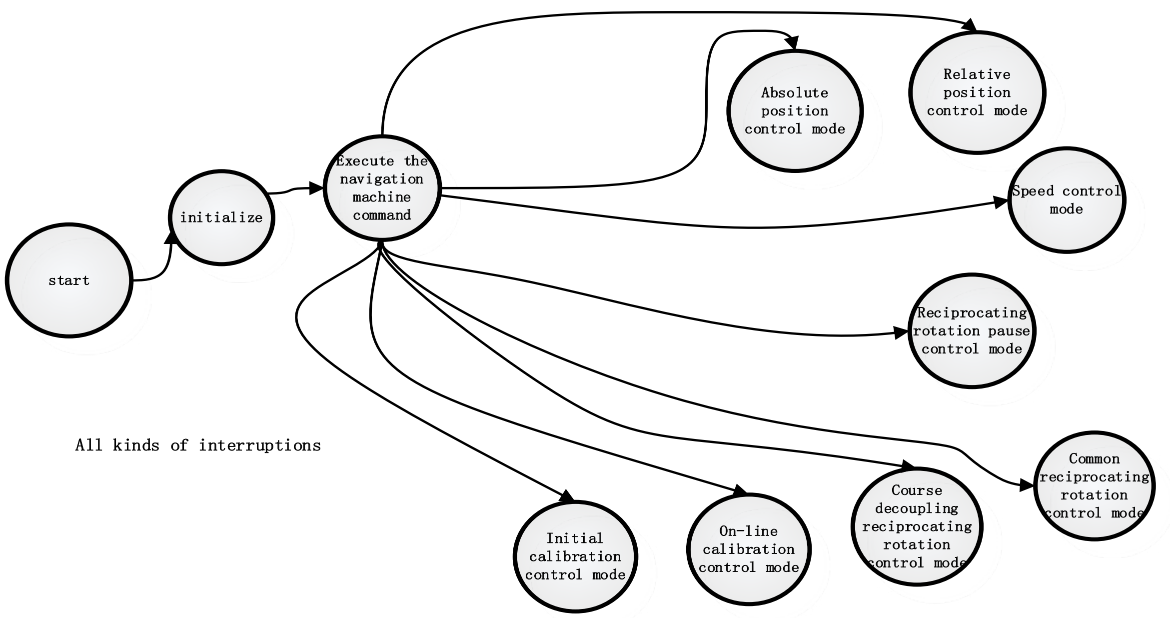

Figure 6. The internal interface of main software components.

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Interrupt source (3 = secondary high priority) TIMER0 OVF: timer 0 interrupt, allowing interrupt nesting;

Interrupt source (4 = medium priority) USART1 RX: interruption of communication serial port 1 receiving end;

Interrupt source (5 = secondary low priority) USART1 TX: interruption of communication serial port 1 sending end;

Interrupt source (6 = the lowest priority) USART2 RX: interruption of communication serial port 2 receiving end.

4.2 Main Program Process

The workflow of the main program of the rotation control software is shown in Figure 7. The functions that the software can realize are as follows: Receive the rate command sent by the INS, and rotate at the set rate and mode; receive the position command sent by the INS, rotate to the required position at a fixed rate, and stabilize at this position; perform the function of power-on self-test and patrol inspection during operation, and send the test results to the INS through the status word.

4.3 PID Algorithm

In the subprogram of incremental speed PID algorithm, the best effect is obtained through parameter tuning. In the subprogram of incremental speed PID algorithm, the best effect is obtained through parameter tuning, and the sequence is checked from small to large: Proportion, integral, differential. The incremental PID control structure is shown in Figure 8, and the simulation results are shown in Figure 9.

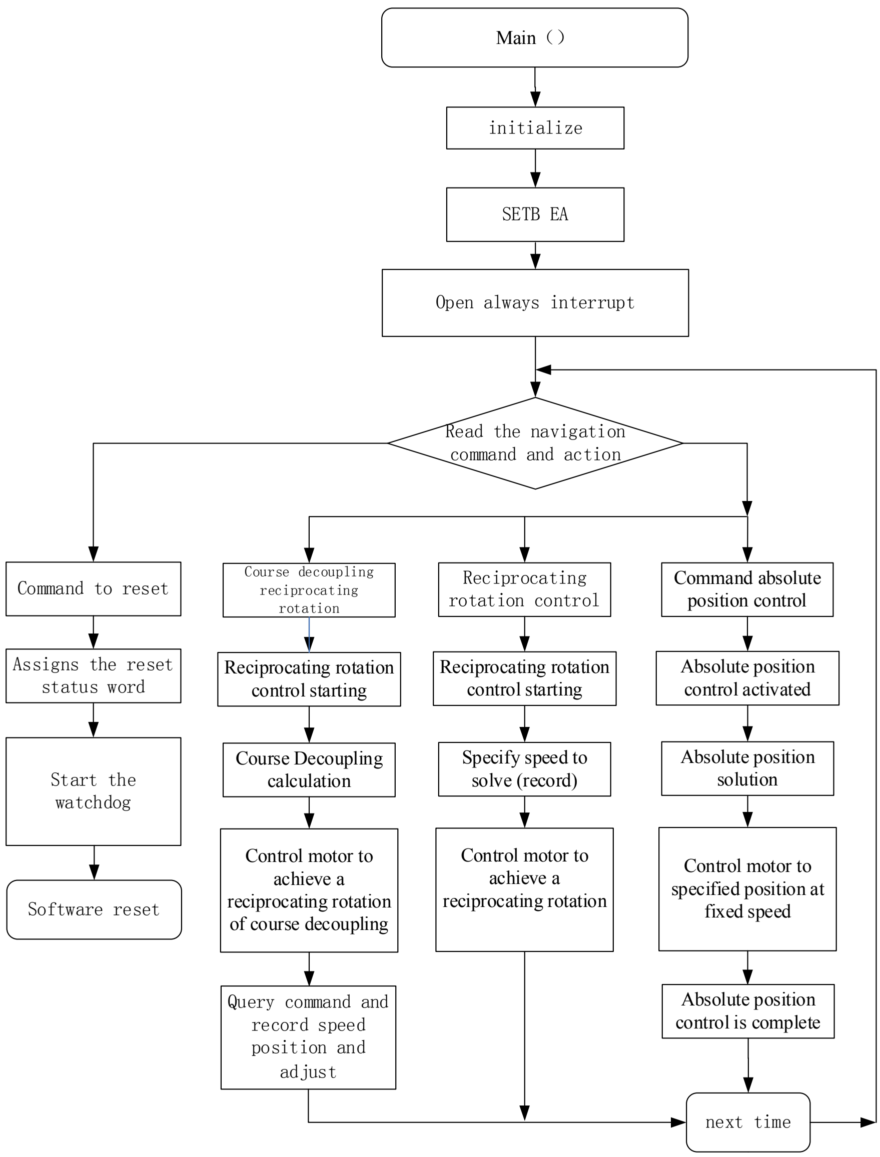

Figure 7. The workflow of the main program of the rotation control software.

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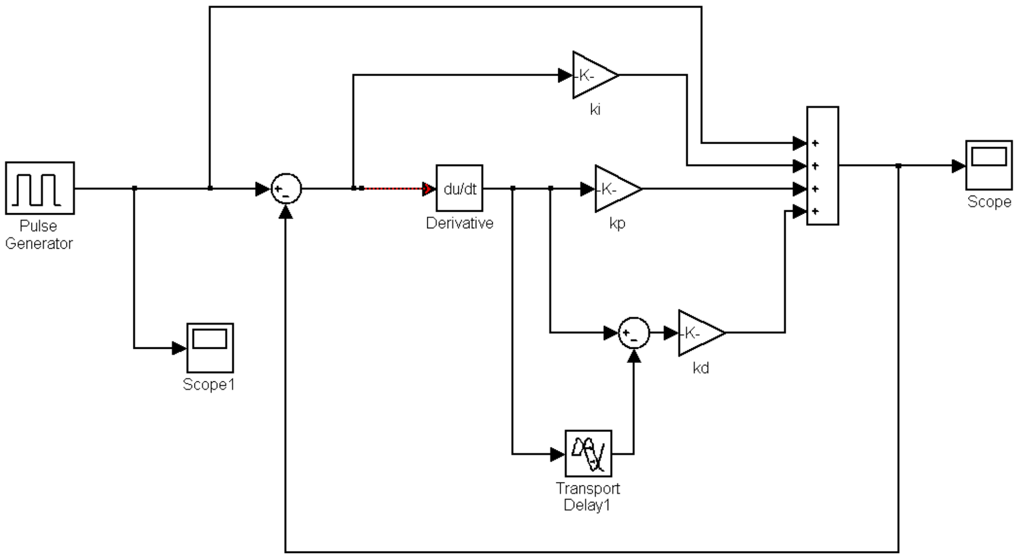

Figure 8. Incremental PID control structure.

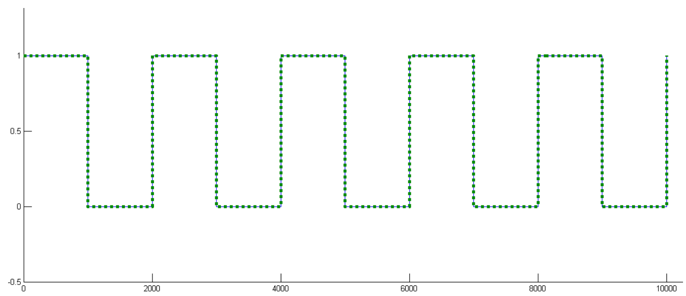

Figure 9. PID control response curve.

4.4 Motor Control

Typical motor steering switching includes three stages: accelerating for starting, uniform motion, and deceleration for braking.

When starting quickly, the analog voltage higher than the normal speed can be provided to improve the speed rising characteristic. The formula of armature starting current of motor is as follows:

$$I_{启动}=\frac{U-\Delta U}{\mathrm{r}_{acp}} \tag{13}$$

where, U is the voltage at the debugging speed; ΔU is the saturation voltage drop of power tube, and r_{acp} is the average resistance of winding.

4.5 Control Method and Working Mode of Rotary Device

The process of rotary device control method includes:

1) Realize the initialization of the central processing unit;

2) Carry out self inspection activities for the rotary mechanism;

3) Interpret navigation commands circularly and executes corresponding actions.

The external computer sends various navigation commands to the biaxial rotating device. The conditions for these commands are:

When the rotary mechanism works abnormally and needs to be corrected, an external command is sent to reset;

When the rotary mechanism is needed to work normally, an external command is sent to control the reciprocating rotation;

When the rotary mechanism needs to be stationary at a certain angle, the external sends the absolute position control command;

When the rotary mechanism needs to track the course and speed changes outside the carrier in real time to real-

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ize the reciprocating rotation relative to the geographical coordinate system, the external sends the course decoupling reciprocating rotation control command;

At any time during the above steps, rotary mechanism responds to different interrupt sources and executes corresponding commands.

The rotating mechanism can provide eight working modes: absolute position control mode, relative position control mode, speed control mode, reciprocating rotation pause control mode, ordinary reciprocating rotation control mode, course decoupling reciprocating rotation control mode, online calibration control mode, and initial calibration control mode.

The functions and valid parameters of various working modes are shown in the Table 2.

The rotation control software starts running after the rotary mechanism is powered on and reset. After each power on, the rotation control software first initializes the system, and then the rotary mechanism enters the normal working state. The software performs corresponding motion control according to the received control instructions from guidance computer. At the same time, the software responds to the interruption of the synchronization signal and returns the status information of the rotary mechanism to the guidance computer.

When the DC motor stops rotating during the movement of the rotating mechanism and fails to normally receive the angular position information of the uniaxial angle measuring device for a long time, the rotary mechanism will enter the fault-safe mode, turn off the DC motor drive output, and be in a free state until the fault is eliminated.

5. Test

The calculation formula of angular rate is:

$$V_{1s计算b} = V_{1s真} + \Delta V_{b} = \theta_{Tb} - \theta_{Tb-1s} \quad (14)$$

where, $V_{1s真}$ and ΔV_b respectively represent the theoretical angular rate value and the actual measurement error with an interval of 1 s; θ_{Tb} and θ_{Tb-1s} respectively represent optical code disk angle of the current and 1 s ago. When $V_{1s真} = 10°/s$, ΔV_b is usually not more than 0.3°/s. Besides, the statistical average value of angular rate with a period of 1 s can be well controlled and adjusted.

According to the environmental stress screening of strapdown inertial navigation, the rotary mechanism completes the static, vibration, impact, high and low temperature tests in turn. The test results show that the functions and performance indicators meet the task requirements. The angular rate and angle curve of the rotary mechanism of a batch are shown in Figures 10-12 respectively, and the comparison of technical indicators is shown in Table 3.

Table 2. Working mode of rotary mechanism.

No.	Mode	Function	Valid parameter
1	Absolute position control mode	The rotary mechanism can be positioned at any angle within 360°.	Angular position commanded
2	Relative position control mode	The rotary mechanism can be positioned at a relative angle within 360°.	Angular position commanded
3	Speed control mode	The rotary mechanism rotates in one direction at the specified speed.	Angular velocity commanded
4	Reciprocating rotation pause control mode	The rotary mechanism pauses during movement until the new command resumes reciprocating rotation.	/
5	Ordinary reciprocating rotation control mode	The rotary mechanism rotates back and forth with the zero position of the uniaxial angle measuring device as the center within 360°.	Angular velocity commanded; angular position commanded
6	Course decoupling reciprocating rotation control mode	The rotating mechanism rotates back and forth with the initial course angle as the center within 360° of the geographical coordinate system.	Angular velocity commanded, course angular velocity after demodulation , course angle after demodulation
7	Online calibration control mode	The rotary mechanism stops after 3 consecutive revolutions at the rate of 10(°)/s.	/
8	Initial calibration control mode	The rotary mechanism controls the absolute position to the specified angle and exits.	Angular position commanded

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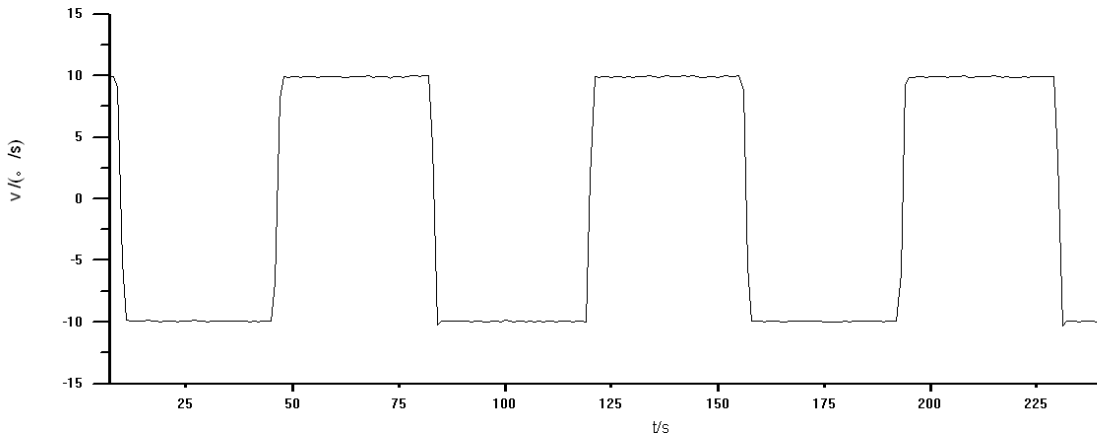

Figure 10. Graph of angular rate (10º/s).

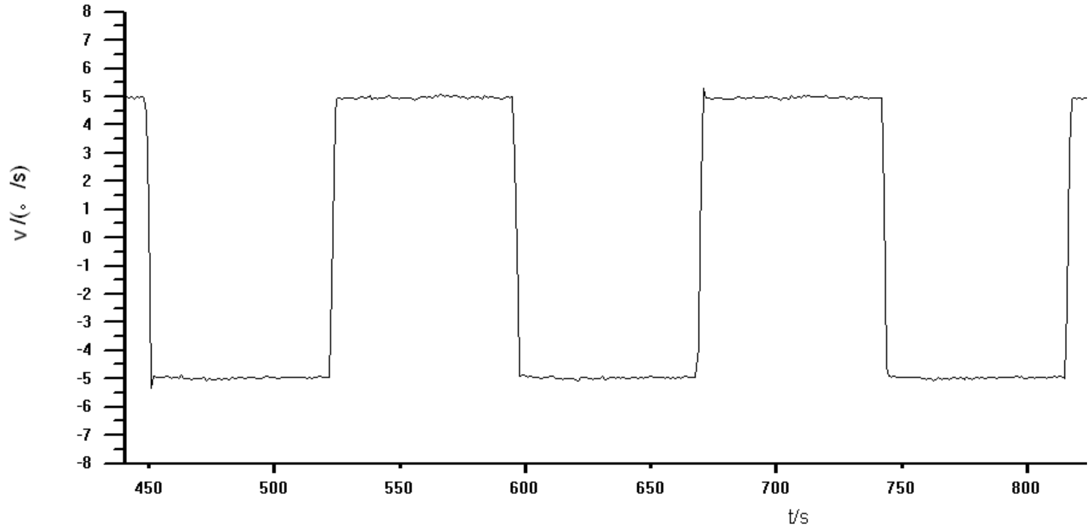

Figure 11. Graph of angular rate (5º/s).

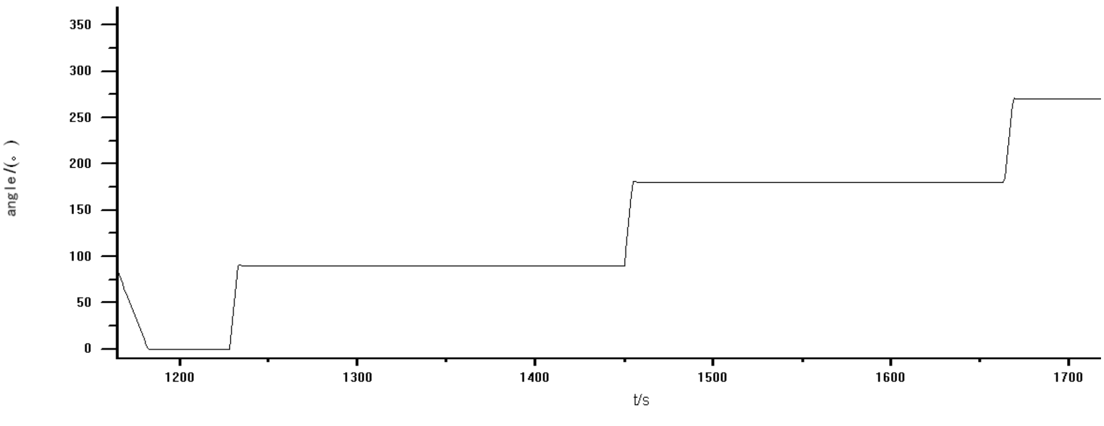

Figure 12. Graph of angle (0º, 90º, 180º, 270º).

Table 3. Comparison table of technical indicators of rotary mechanism.

No.	Indicators	Requirements	Whether the design meets the requirements
1	Reciprocating rotation	Move from 0° to 360° at a specified angular rate reciprocally	Yes
2	Positioning function	Fixed at any position within the range of 0° ~ 360°	Yes
3	Angular rate range (º)/s	Not less than ±25	Yes
4	Angular rate precision	3%	Yes
5	Positioning precision (°)	0.05 (3σ)	Yes
6	Payload (kg)	5±0.4	Yes
7	Steady-state power (W)	<5	Yes
8	Transient power (W)	<7	Yes

6. Conclusions

The continuous rotation alignment has become an effective technical means to achieve high-precision of FOG inertial navigation system. This paper proposed a low-power, low-cost and medium precision scheme of uniaxial rotation navigation system. The results show that the function and performance of the rotary mechanism meet the technical requirements, which provides a strong support for giving better play to the navigation ability of the single-axial rotating FOG-SINS.

References

[1] Sun, W., 2014. Rotary modulation strapdown inertial navigation system. Beijing: Surveying and Mapping Press. pp. 5-7. (in Chinese)

[2] Titterton, D.H., Weston, J.L., 2010. Strapdown inertial navigation technology (2nd edition). Beijing: National Defense Industry Press. 10, 144.

[3] He, Ch.J., Zou, Zh.Q., Zou, Y., et al., 2016. Initial alignment of rotation-modulation strapdown inertial navigation system. Navigation Position & Timing. 3(2), 1-2. (in Chinese)

[4] Gao, Zh.Y., 2012. Inertial navigation technology. Beijing: Tsinghua University publishing house. pp. 224-253. (in Chinese)

[5] Ke, W., Qiao, H.Y., Meng, F.Q., 2012. Analysis of single-axial rotation system for the marine ring laser gyro INS. Ship Science and Technology. 34(12), 67-71. (in Chinese)

[6] Ji, Zh.N., Liu, Ch., Cai, Sh.J., et al., 2013. Improved sixteen-sequence rotation scheme for dual-axis SINS. Journal of Chinese Inertial Technology. 21(1), 46-50. (in Chinese)

[7] Xu, H.G., Guo, Y.J., Li, Zh.F., et al., 2015. Research on north-seeking precision limit of rotation-modulating FOG-SINS. Navigation Position & Timing. 3(2), 11-15. (in Chinese)

[8] Hu, Sh.S., 2016. Principles of automatic control. Beijing: Science Press. (in Chinese)

[9] Wei, Ch.G., 2006. Development of angular measuring system of testing turntable. Harbin: Harbin Institute of Technology. (in Chinese)

[10] Qi, M., Zou, J.B., Liu, Ch.J., 2007. High precision angular measuring system based on round inductosyn. Chinese Journal of Electron Devices. 30(1), 263-266. (in Chinese)

[11] Dong, J.Sh., Sun, H.Ch., Wang, H., et al., 2018. The design of A/D converter circuit with high resolution integral output. Navigation Position & Timing. 5(1), 93-94. (in Chinese)

[12] Liu, J.K., 2016. Matlab simulation of advanced PID control. Beijing: Publishing House of Electronics Industry. (in Chinese)

[13] Liu, F.Q., Zhang, G.Y., Wang, L.Y., et al., 2008. Control system for two-axis turntable based on single chip microcomputer. Journal of Changchun University of Science and Technology. 31(4), 87-90. (in Chinese)

[14] Kim, J.Y., Kim, I.S., Lee, H.N., et al., 2001. A study on the feedback system of ultra precision positioning apparatus using laser inrergerometer. Insdutrial Electronics. Pusan, KOREA:IEEE int symp. 1, 596-601.

[15] Zhang, L.D., Lian, J.X., Wu, M.P., et al., 2012. Research on yaw angle isolation method of inertial navigation system based on single-axis rotation. Chinese Journal of Scientific Instrument. 33(6), 1247-1250. (in Chinese)

[16] Gao, Y.B., Guan, L.W., Wang, T.J., 2013. Compensation for inclination angle deviation of single-axis rotation modulation SINS. Journal of Chinese Inertial Technology. 21(4), 446-448. (in Chinese)

  DOI: https://doi.org/10.26549/met.v7i1.11641