Research on trajectory detection technology of cavern flow based on inertial navigation

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Abstract. The trajectories detection of carven flow is estimated generally through the calculation of changes in various physical fields and the hydrogeological conditions. This paper uses inertial components to solve the trajectory of carven flow. Due to the characteristics and the complex movement attitude of the inertial components in the flow, the calculation error accumulate over time, even cover the true trajectory. Based on the characteristics of carven flow and inertial components, this paper proposes a new trajectory detection technology to obtain relatively accurate trajectory.

1 Introduction

The detection of groundwater trajectory in caves has always been an important direction of groundwater exploration. The main detection methods include remote sensing technology^[1], salinity method^[2], radioelement method^[3], engineering physical exploration method^[4], and so on. Many hardware facilities need to be installed, which is both costly and time-consuming. Inertial navigation is an autonomous navigation method that does not radiate signals and is not subject to external interference. It can be applied to groundwater flow detection to obtain hydrological information such as flow velocity, flow direction and trajectory. However, due to the complexity of groundwater flow movement and the low cost of low-cost inertial navigation, the traditional navigation data processing needs to be improved and optimized to adapt to groundwater detection. Based on the characteristics of groundwater environment and inertial components, this paper proposes a new detection technology based on inertial components, which provides relatively accurate hydrological information such as groundwater trajectory, flow direction and flow velocity for groundwater detection.

2 INERTIAL NAVIGATION CLASSIC SOLUTION ALGORITHM

The classical inertial navigation data processing method^[5] generally includes the initialization of the initial alignment system, the error compensation of the inertial instrument, the attitude matrix calculation combined with the Kalman fusion algorithm, the carrier position, the speed calculation, the guidance, and control information extraction, etc. . However, various error sources (such as

principle errors, structural errors, process errors, etc.) that exist objectively by inertial navigation sensors, especially for inertial devices operating in the strapdown environment, the complex dynamic motion of the carrier will provoke a variety of Formal error^[6].

Taking the system speed error as an example, when only the deterministic error, attitude error, and gravity acceleration error existing in the actual system solution process are considered, the actual speed calculation value should be determined by the following equation^[7].

$$\dot{V}^c = \hat{C}_b^n \tilde{f}^b - (2\omega_{ie}^c + \omega_{en}^c) \times V^c + g^c \quad (1)$$

The parameters in the formula represent the following meanings:

$V^c = V^n + \delta V^n$ is the speed value with δV^n speed error;

$g^c = g^n + \delta g$ is the gravitational acceleration with δg error;

$\hat{C}_b^n = C_n^{n'} C_b^n = (1 - \phi^n \times) C_b^n$ is an attitude matrix with errors.

$$\phi^n \times = \begin{bmatrix} 0 & -\phi_u & \phi_N \\ \phi_u & 0 & -\phi_E \\ -\phi_N & \phi_E & 0 \end{bmatrix} \text{ is the attitude error}$$

matrix;

ϕ_E , ϕ_U and ϕ_N are the attitude error angle of the local Cartesian coordinates coordinate system;

$\tilde{f}^b = (I + [\delta K_A])(I + [\delta A])f^b + \nabla^b$ is an acceleration sensor output value with zero drift, scale factor error, installation error, etc.

∇^b is the zero drift error;

$[\delta K_A] = \text{diag}[\delta K_{Ax} \quad \delta K_{Ay} \quad \delta K_{Az}]$ is the scale factor error;

δK_{Ai} and δA_i ($i = x, y, z$) are the scale factor error and the installation error angle of the accelerometer.

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$$[\delta A] = \begin{bmatrix} 0 & \delta A_z & -\delta A_y \\ -\delta A_z & 0 & \delta A_x \\ \delta A_y & \delta A_x & 0 \end{bmatrix} \text{ is the installation error.}$$

Finally, the speed error equation can be obtained as shown below:

$$\begin{bmatrix} \delta V_E^c \\ \delta V_N^c \\ \delta V_U^c \end{bmatrix} = \begin{bmatrix} 0 & \phi_U & -\phi_N \\ -\phi_U & 0 & \phi_E \\ \phi_N & -\phi_E & 0 \end{bmatrix} \begin{bmatrix} f_E^b \\ f_N^b \\ f_U^b \end{bmatrix} + C_b^m \times \begin{bmatrix} \delta K_{Ax} & \delta A_z & -\delta A_y \\ -\delta A_z & \delta K_{Ay} & \delta A_x \\ \delta A_y & -\delta A_x & \delta K_{Az} \end{bmatrix} \begin{bmatrix} f_x^b \\ f_y^b \\ f_z^b \end{bmatrix} + \begin{bmatrix} 0 & -\delta V_U & \delta V_N \\ \delta V_U & 0 & -\delta V_E \\ -\delta V_N & \delta V_E & 0 \end{bmatrix} \times (2\omega_{ie}^c + 2\omega_{en}^c) + \begin{bmatrix} \nabla_E \\ \nabla_N \\ \nabla_U \end{bmatrix} \quad (2)$$

ω_{ie}^c , ω_{en}^c are the rotation rate and position rate of the earth.

The positional equation can be obtained by integrating the velocity, and the position error equation can be obtained by the same method. However, during the groundwater detection process, the inertia component will cause the speed error to accumulate with time as the water flow flips, flips, and collides. Among various error sources, the error of the attitude can be greatly reduced by the Kalman filter algorithm, and the deterministic error can be removed by the accurate calibration experiment, but the accumulation of errors over time cannot be avoided. This results in very low trajectory resolution, even for static and random error compensation of inertial components. This limits the application of the classical inertia solving algorithm in the detection of groundwater flow velocity.

3 GROUNDWATER DETECTION MODEL AND ALGORITHM FLOW

When the groundwater flow is actually detected, the inertial components are directly used due to environmental factors, and problems such as the inability to solve the trajectory often occur. In this paper, by improving the appearance model of the device, it is ensured that the inertial component is consistent with the flow of water in the flow; the solution method of inertial navigation and GPS information fusion is used, and the GPS data of the starting position is used as the basis for inertial navigation speed and direction correction, so as to obtain more accurate Trajectory data.

3.1 Shape structure of the model

During the actual cave water flow detection process, the inertial component motion exhibits complex motion states such as flipping, flipping, colliding, rotating, etc. of the water wave, and the speed error gradually increases with time. In order to make the system more stable in water and reduce the situation of the unsatisfactory state, the model structure of the model designed in this paper is shown in Figure 1, and the sectional view is shown in Figure 2. The head is a conformal structure, which can divert the water flow to ensure that the heading of the model is consistent

with the flow direction of the water flow. When the heading of the model deviates from the direction of the water flow, the water flow can exert a resistance effect on the side of the paddle to correct the heading of the model to the water flow. direction. This ensures that the heading angle of the model is consistent with the direction of motion of the water flow.

Fig. 1. The model of the device

Fig. 2. The cross-section of the device

3.2 The components of the probe module

The block diagram of the hydrological detection module used in this paper is shown in Figure 3. It consists of a nine-axis inertial measurement unit (MEMS-IMU), a central processing unit, a GSM communication module, an image sensor, and an LED module. The inertial measurement unit acquires information such as acceleration, angular velocity and magnetic strength of the module during the movement of the water flow; GPS module can output precise location information. The position information of the time together completes the acquisition of hydrological information such as groundwater flow velocity and trajectory. The system's loaded image sensor is used to capture the surrounding environment of the groundwater, but due to insufficient groundwater ambient brightness, the LED module can be used to increase the exposure. The central processing unit stores the inertial navigation and the acquired image data in the SD module. When the system leaves the groundwater environment, when the base station signal is received, the central processor triggers the interrupt system, and the GSM communication module sends AT commands [8], and the base station sends the module GPS positioning data to the user's mobile phone, and the buzzer is made. It is convenient for users to recovery equipment to read and calculate relevant hydrological information.

Fig. 3. The diagram of the hydrologic detection unit

3.3 Trajectory solving algorithm flow

The algorithm solution flow is as follows:

1. Preprocessing: GPS signals can be received before the module enters the water. The central processor can automatically correct the zero position error of the IMU unit by using GPS information and related algorithms [9]. During the module's movement with the water flow, the central processor stores the received inertial navigation data, the head and the end position and the received GPS signal into the SD card.

2. Removal of the unsatisfactory state: In the process of groundwater detection, the system may be some unsatisfactory states, which will have a negative impact on the trajectory calculation. The unsatisfactory state in the sensor output data is mostly reflected in sudden change, short-time spikes, and other unstable signals. The processing method is to give the maximum change threshold of the signal before solving the trajectory, and once the change threshold is exceeded, the data should be removed. Because this state is abrupt, it will not have a great impact on trajectory calculation after removal in a short time. Then calibrate the sensor error [10], and the inherent errors of sensors such as constant error and random error should be removed to complete the data preprocessing process.

3. The solution of attitude matrix: The pre-processed sensor data are fused by Kalman [11] algorithm to obtain accurate roll, pitch and heading attitude information. By calculating the output data and removing the gravity acceleration, the combined acceleration of the system can be obtained, and then the acceleration of each axis can be obtained by distributing the acceleration to the three axes of the geographic system.

4. Average velocity solution: When the GPS signal of the first and last position is converted to the geodetic coordinate system, the distance of the first and last position can be obtained, divided by the detection time, the average velocity V_{ave} can be get.

$$V_{ave} = \frac{(S_{end} - S_{begin})}{t} \quad (3)$$

S_{begin} and S_{end} are the begin position and the end position. Based on this average speed, the upper limit is

set of $V_{inferior}$ and lower limit is set of V_{lower} . When the speed of the solution exceeds the upper limit or falls below the lower limit, the speed does not change. In this way, This can avoid the disadvantage that the error of inertial navigation speed calculation is getting bigger and bigger.

5. Head and end trajectory correction: The shape of the detection system can ensure that the heading angle of the system is consistent with the direction of the flow. Taking this as the direction of motion, the velocity and trajectory of water flow can be obtained by integrating the acceleration of each axis. Through the first and last position obtained by GPS signal and the position information obtained during the detection, the corresponding time position can be corrected to the position information obtained by GPS. This method can effectively avoid the disadvantage of inertial navigation position calculation error increasing with time accumulation.

$$\Delta S_x = \frac{S_{GPSend_x} - S_{INERend_x}}{t} \quad (4)$$

$$\Delta S_y = \frac{S_{GPSend_y} - S_{INERend_y}}{t} \quad (5)$$

$$S_{resultx_t} = S_{INERendx_t} + \Delta S_x, \quad (6)$$

$$S_{resulty_t} = S_{INERendy_t} + \Delta S_y \quad (7)$$

ΔS_x and ΔS_y are the correction value of X and Y directions for each time interval; S_{GPSend_x} and S_{GPSend_y} are the end position of X, Y direction obtained by GPS; $S_{INERend_x}$ and $S_{INERend_y}$ are the end position of X direction and the end position of Y direction obtained; $S_{INERendx_t}$ and $S_{INERendy_t}$ are the X, Y direction position of inertial navigation solution at t-Time; $S_{resultx_t}$ and $S_{resulty_t}$ are the corrected positions of X and Y direction at t time respectively.

3.4 Experimental results and analysis

The experiment was carried out using the experimental unit designed in this paper. The experimental site was in the artificial canal of Chaotian Town, Lingchuan County, Guilin City. First, the actual flow direction of the artificial canal is mapped. Then the detector is placed at the starting point of the artificial canal and moves along the direction of water flow to collect data. Finally, the motion trajectory is obtained by calibrating the output data of the detector.

It can be seen from the comparison that the groundwater detection method proposed in this paper can obtain a more accurate trajectory by designing a new device structure, combining the first and last position information, using the reference speed, the first and last trajectory correction, etc., which can provide an important reference for groundwater detection.

Fig. 4. Actual water flow trajectory

Fig. 5. Calculated trajectory map (Arrows show the direction)

4 CONCLUSION

This paper introduces a groundwater detection system based on inertial navigation, which can obtain reliable inertial data. This method has the following distinct advantages over the currently used groundwater flow detection technology:

1. The detection method is low in cost, small in size, light in weight, low in power consumption, easy to integrate, and reduces instrument loss due to the complicated environment of groundwater detection.
2. This detection method has a high degree of autonomy. The inertial system is an autonomous detection system that does not radiate signals and is free from external interference. Compared with other geophysical techniques, the detection is more concise.
3. This detection method has high precision. The detection system adopts the data solving method, and the precision is greatly improved compared with the traditional inertial solution solving method, which provides an important basis for groundwater detection.
4. This detection method can get more hydrological information. By processing the output data, we can get the track of groundwater, the velocity of water flow, and even find the undercurrent and eddy by analyzing the change of water flow. The images obtained in exploration also provide important reference for exploration.
5. This detection method is scalable. The scheme designed in this paper can carry more modules in the future, such as carrying gas sensors such as detecting carbon dioxide and helium, which can obtain more groundwater flow information and provide more help for field exploration.

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