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MEASUREMENT OF MAGNETIC FIELD USING SYSTEM-ON-CHIP SENSORS*

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Abstract

Magnetic sensors have been developed utilizing various physical phenomena such as Electromagnetic Induction, Hall Effect, Tunnel Magnetoresistance (TMR), Giant Magnetoresistance (GMR), Anisotropic Magnetoresistance (AMR) and Giant Magnetoimpedance (GMI). The compatibility of solid-state magnetic sensors with complementary metal-oxide-semiconductor (CMOS) fabrication processes makes it feasible to achieve integration of sensor with sensing and computing circuitry at the same time, resulting in systems on chip. We discuss cost-effective multi-channel applications of AMR, TMR and Hall effect integrated sensors for precise measurements of 3D static magnetic fields in wide range of magnitudes from 10^{-6} T to 0.2 T and for pulsed magnetic fields up to 0.2 T.

INTRODUCTION

Rapid grow of development and production of system-on-chip magnetic field sensors started in around 2010, driven by demand in consumer electronics and automotive industry. The commercially-available system-on-chip 3-axis magnetic sensors (smart sensors) are very compact multi-chip modules designed for low to medium field magnetic sensing with a digital interface for applications such as low-cost compassing, magnetometry and mechanical measurements. The Smart Sensor consist of a 3-axis magneto-sensitive sensor and an ASIC containing analog signal processing, calibration control and a digital interface. The typical area of application of magnetic field sensors is shown in Fig.1

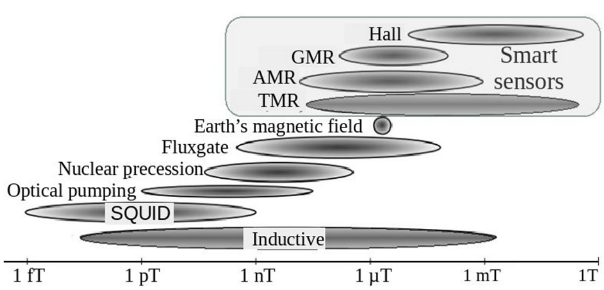

Figure 1: Typical area of applications of magnetic field sensors [1].

For very small magnetic field SQUID sensors are used, for small magnetic fields flux-gate sensors, for medium values are used MR (magnetoresistive) sensors and for high magnetic field Hall sensors.

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The majority of commercial Smart Sensors are build using AMR effect for magnetic fields lower than 1 mT. The TMR sensors are available for low and high magnetic fields. The Hall-effect Smart Sensors cover magnetic field range up to ±0.26 T.

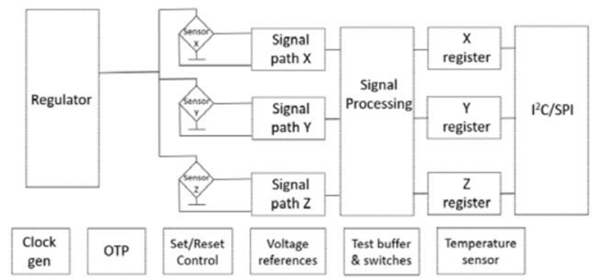

Figure 2: Schematic diagram of a smart sensor.

The schematic diagram of a typical Smart Sensor is shown in Fig. 2.

MAGNETIC FIELD SENSORS

AMR sensors [1]. Very simple in preparation, produced in large volumes, mainly for cell phones. They have better sensitivity than GMR and Hall effect sensors. AMR technology is robust against ionizing radiation up to 200 krad [2]. The typical sensor size 3x3 mm. The disadvantages of AMR sensors are as follows:

- relative small change of resistance, not exceeding 2%, magnetic remanence,
- sensitivity to orthogonal component.

Hall effect sensors [1]. They have many advantages but one quite important drawback – low sensitivity, not exceeding 5mV/mT. The Hall sensors are sensitive to ionizing radiation. The advantages are as follows:
simple design and technology of manufacturing,

- possibility to design very small sensors, with dimensions of several microns,
- non-invasive measurements – lack of ferromagnetic elements.

TMR sensors [1]. The TMR sensor element is using the Tunnel Magneto-Resistance effect, discovered in 1995. They have higher sensitivity than AMR and GMR sensors but suffer from higher noise. The advantages are as follows:

- high sensitivity, ten times higher than that of AMR,
- high tolerance to ionizing radiation (100 krad) [3],
- high sampling rate.
- small size and low power consumption.

Analog Sensors

Analog sensors cover wider range of magnetic field and have wider bandwidth than the digital sensors. They mainly measure one axis of the field. Output of the analog

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sensors is voltage, proportional to magnetic flux density. The functional diagram of the typical analog sensor is shown in Fig. 3. Main parameters of analog sensors are shown in Table 1.

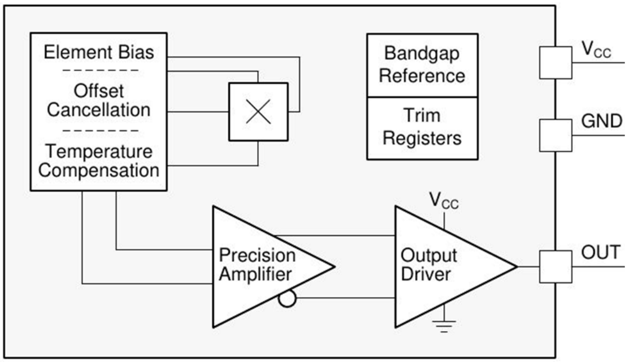

Figure 3: Functional diagram of ratiometric linear magnetic sensor.

Table 1: Specifications of Analog Sensors

Sensor Ref.	Linear Range (mT)	Sensitivity mV/V/mT	Non-Linearity %	RMS Noise at 1Hz nT/√Hz	Band-width kHz
		TMR Sensors			
ALT021-10 [20]	-0.25 +0.25	500	3	4.0	350
ALT025 [20]	-10 +10	30	10	1300.0	350
[20]	50 800	50	2		50
		AMR Sensors			
AMR2501 [21]	-0.1 +0.1	3.5	1	0.1	5000
		Hall Sensors			
DRV5055A4 [22]	-176 +176	12.5	1		20
DRV5055A1 [22]	-21 +21	100	1		20
DRV5053 [23]	-9 +9	90	1		20

Digital Sensor Modules

The commercial-off-the-shelf 3-axis magnetic sensors can measure magnetic fields in the range from 10 µT to 0.2 T. They have following features:

- Digital communication interface (I2C or SPI). The sensors can be located as far as 5 m from the system controller. With additional plug-in I2C repeaters the distance could be extended up to 30 m.
- Multi-channel arrangements. Many channels could be connected to a system controller using I2C multi-plexers.
- Sensors with different sensitivity and field range could be mixed.
- Sampling rate up to 15 kSps [4].
- Small size, 0.8 mm * 0.8 mm * 0.4 mm [5].
- Tolerance to ionizing radiation [2, 3].
- The terminal sensor modules are easily replaceable.

The main parameters of 3-axis digital sensor modules, which have been used in this work are shown in Table 2.

Table 2: Specifications of Digital Sensor Modules

Smart Sensor	Type, ADC	Linear range mT	RMS Noise	Speciality
MMC5983 [5]	AMR, 18 bit	±0.8	40 nT	High sen-sitivity
HMC5883L [6]	AMR, 12 bit	±0.8	200 nT	Standard
QMC5883L [7]	AMR, 16 bit	±0.8	200 nT	
MMC5603 [5]	AMR, 20 bit	±3.0	200 nT	Small size, 0.8 mm
TLV493D [8]	Hall, 12 bit	±130	85 µT	10 kSPS
TMAG5273A2 [9]	Hall, 12 bit	±260	88 µT	20 kSPS

All sensors have built-in temperature stabilization, and offset compensation. Detailed report on sensor stability and magnetic remanence could be found in [10]. The most advanced low field sensor is MMC5983.

All modules, used in this work, were low-cost commercial-off-the-shelf parts from different vendors. They are compatible with the Qwiic Connect System [11] for I2C peripherals. The 4-pin Qwiic connectors have no ferromagnetic components, which makes them suitable for high sensitivity measurements. Modules are very compact and easily replaceable in the field.

SYSTEM CONTROLLER

The system controller consists of Raspberry Pi (RPi) with custom HAT (Hardware Attached on Top) board, which contains 8-channel I2C multiplexer and connectors for sensor modules. The cable connectors on the PCB are stacked USB Type-A connectors. The schematic diagram of the system controller is shown in Fig. 4. The photo of a 4-channel prototype system is shown in Fig. 5. The sensor cables are standard USB-2 cables, with one terminal connector replaced by a Qwiic header. The system have been tested with 5 m cables. The distance between controller and sensors can be increased up to 30 m by plugging in an I2C extender dongle [12].

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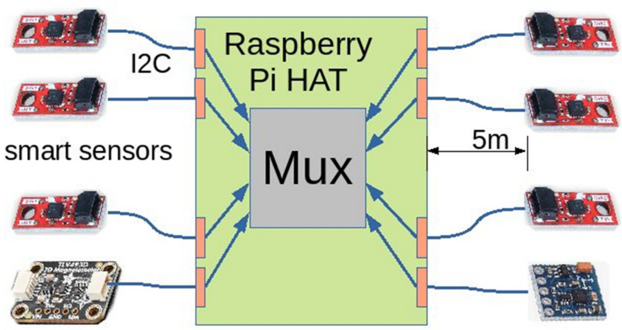

Figure 4: Schematic diagram of the system controller with eight Smart Sensors connected.

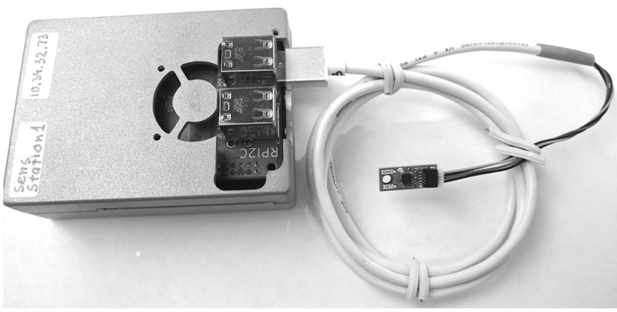

Figure 5: Photo of a 4-channel magnetometer with Raspberry Pi system controller and one sensor module MMC5983 connected.

Software

The control and monitoring of the sensor modules is managed by a LiteServer [13] server, which provides network access to sensor parameters using UDP protocol. A graphical user interface [14] is available for parameter editing and monitoring. The data logging and visualization a provided by companion Python packages apstrim [15] and pvplot [16]. The sensors are integrated into the main RHIC accelerator control system using an automatic software bridge.

The access to peripheral devices on Raspberry Pi is implemented using pigpio [16] library. It runs as a daemon and provides a semi real-time feature – a callback when any of input pins change state.

The maximum update rate of field measurements is 300 Hz.

Pulsed Magnetic Field Measurements

The fastest smart sensors with I2C interface have sampling rate of several kilosamples per seconds. The reaction time on a trigger on Raspberry Pi using pigpio library is 1 ms. That could be sufficient for many applications.

For real-time pulsed magnetic field measurement we have developed a prototype system controller based on STM32G431 [18] microcontroller using bare metal programming. The trigger reaction time of this system controller is 7 ns (one CPU clock) and the on-chip ADCs allows for sampling rate of 1 MHz.

DEPLOYMENTS AND DEVELOPMENT

The 3-channel magnetometer setup have been used during RHIC operations for precise measurement of static stray magnetic fields in different areas of RHIC tunnel. This measurements help to estimate impact of external magnetic field on luminosity loss for future EIC collider. The magnetic field range was ±0.8 mT. max sampling rate 1 kHz. Measurement of the X-component of a magnetic pulse with amplitude 2 µT and duration of 0.2 s is illustrated in Fig. 6. The RMS noise is 75 nT (0.75 mG).

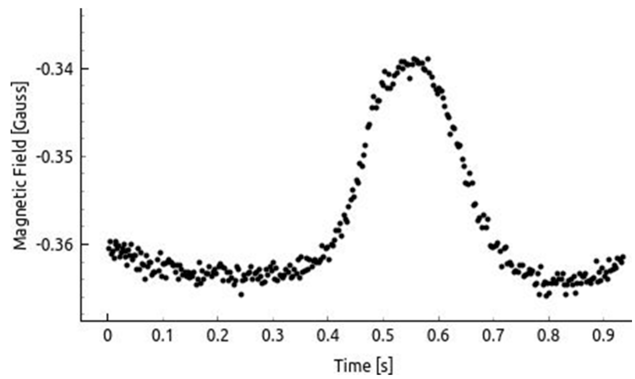

Figure 6: Sampling of X-component of the magnetic field with MMC5983MA sensor. Sampling rate 300 Hz, sensor bandwidth 800 Hz. RMS noise is 0.75 mG.

The 8-channel setup with range ±0.2 T is prepared for monitoring static fields of the solenoids and quadrupoles of the Coherent Electron Cooling experiment at RHIC.

The 1-axis pulsed magnetic field measurement system based on STM32G431 MCU with DRV5055 [19] Hall sensor have been used to map the magnetic field of a spin-flip solenoid of the polarized He3 transfer line at RHIC Linac. The maximum field range was 0.17 T. The measurements were externally triggered and sampled at 6 kHz by an internal ADC.

The demand for magnetic measurements at RHIC and EIC complex is growing. The future development will be focused on:

- Improvement of calibration procedures of the sensor modules.
- Performance improvement of the dynamic and pulsed magnetic fields measurements with RPi and MCU system controllers.
- Integration of the RPi system controller to EPICS infrastructure.
- Measurement of power spectral density of stray magnetic field.

CONCLUSION

The system-on-chip sensors are compact multi-chip modules designed for low to medium field magnetic sensing with a digital interface. The AMR sensors are produced in large volumes for consumer electronics and automotive industry. They have high sensitivity for magnetic field range of ±2 mT. The TMR sensors have higher sensitivity than AMR and cover wider field range.

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The AMR and TMR sensors are tolerant to ionizing radiation. The Hall sensors have sensing range of ±0.2 T but much lower sensitivity and lower radiation tolerance. The system-on-chip sensors are easy to integrate into multi-channel distributed system. Several low-cost 8 channel systems have been built using Raspberry Pi as a system controller and they are used in various magnetic field measurements at RHIC.

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