Small, Low Power, High Performance Magnetometers

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Summary

Recent work by Geometrics, along with partners at the U.S. National Institute of Standards and Technology (NIST) and Sandia National Laboratories, has shown the feasibility of producing total field magnetometers the size of a grain of rice (0.1cc) and consuming less than 100mW of power. This work has generated a great deal of interest, since it promises to greatly increase the types and number of applications for which magnetometers may be used. This paper will present recent progress towards commercializing such Micro-Fabricated Atomic Magnetometers (MFAM), along with several applications where they may be used.

We will first present some background in the use and operation of magnetometer sensors and their principles of operation. Then we will introduce our recent work, and present the results of performance measurements. Next, we will identify the design and performance issues that may be addressed, as well as the range of commercial products that are being developed. Finally, exciting applications made possible by this new technology will be discussed.

Introduction

Atomic magnetometers are a type of total field magnetometer. Total field magnetometers measure the magnitude of the magnetic field while vector magnetometers measure the x-y-z components of the magnetic field. Vector magnetometers often suffer from high noise levels caused by sensor motion and vibration. In contrast, total field magnetometers give readings that are largely insensitive to orientation and vibration. Therefore, total field magnetometers are widely used in geophysical and object search surveys where the sensor is in rapid motion. Applications include oil and mineral exploration, unexploded ordnance (UXO) detection and discrimination, Improvised Explosive Device (IED) detection, vehicle detection, and unattended ground sensors (UGS).

Commercial magnetometers such as the Geometrics G-858 or G-822 are large and bulky. The sensor itself is about 350 cc, while the electronics are contained in a housing about twice that size. Together, they consume about 15 – 20 watts of power. This requires a bulky set of batteries. Sensitivity is about 1 pT per root Hz, and their bandwidth is up to 1 kHz. Such sensors typically are operated at an output data rate of 10 to 100 Hz.

Systems based on chip scale sensors, on the other hand, can have a power consumption of a few hundred mW, can have a sensor about 0.1cc in size, and could have an electronics board of only a few square inches. Sensitivity can be about 5 pT per root Hz up to about 100 Hz. Wide bandwidths are achievable up to about 15 kHz.

In order to better understand the design tradeoffs and the commercialization steps towards those goals, it is useful to first review the principle of operation of atomic magnetometers in general.
Methodology

Atomic magnetometers operate by measuring the precession frequency of a large number of atoms in a magnetic field. The precession frequency is proportional to the background magnetic field and, therefore, provides a convenient method of measuring the magnitude of that field. Since frequency is an easy quantity to measure to very high precisions, this allows for the great sensitivity of atomic magnetometers.

The basic elements of an atomic magnetometer are shown in Figure 1. A light source is required to generate light of the correct frequency. Existing commercial sensors use a Cs discharge lamp, as this is the simplest way to produce light of the proper frequency to be absorbed by the Cs atoms in the cell. Shining light through the cell polarizes the Cs atoms there in a process known as optical pumping. Once polarized, the atoms precess about the magnetic field at a characteristic frequency. This precession modulates the intensity of the light passing through the cell, which is detected in a photocell. The magnetic field is proportional to the frequency of this signal.

In order to reduce the power consumption, the Cs discharge lamp was replaced by a laser diode. This alone reduces the power consumption by one-third. Further reductions in power consumption come by reducing the size of the Cs cell. Since the cell is operated at 50-70 degrees C, considerable power is lost due to heat dissipation. Reducing the size of the cell correspondingly reduces the power consumption. Finally, we researched several methods of signal interrogation, characterizing each in terms of desired performance parameters.

Geometrics further developed the capability to model the performance of a magnetometer based on many design parameters. There are several key performance considerations, including sensitivity, power consumption, heading error, dead zones, bandwidth, size and cost. The design parameters we may use to make tradeoffs between these performance considerations are optical ray paths, light beam geometry, method of precession measurement, cell size, buffer gas pressure, operating temperature, and method of feedback. This provides a rich ability to tailor the performance of a sensor to the particular application for which it is desired.

Figure 2 shows the two curves indicating the dependence of sensitivity and bandwidth on cell temperature. Increasing the cell temperature increases the vapor pressure Cs, creating a greater density of Cs gas in the cell. The larger number of atoms present increases the signal and, hence, the sensitivity. The increasing density also increases the collision rate of the Cs atoms with each other,
which reduces the relaxation time of the spin polarization. This effect increases the bandwidth of the sensor.

This also increases the optical depth of the cell, by increasing the rate at which the light beam is absorbed. This tends to decrease the sensitivity of the system. By switching from the traditional absorption method of interrogation to a polarization rotation method, additional sensitivity is gained, offsetting the reduction due to the extra absorption.

![Figure 2. Sensitivity and bandwidth vs cell temperature and interrogation method](image)

**Applications**

In order to determine the source of a magnetic field anomaly, the magnetic field must be measured over a region of space appropriate for the particular target being located. For UXO applications, the goal is to calculate a dipole source which best produces the observed anomalous magnetic field. This process, shown in Figure 3, occurs after the data is collected and mapped. This several-step process is necessitated because of the previous impossibility of fielding a large enough number of sensors to gather data over the required region all at once.

![Figure 3. Traditional approach to anomaly analysis](image)
However, we may now deploy a reasonably-sized array, as shown in Figure 4. This array of nine sensors creates a 2-D anomaly map 10 times per second. The dipole matching algorithms currently used to analyze total field magnetometer data may be efficiently programmed to run in real time. This allows the user to see a real-time sequence of complete snapshots of the target properties, much like a movie. With a linear array, or even worse a single sensor, the user must settle for the results of a slowly scanned image, somewhat like the operation of a fax machine.

Detecting possible intruders either on surface craft or underwater is of considerable interest for protecting harbors and their related infrastructure. Low power sensors may be deployed in greater numbers to allow for complete coverage of harbor entrances. MFAM sensors have the sensitivity and bandwidth required for detecting and locating intruders. When combined with other sensing methods, such as acoustics, magnetometers may significantly reduce false alarm rates associated with those sensors.

![Figure 4. Possible applications of low power sensors](image)

This capability is the result of advances on four key technology areas, and shown in Figure 5. On the sensing side, we are taking existing large, bulky sensors, and replacing them with low power, miniature sensors of the same sensitivity. On the electronics side, we are taking large printed circuit boards and converting them to small integrated circuits. On the array design, we are moving from linear arrays used in the past to scan over a region, and using 2-dimensional arrays to provide a series of complete pictures of the target of interest. Finally, we are converting existing algorithms used only in post processing of data in order to utilize them in real-time to provide an immediate indication of the properties and location of the target.
References