Tailored Drone-Magnetometer Design for Geothermal Exploration

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ABSTRACT

Geothermal fields, often nestled in mountainous regions with challenging topography and dense vegetation, can be difficult to access for direct ground measurements. To overcome these obstacles, the magnetic method offers a viable geophysical approach for geothermal exploration. Leveraging advanced technology, Unmanned Aerial Vehicles (UAVs) equipped with magnetometers can provide faster than land magnetometer, more accurate with high sensor accuracy, and efficient magnetic mapping use flight control tracking, making them an invaluable tool for achieving operational targets. This article presents the design of a drone magnetometer using a custom-built UAV for magnetic mapping in geothermal fields. This method validated by acquisition in the same place and time with land magnetometer, have a same pattern anomaly. The UAV is specifically designed with a large payload capacity (6-8 kg) and extended flight duration (>60 minutes). It is equipped with a 3-Axis Fluxgate Magnetometer FGM3D/100 from Sensys, which has a measurement range of ±100 µT. The designed system was validated using a PPM scalar magnetometer from GEOTRON, with highly satisfactory results, suggesting it is well-suited for practical geomagnetic mapping in geothermal fields.

Keywords— Drone, Geomagnetic, Geophysics, Geothermal, Magnetometer

INTRODUCTION

One of the significant challenges in geophysical measurements for geothermal exploration is the difficult terrain, particularly in mountainous regions with dense vegetation. Traditional geomagnetic measurements commonly used in geothermal exploration can be hindered by such landscapes when conducted on the ground. Therefore, utilizing drones for these measurements offers a more efficient, cost-effective, and rapid solution.

To address these challenges, the development and application of innovative methods or technologies are essential to make geothermal field exploration and development more cost-effective. One promising approach is the use of Unmanned Aerial Vehicles (UAVs). UAVs offer numerous advantages in geothermal exploration, such as being equipped with video recorders/cameras, GPS, and other advanced components. They enhance the efficiency of field research by enabling geophysical data acquisition in areas with extreme topography and dense vegetation, speeding up the process, and significantly reducing operational costs.

One widely used technique in geothermal exploration is geomagnetic surveying, which employs magnetic sensors that can be carried by drones. In practice, a magnetic sensor is mounted on a drone, allowing operators to conduct surveys remotely. The drone measures magnetic variations across the Earth's surface, following a grid pattern at specific altitudes and line intervals, which are crucial for determining the resolution of the collected data.

According to Zheng et al. (2021), multi-rotor UAVs, despite being the latest type of UAV are the most commonly used for magnetic UAV surveys. Their popularity stems from several advantages: they are relatively inexpensive, making them accessible for researchers conducting geophysical exploration in remote regions.

Additionally, their capability for automatic flight simplifies the execution of magnetic surveys in remote areas.

Magnetic UAV surveys involve the installation of a magnetometer sensor to detect anomalies in the Earth's magnetic field. The magnetometers utilized in these surveys are classified into two types: vector and scalar magnetometers. Scalar magnetometers are simpler and measure just the intensity of the magnetic field, useful for broad regional surveys where direction is less important. Vector magnetometers measure the three components of the magnetic field, providing more detailed data for directional analysis and precise mapping of magnetic anomalies. Both types offer similar accuracy in data acquisition; however, vector magnetometers stand out due to their lighter weight and lower power consumption compared to scalar magnetometers. Additionally, vector magnetometers are more affordable, making them accessible to a wider range of researchers (Gavazzi et al., 2020).

Magnetic interference, or noise, remains a significant challenge in utilizing UAVs for geophysical surveys. In fixed-wing UAVs, the primary sources of magnetic noise stem from engines, servos, and other ferromagnetic components (Forrester et al., 2013; Yoo et al., 2021). This interference can create quadrupole or dipole effects (Kaneko et al., 2011; Tuck et al., 2021).

To mitigate magnetic interference, two main approaches can be employed for acquisition magnetic methode use UAV: suspending the magnetometer beneath the UAV on a rope of at least 3 meters or mounting it rigidly to the UAV frame using a rod (Jiang et al., 2020). Additionally, minimizing the magnetic signature of the UAV platform itself is crucial, which can be achieved by replacing ferromagnetic components and shortening DC cables (Sterligov et al., 2016). Another effective method is to install the magnetometer at the wingtips of the aircraft to further reduce minor magnetic noise.

For small multi-rotor UAVs, ferromagnetic components can induce a magnetic dipole effect (Cherkasov et al., 2018; Parvar et al., 2016). Research by Cunningham et al. (2018), Schmidt et al. (2020), Shahsavani et al. (2021), and Kaneko et al. (2011) demonstrates that interference from multi-rotor UAVs on magnetic sensors can be analyzed through data recorded at varying distances from the UAV, both in the time and frequency domains. multi-rotor UAV interference impacts magnetometer readings by introducing local magnetic fields from the drone’s components, which vary dynamically during flight. These interference sources, combined with the movement of the UAV itself, make it challenging to interpret magnetic data accurately during maneuvers. By understanding the sources of interference and employing strategies such as calibration, shielding, and optimized flight paths, it’s possible to reduce these effects and improve the accuracy of drone-based geomagnetic surveys. However, the interference characteristics during multi-rotor maneuvers remain unclear, as most studies have focused on static conditions. Various methods for mounting magnetometer sensors on UAVs, including adjusting distances and assembly modes, have been explored in several studies to minimize these interference effects.

DRONE-MAGNETOMETER DESIGN

A custom-built hexacopter UAV will be used as a magnetometer rover. This UAV, with a substantial payload capacity of 6-8 kg, will be equipped with a fluxgate vector magnetometer sensor. The magnetic sensor and data acquisition system are designed for easy attachment and removal from the drone's landing gear. The rover is equipped with two triple-axis (X,Y,Z) fluxgate magnetometer sensors, each with a range of ±100μT. These sensors are positioned parallel to each other, spaced 1 meter apart. The sensor output is an analog voltage ranging from ±10 V.

The analog voltage is routed to the signal conditioning module, which includes ESD protection and a zero-drift operational amplifier that buffers the sensor signals. The output from this operational amplifier then enters a summing circuit, which incorporates an offset circuit with a range of ±10 V. This offset helps shift the magnetic baseline closer to 0 V, allowing magnetic anomalies to be amplified with a higher gain.

The output from the summing circuit is fed into a low-pass anti-aliasing filter with a zero-drift amplifier, featuring a cutoff frequency of 1 kHz (adjustable as needed). This filter helps to eliminate noise from the surrounding environment, including interference from the drone's brushless motors. The filtered signal is then routed to the Data Acquisition Module, where it is digitized and stored for subsequent analysis. This version provides more technical clarity by indicating that the signal is digitized and stored, which is typical in many data acquisition systems, where it first passes through an analog multiplexer before reaching a 24-bit ΣΔ ADC.

The digital data is subsequently processed by a 32-bit microcontroller. This micro-controller integrates the digital ADC data with information from the RTC (Real-Time Clock) and other relevant data, formatting it into a specific data structure. The formatted data is then stored on a µSDHC card on the board and can also be transmitted directly to a host PC via WiFi, USB 2.0, or TCP-IP through an Ethernet port.

The data acquisition section also features a 12-bit DAC that adjusts the offset value within the signal conditioning module. Power for the magnetic sensors, signal conditioning modules, and data acquisition modules is supplied by a power supply module, which includes circuits for voltage reduction (buck), voltage increase (boost), and inversion, along with low-noise linear regulators. This module outputs 5V and ±15V, with expected voltage noise below 100µV.

The power supply module accepts input voltages ranging from 7 to 14 V, allowing it to directly utilize the Lithium-Ion batteries (2S and 3S) on the rover module as well as the 12V battery or power supply on the base station. This configuration ideal because fit for batteies health and endurance acquisition. The system will use prismatic Lithium-Ion batteries with a minimum capacity of 3000 mAh, supporting both 2S (7.4V) and 3S (11.1V) configurations, and will be optimized for weight efficiency across the entire system. The DAQ electronic system, both for rover and base station, is composed of five system blocks, namely Fluxgate Sensor, PSU Modular Block, AFE Modular Block, DAQ Module, and Single Board Computer.

The rover design features fluxgate sensors mounted on both the right and left sides of the data logger, with a total length of approximately one meter. Positioning the sensors on either side enhances data accuracy and helps maintain the drone's balance during flight, preventing stalling. The mechanical and electronic systems of the rover are engineered to be as lightweight as possible, optimizing flight time.

The magnetic sensor employed is a 3-Axis Fluxgate Magnetometer FGM3D/100 from Sensys, featuring impressive specifications. It offers a measurement range of ±100µT, a frequency range of 0-4 kHz, and exceptionally low noise between >10pT and <20pT (standard). The compact body is made of POM (Polyacetal) with dimensions of 26×26×140 mm and a 12-pin connector.

We use a custom-assembled drone to carry the magnetometer for geomagnetic mapping in geothermal fields, which are generally expansive, hilly, and subject to strong winds and occasional turbulence. Therefore, the drone requires specific capabilities: a substantial payload capacity for enhanced stability, the ability to withstand high winds, and an extended flight duration to cover large areas in a single mission. To meet these demands, we built a hexacopter with a payload capacity of 6-8 kg and a flight time exceeding 60 minutes per flight. This payload and flight duration have a good performance and ideal to acquisition for geothermal field compared to other equipment. Positioning is achieved using RTK GPS. The drone’s configuration with the magnetometer can be seen in the Figure 1.

Fig. 1 Configuration of the drone magnetometer

TESTING AND VALIDATION

The magnetic sensors for rover (SENSYS-1 and SENSYS-2) and for base station (SENSYS-3) were validated by comparing data from the GEOTRON ground magnetic sensors (PPM-1 and PPM-2). Both sensor systems recorded data simultaneously at the same stationary location, enabling a direct comparative analysis of their respective magnetic data curves.

Figure 2 presents the results of the daily variation test, with curves displayed in blue, orange, gray, yellow, and green. The blue curve corresponds to data from PPM-1 dan the orange from PPM-2, these two sensors will be installed on land magnetometers for validated respons actual. The gray from SENSYS-1, the yellow from SENSYS-2, and the green from SENSYS-3 these three sensors will be installed on the drone magnetometer. All sensors show responses within the 100 nT range, suggesting minimal magnetic noise at the test site, this indicates acceptable noise levels or the actual magnetic variation. This confirms the reliable performance of the Sensys sensors, as the observed value fluctuations are consistent with previous tests in areas with higher magnetic interference.

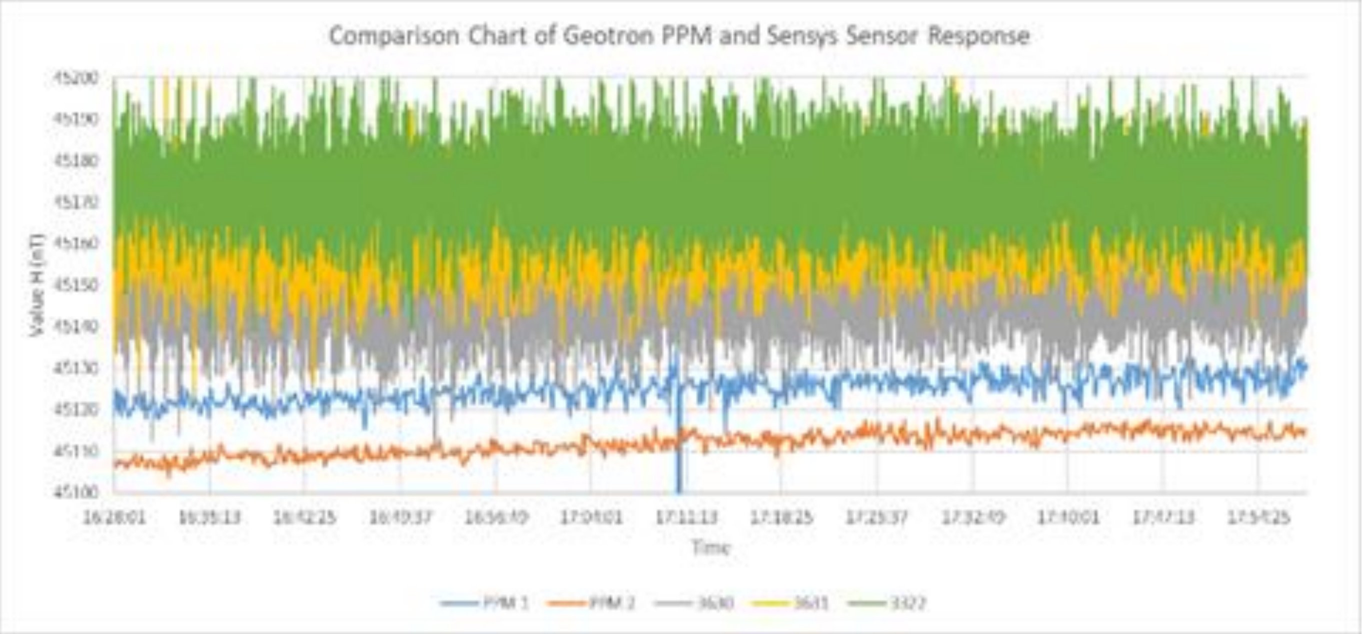

Fig. 2 Daily variation of the sensys sensor and the ground magnetic sensor (PPM).

The subsequent test involved flying the drone at azimuth angles of 90° and 0°. For each flight, the drone was flown at prede-termined altitudes of 5, 10, 15, 20, 30, 40, and 50 meters to monitor sensor responses. Each flight lasted 1 minute, enabling the assessment of sensor performance at different altitudes. Figure 3 (a) shows data with the drone oriented at an azimuth of 90° to the East, while Figure 3 (b) presents data with the drone oriented at an azimuth of 0° to the North. These specific azimuths were chosen for the tests because to align with the poles. Takeoff effects are correlated by sensor height to object in surface.

In Figure 3 (a), a sharp initial decrease in value is observed, likely due to the drone's takeoff, as the rover sensor moves away from a nearby magnetic anomaly. As the drone ascends, the sensor readings stabilize, suggesting that higher altitudes help reduce magnetic noise in the measurement area. In Figure 3 (b), the curve initially shows a rise, corresponding to the drone’s shift in orientation from East to North, while maintaining a constant altitude of 50 meters. The changes in magnetic readings based on orientation and altitude effected by magnetic object in surface. The closer or towards the magnetic object, the greater the magnetic value that will be read. The data reveal a consistent trend, with the sensor registering higher values when the drone is aligned along the East-West axis compared to the North-South alignment.

Consequently, it is crucial to standardize the sensor's orientation and maintain a consistent flight direction for the drone. While the sensor’s response to altitude changes remains consistent, regardless of whether the drone is facing East, the recorded values shift due to variations in sensor alignment.

Fig. 3 Altitude variation testing with drone face azimuth (a) 90° East and (b) 0° North.

CONCLUSION

The Customized Drone-Magnetometer offers an effective solution for magnetic mapping in areas with challenging access. By leveraging UAV technology, after being tested and compared with land magnetometer sensors, this system has the same pattern and high sensitivity, making it faster than land magnetometer, more accurate, and effective mapping using remote flight control. It is particularly well-suited for identifying magnetic anomalies in geothermal fields for areas of dense vegetation and extreme mountainous topography.

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