Design of Magnetic Gradient Tensor System for UAV

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Abstract: The detection method based on UAV has attracted more and more scholars' attention. In this paper, the basic principle of gradient tensor is discussed firstly, and then the composition of gradient tensor system and the structure are described. After the length of baseline is determined by simulation, a signal collector based on ARM CortexM3 is designed. Through the collector, 12 channels of signals can be collected synchronously, and RTK time and position information are integrated into each frame. The information after framing is transmitted to the ground station for further processing.

1. Introduction

According to different characteristics, there are two kinds of magnetic detection, total magnetic field detection and magnetic vector detection. Total field detection is relatively easy to implement, but it has inherent shortcomings compared with magnetic vector detection. Such as it contains little information and cannot reflect all the characteristics of the magnetic field. In practice, a base station magnetometer is usually installed to observe the diurnal variation and correct the measured data[1,2,3].

The method based on total field is to make the magnetic target equivalent to a magnetic dipole or a hybrid model. The nonlinear equations are established according to the model, and then solved by various optimization algorithms. This method has a large amount of computation and is not good enough in real-time.

Compared with the total field detection, the magnetic vector contains more characteristic information, which can better analyze the magnetic field information. In recent years, the magnetic gradient tensor based localization method has become a hot spot in the research of magnetic target localization because of its fast positioning speed and high positioning accuracy.

Jia[7] used a single vector magnetometer to locate. Whose method is to obtain the magnetic gradient tensor contained in Eulerian equation by rotation synthesis. The influence of inclination angle, rotation angle and baseline length on the positioning accuracy of magnetic target is analyzed. This provides a reference for the parameter setting of the rotating device. However, the method proposed in this paper is only applicable to situations with low real-time requirements.

Firstly, a cylinder model of three-dimensional body suitable for aeroelastic magnetic detection is established in Ge’s research. The ΔT magnetic anomaly and vertical magnetic gradient anomaly are simulated and compared. Then the background magnetic field interference and physical model experiments are carried out to verify the feasibility and advantages of the magnetic gradient method.

In 1972, Wynn[4] first proposed the idea of locating a magnetic dipole using a single point magnetic gradient tensor, but the analytical solution of the tensor equation was not obtained. Then Frahm obtained the analytical solution of the tensor equation and proposed a complete method of magnetic dipole tensor inversion positioning. Nara et al. have established a concise linear equation system by analyzing the
relationship between magnetic gradient scale, target position vector and target magnetic field three components. The resolution solution of the target position vector was obtained, which improved the positioning method of this class and obtained better results.

The use of magnetometers for target location, which is carried by hand-held, vehicle-mounted, aerial vehicles and other means. Due to the rapid, efficient and safe characteristics of UAV, more and more scholars pay attention to it. In this paper, a specific design method of gradient tensor system is designed, including baseline length simulation design, collector hardware and software design, which has high practical value[5].

2. Overview of gradient tensor methods
The earth is surrounded everywhere by a magnetic field of 30,000 nT to 70,000 nT, and the field consists of three components. The magnetic gradient tensor reflects the change rate of the three components of the magnetic field in each direction of the three-dimensional space, as shown in formula (1).

\[
G = \begin{bmatrix}
\frac{\partial B_x}{\partial x} & \frac{\partial B_x}{\partial y} & \frac{\partial B_x}{\partial z} \\
\frac{\partial B_y}{\partial x} & \frac{\partial B_y}{\partial y} & \frac{\partial B_y}{\partial z} \\
\frac{\partial B_z}{\partial x} & \frac{\partial B_z}{\partial y} & \frac{\partial B_z}{\partial z}
\end{bmatrix} = \begin{bmatrix}
B_{xx} & B_{xy} & B_{xz} \\
B_{yx} & B_{yy} & B_{yz} \\
B_{zx} & B_{zy} & B_{zz}
\end{bmatrix}
\]

(1)

Because the divergence and curl of the magnetic field are both zero in the passive space, only five of the nine components are independent, as shown in equation (2).

\[
\begin{align*}
B_{xy} &= B_{yx} = \frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y} = \frac{\Delta B_y}{\Delta y} \\
B_{yz} &= B_{zy} = \frac{\partial B_z}{\partial y} = \frac{\partial B_y}{\partial z} = \frac{\Delta B_z}{\Delta z} \\
B_{xz} &= B_{zx} = \frac{\partial B_z}{\partial x} = \frac{\partial B_x}{\partial z} = \frac{\Delta B_z}{\Delta z} \\
B_{xx} &= \frac{\partial B_x}{\partial x} = \frac{\Delta B_x}{\Delta x} \\
B_{yy} &= \frac{\partial B_y}{\partial y} = \frac{\Delta B_y}{\Delta y} \\
B_{zz} &= \frac{\partial B_z}{\partial z} = \frac{\Delta B_z}{\Delta z}
\end{align*}
\]

(2)

Where \(\Delta x, \Delta y, \Delta z\) are the distances between the two fluxgate sensors on opposite corners, which is called the baseline length of the gradient tensor system. To solve 5 unknowns in equation (2), five separate equations need to be constructed. Full tensor information is achieved by measurement of Bxx, Bxy(or Byx), Bxz(or Bzx), Byy, Byz(or Bzy).

3. Design of gradient tensor system
3.1. System architecture
As described in the literature[5,6], the cross structure is constructed, as shown in Figure 1.
The tensor system is mainly composed of four 3-axis fluxgate sensors, collector and RTK modules. The whole system is designed to be carried on the UAV and can receive the data of RTK module on the aircraft through serial port. The main purpose is to realize the real-time acquisition of magnetic field information above the flying area by UAV equipped with tensor system. The collector is responsible for fusing RTK position, time and magnetic data and then transmitting them to the ground station. The ground station obtains the target position after data processing.

3.2. Baseline length calculation
Bartington mag648 probe is selected in the system, and then the baseline length is confirmed. The simulation is based on magnetic dipole, assuming that the tensor system is fixed and the magnetic dipole moves.
Taking the center of magnetic dipole as the origin of coordinate system. The scope of the simulation experiment is the area surrounded by the coordinate point (50,-50,10), (50,50,10), (-50,50,10), (-50,-50,10). The plane is divided into several grids with equal area. The grid size is 1m × 1m. Suppose that the magnetic moment of the target magnetic dipole is equal to $M=[20000,10000,30000]$ T·m, and set gaussian noise with standard deviation of 10nT. The baseline length of tensor measurement system is 0.1M, 1M, 2m, 3M and 4m respectively. In Figure 4 (a)(b)(c)(d)(e), the blue point means the successful localization position. The experimental results are shown in (f) of Figure 4.

![Figure 3. The diagram of simulation scheme.](image)

![Figure 4. Localization results of different tensor measurement baseline lengths.](image)
It can be seen from the above figure that the positioning effect first gets better and then worse with the increase of baseline length, and there is an optimal baseline length. The system is mounted on the UAV platform, the baseline is set to 1m and the material is carbon fiber structure.

3.3. Hardware design of collector

3.3.1. Design of main control circuit
The main control chip is stm32F1 series RISC processor of high performance Cortex-M3 from ST Microelectronics company. Whose operating frequency is 72MHz with built-in rich peripherals to meet the needs of multi-purpose applications. The circuit diagram is shown in Figure 5.

![Design of main control circuit](image)

Figure 5. Design of main control circuit.

3.3.2. Peripheral circuit design
The peripheral circuit includes indicator circuit, Usb-232 communication isolation circuit, EEprom circuit, TF card circuit, RS-232 isolation interface circuit, TTL isolation interface circuit. The peripheral circuit design is shown in Figure 6.

Usb-232 communication isolation circuit, is mainly composed of ch340t, a production of Nanjing Qinheng Microelectronics Co., Ltd., and peripheral isolation circuit. The main function of which is data communication and debugging output information.EEprom circuit is usually used in data transmission, remote communication, PC and military system industry. The function of this design is to save the calibration information of sensors when power is shut down.TF card circuit ensures real-time and reliable data storage.RS-232 isolation interface circuit converts TTL level of arm to RS232 level for communication.
3.3.3. Power circuit

The power supply includes DC buck circuit, MCU power supply circuit, sensor power supply circuit and AD power supply circuit. The overall circuit design of the power supply is shown in Figure 7.

DCDC buck circuit realizes the conversion from high voltage to low voltage, which ensures the high reliability and high efficiency of the power supply. The power supply circuit of MCU can provide a stable current of 500mA, which ensures the stable operation of MCU for a long time.

The sensor power supply circuit has the characteristics of low noise, which ensures that the noise output of the sensor is at a low level.
The ad circuit consists of high precision reference circuit and ad analog circuit. Figure 7 is one of the AD designs.

The high precision reference circuit is composed of adr4530 high precision voltage reference chip of ADI company, whose output noise (0.1 Hz to 10 Hz) is less than 1μV p-p, initial output voltage error is ± 0.02% (maximum value). It is mainly used in high precision measurement, precision data acquisition system and other occasions. Then the buffer voltage is sent to the reference input of 12 channels ad through ada4522-2 chip to ensure the high accuracy and low noise of AD acquisition.

Ad analog circuit adopts ADI's 24bit high-precision ad7175-2 chip, which has the characteristics of 24 bit noiseless resolution.

3.4. Software workflow

The workflow of the software is shown in Figure 9.

![Software flow chart](image)

**Figure 8. AD circuit design (1 channel).**

**Figure 9. Software flow chart.**
The software processing flow is as follows:

- **Power on initialization operation**, including RTK serial port, debug serial port, data transmission serial port and TF card.
- **After initialization**, it will wait for RTK to return data. If data returns, it indicates that RTK is working normally. Otherwise, it will skip into no RTK mode.
- **After that**, wait for the RTK signal to trigger, and each time the ad data is triggered, 12 channels of data will be collected, then Upload data through RS232, if TF Card exists, the data will be written to TF card. The AD processing module has a synchronous trigger function, and the main control uses GPS return signal to trigger the acquisition function of 12 ADs to achieve the purpose of synchronous acquisition.
- **Debug serial port 1** will be in the mode of waiting for interrupt, and it will work only after receiving external data. This interface is used to write parameters and debug data.

### 4. Conclusion

According to the needs of Engineering practice, a set of magnetic gradient tensor positioning system equipped by UAV is designed. It mainly includes the baseline length simulation of the tensor system and the design of the collector. Tensor signals are collected, which combine RTK position and time information. The data is transmitted to the MESH module by serial port, and then transferred to the ground station for algorithmic positioning.

### References

[1] Jian G, Lu C, Dong H, et al. The detection technology of near-surface UXO based on magnetic gradient method and Overhauser sensor[J]. Chinese Journal of Scientific Instrument, 2015, 36(5):961-974.

[2] Chi C, Ren J, Junwei L, et al. Linear Localization Method Based on Magnetic Gradient Tensor of Multi-points. Journal of Detection & Control, 2017.

[3] Dai Z, Zhou S, Shan S. A Localization Method of Two-point Magnetic Gradient Tensor. Journal of Detection & Control, 2018.

[4] Wynn W M, Frahm C P, Carroll P J, et al. Advanced superconducting gradiometer/Magnetometer arrays and a novel signal processing technique[J]. Magnetics IEEE Transactions on, 1975, 11(2):701-707.

[5] Dou Z Y, Research on Key Technology of Horizontal Magnetic Gradient Measurement for Optical Pump Based on Rotor UAV[D], Jilin University,2018.

[6] Liu L M, Configuration Design, Error Analysis and Underwater Target Detection of Fluxgate Tensor Magnetometer[D], Jilin University, 2012.

[7] Jia W D, et al. Research on Magnetic Target Location Method Baseed on a Single Magnetic Gradiometer[J], ACTA ARMAMENTARII, 2017.

[8] Ge J, et al. The detection technology of near-surface UXO based on magnetic gradient method and Overhauser sensor[J]. Chinese Journal of Scientific Instrument, 2015.