DEVELOPMENT OF A MAGNETOMETRY SYSTEM FOR AN UNDERWATER GLIDER

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Abstract

The development of a magnetometry system for an underwater glider is detailed in this paper. The system is designed for low noise, low sampling rates and high accuracy measurements. The integration progress into a 200 m Slocum Electric glider is presented in addition to an evaluation of the electrical and system noise levels. A calibration algorithm is evaluated for correcting sensor errors as well as hard and soft magnetic effects due to the glider.

Introduction

The use of magnetic measurements as a heading reference for navigation in underwater vehicles has been well established [1]. In recent work earth magnetic information has also been suggested for possible use in total-field map based relative navigation techniques [2, 3]. Geomagnetic data is also used by geophysicists for resource mapping and seafloor process modelling. The sensors are typically towed at a constant depth behind a surface vessel but the usability of underwater vehicles has also been successfully demonstrated [4].

To facilitate mapping and navigation using magnetic data a magnetometry system is being developed for use with a Slocum Electric underwater glider. The main objectives for the design of the system are that it will be accurate enough to be used for geophysical surveying, very low power to minimize the impact on the glider’s endurance, and provide information which can be used to develop new low power, surface independent navigation algorithms.

The chosen sensor is the low power tri-axial Mag-648 fluxgate magnetometer by Bartington® Instruments with power requirements on the order of tens of milliwatts [5]. Low power fluxgates of this type are often subject to higher degrees of noise, orthogonality errors, and offset errors than those with higher power coils. While noise is mitigated through low frequency sampling requirements, the orthogonality errors and offset errors require calibration.

This paper outlines the system configuration and layout. Specifically, the necessary modifications to a standard Slocum electric glider are described in greater detail. The magnetic sensor system and data-acquisition system is presented and described with respect to the electrical noise and sampling. A recently published calibration algorithm based on a geometric fit to an ellipsoid [6] is applied to a first set of data collected with the sensor separate from the glider. The initial results are shown and discussed.

System Design

The preliminary design has the sensor mounted at one of the wing tips of the glider, see Fig. 1, to remove it from some of the magnetic effects of the vehicle. For this purpose, new wings are designed .
with a high degree of stiffness as well as room for internal wiring. These wings are a swept NACA 0012 foil shape, with a planform similar to the existing glider wings, with mounting arrangements for the sensor payload at the tip and a faired mounting bracket at the root. The general arrangement of the system is shown in Fig. 1. A NACA section was selected for stiffness and for better lift characteristics over flat plate wings. The polar plots for several NACA foil sections as well as a flat plate foil are computed using XFOIL and shown in Fig. 2 for a Reynolds number of 30000.

These plots suggest a delayed stall angle and a higher lift to drag ratio for the NACA 0012 over the flat plate and lower aspect ratio foils. The performance here has yet to be verified by experimental data and will likely be less than ideal due to the difficulties of modelling low Reynolds number flow in XFOIL and the additional disturbances at the tip and root.

The fluxgate sensor is to be mounted in a strap-down configuration and initial data collection will focus on the total field data. Further developments will focus on providing vector field measurements in the inertial frame. This task is made challenging through the lack of non-magnetic precision yaw sensors which fit within the glider’s power budget.

Even with the measurements rotated into the inertial frame secular drift of the earth’s magnetic field can create uncertainty in the measurement. To mitigate the effect of secular drift a base station is often used in surveying and the data corrected afterwards.

Another method of dealing with secular drift is to use gradiometric measurements. Gradiometry makes use of the difference between spatially separated measurements. These differences may be pieced together to form a picture of the whole field.
based on initial readings. If the rate of secular variation is much lower than the speed of the vehicle then the motion of the vehicle may be used to form spatially separate values.

The magnetic sensor selected is the $\pm 100\mu T$ low noise Mag-648 by Bartington® Instruments. The sensor is a tri-axial fluxgate sensor with a power consumption of 14 mW and a noise floor of 0.01 nTrms/$\sqrt{Hz}$. Other sensors considered included total field sensors and micro-electromechanical systems (MEMS) sensors. The total field sensors require more power than fluxgate sensors but meet the accuracy requirements. MEMS sensors fall within the power requirements but fall short in accuracy. An interesting upcoming development is the chip scale atomic magnetometer (CSAM) based on the Cesium vapour cell developed at National Institute for Standards and Technology for the chip scale atomic clock program [7]. The CSAM has the potential to be ultra-low power and accurate and is currently in the commercialisation stages.

The differential output voltages of the sensor are read by the 24-bit AD7794 sigma-delta analog to digital converter (ADC). This ADC uses several different internal low pass filters and modifies the filter coefficients based on the sampling rate selected. The effective resolution of the device is therefore variable with the sampling rate. The inputs to the ADC have anti-aliasing filters with a corner frequency of 80 Hz. The ADC uses the serial peripheral interface (SPI) to communicate with the Glider Science computer, the Persistor CF1. To prevent noise from crossing across the signal, power and ground lines the SPI lines are isolated using the ADuM2401 digital isolator and the ADC and fluxgate power is supplied from 3 AA lithium primary cells. The voltage from these cells is brought down to the 3.5 V digital rail using a precision linear regulator with a drop out voltage of 3.55 V. The fluxgate also draws its power from the 3.5 V digital rail. A precision 3.3 V reference supplies the analog reference voltage for the ADC. The electrical system diagram is shown in Fig. 3.

**Figure 3 Electrical system diagram**

The supply requirements for the ADC side when the fluxgate is also connected are 4.5 mA. The lithium primary cells have 3300 mAh of energy resulting in a sensor endurance of 30.5 days. This endurance is approximately the same as that of the Slocum glider running on the standard 2.1 kWhr alkaline cells.

**System Characterisation**

The system is characterised through analysing the noise performance of the data acquisition and signal conditioning electronics with and without the fluxgate sensor connected. The ADC is configured in a bipolar arrangement with a reference voltage of 3.3 V resulting in a least significant bit resolution of 0.3934 $\mu V$. In reality the achievable resolution is somewhat higher than this. To determine the achievable resolution the noise levels are characterised first by short circuiting the differential inputs of each analog input channel on the ADC to ground. This test is performed for update rates of 4.16 Hz, 9.8 Hz, 16.6 Hz and 31 Hz for a single channel corresponding to roughly 1, 3, 5 and 10 Hz for all three channels. The root mean square (RMS) and peak to peak (P-P) electrical noise on channels one two and three on 5 minutes of recording is shown in Fig. 4.
Figure 4 Short circuit noise results for the ADC

Since the sensor’s range is 200 μT and the reference voltage of the ADC is 3.3 V, there are 16.5 μV/nT. The expected sensitivity of the ADC coupled with the fluxgate sensor is shown in Fig. 5. The expected noise levels from Fig. 5 match well to the published noise levels of the fluxgate sensor of 0.01 nTrms/√Hz.

The noise when the fluxgate sensor is connected may also be characterized in a similar manner. For the magnetic noise the sensor is left stationary on the bench in the lab and 5 minutes of data recorded. A sample of the raw data from the 3 Hz data set is shown in Fig. 6.

Figure 6 Raw magnetic data at 3 Hz recorded on lab bench

The data is de-trended to remove the effects of the secular drift and any nearby disturbances using a least squares fit to a 6th order polynomial. The de-trended data from the 3 Hz data set is shown in Fig. 7. The de-trended data shows a high random noise in the X axis while low random noise but slight persistent changes in the Z axis. All three axes show higher P-P noise than the expected 0.3 nT and it remains to be seen if this is purely environmental noise.

Figure 7 De-trended magnetic data at 3 Hz showing noise levels on lab bench

The P-P and RMS noise from all the lab bench tests with the fluxgate connected are shown in Fig. 8. These tests show higher RMS and P-P magnetic...
noise than the expected resolution shown in Fig. 5 and it remains to be seen if this is due to process or system noise.

![Figure 8 Magnetic noise during lab bench tests as function of the sampling frequency](image)

**System Calibration**

The system must be calibrated to account for the influences of the glider on the measured magnetic field as well as the imperfections of the sensor. The factors affecting the magnetic field due to the glider may be broadly categorized into three main areas of hard, soft and induced magnetic effects. Hard magnetic effects arise due to ferrous materials which have become magnetized, resulting in their own magnetic field distorting the main field. Soft magnetic effects are a result of ferrous materials distorting the main field due to significant decrease in reluctance versus air; the field is therefore concentrated more in the soft ferrous materials. Induced magnetic effects are a result of electric currents passing through nearby conductors, creating magnetic fields which distort the main field.

Test data using a previously integrated inertial measurement unit (IMU), which also employs a three axis MEMS magnetometer, have shown that during steady state manoeuvres the glider exhibits low levels of induced magnetic interference. The hard and soft magnetic effects are primarily due to the vehicles batteries and actuation systems and are always present. These effects must be accounted for in the calibration algorithm.

The sensor itself also presents some errors which must be calibrated out. These errors include the zero offset error which presents itself as a static offset in the output voltage after the device has been turned on. This offset voltage can change during the sensor being turned off and on, requiring the sensor to be calibrated after it is turned on and have remain on for the duration of the measurements. Additional sources of error are the non-orthogonality of the sensor axis with respect to each other; the scaling error of each sensing axis; the linearity error over the full measurement range; the hysteresis of each sensing axis and errors due to temperature variations.

A recent publication has proposed a method to address the sensor errors as well as the hard and soft magnetic effects based on a geometric approach. The algorithm is based around the idea that in a perfectly calibrated system all of the measurements plotted in three dimensions and normalized to the magnitude would be on the surface of a unit sphere centered at the origin. In reality, due to the sensor errors, hard and soft magnetic effects, the measurements are on the surface of an ellipsoid which is the translated, scaled and rotated version of the perfectly calibrated unit sphere. The task of calibrating the system then becomes determining the coefficients for the rotation, scaling and translation matrices which transform the data back to the unit sphere centered at the origin.

The proposed algorithm uses a least squares estimate of the ellipsoid, fit to the data as the initial conditions for a maximum likelihood estimator which optimizes the estimate of the ellipsoid. An initial attempt at a calibration of the system using this method was done in the lab. The raw results plotted against a sphere with radius equal to the mean of the magnitude of the measurements are
shown in Fig. 9 with the error between the measurements and the magnitude in Fig. 10.

Figure 9 Data against a sphere with radius equal to the mean of the magnitude

Figure 10 Error between the measurements and the mean of the magnitude

The data roughly lies around the sphere shown in Fig. 9. The large errors shown in Fig. 10 are partially due to the sensor being uncalibrated for the environment and partially due to the sensor not remaining in a constant field. The calibration algorithm was run and was found to converge for the data set shown in Fig. 9. The raw data is shown plotted against the calibration ellipsoid in Fig. 11.

The data actually shows a worse fit to the calibration ellipsoid than the sphere in Fig. 9. This discrepancy is thought to be due to the center of the sensor being moved through different spatial locations which have a significantly different magnetic field. The degree of this difference was seen on the bench as a shift of several centimeters caused the measured field in each axis to be different by up to several thousand nano-Teslas. Additionally, the limited number of data points over large portions of the data space create difficulties in finding a global solution to the maximum likelihood estimation process.

Figure 11 Data against the calibration ellipsoid

Figure 12 Error between the data and the surface of the sphere or ellipsoid normalized to the mean of the magnitude
Conclusion
The development of a magnetometry system for a Slocum Electric underwater glider has been presented. The general arrangement is shown with the sensor located at the tips of the wings. The wings are custom built NACA0012 swept foils with allocations for the sensor mounting at the tip, a faired attachment at the root and internal space for cables to the sensor.

The selected sensor, the Mag648, has a noise floor of 0.01 nTrms/√Hz. The data acquisition and signal conditioning circuitry are shown to match the sensor noise well with a resolution of 0.025nTrms at 1 Hz and increasing with higher sampling rates. The system is capable of logging data at rates of up to 10 Hz. The noise when the sensor is integrated with the data acquisition electronics and tested in the lab is shown to be higher than expected. This is thought to be a result of the process noise and not the system noise.

A calibration process based on a least squares estimate an ellipsoid fit to the data from the sensor rotated in a constant field is evaluated. The algorithm is found to converge but so far has not been found to improve the quality of the data due to a highly spatially variant magnetic field within the lab. Further calibration testing is ongoing to find a site with a more uniform field and to spread the sampling more evenly over the data space. Once the calibration process is verified the system will be assembled into the glider. The calibration of the system while installed on the glider will be the next priority followed by initial field tests.

References