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A Survey on Magnetic Sensing and Communication: Technologies, Sensors, and Applications

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***Abstract*—Magnetic sensing and communication technologies have undergone rapid advancements, playing a critical role in modern applications. From consumer electronics to industrial systems, magnetic sensors, such as Hall effect (HALL) sensors, Giant Magnetoresistance (GMR) sensors, Anisotropic Magnetoresistance (AMR) sensors, and Tunnel Magnetoresistance (TMR) sensors, have emerged as essential components due to their contactless operation, durability, and resistance to environmental factors. This survey provides a comprehensive review of technologies, sensors, and applications of magnetic sensing and communication. In this survey, we first introduce the sensing principle and hardware platform of these four different types of magnetic sensors. We then provide a comprehensive review of existing magnetic sensing and communication works. We further explore magnetic sensing and communication tasks and their application in fields including automotive systems, smart grid management, medical equipment, and security systems. We also discuss current research challenges and potential directions for future development in magnetic technologies.**

***Index Terms*—Magnetic sensor, sensing, communication**

I. Introduction

With the rapid advancement of the Internet of Things (IoT), sensing and communication technologies have become increasingly essential in a variety of sectors. These systems now rely on sensors for gathering and processing critical parameters such as current, speed, position, and more. Magnetic sensors, in particular, have seen significant developments and are becoming indispensable in modern applications. These sensors operate by detecting changes in magnetic fields and converting them into electrical signals, which can then be used for measurement, control, and communication purposes. Magnetic sensors are crucial in industries ranging from consumer electronics to advanced industrial systems, offering several advantages such as contactless operation, durability, and resistance to environmental factors.

While traditional sensors such as photoelectric and piezoelectric sensors offer certain benefits—such as fast response times, high reliability, and compact size—these sensors also have notable limitations. Photoelectric sensors, for instance, are highly susceptible to environmental factors, leading to lower sensitivity and weaker resistance to interference. Similarly, piezoelectric sensors, despite their high precision and rapid frequency response, require physical contact and are unsuitable for detecting slow-changing or DC signals, limiting their application range.

In contrast, magnetic sensors, particularly those based on technologies like the Hall Effect (HALL), Giant Magnetoresistance (GMR), Anisotropic Magnetoresistance (AMR), and Tunnel Magnetoresistance (TMR), stand out due to their contactless operation. This feature minimizes wear and tear, enhances durability, and ensures long-term reliability. Moreover, magnetic sensors are resistant to environmental influences such as dust, humidity, and temperature fluctuations, making them highly suited for harsh environments. They can also function through non-magnetic materials, allowing them to be used in applications where direct line-of-sight is not possible. Additionally, compared to mechanical sensors, magnetic sensors offer faster response times and greater accuracy, which are essential for high-speed and precision applications.

Magnetic sensors have a wide range of applications across various industries, including smart grids, automotive systems, industrial automation, and medical equipment. In the context of smart grids, magnetic sensors enable non-invasive broadband current detection, power monitoring, and partial discharge diagnostics, among other functions. In the automotive sector, these sensors are pivotal in systems such as wireless charging, automatic obstacle detection, and position sensing, thereby enhancing vehicle safety and performance. Furthermore, magnetic sensors play a key role in the development of new energy vehicles, providing a new technological pathway for the automotive industry. In the medical field, magnetic sensors are utilized in applications like magnetic cytology and immune receptor detection, offering critical data for diagnostics and patient care.

In addition to their use in traditional fields such as smart grids, automotive systems, and medical equipment, magnetic sensors are expanding into more innovative areas, particularly in underwater, underground, and biological communication. These sensors are pivotal in underwater communication systems, where magnetic fields can traverse through water, and underground communication, where traditional radio waves struggle to propagate. Biological communication, such as detecting biomagnetic fields for medical applications, is another exciting frontier. The weak magnetic fields generated by living organisms present unique challenges, including susceptibility to noise and interference. Addressing these challenges to achieve accurate and reliable biomagnetic signal detection is a critical area of ongoing research.

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In the field of communication, magnetic sensing is playing an increasingly important role. By integrating magnetic sensors into communication systems, new methods of wireless data transmission, position tracking, and remote sensing are being explored. Magnetic sensors offer advantages over traditional communication technologies, such as robustness to environmental factors and the ability to transmit information through various media, including water, earth, and biological tissues.

This paper presents a comprehensive review of the latest developments in magnetic sensing and communication technologies. The goal is to explore the principles, technologies, and applications of magnetic sensors, particularly in sensing and communication contexts. Specifically, we focus on applications in underwater, underground, and biological communication systems, where magnetic sensors offer unique advantages over conventional approaches. This paper also discusses the challenges in these areas and highlights potential future directions for research and development in magnetic sensing and communication technologies.

The main contributions of this paper are as follows:

- **Detailed technical focus.** Our study provides a more specific and in-depth analysis, emphasizing the magnetic sensor's structure while introducing its hardware model and manufacturing process based on physical principles.
- **Diverse applications.** We explore a wide range of sensing and communication applications, from current/speed/position/material/medical sensing to biological/underwater/underground communication in different scenarios such as smart grid management, automotive transportation, security surveillance, and medical health.
- **Comprehensive literature review.** Our work includes an extensive comparison and analysis of existing research on magnetic sensors. This helps readers gain a thorough and up-to-date understanding of the field.
- **Challenges and future directions.** Beyond discussing specific sensor technologies, we also elaborate on the broader applications and emerging trends in magnetic technology, which may inspire further research in this area.

There have been some related surveys for magnetic sensor sensing. We compare and summarize them in detail in the next section. We find that none of the existing surveys provides an in-depth comparison among these key sensor technologies, particularly in terms of performance and application specificity. In addition, existing surveys lack attention to biosensing, wearable techniques, stretchable sensors, and other merging applications. As we mentioned, a comprehensive survey is necessary and important for researchers and application developers. Our survey is expected to inspire further exploration into the development of magnetic sensor technologies, ultimately helping to build a wide range of applications that achieve accurate, ubiquitous, and stable magnetic field sensing and communication in real-world settings.

Roadmap. As shown in Fig. 1, the structure of this survey is as follows. Sec.II summarizes the related surveys and points out the salient novelties of our paper. Sec.III introduces the physical principle, hardware structure, typical hardware design, and application fields of HALL, AMR, GMR, and TMR sensors in detail, giving readers a more comprehensive cognition. In Sec.IV, according to the characteristics of magnetic sensors and market demand, we divide the sensing task into five categories: current sensing, angle and position sensing, tactile sensing, velocity sensing, and material detection. In Sec.V, we introduce the magnetic technologies in underwater, underground, and biological communication systems. Sec.VI mainly introduces the specific application scenarios of magnetic sensors, including smart grid management, automotive and transportation, security and monitoring, and medical and biotechnology. Based on an analysis and summary of these efforts, Sec.VII discusses potential challenges and future directions.

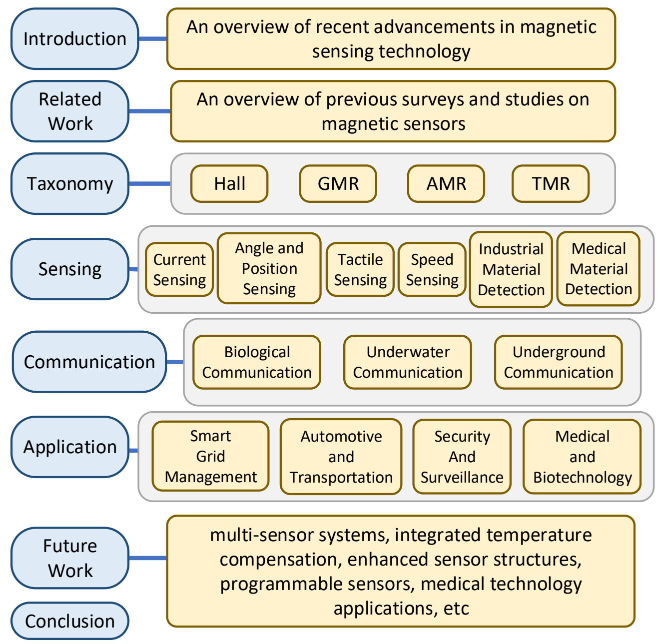

Fig. 1. Survey organization.

II. Related Work

There have been numerous surveys on magnetic sensors, exploring various types, materials, principles, and their applications. This section begins by providing an overview of these related works, summarized in Table I. Following this, the differences between the most related works and our survey are discussed in detail. Finally, we highlight the key novelties of our work in comparison to existing studies.

One of the earliest comprehensive comparisons was conducted by J.E. Lenz et al. [1], where eleven techniques that widely used for magnetic sensor sensing were examined. These techniques included coil, flux-gate, optically pumped, nuclear precession, SQUID, Hall-effect, magnetoresistive, magnetodiode, magnetotransistor, fiber optic, and magnetooptic technologies. Their work focused on assessing the applications of these sensors at three different sensitivity levels, providing valuable insights into the performance of each sensor type.

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TABLE I
SUMMARY OF RELATED SURVEYS ON MAGNETIC SENSORS

Reference	Sensor Type	Application Scenarios	Feature	Taxonomy	Comparison
J. E. Lenz et al. [1]	Search coil, flux-gate, optically pumped, nuclear precession, SQUID, Hall-effect, magnetoresistive, magnetodiode, magnetotransistor, fiber optic, and magnetooptic technologies.	Non-contact detection.	Noncontact switching, magnetic anomaly detection, magnetic compassing, and brain-function mapping	Non-contact detection of magnetic sensors.	We emphasize the structure and principle of magnetoresistive sensors.
Pavel Ripka et al. [2]	AMR, GMR, SDT and fluxgate sensors.	Angel and magnetic signal detection.	AMR: Induction read hard disk. GMR: angular sensing SDT: magnetic microbeads for medical applications Fluxgate sensors: Digital fluxgate magnetometers.	Angle and magnetic field detection based on AMR, GMR, SDT, and Fluxgate sensors.	We added Hall and TMR to expand the application range of magnetoresistive sensors.
Carlos Morón et al. [3]	Magnetic sensors based on amorphous ferromagnetic materials.	Security devices, weapon detection, and magnetic maps.	Measurement of torques, deformation, and the components of the Earth's magnetic field.	Safety detection application of magnetic sensors based on amorphous ferromagnetic materials.	We mainly focus on the research of magnetoresistive sensors, and deeply explore the communication tasks and sensing detection of magnetoresistive sensors.
Mirza Bichurin et al . [4]	ME magnetic field sensors.	Biomedicine.	Measurements of weak magnetic fields and magnetoencelographic signals.	Biomedical applications based on ME magnetic field sensors.	We have expanded the application range of magnetoresistive sensors.
Mirza Bichurin et al. [5]	Solid state magnetic field sensors.	Biosensors, ubiquitous sensor networks, wearables, smart things etc.	Characteristics of amorphous, high sensitivities and low coercive fields. decrease in eddy current losses.	Smart wearable devices based on solid state magnetic field sensors.	We added several emerging technologies about reluctance sensors, such as machine learning, fusion sensing, and so on.
Alberto et al. [6]	The optical fiber magnetic field sensors using MF.	Biomedical detection, the aviation industry, space and geophysical research, and controlled nuclear fusion.	High anti-interference ability, immunity to electromagnetic interference, small size, remote sensing capabilities, and resistance in hazardous environments.	High anti-interference device based on magnetic fluid (MF).	We introduce the main hardware, physical structure, principle, and related application of reluctance sensors.
J. Heremans. [7]	Magnetic field sensors based on semiconductors and on magnetic metals.	Magnetic recording technology and position sensing.	Sensitivity to low magnetic fields and reliable translation of mechanical movement into an electrical signal.	Magnetic recording and position detection based on magnetic field sensors.	We have increased the application field of magnetoresistive sensors and added a number of emerging technologies.
M. Melzer et al. [8]	Stretchable magnetic field sensors.	A variety of novel technologies, like electronic skins, smart textiles, soft robotics and actuators, active medical implants, and soft consumer electronics.	Stretchable magnetoelectronic sensors.	Flexible electronic devices based on stretchable magnetic field sensors.	In addition to GMR, we have also added the introduction and application of AMR, TMR, and HALL.
Chi Liu et al. [9]	Optical fiber magnetic field sensors based on magnetically sensitive materials.	Optical fiber communication, optical fiber sensing, medicine, national defense, etc.	Good insulation properties and suitability for long-distance transmission and low loss.	Communications, medical and defense applications based on optical fiber magnetic field sensors.	We introduce the main hardware, physical structure, principle, and related application of reluctance sensors.
Dmitry Murzin et al. [10]	Dc SQUIDs, search coils, fluxgate, GMI, AMR, GMR, TMR, optically pumped, cavity optomechanical, Hall, magnetoelastic, spin wave interferometry magnetometers, and so on.	Magnetocardiography, magnetotomography, magnetomyography, magnetoneurography, or their application in point-of-care devices.	Measuring a magnetic field produced by human organs and detecting magnetically labeled biomolecules.	Medical applications based on various magnetic sensors.	We have expanded our application areas to include the Internet of Things, machine learning, and converged sensing.

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In another significant contribution, Pavel Ripka et al. [2] explored the advancements in the miniaturization of fluxgate sensors and provided a brief discussion on SQUIDs, resonant sensors, giant magneto-impedance (GMI), and magnetomechanical sensors. Their study emphasized the growing potential of miniaturized magnetic sensors in various applications. Carlos Morlón et al. [3] introduced the major types of magnetic sensors developed over time and focused on their applications in modern technology. Their work highlighted the use of magnetic sensors based on amorphous ferromagnetic materials, which have become increasingly relevant in technological advancements. Mirza Bichurin et al. [4] provided a detailed analysis of magnetoelectric (ME) sensors, presenting comparative characteristics of various magnetic field sensors. Notably, ME sensors were shown to possess high sensitivity, comparable to that of superconducting quantum interference devices (SQUIDs). Bichurin also discussed the diverse application areas for ME sensors.

Further expanding on magnetic field sensor technologies, Bichurin et al. [5] investigated solid-state magnetic field sensors, emphasizing their suitability for miniaturization and integration. This is particularly important for emerging fields such as biosensors, ubiquitous sensor networks, wearable devices, and smart devices, where compact and efficient sensors are in high demand. Alberto et al. [6] explored fiber optic magnetic field sensors that utilize magnetic fluids (MF) as the sensing elements. They discussed various sensing configurations, including fiber Bragg gratings, interferometry, surface plasmon resonance (SPR), and approaches involving customized fibers, such as etched, tapered, and U-shaped designs. Their work demonstrated the growing role of fiber optics in magnetic sensing.

Further, the characteristics of semiconductor-based magnetic field sensors, such as Hall generators and magnetoresistance sensors, along with magnetic metal-based sensors (like Permalloy and the recently discovered giant magnetoresistance metal multilayers), were discussed in [7]. The focus here was on their applications in fields like magnetic recording technology and position sensing. M. Melzer et al. [8] reviewed cutting-edge developments in stretchable magnetic field sensors, which leverage a combination of thin metal films and elastic materials. These sensors exhibited significant magnetoresistive effects, offering promising applications in flexible electronics and wearable technologies. Chi Liu et al. [9] provided a comprehensive review of fiber-optic sensors, particularly focusing on current and magnetic field sensors based on magneto-sensitive materials. Their work highlighted the increasing use of fiber optics in highly sensitive and precise sensing applications. Lastly, Dmitry Murzin et al. [10] focused on magnetic field sensors suited for biomedical applications, providing an in-depth review of the latest research from a physical perspective. Their work underscored the potential of magnetic sensors in medical diagnostics and treatment.

In this paper, anisotropic magnetoresistance (AMR) sensor, giant magnetoresistance (GMR) sensor and tunnel magnetoresistance (TMR) sensor are the main topics for the following reasons: the above papers mainly focus on magnetic fluid fiber sensor, magnetoelectric (ME) sensor, amorphous ferromagnetic material sensor, etc., but the production of magnetic fluid fiber sensor is difficult and easy to damage; Superconducting quantum interference devices (SQUIDs) need to operate at low temperatures, which is costly and difficult to miniaturize. The mainstream magnetic sensor usually adopts the reluctance principle, has a large market share, mature preparation technology, and broad application prospects, and is manufactured by planar micro-machining process, which can provide high sensitivity in a relatively compact package. The compatibility of solid-state magnetic sensors with complementary metal-oxide-semiconductor (CMOS) manufacturing processes makes it possible to integrate sensors with sensing and computing circuits simultaneously. However, we found that the field of magnetoresistive sensors was not well covered by the existing research reviews on magnetic sensors, so to fill this gap, we focused on HALL, AMR, GMR, and TMR sensors.

Compared with these works, our paper presents new results in the following aspects: (1) Our paper is more inclusive and contains the latest advances in the field of magnetic technologies. (2) We propose a comprehensive taxonomy of magnetic sensor sensing and communication. According to the type of magnetic sensors, our paper classifies the existing works into four categories: Hall, AMR, GMR, and TMR sensors. We compare their performance across various applications, offering a more targeted analysis of these sensor technologies. (3) The scope of study in our paper is broader. Besides traditional applications of magnetic sensors, we also introduce emerging fields such as biosensing, wearable technologies, device miniaturization, fiber-optic magnetic sensors, and others.

III. Taxonomy

A. Hall Sensor

Sensing Principle. The Hall sensor operates based on the Hall effect, a phenomenon discovered in 1879 by American physicist Edwin Herbert Hall using gold leaf [24]. The Hall effect occurs when a conductor carrying an electric current is placed in a perpendicular magnetic field. Under these conditions, the charge carriers within the conductor accumulate on one side due to the influence of the magnetic field, creating a transverse electric field. This electric field is orthogonal to both the magnetic field and the direction of the current and can be described as

$$Rh = Ey/(jx * B) \tag{1}$$

where Ey is the induced electric field, jx is the current density along the axis, B is the applied magnetic field. Based on this linear relationship, the external magnetic field can be measured.

Hardware Structure. A typical Hall effect sensor consists of a thin layer of conductive material, such as silicon (Si), gallium arsenide (GaAs), or indium antimonide (InSb). At the core of the sensor is the Hall plate. When an electric current passes through the Hall plate and encounters a magnetic field perpendicular to the current, it generates a Hall voltage across the plate. This voltage can be measured to accurately determine the strength of the magnetic field. As a result, the sensor can effectively detect the presence, polarity, and

TABLE II
LINEAR HALL-EFFECT SENSORS

Product	Supply Voltage (V)	Resistance	Temperature (°C)	Field Range (mT)	Sensitivity (mV/mT)	Bandwidth (kHz)
TMAG5253 [12]	1.65–3.6	N/A	–40 to 125	12–80	51–69	15
DRV5057-Q1 [13]	3–5.5	N/A	–40 to 150	N/A	1.88–2.12 (%D/mT)	1
DRV5056-Q1 [14]	3–5.5	N/A	–40 to 150	20–158	20–200	20

TABLE III
HALL-EFFECT SWITCHES

Product or Part number	Type	Operate point (max) (mT)	Release point (min) (mT)	Supply voltage (V)	Bandwidth (kHz)	Supply current (μA)	Rating	Output
TMAG5131-Q1 [15]	Omnipolar switch	±0.004	0.5	1.65-5.5	0.02	1.3,2	Automotive	Open drain,Push-Pull output driver
TMAG5115 [16]	Latch	1.7,4	-4,-1.7	2.5-26	60	6000	Catalog	Open drain
TMAG5124-Q1 [17]	Unipolar switch	5, 7, 11, 16.1	1,3,6.8,11.4	2.5-38	40	3500, 6000	Automotive	Current

magnitude of the magnetic field [11]. Hall effect sensors are mainly divided into linear Hall effect sensors and switch Hall effect sensors. Below are some of the latest Hall effect sensors produced by Texas Instruments:
(1) *TMAG5253*, a low-power linear Hall effect sensor that responds proportionally to magnetic flux density, features an enable pin that allows it to enter an ultra-low power (nA) shutdown mode. TMAG5253 has a very short startup time ($<25\mu$s) and is designed for low-power position detection applications. This device comes in an industry-leading 1.54 mm^2 ultra-small package, suitable for space-constrained applications [12].
(2) *DRV5057-Q1*, a linear Hall effect sensor with a ratiometric PWM output type, is primarily used for precise position detection, such as in automotive applications including brake pedals, throttle pedals, and clutch pedals [13].
(3) *DRV5056-Q1* is another linear Hall effect sensor, similar to the DRV5057-Q1, but it has a ratiometric unipolar output type and offers a larger bandwidth [14].
(4) *TMAG5131-Q1* is an ultra-low power, low voltage, high-precision Hall effect sensor designed for compact and battery-critical automotive applications. It provides various magnetic thresholds, sampling rates, and output types, and is mainly used in applications like door handles and electronic locks [15].
(5) *TMAG5115*, a high-performance Hall effect latch sensor with fast propagation delay and low jitter, has a wide operating voltage range of 2.5V to 26V and is designed for various industrial and commercial applications such as cordless power tools and robotic vacuum cleaners. It also features internal protection against output short circuits, overcurrent, and overheating [16].
(6) *TMAG5124-Q1*, a high-precision Hall effect sensor that offers a two-wire interface, has a wide operating voltage range and reverse polarity protection, making it suitable for various automotive applications [17].

The relevant parameters of the Hall effect sensors mentioned above are shown in Table II and Table III.

Core Challenges: (1) Temperature drift. The Hall coefficient changes nonlinearly with temperature (typical temperature drift 0.02–0.1%/°C), causing the output signal to shift. (2) Low magnetic field sensitivity. The signal-to-noise ratio (SNR) under the weak magnetic field (1mT) is insufficient, such as the geomagnetic field detection is easy to be submerged by circuit noise. (3) Noise interference. If noise is significant in low-frequency bands ($<$1kHz), and thermal noise affects high-precision measurements in broad bands. (4) Power consumption limitation. Traditional Hall components require a continuous power supply of several mA levels, which is difficult to meet for the microamperage standby requirements of IoT devices.

Solution: (1) Temperature compensation. Integrated temperature sensor (such as PTAT circuit) real-time monitoring of chip temperature, combined with differential hall pairs (such as dual-element symmetrical layout) to offset common mode temperature drift, compensation accuracy up to ±0.01%/°C. (2) Material optimization. High mobility semiconductors such as InSb (mobility $> 50{,}000\ \mathrm{cm^2/V{\cdot}s}$) or GaAs are used to increase the sensitivity to 50–$200\ \mathrm{mV/mT}$; SiC substrate can extend the operating temperature to more than $200\,°\mathrm{C}$. (3) Noise reduction technology. Chopper stabilization technology (Chopper) moves low-frequency noise to high frequency through modulation-demodulation, and band-pass filtering can reduce the equivalent noise density to 10 nV/Hz. (4) Low power design. CMOS process integration (such as TI DRV5055) uses pulse power supply mode and sleep power consumption, while supporting the magnetic field threshold wake-up function.

Applications. The Hall effect sensor can be utilized in precision measurement applications such as current sensors, position sensors, and velocity sensors, and can also serve as a transducer. For example, a wide-band current sensor based on the Hall element has been designed, capable of displaying a 1 MHz acquisition bandwidth when the spin frequency is 16 MHz. If a magnetic flux sensor is applied to horizontal position detection, it can enable precise position prediction for magnetic permeability robots. Numerous studies have highlighted the application of Hall elements in high-frequency current measurement, magnetic material detection, and tactile sensing.

B. AMR Sensor

Sensing Principle. The AMR (Anisotropic Magnetoresistance) sensor operates based on the principles of magnetic anisotropy [18] and spin-orbit coupling [19]. Magnetic anisotropy refers to the phenomenon where a material's magnetic properties vary depending on direction. This is primarily observed through changes in the magnetic susceptibility of weak magnets and in the magnetization curve of ferromagnets as the direction of magnetization changes. Spin-orbit coupling describes the interaction between an electron's spin freedom and its orbital freedom, which influences the directional dependence of electrical resistance. These two principles enable the AMR sensor to detect changes in external magnetic fields by varying its resistance, providing high sensitivity and accuracy in measuring magnetic fields.

Hardware Structure. According to hardware structure, AMR sensors can be mainly divided into single-layer and quadruple-layer types. (1) In the design of single-layer AMR sensors, thin film elements with meander-shaped geometry are commonly used. These elements can induce strong magnetic anisotropy for precise sensor orientation and amplify resistance changes. Signal output in single-layer AMR sensors typically follows a quadratic trigonometric function, enabling accurate monitoring of a 180° angle. To extend observation to a full 360° rotation, commercial rotational speed or angle sensing devices often employ two Wheatstone bridges shifted by 45° [19]. (2) The quadruple-layer AMR sensor integrates multiple ferromagnetic thin layers. These layers have evenly distributed alignments from 0° to 180° [20], minimizing detection errors due to magnetic anisotropy. Titanium spacer layers are present between ferromagnetic layers. These spacer layers maintain magnetic isolation and promote grain growth, ensuring reliable sensing performance. Below are some of the latest AMR sensors.

(1) *HMC100X* is recognized for its integrated design [21] and low noise performance [22]. Its structure is shown in Fig. 2. It boasts an open-loop bandwidth of 5 MHz. Its planar structure includes essential components such as offset and Set/Reset coils, which are tightly integrated with AMR sensing elements. With a noise level of 15 pT/$\sqrt{Hz}$ at 1 kHz, it is suitable for applications requiring moderate noise levels. Additionally, it has a field scale constant of approximately HSC $\approx$ 0.8 mT [23].

(2) *KMZ51* is renowned for its robust design and versatile functionality [24]. It comprises four magnetoresistors crafted from a thin nickel-iron (permalloy) film. This film is intricately deposited onto a silicon wafer and patterned into distinct resistive strips. These resistors are housed within a solid-state body [25].

(3) *AFF755B* demonstrates superior performance in offset stability and noise behavior. Electronic noise measurements reveal that the AFF755B sensor exhibits higher noise levels

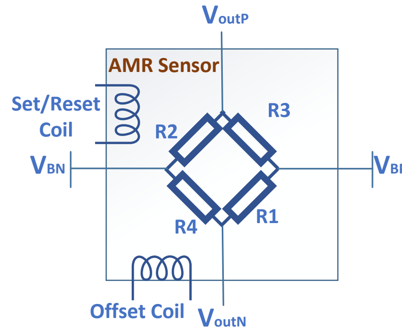

Fig. 2. Internal circuit of AMR sensor HMC100X.

in flipped mode compared to the HMC1021 sensors [26]. Additionally, the AFF755B sensor demonstrates superior sensitivity, particularly at cryogenic temperatures [27].

The relevant parameters of the AMR sensors mentioned above are shown in Table IV.

Core Challenges: (1) Nonlinear response. The output is the cosine of the magnetic field Angle, and the biased magnetic field needs to be linearized. (2) Large temperature coefficient. NiFe resistance temperature coefficient significantly affects the accuracy. (3) Hysteresis effect. The irreversible reversal of the magnetic domain leads to a return error (typical 0.5%-1%). (4) Orthogonality error. Non-ideal orthogonality response due to Barber electrode layout.

Solution: Integrated planar coils provide bias current (current flip technology). Permanent magnet bias (such as SmCo magnetic strips) enables a fixed bias field. Wheatstone bridge structure has AMR elements in orthogonal arrangement. Digital compensation algorithms leverage least squares to fit temperature curves. Magnetic field annealing (200°C, 0.5T) eliminates residual stress and reduces hysteresis.

Applications: AMR sensors are widely used in position detection, motion sensing, current sensing, and angle measurement across various fields such as automotive, industrial automation, consumer electronics, and medical devices. For example, applying AMR sensors in the field of autonomous driving can enable vehicles to avoid obstacles in advance, thereby enhancing the safety performance of unmanned vehicles. Another example involves combining AMR sensors with fishbone magnetic films to create biosensors that actively attract magnetic cells, allowing for the active detection of specific cells and providing valuable information for future biochip research and applications.

C. GMR Sensor

Sensing Principle. The GMR (Giant Magnetoresistance) sensor operates based on the GMR effect. As demonstrated by Baibich et al. [31] and Binasch et al. [32], when an external magnetic field changes, the magnetic moment within certain materials shifts, which affects the movement and scattering of internal electrons, leading to a change in resistance—this is known as the GMR effect. The GMR sensor consists of a free layer and a fixed layer. When exposed to an external magnetic field, electron scattering between these two layers

TABLE IV
AMR SENSOR

Product	Supply Voltage (V)	Resistance(Ω)	Temperature (°C)	Field Range (mT)	Sensitivity (mV/mT)	Bandwidth (kHz)
HMC1001/1002 [28]	2-12	600-1200	–40 to 85	±0.2	82.5–132	5
KMZ51 [25] [29]	5-8	1000-3000	–40 to 125	±0.25	498–664	1
AFF755B [30]	1.2-9.0	2200-2800	–40 to 125	±0.20	514–674	1

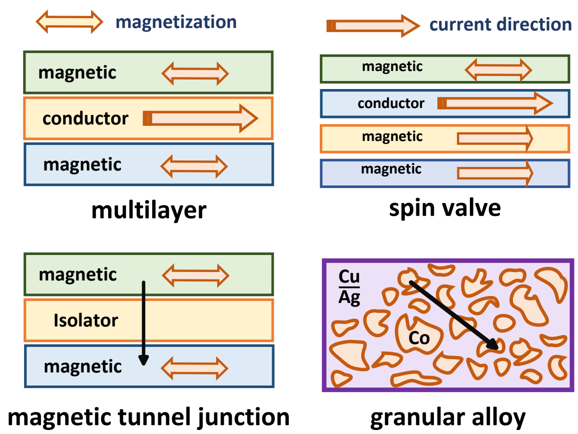

Fig. 3. Four types of GMR sensors.

is influenced, and the magnetic moment directions of both the free and fixed layers are altered, resulting in a change in resistance. This allows for the determination of the magnitude and direction of the external magnetic field.

Hardware Structure. There are four main structures for GMR sensors shown in Fig. 3. (1) Multilayer. Multilayered structures are composed of two or more magnetic layers. These layers are made of a Fe–Co–Ni alloy, such as permalloy. An extremely thin non-magnetic conductive layer, such as copper, separates these magnetic layers [33]–[35]. This configuration has imparted the samples with increased thermal stability and enhanced magnetoresistance levels. (2) Spin valve. The inception of spin valves represents a specific instance within the realm of multilayered structures [36]. In spin valves, an extra antiferromagnetic (pinning) layer is introduced at either the top or bottom of the structure. Within such configurations, achieving antiparallel alignment does not require external excitation. (3) Magnetic tunnel junctions. The magnetic layers are separated by an insulating layer and this insulating layer is extremely thin. The configuration follows a current-perpendicular-to-plane (CPP) arrangement. Electrons can traverse this thin film through the quantum tunnel effect [37]. (4) Granular alloys. Granular films containing Co–Cu and Co–Ag also demonstrate a significant GMR effect [38], where the GMR effect originates from spin-dependent scattering.

There are numerous models of GMR sensors. Below are examples of several commonly utilized models of GMR sensors.
(1) *HMC2003*, produced by Honeywell, is a three-axis sensor and serves as a highly sensitive, three-axis magnetic sensor hybrid component primarily utilized for measuring low magnetic field intensity. Its principal applications include Precision Compassing and aerospace navigation [39].
(2) *AA004-02E*, manufactured by NVE, is an analog magnetic sensor capable of detecting absolute magnetic fields. With a sensitivity range from 50Oe to 350Oe and sensitivity ranging from 0.9mV/V-Oe to 1.3mV/V-Oe, it boasts high sensitivity to externally applied magnetic fields, excellent temperature stability, low power consumption, and small size. It finds suitability across various applications, spanning from rugged industrial and automotive position, speed, and current sensors to low-voltage battery-powered sensors for handheld instruments and implantable medical devices [40].
(3) *TLE5014*, produced by Infineon Technologies, is an angle sensor specifically tailored for angular position sensing in automotive applications. Throughout its operational lifespan and temperature range, it maintains an angle error of less than 1°, featuring a 360° absolute angle measurement range with 12-bit resolution [41].

The relevant parameters of the GMR sensors mentioned above are shown in Table V.

Core Challenges: (1) Multi-layer film process. Ultra-thin multi-layer films such as Co(1nm)/Cu(2nm)/Fe need precise control by magnetron sputtering, and the interface roughness affects the spin-dependent scattering efficiency. (2) Temperature stability. Curie temperature limit of the ferromagnetic layer (for example, Co is 1131 °C), the actual working range is affected by thermal demagnetization (typical -40 150 °C). (3) Nonlinear response. Magnetization saturation at high magnetic fields results in decreased sensitivity, and the linear region only covers ±5mT. (4) Stress sensitive: Package or substrate deformation causes magnetic anisotropy changes, and the output drift is 1-5%.

Solution: (1) Temperature compensation. Dual Wheatstone bridge design (sensing bridge + reference bridge), using the reference bridge no magnetic field response characteristics through the differential output to offset the temperature coefficient. (2) Linearized design. Hard magnetic bias layers (such as CoPtCr) provide a fixed bias field, extending the linear region to ±20mT; External permanent magnet bias tunable linear interval. (3) Stress suppression. The membrane stress gradient is optimized (<100MPa) and the mechanical coupling effect is reduced by using a flexible substrate such as polyimide.

Applications. GMR sensors have been utilized in various fields, including power and energy control, autonomous vehicles, and smart home technologies. For example, GMR sensors are applied in smart grids for real-time detection of DC current, frequency, and harmonic currents on both the power supply and network sides. In the medical field, GMR sensors are widely used, such as in the development

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TABLE V
GMR SENSOR (Unified Units)

Product	Supply Voltage (V)	Resistance(Ω)	Temperature (°C)	Field Range (mT)	Sensitivity (mV/mT)	Bandwidth (kHz)
HMC2003 [39]	6–15	4.5	–40 to 125	±0.2	9800–10200 (mV/mT, unnormalized)	1
AA004-02E [40]	1–24	5000	–50 to 125	0.5–3.5	30–43	100
TLE5014P16 [41]	4.2–5.5	N/A	–40 to 125	25–80	N/A	0.2–2.2 (PWM freq.)

of multi-biomarker immunoassay sensors by combining GMR technology with biotechnology. These sensors can detect up to 12 tumor markers simultaneously, with the inherent physical properties of GMR sensors ensuring high sensitivity, accuracy, and stability during detection. Numerous studies highlight the potential future applications of GMR sensors in medical diagnostics, magnetic field imaging, and other areas, demonstrating their versatility and effectiveness.

D. TMR Sensor

Sensing Principle. The TMR sensor operates based on the TMR effect. Its structure consists of a sandwich configuration: a fixed ferromagnetic layer, a non-magnetic insulating layer, and a free ferromagnetic layer. When the TMR sensor is exposed to an external magnetic field, the field influences the magnetization directions of the two ferromagnetic layers, which in turn affects the tunneling probability of electrons between them, leading to a change in tunneling conductance. If the magnetization directions of the two ferromagnetic layers are parallel, the probability of electron tunneling increases, resulting in a higher tunneling current and greater conductivity. Since only the magnetization direction of the free layer varies with the applied magnetic field, the resistance of the TMR sensor is proportional to the relative angle between the two ferromagnetic layers. By altering its resistance, the TMR sensor can measure both the direction and magnitude of the applied magnetic field.

Hardware Structure. The TMR sensor has a similar magnetic structure to the GMR sensor, but while the GMR current flows parallel to the film surface, the TMR current flows perpendicular to it. The TMR sensor is made using advanced thin-film technology and consists of two magnetic layers (free and fixed) separated by a thin insulating layer of about 2nm. As shown in Fig. 4, in the TMR sensor, the fixed layer's magnetization direction stays constant, while the free layer's magnetization changes with the external magnetic field, affecting the resistance. When the magnetization directions of both layers are parallel, resistance is low, allowing more current to pass through. When they are opposite, resistance is high, and very little current flows. This change in resistance based on the magnetization direction is known as the TMR effect. The strength of this effect depends on the spin polarization of the two magnetic layers—the higher the spin polarization, the stronger the TMR effect.

Below are some of the latest TMR sensors.

(1) *TMR2001*, developed by MultiDimension Technology, excels in performance and has a broad application range. It has several advantages [42]. First, it is compact and small, measuring only $3\,\mathrm{mm} \times 3\,\mathrm{mm} \times 1.45\,\mathrm{mm}$, and it is cost-effective. Compared to the large and expensive current probes and current transformers (CTs) used in current research, it shows clear benefits in current detection [43]. Second, the sensor can provide a high sensitivity of 80 mV/V/mT, allowing it to accurately detect magnetic fields under a wide range of experimental conditions [44]. Third, it is designed for non-contact current sensing, providing a less invasive alternative compared to traditional methods [45].

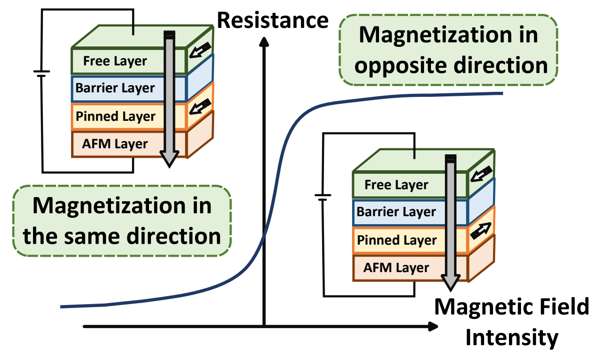

Fig. 4. Illustration of the hardware structure and resistance change of the TMR sensor.

(2) *TMR2104*, developed by MultiDimension Technology, features a unique push-pull Wheatstone full bridge structure using four TMR sensor elements. When the external magnetic field changes parallel to the sensor's sensitive direction, this Wheatstone bridge provides a differential voltage output with excellent temperature stability [46]. TMR2104 sensor has a one-dimensional sensitive axis [47] and demonstrates a nonlinearity of 1.5% at a magnetic field of about $6.4\mathrm{kAm}^{-1}$. Currently, TMR2104 is widely used in current detection applications [48].

(3) *TMR2301*, developed by MDT features good temperature stability. It has a saturation magnetic field of up to ±500 Oe and a high sensitivity of 1 mV/V/Oe. The bandwidth is broad, at 200 kHz [49].

(4) *TMR2701* has a structure similar to the TMR2104 and also features a push-pull Wheatstone full bridge design. The module includes four highly sensitive TMR sensor elements. When the external magnetic field changes parallel to the sensitive direction of the TMR module, the Wheatstone full bridge outputs a differential voltage [50].

The relevant parameters of the TMR sensors mentioned above are shown in Table VI.

Core Challenges: (1) High impedance matching: tunnel junction impedance (1-10kw) and CMOS circuit input impedance

TABLE VI
TMR SENSOR

Sensor Type	Supply Voltage (V)	Supply Current (μA)	Resistance (Ω)	Sensitivity (mV/V/mT)	Saturation Field (mT)	Non-Linearity (%FS)	Offset Voltage (mV)	Hysteresis (mT)
TMR2001 [42]	1.0–7.0	16	63k	80	–2.5 to 4.0	1.2	–30 to 30	0.04
TMR2104 [48]	1.0–7.0	1000	1000	31	–15 to 15	1.5	–10 to 10	0.05
TMR2301 [51]	1.0–7.0	200	15k	10	–50 to 50	1.5	–25 to 25	1%FS
TMR2701 [52]	1.0–7.0	12.5	80k	120	–5 to 5	1	–30 to 30	0.03

mismatch, easy to introduce thermal noise. (2) Barrier layer defects. MgO single crystal barrier (thickness 1nm) pinhole defects lead to leakage current, reducing the reluctance ratio. (3) Thermal stability. The thermal disturbance energy of the free layer, and the probability of random flipping of the magnetic moment increases at high temperatures.

Solution: (1) Signal conditioning: Spin-Torque Oscillator enhances the tunneling magnetoresistive effect and increases SNR by 20dB; Low noise instrumentation amplifier (e.g. AD8429). (2) Process optimization: Atomic layer deposition (ALD) grew MgO barrier, thickness uniformity ±0.02nm; CoFeB/MgO/CoFeB structure is annealed at 300°C to form (001) texture, TMR>300%. (3) Thermal management: On-chip integrated micro TEC (thermoelectric refrigeration) temperature control accuracy of ±0.1 °C, combined with differential output (e.g. TDK TMR3901) to offset thermal drift.

Applications. TMR sensors have been utilized in a variety of applications, from current sensing to automotive systems and consumer electronics. For instance, integrating TMR-based sensor arrays with Rogowski coils has significantly extended the bandwidth from DC to several hundred megahertz, overcoming the frequency limitations in current measurement. Additionally, TMR sensor arrays have been proposed for use in misalignment-tolerant wireless charging systems for electric vehicles on roadways. Combined with a simple-to-manufacture coil design, this solution effectively addresses misalignments over a wide range, ensuring high power transmission and charging efficiency. Numerous studies have highlighted the broad applications of TMR sensors in fields such as intelligent public security detection, metal detection, and magnetic field imaging, demonstrating their versatility and effectiveness in advanced technological applications.

E. Other Sensors

Giant Magnetoimpedance Sensor. Giant Magnetoimpedance (GMI) sensors represent a significant advancement in magnetic sensing technology, offering pico-tesla (pT) sensitivity and robust performance in challenging environments. These sensors operate efficiently within a 50–70 kHz bandwidth, enabling reliable kbps-level data transmission, and require minimal power, functioning stably at just 50 mV AC voltage. Their compact design and flexibility tolerance make them ideal for wearable devices and micro-robotic systems, particularly in biomedical applications where safe, low-field communication is critical. Unique among magnetic sensors, GMI devices can distinguish magnetic polarities, a feature absent in traditional magnetoresistive technologies. Validated for underground and underwater communication up to 300 meters, they also show promise in wireless sensor networks (WSNs) for disaster monitoring in RF-hostile zones. Recent innovations include multimodal functionality, combining touchless magnetic field detection with contact-based tactile pressure sensing, all while maintaining signal integrity under mechanical stress.

Superconducting Quantum Interference Devices. Superconducting Quantum Interference Devices (SQUIDs) deliver femto-Tesla (fT) sensitivity, essential for detecting neural activity in magnetoencephalography (MEG) or cardiac signals in magnetocardiography (MCG). Their principle of operation is based on quantum interference in superconducting loops incorporating Josephson junctions, which allows them to detect minute changes in magnetic flux. However, this extreme sensitivity also brings significant complexity. To operate properly, SQUIDs must stay in a superconducting state, which requires cryogenic temperatures—usually just a few degrees above absolute zero. This is typically achieved with liquid helium, or sometimes liquid nitrogen. Such cooling systems limit portability, increase system size, and raise costs. Because of this, SQUIDs are not suitable for mobile applications, especially when small size, low power, or room temperature operation is needed. Moreover, SQUIDs are easily affected by magnetic noise from the environment. They often require magnetic shielding to maintain accurate readings, adding further difficulty to integration. Despite their limitations, SQUIDs remain the preferred choice in certain applications where extreme sensitivity is essential. In biomagnetism, for instance, they are used in magnetoencephalography to detect the tiny magnetic fields produced by brain activity. SQUIDs are also applied in magnetic anomaly detection, airborne electromagnetic surveys, and even archaeological exploration, such as detecting buried tombs.

Fluxgate Sensors. Fluxgate magnetic sensors work based on Faraday's law of electromagnetic induction. They are known for their high sensitivity and resolution when detecting weak magnetic fields. However, they are not suitable for many applications because of their limited bandwidth. Most fluxgate sensors can only respond to signals up to about 10 kHz [53]. Their relatively large size, complex structure, and higher power consumption also make them less ideal for compact or battery-powered systems. Even so, fluxgate sensors are used in fields that demand high precision, such as geophysical exploration, space science, and non-destructive testing. For example, China's Tianwen-1 and NASA's Juno missions used them to measure the magnetic fields of Mars and Jupiter [54]. On Earth, they are used in magnetic anomaly detection through ground surveys, helicopter-based measurements, and increasingly, unmanned aerial vehicles. In these applications, their stability, directional accuracy, and low drift are major advantages. Meanwhile, magneto-optical sensors, while leveraging Faraday or Kerr effects for optical readout, lag behind with micro-tesla sensitivity and an inability to discern magnetic polarity. Their reliance on precise optical alignment further limits cost-effective scalability.

F. Recent Advancements in Magnetic Sensor Technologies

Quantum Magnetic Sensor Breakthroughs. Recent advancements in quantum magnetic sensing are redefining measurement limits. Nitrogen-vacancy (NV) diamond sensors, such as MIT's 2023 prototype, now achieve unprecedented resolution, enabling non-invasive detection of neural activity and mineral deposits. Cold atom interferometers have reached extreme excellent sensitivity, revolutionizing underground resource mapping and inertial navigation. Concurrently, miniaturized superconducting quantum interference devices (SQUIDs) with sub-5-mm footprints are unlocking portable biomagnetic imaging, such as magnetoencephalography (MEG), while operating at cryogen-free temperatures. These technologies bridge quantum physics and real-world applications, offering solutions for healthcare, defense, and geophysics.

Smart Integrated Magnetic Systems. The fusion of magnetic sensors with advanced electronics is driving intelligent, multi-functional systems. STMicroelectronics' 2024 CMOS-MEMS hybrid sensors integrate AI accelerators for real-time noise cancellation and adaptive calibration, enhancing accuracy in dynamic environments. Energy autonomy is now achievable through magneto-electric harvesters, like Nanyang Tech's 2023 design, which converts magnetic field fluctuations into power with 35% efficiency. Meanwhile, 3D Hall sensor arrays paired with deep learning algorithms, such as those in Tesla's Full Self-Driving (FSD) platform, dynamically compensate for electromagnetic interference in autonomous vehicles. These systems prioritize miniaturization, energy efficiency, and edge computing, making them ideal for IoT, robotics, and smart infrastructure.

Emerging New Materials for Magnetic Sensors. Novel material innovations are overcoming traditional limitations in magnetic sensing. Antiferromagnetic Cr_2O_3-based sensors eliminate the need for external bias fields, enabling ultra-low-power operation in aerospace and industrial systems. 2D heterostructures, such as graphene-MoS_2 layers, demonstrate $>$1000 T/Wb magnetoresistance, 10$\times$ higher than conventional TMR sensors, for high-density data storage applications. Additionally, KAIST's 2024 flexible magnetic e-skin, crafted from ultrathin (0.1 mm) polymer composites, achieves sub-mT sensitivity while bending to 180°, paving the way for wearable health monitors and soft robotics. These materials push the boundaries of sensitivity, durability, and form-factor adaptability, addressing demands from quantum computing to next-generation electronics.

IV. Sensing Task

Sensing plays a crucial role that enables precise and reliable data acquisition across various applications [55]–[62]. According to the magnetic sensors' characteristics and the market demand, we divide their sensing works into five categories: current sensing, angle and position sensing, tactile sensing, speed sensing, and material sensing. We will introduce these works in the following. Finally, we summarize the lessons learned to help readers conduct their research more smoothly. In order to better demonstrate the advantages of magnetic field sensing, we will make a brief comparison between magnetic field sensing technology and other wireless or wearable sensing technology.

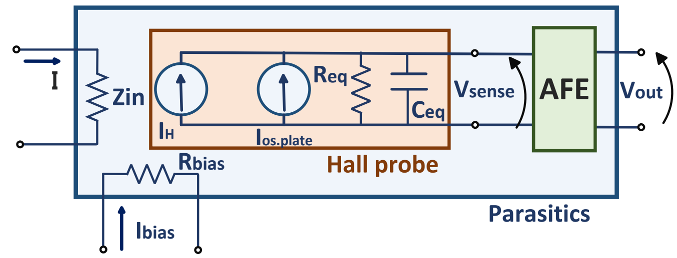

Fig. 5. Equivalent-circuit representation of the Hall-based sensor.

A. Current Sensing

Magnetic techniques are widely used for current detection in various applications due to their non-contact, isolated, and high-precision measurement capabilities. In industrial systems, they monitor motor currents and power grid conditions for overload protection. Renewable energy systems, such as solar inverters and battery management, rely on them for efficient power conversion. Consumer electronics, including smart appliances and fast-charging devices, utilize these sensors for accurate current measurement. Electric vehicles and rail transport employ them in traction control and overcurrent protection. Medical equipment and precision instruments benefit from their isolation properties for safe operation. Additionally, they are essential in data centers, telecom base stations, and aerospace systems, ensuring reliable and efficient current monitoring across diverse environments [63] [64].

A typical Hall-Effect Current Sensors (HECS) model comprises a current-to-magnetic field transducer, a Hall probe, and an analog front-end (AFE) [65]. The equivalent circuit of the Hall sensor is shown in Fig. 5. Non-idealities remain a major challenge for all three components. Recent research has established a mathematical model of HECS output as

$$V_{sense} = \frac{R_{eq}(I_{os,plate} + I_H)}{1 + j2\pi f R_{eq} C_{eq}} \tag{2}$$

where f represents the frequency. This model is crucial for fully utilizing the capabilities of electronic circuits to compensate for the intrinsic non-idealities of the Hall plate.

Ref. [47] enhances the linear range of current sensors by employing an angled sensor arrangement, which improves sensitivity and significantly reduces the size of TMR current sensors. By accounting for the influence of inclined conductors, this work enables the accurate measurement of eccentric and inclined conductor currents over a wide dynamic range.

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This is achieved through a correction algorithm and four three-dimensional sensors arranged in a specific pattern to determine the intersection and inclination points. A measuring system consisting of three TMR sensors is designed to measure the magnetic field generated by the current in a rectangular bus, with the sensors placed at a specific distance from the bus.

In addition, GMR sensors have advantages in linear response range, bandwidth, sensitivity, temperature stability, structure, and cost. Therefore, GMR sensors emerge as the most viable option for distributed supervision in current detection. The high-precision current sensor developed by [66] is based on the coupling architecture of GMR chip and ring magnetic core-feedback winding, eliminating the influence of temperature drift through the closed-loop feedback mechanism, and strictly controlling the linear error within 0.7%, achieving a high frequency response of over 100KHz bandwidth and less than 0.1% full scale hysteresis error. It can carry out weak current detection, providing a solution for high-precision industrial measurement.

B. Angle and Position Sensing

Magnetic techniques are extensively used for position and angle detection across multiple industries due to their contactless operation, high precision, and durability. In automotive systems, they measure steering wheel angles, throttle positions, and pedal movements for enhanced control and safety. Industrial automation relies on them for robotic arm positioning, linear actuators, and rotary encoders in motors. Consumer electronics, such as smartphones and gaming controllers, use them for orientation sensing and joystick [67]. In aerospace and defense, they monitor flight control surfaces and landing gear positions. Additionally, medical devices leverage magnetic sensors for precise instrument alignment, while renewable energy systems employ them in wind turbine pitch control and solar panel tracking. Their robustness and reliability make them ideal for harsh environments like heavy machinery and underwater equipment.

AMR sensors play a significant role in vehicle detection, utilizing magnetic field modulation caused by passing vehicles to identify their presence and movement [68]. Zusheng Zhang et al. [69] developed the ”Parking Occupancy Detection Algorithm Based on AMR Sensor,” which leverages AMR sensors to detect fluctuations in magnetic fields as vehicles enter, park, and exit parking spaces. By extracting key features from these magnetic signals—such as fluctuation frequency and stable drift—the algorithm accurately classifies parking spaces as vacant or occupied. This approach enables real-time monitoring of parking occupancy, facilitating efficient parking management and optimization.

Additionally, the AMR proximity sensor accurately detects the presence of ferromagnetic or conductive objects by measuring the resistance of a thin film Permalloy strip with built-in demodulation [70]. Its integrated demodulation capability eliminates the need for external demodulation circuits, simplifying the system design and enhancing efficiency.

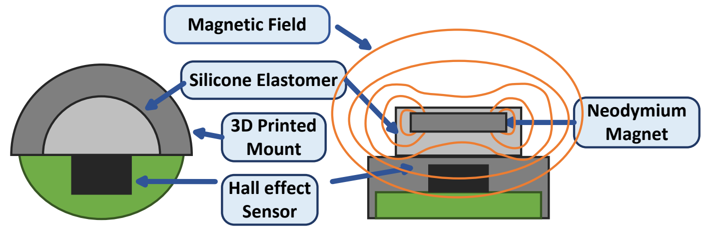

Fig. 6. Components of the soft Hall effect tactile sensor.

C. Tactile Sensing

Magnetic techniques enable precise tactile detection in applications requiring contactless force/position feedback. In robotics, they measure gripper pressure and object proximity for delicate manipulation. Medical devices use them for surgical tool force sensing and prosthetic touch sensitivity. Automotive interfaces integrate them into touch-sensitive controls and haptic feedback systems. Consumer electronics employ these sensors in pressure-sensitive touchscreens and adaptive gaming controllers. Industrial equipment leverages them for collision detection and assembly line quality control. Their immunity to environmental interference makes them ideal for sterile (medical) or harsh (factory) environments where traditional tactile sensors may fail. Emerging applications include VR gloves and smart textiles that require distributed pressure mapping without physical wiring constraints.

Two types of pressure sensors are widely used across various fields of engineering. The first is piezoelectric tactile sensors, known for their high sensitivity and signal-to-noise ratio. These sensors operate based on the piezoelectric effect, where mechanical stress applied to specific materials generates an electrical charge. Their high natural frequency makes them ideal for applications requiring rapid and precise touch sensing, such as robotic fingertips and medical diagnostic tools. The second type is capacitive tactile sensors, valued for their simplicity and versatility. These sensors detect changes in capacitance caused by the deformation of a dielectric material between two conductive plates. Their ability to measure both pressure and force distribution makes them useful in applications requiring detailed touch mapping.

It is essential to consider specific sizes and geometries for different applications, as both normal and shear forces must be measured to respond appropriately to contact forces. JJ Clark et al. first proposed the use of Hall effect sensors and magnets for measuring tactile responses [71]. Currently, a common sensor type is based on 3-axis force sensing [72]. As shown in Fig. 6, using four 3-axis sensors, CM Oddo et al. developed a robotic fingertip capable of more accurate force sensing [73]. Similarly, recent research by Dominic Jones et al. introduced a 3-axis tactile sensor for use in a thumb immobilization splint. A 4 mm radius, 3 mm-thick sensor was identified as meeting the required range and sensitivity, with a prototype sensor exhibiting a pressure range of 45 kPa for normal forces and 6 kPa for shear forces [74].

D. Speed Sensing

Magnetic techniques are widely used for speed detection in various applications due to their non-contact operation, high reliability, and environmental robustness. In automotive systems, they measure wheel speed for ABS and transmission control, while also monitoring engine RPM. Industrial applications include motor speed regulation in conveyor systems and CNC machinery. Consumer electronics utilize them in cooling fan speed control for computers and appliances. Transportation systems rely on magnetic speed sensors for railway axle monitoring and e-bike motor management. Additionally, they play critical roles in wind turbine speed regulation, drone motor control, and fitness equipment like treadmills. Their ability to function in harsh conditions (dust, moisture, and extreme temperatures) makes them particularly valuable for agricultural machinery, marine propulsion systems, and aerospace applications where traditional sensors may fail.

Jiang et al. [50] proposed a method for speed and position detection in high-temperature superconducting (HTS) maglev trains using TMR sensors and magnetic arrays. This method effectively mitigates electromagnetic noise interference within the levitation air gap. Additionally, they applied an improved Automatic Peak Detection (AMPD) algorithm based on multi-hysteresis, achieving speed accuracy between 95% and 97% and positioning accuracy ranging from 1 cm to 3 cm. This approach provides a pathway for enhancing the performance of HTS maglev train control systems. Due to their high sensitivity, low noise, negligible hysteresis, and robustness to harsh environmental conditions, magnetoresistance (MR) sensors are also frequently used for speed sensing in automotive applications.

Magnetorheological sensors for wheel speed applications primarily feature four magnetic sensing elements arranged in Wheatstone Bridges to increase output voltage and reduce temperature and lifetime drift. [75] proposes a new type of reluctance wheel speed sensor whose transfer function is linearized in the frequency domain. This directly improves the reliability of the sensor, as temperature and lifetime drift are significantly reduced. In addition, the device can measure interference fields perpendicular to the sensing direction.

Magnetic field sensors can not only measure wheel speed, but are also expected to enter the Internet of Things field in combination with vision sensors. [76] proposes a new method for road traffic monitoring via a single magnetic sensor that is small and easy to install. The developed magnetic sensor system is wirelessly connected, cost-effective and environmentally friendly. Moving vehicles are magnetically modeled and vary according to the type of road vehicle. By modeling local magnetic field perturbations caused by moving vehicles, we extract the characteristics of magnetic waveforms for vehicle identification and speed estimation. High accuracy, can adapt to fog, cloudy and other poor light natural environment.

E. Industrial Material Sensing

Magnetic techniques enable precise industrial material detection by measuring magnetic properties and field variations in diverse applications. They identify material composition in metal sorting systems, detect defects in pipelines and welds through magnetic flux leakage testing, and monitor ferrous content in mining/mineral processing. Quality control systems use them to verify material thickness in steel production and coating applications. Automotive/aerospace manufacturers employ these sensors for component integrity testing, while logistics operations utilize them for metal contamination detection in food/pharmaceutical production lines. Their non-contact operation allows inspection of moving materials on conveyor systems, and their sensitivity to subtle magnetic variations supports applications ranging from structural health monitoring in bridges to authenticity verification in currency/security printing. The technology's robustness in harsh industrial environments makes it indispensable for foundries, oil/gas infrastructure, and recycling facility material separation systems.

The AMR gradiometer is a highly effective tool for mine detection [77], as it measures the gradient field of magnetic objects to distinguish between hazardous and harmless debris. The gradiometer employs strategically arranged AMR sensors, such as the KMZ51 type, to suppress large AC excitation fields while maintaining sensitivity to both DC and AC field gradient responses. These sensors offer high spatial resolution and can detect objects at considerable depths, facilitating efficient mine clearance operations. The KMZ51 AMR sensor series plays a critical role in detecting anomalies induced by buried magnetic materials within soil environments [78]. By detecting variations in magnetic flux density, these sensors precisely locate and characterize buried magnetic anomalies. Advanced data processing techniques, such as artificial neural networks trained with Levenberg-Marquardt backpropagation algorithms, enable the accurate detection, assessment, and visualization of buried magnetic materials, benefiting fields like geophysics, archaeology, and civil engineering.

GMR sensors are also widely used in structural and crack detection, where the current is intentionally induced in test structures to reveal defects through magnetic field anomalies. Compared to traditional current sensing, the structural/crack detection based on GMR sensors does not focus on detecting the specific value of the current but rather on the differences of current variation. N.V. Nair et al. [79] introduced a novel GMR-based eddy current field measurement system, designed to inspect components at rates comparable to magnetic optic imaging (MOI) sensor systems, which is a non-contact high-resolution sensing technology that combines magnetic fields with optical techniques. It uses polarized light and magnetic materials to interact, causing changes in the polarization state of the light to depict the distribution of magnetic fields. This system retains the MOI system's current excitation scheme but replaces the optical sensor with a GMR-based field sensor, preserving MOI's rapid inspection speed while achieving quantitative field measurement.

Mao et al. [80] proposed a novel metal detection system based on a TMR sensor array. By leveraging the small size and high sensitivity of TMR sensors, along with a proposed magnetic anomaly signal model and matched filtering, the system achieves a spatial resolution of 1 mm for metal particle localization and 3 cm for spatial resolution, overcoming the

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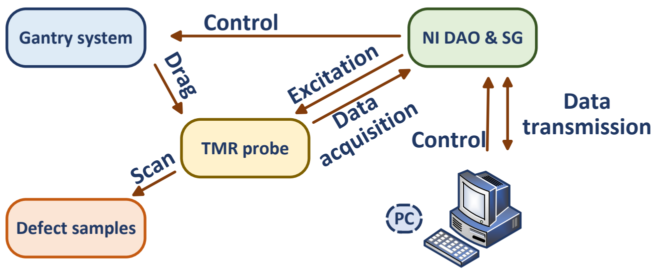

Fig. 7. Experiment setup for magnetic detection.

limitations of traditional coil metal detectors that can detect metals but lack precision in locating fragments. Sun et al. [81] shown in Fig. 7 introduced an eddy current testing (ECT) probe with a high-resolution TMR array sensor for vector magnetic field measurement. This probe excites test materials via electromagnetic induction, and the integrated TMR arrays monitor and record the vector magnetic field patterns, enabling high-resolution imaging of all three magnetic field components and facilitating the three-dimensional detection of metal structures.

F. Medical Material Sensing

Magnetic techniques enable innovative biological detection by measuring biomagnetic signals and magnetic nanoparticle labels with high sensitivity. They are used in medical diagnostics for detecting cardiac (MCG) and neural (MEG) activities through ultra-sensitive magnetometers. In-vitro diagnostic devices employ magnetic immunoassays to identify biomarkers for diseases like cancer or infections. Point-of-care testing systems utilize magnetic sensors to count labeled cells or detect DNA sequences. Pharmaceutical research applies them for drug discovery by monitoring magnetic bead-bound molecular interactions. Food safety inspections leverage this technology to identify bacterial contamination through magnetic separation techniques. Emerging applications include implantable sensors for real-time glucose monitoring and portable devices for detecting waterborne pathogens. The technology's ability to perform label-free, non-invasive detection makes it valuable for neuroscience research, while its compatibility with microfluidics supports lab-on-a-chip diagnostic platforms. These sensors overcome optical limitations in turbid samples, offering advantages for whole-blood testing and in-field biological threat detection [82].

GMR sensors are widely used in biology and medicine. Kubera Kalyan et al. [83] introduce a straightforward heart rate (HR) monitoring system using a GMR sensor. The GMR sensor is placed on the human wrist to capture the magnetoplethysmographic signal. This signal is then processed through basic analog and digital instrumentation stages to provide the heart rate reading. This system consists of two main components: the GMR sensor unit and the signal conditioning unit. The prototype uses the AA004-02 GMR IC from NVE Corporation. This proposed method offers an efficient alternative to traditional HR monitors and is especially suitable for remote and continuous HR monitoring.

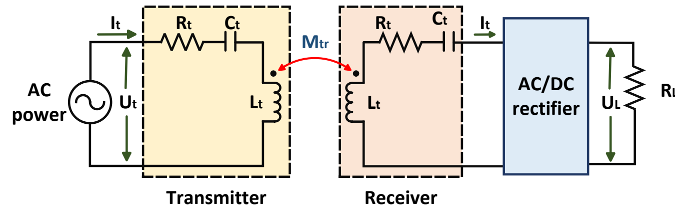

Fig. 8. Schematic view of the IPT-based WPT system.

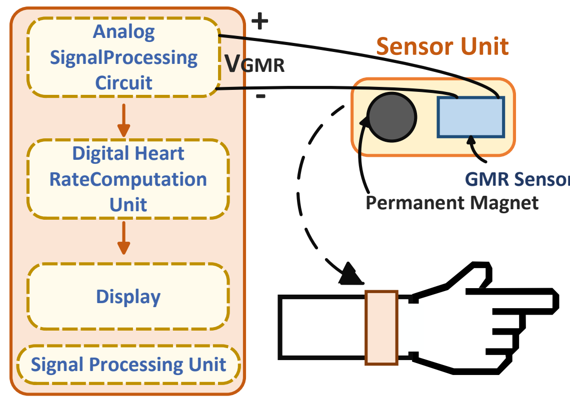

Fig. 9. A simplified architecture of vital sign monitoring.

GMR sensors also show adaptability for integration into lab-on-chip systems for portable biomolecular identification. GMR-based sensors hold significant promise for biomarker detection. Neeraja Ravi et al. [84] introduced a gene expression analysis platform utilizing a GMR biosensor array, enabling cost-effective magnetic detection for multiplexed transcript identification and quantification. Their study focused on characterizing the sensitivity, dynamic range, and quantification accuracy of PCR-amplified cDNA using GMR sensors, specifically targeting the reference gene GAPDH. The results revealed a dynamic range spanning four orders of magnitude, with detection limits of 1 pM for 15-cycle amplified synthetic GAPDH PCR products and 0.1 pM for 18-cycle amplified products.

To better meet the measurement requirements in the medical field, GMR sensors have been developed in various structures and forms. D.A. Hall et al. [85] highlighted the growing adoption of giant magnetoresistive biosensors for highly sensitive biomolecular detection. They introduced a scalable circuit architecture designed for larger sensor arrays (64 individually addressable sensors), which achieves rapid readout using a combination of time-domain and frequency-domain multiplexing, allowing the entire array to be scanned in under four seconds. A novel high-sensitivity sensor system based on GMR [86] was implemented in a magnetic field microscope. This system, utilizing a magnetoimpedance (MIP) sensor as a highly sensitive magnetic probe, demonstrated a detectivity of 13 $pT/\sqrt{Hz}$ at 100 Hz. J.C. Rife et al. [87] developed the Bead Array Counter (BARC), a biosensor system using GMR sensors on a chip to capture and detect micron-sized paramagnetic beads. C. Marquina et al. [88]

employed magnetic labels for high-sensitivity analyte quantification, utilizing the magnetoresistive response of a spin-valve GMR sensor near magnetic nanoparticles in a lateral flow strip, providing a precise detection mechanism.

G. Comparison with Other Sensing Techniques

Comparison with Wireless Sensing. Magnetic sensing offers distinct advantages over other wireless sensing technologies. Unlike motion sensors that require wearable devices, vision-based systems limited by lighting/obstructions, or acoustic methods vulnerable to noise and short-range attenuation, magnetic sensors leverage magnetoresistive effects to detect multidimensional field changes (direction/intensity) with strong anti-interference capability, low power consumption, and flexible deployment.

Comparison with Wearable Sensing. Wearable sensing technologies each have distinct limitations compared to magnetic sensing. First, PPG measurements can sometimes be affected by variations in skin color and tone, as they rely on light absorption and reflection. Magnetic sensors are less sensitive to these variations, potentially making them more reliable across a wider range of individuals. Second, magnetic sensors allow for completely contactless monitoring as the signal can propagate through the skin tissue, body fluids, and fabrics. This eliminates the need for physical contact with the skin, reducing discomfort and potential skin irritation that can occur with PPG sensors.

Resistive sensors offer fast response but suffer from high power consumption and temperature drift. Capacitive sensors face challenges in signal acquisition, complex circuits, and crosstalk. Piezoelectric/triboelectric types provide high sensitivity yet are prone to environmental interference and signal processing difficulties.

For example, in Ref. [89], a permanent magnet is placed on the radial artery of the wrist, and a Wheatstone bridge composed of two parallel GMR units and two anti-parallel GMR units is used to detect subtle changes in the magnetic field, and the induced biological magnetic field is modeled to obtain the respiration rate and heart rate of the wearer. In order to eliminate the interference of external magnetic field noise, it can be used to add a shielding layer and a high bias magnetic field. In terms of the miniaturization of the device, because the magnetic field sensor does not need too much signal processing circuit, it can be made by using the inside-out winding method and flexible PCB, so as to achieve the production of wearable devices.

Comparison with Optical Sensing. Magnetic sensors excel in environments where non-line-of-sight detection, immunity to ambient light, and operation in opaque or harsh conditions (e.g., dust, fog, or smoke) are critical. They are ideal for measuring magnetic fields, detecting ferrous materials, or monitoring moving components in industrial settings. In contrast, optical sensors provide superior spatial resolution, high-speed data acquisition, and precise measurements of parameters like displacement, temperature, or chemical composition. However, they are sensitive to environmental interference such as obstructions, ambient light fluctuations, or reflective surfaces, limiting their reliability in cluttered or dynamic settings.

Comparison with Acoustic Sensing. Magnetic and acoustic sensors differ fundamentally in their sensing mechanisms and use cases. Magnetic sensors detect changes in magnetic fields, making them suitable for proximity sensing, navigation (e.g., compasses), and current measurement in electronics, with minimal interference from acoustic or vibrational noise. Acoustic sensors, on the other hand, rely on sound waves to measure parameters like pressure, flow, or structural integrity. While acoustic sensors perform well in liquid media and can penetrate dense materials, they face challenges in noisy environments due to signal attenuation and susceptibility to ambient vibrations.

V. Communication

Reliable communication is fundamental to modern technological advancements across industries [90]–[96]. Magnetic technology is gaining attention for its unique advantages in challenging communication scenarios. Magnetic Induction (MI) communication uses near-field coupling between coils, generating signals via Faraday's law. In biological systems, it enables efficient, non-invasive communication for medical and wearable devices. Underwater, magnetic fields outperform RF signals by minimizing attenuation. Underground, they bypass conductivity issues that hinder traditional methods. This versatility makes magnetic technology valuable across diverse fields.

The most suitable type of magnetic sensor for specific scenarios is shown in Table VII. AMR and GMR sensors detect changes in magnetic field direction using magnetoresistance. AMR sensors, used in body area networks (BANs), achieve Mbps data rates with compact coils, making them suitable for wearable devices [97]. GMR sensors offer higher sensitivity, supporting high-speed data transfer in noisy environments. Fluxgate sensors measure low-frequency magnetic fields (<10 kHz) by saturating a ferromagnetic core. They detect geomagnetic changes for navigation and remain stable in dynamic environments, such as underwater currents, making them useful for military applications. SQUID sensors detect ultra-weak magnetic fields (fT-level) through superconducting quantum effects, enabling biomagnetic communication like neural signal monitoring. OPM sensors, using optically pumped atomic vapor, offer high sensitivity without cryogenics but operate at low frequencies (<10 Hz), requiring specialized modulation [98]. Hall effect sensors generate a voltage proportional to magnetic field strength, enabling simple binary communication, such as proximity detection. Their low cost and fast response suit industrial control, but their high detection threshold limits range to under 1 meter.

The integration of magnetic sensors in communication systems focuses on optimizing performance while adapting to environmental constraints. Giant Magnetoimpedance sensors offer high sensitivity, compact size, and ease of use, making them more practical than OPM and SQUID sensors, which require cryogenic cooling or shielding [98]. Magnetic sensors also enable precise localization by using received magnetic field strength (RMFS) and rotation matrix-based algorithms to achieve sub-meter accuracy in underwater networks [99].

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TABLE VII
COMPARISON OF MAGNETIC SENSORS FOR DIFFERENT COMMUNICATION APPLICATIONS

Sensor Type	Main Applications	Advantages
Magneto-Inductive	Near-field magnetic communication, magnetic compasses, mineral prospecting	High sensitivity, suitable for low-power applications
Fluxgate	Navigation systems, Earth's field measurement, munitions fuzing	High precision, good stability for low-frequency signals
Hall Effect	Non-contact switching, magnetic memory readout, current sensing	Simple design, cost-effective, widely used in industrial applications
Anisotropic Magneto-Resistive (AMR)	Magnetic field communication, flexible electronics	Compact size, good sensitivity, low power consumption
Giant Magneto-Resistive (GMR)	Magnetic storage, Earth's field perturbation measurement	High sensitivity, fast response time
Superconducting Quantum Interference Device (SQUID)	Brain function mapping (MEG), magnetic anomaly detection, MRI	Ultra-high sensitivity (femto-Tesla level), suitable for biomagnetic measurements
Optically Pumped Magnetometer (OPM)	Magnetoencephalography (MEG), magnetocardiography (MCG), communication	High sensitivity, portable compared to SQUID, no need for cryogenic cooling

Applications range from wearable devices, where resonant mHBC coils reduce path loss by 20 dB in biological tissues, to underwater sensor networks, where MI sensors operate efficiently in freshwater (20 m range) and seawater due to their low energy consumption and resistance to conductive media. These advancements improve privacy, energy efficiency, and adaptability in dynamic environments [100].

A. Biological Communication

Magnetic technology has shown great potential for applications in human body communication (HBC), offering an alternative to traditional methods. In the field of HBC, the primary communication method has been electric field-based HBC (eHBC) [100], where the human body or textile clothing serves as the communication channel. eHBC is typically divided into two modes: galvanic coupling and capacitive coupling, both using electric fields. However, galvanic eHBC suffers from significant path loss due to the low conductivity of the human body. On the other hand, capacitive eHBC requires large ground planes to improve coupling and reduce path loss, but it is highly sensitive to environmental factors, leading to instability.

To address these challenges, a new approach called magnetic human body communication (mHBC) has been developed in recent years, which utilizes magnetic sensors for communication. mHBC offers several advantages over eHBC. Magnetic fields experience less attenuation within the human body, allowing for more efficient signal propagation. Magnetic field sensors are highly sensitive and accurate, enabling lower path loss and reducing the impact of environmental factors and posture changes. This results in lower power consumption and a wider communication range.

Furthermore, since the permeability of most biological tissues is similar to that of air, magnetic fields can propagate more freely through the body. Although human tissues exhibit slightly lower magnetic permeability than free space, showing diamagnetic properties, the opposing magnetic fields produced by the tissues are weak [100], and this effect is negligible. Additionally, the low electrical conductivity of human tissues at lower frequencies minimizes the formation of eddy currents, further reducing losses. Consequently, mHBC technology has shown promise in integrating into wearable devices, where magnetic field sensors can be used to collect biological data for applications in both wearable and medical technologies.

Communication paradigm	Propagation speed	Data rates	Communi cation ranges	Channel dependency	Stealth operation
MI	3.33×10^7 m/s	~ Mb/s	10-100 m	Conductivity	Yes
EM	3.33×10^7 m/s	~ Mb/s	⩽10m	Conductivity, multipath	Yes
Acoustic	1500 m/s	~ Kb/s	~ Km	Multipath, Doppler, temperature, pressure,salinity,environmental sound noise	Audible
Optical	3.33×10^7 m/s	~ Mb/s	10-100m	Light scattering, line of sight communication, ambient light noise	Visible

Fig. 10. Comparison of underwater MI, EM, acoustic, and optical communications.

B. Underwater Communication

In underwater wireless communication, three primary methods are commonly used: acoustic, optical, and electromagnetic (EM) communications. Figure 10 compares these approaches with MI. Among these, acoustic communication is the most widely adopted, but it faces several challenges. The low propagation speed of sound underwater and the limited available acoustic bandwidth result in significant transmission delays, often measured in seconds, and lower data rates, typically in the kilobits per second (Kbps) range. Additionally, acoustic signals are prone to severe multi-path fading and highly variable channel conditions. Another concern is the potential

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disruption of marine life, particularly species like dolphins and whales, which are sensitive to sound disturbances.

MI has emerged as a promising alternative for underwater wireless communication, offering several advantages over traditional methods. MI communication provides more predictable and stable channel responses, negligible signal propagation delay, and cost-efficient, stealthy operation underwater [101]. These benefits make MI particularly suitable for applications such as communication between groups of underwater robots, including agile robotic fish. Through MI, these robots can exchange control signals and environmental data, mimicking the collective behavior of natural fish schools.

This capability enables robotic swarms to collaboratively track pollution sources, toxins, and biological hazards. In challenging underwater environments like flooded submarine compartments, shipwrecks, or submerged structures, traditional acoustic communication and larger underwater vehicles struggle to perform effectively. In contrast, small, maneuverable underwater robots with compact coil antennas are better suited for navigating tight spaces. MI communication ensures reliable, real-time data transmission, supporting efficient onsite hazard assessments and timely rescue operations. Furthermore, since MI uses non-audible and non-visible magnetic waves [102], it is ideal for both civilian and military applications, including submarine communication.

C. Underground Communication

Wireless underground communication using traditional EM wave techniques faces three major challenges: significant path loss, unpredictable channel conditions, and the need for large antennas. These limitations restrict the effective communication range to very short distances, making it difficult to achieve reliable coverage.

MI technology offers a promising alternative, effectively addressing two of these challenges—dynamic channel conditions and the need for large antennas. MI communication remains stable in dense media like soil and water because these materials have similar magnetic permeability (μ) to air. This minimizes signal loss and ensures reliable performance in different environments. Unlike traditional EM systems that need large antennas, MI uses small wire coils for transmission and reception. These coils can be made very small, allowing for compact and lightweight designs ideal for underwater robots and wearable devices [101].

However, MI systems still suffer from considerable path loss, a challenge that is even more pronounced compared to traditional EM waves. To mitigate this, MI waveguide techniques have been developed, providing an efficient solution by reducing path loss and improving communication performance in underground environments [103].

Wireless Underground Sensor Networks (WUSNs) are increasingly utilized across various fields, including environmental monitoring, seismic risk assessment, and communication in underground tunnels or mines [104]. WUSNs play a critical role in monitoring infrastructure, agricultural soil health, and the structural integrity of buildings. For example, sensor nodes deployed in agricultural fields can operate without interfering with tractor activities, while in construction, sensors can be embedded in foundations or walls to assess building health [105]. Moreover, WUSNs are valuable for localization tasks, such as tracking wildlife or locating personnel and robots within mines.

However, challenges persist, particularly in MI-based localization, where factors like coil misalignment or deployment inconsistencies can lead to signal uncertainties [105]. Despite these obstacles, WUSNs continue to enhance security and offer promising solutions for a range of underground applications.

D. Cross-Environment Communication

Recent advances in MI communication demonstrate its potential for cross-environment applications. Notably, air-to-water and water-to-air scenarios benefit from MI's unique propagation characteristics. Unlike conventional EM waves, which suffer severe attenuation at the air-water interface, the magnetic field component of MI signals penetrates this boundary with minimal attenuation [106]. This enables efficient bidirectional communication across media. For example, underwater telemetry systems utilize MI for remote control of autonomous underwater vehicles (AUVs), achieving reliable data transfer between submerged devices and surface vessels [99].

The feasibility of such cross-environment communication arises from the near-uniform magnetic permeability (μ) of heterogeneous media (e.g., air, water, soil) [101]. Specifically, since μ remains consistent across these environments, MI signals maintain stable penetration depths and communication ranges. This capability supports diverse applications, including underground-to-air IoT networks and subsea infrastructure monitoring.

Despite these advantages, challenges persist in extending the operational range of cross-environment MI systems. Cooperative relay strategies have been proposed to address rapid power decay in short-range medical implants [107]. However, their application to larger-scale scenarios, such as underwater sensor networks, still needs further research. Recent studies propose hybrid architectures to overcome this limitation. These systems combine acoustic and magnetic modalities, using acoustic waves for long-range detection and MIC for low-latency, high-accuracy data transmission at medium ranges [101].

E. System Security

Physical-layer Security Benefits. Magnetic communication provides inherent spatial confinement due to its near-field propagation characteristics. Magnetic fields decay rapidly with distance (following a sixth-order path loss model [101] and are localized around the coils, which naturally reduces the risk of eavesdropping. For example, in magnetic human body communication (mHBC), the energy primarily remains within the magnetic near-field, minimizing signal leakage to external devices and enhancing privacy for medical applications [100]. This "bounded broadcast" property significantly reduces the attack surface compared to traditional wireless technologies.

Identified Threats and Limitations. Despite these advantages, magnetic networks still face security vulnerabilities.

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A SWOT analysis of MI-based wireless underground sensor networks highlights ”insecure networks” as a critical threat, although specific attack methods are not yet thoroughly studied [104]. Additionally, the directional sensitivity of magnetic links poses a security challenge. While misaligned coils can degrade legitimate communication (e.g., SNR drops to zero at 90° misalignment [99]), attackers could exploit this by physically adjusting rogue coils to intercept signals.

To address these issues, cross-layer protocols like the Distributed Environment-Aware Protocol offer improved security with lower energy consumption and complexity. Furthermore, recent developments in IIoT enhance secure data transmission and flexible network management, helping to mitigate emerging underground threats.

F. Comparison with Electromagnetic and Optical Communications.

Comparison with Electromagnetic Communication The key difference between MI communication and conventional EM wave communication is how they transmit signals and adapt to different environments. MI transfers energy through inductive coupling between coils instead of radiating waves, which helps it avoid multipath fading and environmental interference common in EM wave transmission. EM waves weaken significantly in conductive media like water or soil, requiring large antennas and high power for effective communication [102]. In contrast, MI can transmit over 10–100 meters underwater using small coils because magnetic fields penetrate water with minimal loss. MI also has negligible delay and stable channel behavior, while EM waves are affected by impedance mismatches at material boundaries. Additionally, MI outperforms EM in cross-environment communication.

Comparison with Optical Communication. Optical communication achieves high data rates and low latency in clear water, but its performance is limited by water turbidity and the need for precise beam alignment. Optical waves are easily absorbed and scattered by water molecules and particles, causing severe interference and restricting the transmission range to less than 100 meters [101]. Additionally, maintaining accurate laser beam alignment is difficult in dynamic underwater conditions. In contrast, MI communication offers a stable and predictable channel, as it is not affected by multipath fading or Doppler effects. Unlike optical communication, MI does not rely on line-of-sight transmission and is unaffected by water turbidity, making it more reliable in complex underwater environments [102] [99].

G. Advances in MI Communication Systems

Integration of Magnetic Sensors in Communication. The integration of magnetic sensors in communication systems focuses on optimizing performance while adapting to environmental constraints. Giant Magnetoimpedance sensors offer high sensitivity, compact size, and ease of use, making them more practical than OPM and SQUID sensors, which require cryogenic cooling or shielding [98]. Magnetic sensors also enable precise localization by using received magnetic field strength and rotation matrix-based algorithms [99]. In wearable technology, resonant mHBC coils reduce path loss by 20 dB in biological tissues. These advancements improve privacy, energy efficiency, and adaptability in dynamic environments [100].

While the integration of magnetic sensing and communication holds great promise for applications such as wearable devices, human–machine interfaces, and underwater monitoring, there are still several challenges to be addressed. Firstly, magnetic field communication suffers from significant sensitivity to coil alignment. Due to the directionality of magnetic fields, even small deviations in orientation between the transmitter and receiver can lead to substantial degradation in signal strength [108]. This issue becomes more pronounced in dynamic or wearable scenarios where precise alignment cannot be guaranteed. Moreover, in harsh environments such as underwater or underground, the performance of magnetic induction communication is constrained by magnetic moment limitations, as increasing the magnetic moment to extend communication range often requires a trade-off with coil size and power consumption [109]. These factors collectively present key obstacles to the practical deployment of integrated sensing and communication systems.

Bandwidth and Data Rate in MI Communication. The bandwidth and data rate of MI communication involve trade-offs between environmental adaptability and system complexity. Conventional MI systems usually operate with narrow bandwidths (1-100 kHz) and low data rates (Kbps) [101]. These are suitable for basic monitoring but not for high-data-rate applications. For example, in underground environments, MI systems typically provide 1–2 kHz bandwidth and Kbps-level data rates. MI waveguide-enhanced systems can extend transmission range but still face similar bandwidth limitations. Advanced techniques like multi-band MI (MB-MI) and MIMO-MI can improve performance. MB-MI splits the frequency to create parallel subchannels, enabling data rates up to 50 Mbps over short distances (10 cm) in controlled conditions. MIMO-MI further enhances capacity by using orthogonal coil pairs to transmit independent data streams. Environmental factors also affect achievable rates. Underwater MI systems suffer bandwidth compression due to conductive media, reducing effective bandwidth to less than 10 kHz. This limits data rates to around 100 Kbps within 2 meters in freshwater [99]. Although these systems support low-power monitoring, further improvements, such as metamaterial coils or adaptive precoding, are needed to meet the demands of real-time video or multi-node communication.

Trade-offs Between Data Rate and Accuracy. Magnetic sensors balance data rate and accuracy through adaptive tuning and system trade-offs. AMR sensors adjust bandwidth to reduce noise, improving accuracy but lowering data rates. In localization, resource-limited nodes use lightweight algorithms like distance-based MLE, trading some precision for efficiency [99]. Tridirectional coil architectures enhance reliability with orthogonal signal aggregation [110] [111], while selective activation reduces power consumption. These strategies optimize performance under bandwidth and energy constraints.

Interference Mitigation in MI Communication. In magnetic

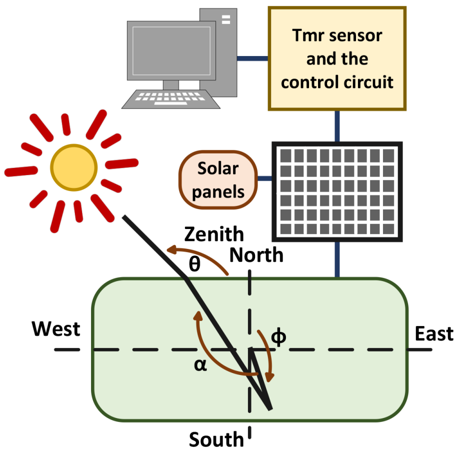

Fig. 11. Solar tracking system using a TMR sensor.

communication, interference between links can occur. MI link interference can be reduced through coil polarization optimization and system design. Aligning coils orthogonally or adjusting their 3D orientations helps minimize cross-coupling [112]. Orthogonal coils generate near-zero mutual flux, which suppresses interference. MI waveguide systems further reduce interference by using passive relay coils with optimized orientations and resonance frequencies. These relay coils confine magnetic fields to predefined paths and limit leakage [101]. In network deployments, dynamic coil reorientation mitigates co-channel interference by aligning transmitter-receiver polarizations [102]. These strategies improve throughput while controlling interference, especially in dense underground or underwater networks.

H. Discussion on Existing Magnetic Communication Surveys.

There are some review works that summarize the progress of magnetic communication, mainly focusing on underwater communication and power transmission. For example, Yuzhou Li et al. [113] propose a survey of underwater magnetic induction communications. The fundamental issues, recent advances, and challenges are discussed in this paper. Hongpeng Wang et al. [114] propose the construction and experimental verification of an integrated dual-mode overhauser magnetometer for marine magnetism survey. In addition, another work [115] focuses on the wireless power transfer and reviews the integrated data and energy communication network.

VI. Application

Magnetic sensors have various practical applications. These applications can be developed and integrated into diverse scenarios. This section will outline the application scenarios of magnetic sensors. These include smart grid management, automotive and transportation, security and surveillance, and medical and biotechnology.

A. Smart Grids Management

The magnetic field sensor can not only learn the fault information of the grid current, but also monitor the status of the transmission line. [116] has developed a new non-contact operation status monitoring technology for high-voltage transmission lines based on magnetic field sensing, which can reconstruct spatial and electrical parameters from the magnetic field emitted by the overhead transmission line, and can detect different states of the transmission line. Including sagging, galloping, and current imbalance. The magnetic field distribution of the line reflects the operating state changes in the transmission line space and electrical configuration. Interference from environmental conditions, such as bad weather conditions, can be completely avoided. Magnetic field sensing technology avoids the installation and maintenance of live wires, and can realize wide-area monitoring of transmission lines.

B. Automotive and Transportation

In the automotive and transportation sector, magnetic sensors play a pivotal role, not only enhancing vehicle performance and intelligence but also significantly improving driving safety and traffic planning efficiency. HECS [65], AMR sensors [117], GMR sensors [118], and TMR sensors sensors [46] are widely used to measure current in vehicles, a critical function for battery management systems, motor control, and other power electronic devices. Moreover, AMR and GMR sensors are employed in automotive systems to detect angular position, rotational speed, and positional data. These sensors are essential in steering systems, engine management, transmission control, and more. For instance, AMR sensors provide accurate linear voltage output in automotive pedal position sensing systems, enabling precise determination of pedal angle position [119]. GMR sensors are also used for angular position sensing and rotational speed detection [120].

Magnetic sensors are shining in the field of new energy, mainly including battery monitoring, location detection, and wireless charging. Ref. [121] is proposed to use a magnetic field sensor and an inverse piezoelectric field sensor for non-invasive current and voltage detection. Three magnetic field sensors and one electric field sensor are lined up without coil and magnetic core, which provides a theoretical basis for the design of a micro-high voltage ammeter. It is expected to be used for battery output monitoring of new energy vehicles or charging current detection in the field of road wireless charging. In addition to detecting the internal current of the vehicle, in order to realize the road charging of new energy vehicles, the location detection of traveling vehicles is also an important scientific research direction. In the field of electric vehicle wireless charging, the optimal power transmission efficiency mainly depends on the physical alignment of the charging coupler. [122] uses a GMR sensor array to track the maximum power point by sensing the magnetic field change of the primary coil to adjust the coil position. Jiang et al. proposed a method using TMR sensors and magnetic arrays for detecting the speed and position of high-temperature superconducting maglev trains. This method ensures efficient operation, safety, and reliable performance of maglev trains [50].

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In conclusion, magnetic sensors are critical for vehicle control, the development of intelligent transportation systems, and the precise monitoring of maglev trains. They are an indispensable technological component in the modern automotive and transportation sectors.

C. Integration with Cutting-edge Techniques

Magnetic techniques can be integrated with other cutting-edge technologies with the following key enhancements.

IoT Synergy. Magnetic sensors have emerged as ideal sensing components for IoT nodes due to their high sensitivity, low power consumption, and electromagnetic interference (EMI) resistance. For instance, [76] proposed a vehicle identification and speed estimation method based on a single small magnetic sensor. Compared with traditional induction loops and video-based image processing methods, magnetic sensors are small in size, low in cost, and environmentally friendly. They can achieve more accurate traffic situation perception in complex urban environments. Moreover, in the future, they can be combined with other sensor information to improve the performance of fine speed estimation, such as visual sensors.

Machine Learning Integration. The deep learning models for multi-sensor data fusion and adaptive calibration algorithms leverage neural networks to compensate for environmental drift. For example, TMR sensors play a critical role in precision detection and high-resolution imaging. Ref. [123] introduces a TMR-based MFL sensor for steel wire rope inspection using the orthogonal test method. Ref. [44] describes a paper currency micromagnetic signal detection system based on TMR sensors, improving banknote recognition accuracy by reproducing individual portraits on dollars and recognizing RMB denominations. Ref. [124] proposes a TMR array composed of 180 sensing elements, suitable for detecting deep-seated defects in multi-riveted structures under ultra-low-frequency excitation. In Ref. [125], TMR sensors employing AC modulation and impedance compensation methods are used to measure MCG signals.

Security Applications. Magnetic sensor technology has also been widely used in the field of security monitoring. These sensors are used for perimeter defense, personal object detection, underground metal detection, and other scenarios for real-time monitoring. In the area of metal detection, AMR gradiometers serve as efficient mine detectors [77], while the KMZ51 AMR sensor series [78] enables precise localization and characterization of underground magnetic anomalies. Mao et al. [126] introduced an intelligent security system based on TMR magnetic sensor arrays, which enhances resolution, though it cannot measure the position of metal fragments. Subsequently, Sun et al. [81] developed an eddy current testing (ECT) probe. This system offers higher resolution and helps detect three-dimensional metal structures. These monitoring solutions ensure the accurate detection, assessment, and visualization of underground magnetic materials, aiding in the identification of dangerous items such as landmines. They are also used in geophysics, archaeology, and civil engineering for precise underground exploration [126], [78].

D. Medical and Biotechnology

In the field of medicine, biomedical detection and heart rate monitoring are critical applications. Kubera Kalyan et al. [83] introduce a simple heart rate (HR) monitoring system that utilizes a GMR sensor, positioned on the human wrist.

A significant application of GMR technology is in biomolecular identification and gene expression analysis. GMR arrays enable cost-effective magnetic detection for multiplexed transcript identification and quantification [84], aiding in the understanding of gene expression and its role in disease mechanisms. GMR technology also shows great potential in pathogen and tumor biomarker detection. By employing GMR sensors for highly sensitive detection, various diseases can be diagnosed promptly [86]. Furthermore, high-sensitivity biomolecular detection represents another important area of medical research [85], [87]. Two DNA detection strategies using a GMR biosensor platform have been developed [127]. Yang Gao et al. [128] designed a GMR multi-biomarker immunoassay biosensor capable of simultaneously detecting twelve tumor markers. The AAL024 GMR sensor integrated with Fe3O4/rGO nanocomposites achieves rapid, highly sensitive BSA detection within 30 seconds, offering a reliable and user-friendly biosensor for real-time albumin monitoring in blood and urine [129].

Due to the weak biological magnetic field, magnetic field sensors should pay special attention to noise interference when used in medical detection. One way to do this is to use the Wheatstone bridge, which can significantly reduce background noise and amplify small signals. Or deploy a reference sensor (away from the detection target, capturing only ambient noise) to generate an anti-belief signal through the LMS (least mean square) algorithm to cancel out the common mode noise in the main channel in real time. For signals with known frequencies, phase-locked amplification technology can also be used to extract signals through narrowband filtering, and the equivalent noise bandwidth can be compressed to 0.1Hz. In addition, multi-sensor fusion detection is also a good choice, such as synchronous acquisition of ECG and MCG signals, using the ECG R wave as a time marker to gate the MCG average and reduce random noise.

E. Sensor Fusion

Sensor fusion is an inevitable direction of future IoT development, and magnetic sensors will play an important role. It can be used in combination with inertial sensors for limb motion capture to understand the movement characteristics of the human body or robotic arm, and it can also cooperate with pulse coherence radar for parking detection in IoT environments. [130] has led to the development of a tool for capturing biomechanical signals in the upper limb, which has been initially applied in industrial robotic arms and as a support tool in the rehabilitation of patients with mild sports injuries. Compared with traditional capture systems that capture human movement through optical motion, its advantage is that it can be used in real environments outside the laboratory, and it is low cost and easy to carry. The introduced magnetic sensor helps to locate the spatial position and joint amplitude of the limb together with the inertial sensor, which improves the system's accuracy. A novel self-calibrating sensing technique using a miniature linear encoder and an inertial/magnetic measuring unit (IMU) is presented in the [131]. The device is composed of an accelerometer, a 3-axis magnetic sensor, a gyroscope, and a miniature linear encoder, which can handle and capture human motion poses. This motion capture device is small enough to be placed in human clothing, and is expected to be used in the design and manufacture of mobile robots, and sports rehabilitation of patients with limb injuries. A new sensing device developed in [132] combines pulse coherence radar and magnetic sensor well for parking detection in the Internet of Things environment. Pulse coherent radar is triggered by a magnetic sensor, which reduces sampling power consumption. The experimental prototype system is tested under various interference conditions. The results show that the combination of magnetic sensors and radar sensors improves vehicle detection accuracy, and the battery-powered sensor node life is more than 5 years.

VII. CHALLENGES

Magnetic sensors based on magnetic fields have seen rapid development and are now widely used in fields such as automation, IoT, industrial inspection, public safety, and biomedical measurement. However, despite their advancements, magnetic field sensors still face numerous challenges due to limitations in their operating principles, complex deployment environments, and manufacturing processes. Sensors designed based on various magnetic field principles remain susceptible to issues like magnetic noise, hysteresis, temperature sensitivity, and narrow linear range, which hinder their further development.

A. Magnetic Noise

Taking weak magnetic sensing as an example, although AMR sensors have advantages over traditional pickup coils in terms of low DC noise, they are still affected by 1/f noise and nonlinearity, severely limiting their performance. This issue is not exclusive to AMR sensors—power supply noise becomes more pronounced when graphene-based Hall probe systems are miniaturized to the nanoscale, leading to complex power management requirements [22]. Stable and accurate measurements of low-intensity magnetic fields remain a key challenge, and the reduction of electronic noise is critical for future applications. In the field of weak magnetic measurement, the high sensitivity of magnetoresistive sensors paradoxically becomes a major obstacle in reducing magnetic noise. While some researchers have explored solutions through design and microstructure, the results have been limited—often requiring complicated fabrication processes or yielding poor generalization. For instance, in MCG signal measurement, traditional methods rely on expensive and non-portable magnetic shielding structures, limiting the possibility of portable applications [125]. Similarly, in public safety, systems based on TMR sensors require distinguishing weak target signals from external noise, which demands a high signal-to-noise ratio [133].

Environmental magnetic noise, such as oceanic eddy currents, increases MI communication errors by adding interference that is hard to distinguish from weak signals. Misalignment between transmitter and receiver coils, caused by ocean currents or vehicle motion, can significantly reduce the signal-to-noise ratio. Multi-directional coil designs, like spherical or polyhedral geometries, help address this issue [99]. However, they also create inter-coil coupling effects, making channel modeling more complex and increasing hardware complexity.

B. Hysteresis Effect and Nonlinear characteristic

The hysteresis effect represents a critical challenge in magnetoresistive sensor performance, particularly for high-frequency magnetic field measurements. While these sensors can detect high-frequency fields within certain ranges, hysteresis significantly impacts measurement accuracy and effective bandwidth. Hysteresis in MR sensors occurs due to the lag between the applied magnetic field and the magnetization response, creating a dependence on field history. This introduces nonlinearity and memory effects, distorting the output, particularly in dynamic conditions. The effective bandwidth—the frequency range for accurate measurements—is limited by hysteresis through (i) phase lag, causing signal delay and high-frequency tracking errors; (ii) nonlinear attenuation, reducing sensitivity at higher frequencies; and (iii) increased noise, lowering SNR and restricting reliable bandwidth. Thus, hysteresis degrades both the upper frequency limit and dynamic performance, necessitating mitigation via material optimization, bias fields, or signal processing for high-frequency applications.

The sensor's nonlinear behavior exhibits inconsistent sensitivity across its operating range, generating second/third harmonic distortions in the output signal - an effect further compounded by temperature variations. Conventional designs often employ iron cores around conductors to concentrate magnetic flux toward the sensor. Although effective for noise reduction, this approach introduces hysteresis, magnetic saturation, and nonlinearity issues that are exacerbated during bipolar field measurements [47]. These limitations constrain the sensor's operational bandwidth and linear range while degrading high-field sensitivity and introducing measurement bias [118]. Several research efforts have attempted to compensate for these errors through GMR hysteresis modeling. While improving accuracy, such models prove computationally intensive and ineffective for asymmetric field measurements. Furthermore, multi-sensor systems face compounded challenges from hysteresis and inter-sensor crosstalk, necessitating either complex modeling approaches or impractical magnetic shielding solutions.

C. Temperature Limitation

Most magnetic sensors are deployed in industrial applications where the environment is often complex, and temperature fluctuations are extreme. The signal generated by the magnetoresistive effect is highly correlated with temperature due to its impact on the resistance of sensor elements. Ideally, a perfectly trimmed resistor should make the sensor's offset (the output in the absence of a magnetic field) independent of temperature, but imperfections lead to errors up to 6% in some cases. This imbalance is proportional to the resistance value and has a greater impact on resistors with lower resistance. In high-temperature swing applications, these temperature effects limit sensor sensitivity. Additionally, the temperature of the external environment may not accurately represent the temperature within the sensor's Wheatstone bridge, leading to measurement discrepancies. While some researchers have implemented thermal compensation using external temperature sensors, the measurement of the bridge temperature remains imprecise. The material properties used in high-temperature applications also limit sensor performance, requiring the use of more temperature-resistant materials to extend the applicable temperature range.

The low-temperature effect also has impact on the performance of magnetic sensors [134]. Sub-zero conditions present unique challenges through three primary mechanisms: (1) reduced coercivity differential between magnetic layers, (2) enhanced spin reversal refraction in oxide layers, and (3) increased interface defect charge capture - all contributing to sensitivity degradation and zero drift. The low-temperature environment has a complex influence on the sensitivity, material stability, and reliability of the magnetic field sensor. Below we point out several ways to reduce the temperature dependence of magnetic field sensors. Ref. [135] starts from the sensor structure and adopts a GMR stack structure with cross anisotropy between the hard layer and the sensing layer - through the design of weakly pinned sensing layer, optimized layer thickness and stripe width, the single-axis and unidirectional magnetic anisotropy of the sensing layer system is precisely controlled, thereby enabling measurement within the temperature range of -40°C to +120°C without being affected by temperature.

In addition, temperature fluctuations significantly alter water conductivity, drastically affecting MI communication ranges. Experiments show that pocket-sized MI devices achieve 20 m in drinking water (low conductivity: 0.0005 S/m), 10 m in lake water (0.005 S/m), but $<$1 m in seawater (high conductivity: 4 S/m) due to eddy current losses [102]. Seawater's high conductivity amplifies energy dissipation, making long-range MI communication challenging.

To overcome the conductivity-induced limitations in MI communication, several strategies have been developed. Omnidirectional coil arrays enhance signal reliability by maintaining alignment in turbulent waters [110]. Adaptive frequency control optimizes the trade-off between range and data rate across varying water types. Passive relay networks extend communication by enabling multi-hop transmission in high-conductivity environments like seawater [99]. Hybrid acoustic-MI systems combine acoustic waves for long-range detection with MI for low-latency data transfer, improving performance in challenging conditions.

D. Narrow Linear Range

Another challenge with magnetic sensors is their limited linear operating range. The linear relationship between the magnetic field and the sensor's output signal is often restricted, requiring pre-configuration or biasing of the magnetic field to ensure measurements fall within the linear range. This limits the application of magnetic sensors in high-frequency measurements. For instance, TMR sensors exhibit a nonlinearity of 1.5% when measuring magnetic fields around 6.4 kA/m [47]. At higher field strengths, the sensitivity decreases, leading to measurement bias. Although recent advancements in current sensor designs address this issue by adjusting the radius of circular arrays, enabling better utilization of the linear range, challenges persist. Some researchers have proposed GMR linearization schemes based on magnetic field feedback, which improves linearity [136]. However, these schemes are sensitive to changes in feedback parameters, and microcontroller-based GMR sensor frontends suffer from long conversion times and high nonlinearity. Other improvements, such as feedback compensation and constant-current excitation, require expensive precision components or instrumentation amplifiers, making the system more costly and complex.

E. Path Loss and Distance Limitations

In these scenarios, MI communication suffers from sixth-order path loss with distance in free space [101], compared to the quadratic attenuation of traditional electromagnetic waves. For instance, MI-based underwater systems operating at 500 Hz achieve only 30-meter ranges even with optimized coils. While resonant coupling and relay coils mitigate near-field losses, long-range applications (e.g., $>$100 m) remain constrained by rapid power decay proportional to the tenth power of distance [110].

While relay coils extend communication ranges energy-efficiently [101], practical deployment faces crosstalk between densely packed coils and non-convex optimization of relay intervals/numbers. Existing models often ignore inter-coil coupling, leading to overestimated network capacity. Moreover, the lack of tailored MAC/routing protocols for MI networks exacerbates spatial interference in multi-hop scenarios.

VIII. Future Work

A. Trends in Magnetic Field Sensors

To address the challenges posed by complex deployment environments and improve sensing accuracy, researchers have made significant efforts in structural design, manufacturing processes, and sensing algorithms. This section explores trends in magnetic sensor applications, focusing on technologies like Hall, GMR, TMR, and AMR sensors, offering insights into future prospects and research directions. Over the past few years, applications of magnetoresistive sensors have expanded rapidly. Looking ahead, we expect these sensors to become more diversified, ubiquitous, and fine-tuned for various use cases.

B. Sensing Enhancement in Complex Environments

Multi-sensor Systems. Recognizing the limitations of individual magnetic sensors, researchers have explored multi-sensor systems to overcome the shortcomings of single-sensor approaches. Traditional magnetic sensors measure only their sensitive axis components, leading to incomplete data. A new TMR sensor array, introduced in [81], arranges multiple TMR sensors in a specialized array to measure three-dimensional magnetic field components, significantly reducing errors in three-axis image fusion. Another innovation uses spherical magnets to minimize crosstalk and hysteresis issues, providing a novel approach to multi-sensor systems that can meet detection needs in specialized environments by altering the magnetic field shape.

Integrated Temperature Compensation. To better adapt to complex and changing environments, future magnetoresistive sensors will incorporate significant improvements in temperature compensation and error correction, especially in extreme conditions where sensitivity and stability fluctuate with temperature changes. Integrated temperature compensation will play a critical role. For example, stainless steel replaces silicone rubber diaphragms to extend Hall sensor performance in high-temperature environments. Reducing heat generated by the system itself is also crucial, as explored by utilizing harmonic modulation to control amplitude and reduce system heat, which prevents pyroelectric effects in piezoelectric materials.

Structural Diversification. Current magnetoresistive sensors generally have simple structures with limited interference resistance. For example, single-layer AMR sensors suffer reduced accuracy under low magnetic fields. To address this, a multi-layer structure proposed in Ref. [137] improves detection accuracy under low magnetic fields, reduces the need for applied magnetic fields, and expands sensor applicability. Another example investigates a closed-loop feedback structure for GMR sensors, where adjusting bias current stabilizes output, improving measurement accuracy and linearity, particularly for bipolar asymmetric magnetic fields. As more advanced sensor structures are developed, magnetoresistive sensors will become more versatile in various sensing tasks.

Programmable Sensors. Since GMR, TMR, and AMR sensors are anisotropic, their measurement range is determined by the magnetic anisotropy field. Research has begun to focus on tunable magnetic field sensors by manipulating magnetic anisotropy at the microscopic level. For instance, the electromagnetic effect in Ref. [138] theoretically increases the measurement range of GMR sensors. Voltage-controlled magnetoelectric coupling effects allow for adjustable operating ranges and sensitivity, paving the way for future IoT applications where sensors can adapt to different environments without recalibration.

C. Magnetic Sensing in Medical Technology

Medical Sensing Applications. As magnetic sensor technology advances in weak magnetic field detection, its applications in medical sensing are expanding. Compared to traditional medical detection methods, magnetic sensors offer higher precision, broader usage scenarios, and significant potential for future medical applications. In Ref. [139], magnetic nanoparticles were creatively combined with GMR sensors to detect E. coli O157 H:H7 , demonstrating accuracy sufficient for clinical diagnosis and early environmental monitoring. The strength of biomagnetic fields, which are often similar to geomagnetic fields, poses a challenge for accurate measurement. Future research will focus on shielding geomagnetic interference to improve biomagnetic field measurement accuracy, as well as enhancing sensor precision for real-time detection in unshielded environments, such as human heart magnetic signals.

Combination with Flexible Materials. The flexibility of magnetoresistive sensors will be a key research direction moving forward. Flexible AMR sensors are designed for special applications and can be integrated into curved or complex-shaped devices, simplifying installation and maintenance. Using polymer substrate materials, these sensors offer a lightweight, low-cost, and high-performance solution, making them particularly suitable for consumer electronics, medical devices, and wearable technology. Flexible AMR sensors will excel in non-planar and dynamic scenarios, such as medical monitoring, industrial automation, smart homes, and robotics. In healthcare, they will provide reliable data for real-time body parameter monitoring, supporting telemedicine and health monitoring.

D. Integrated Magnetic Sensor Systems

Most current magnetoresistive sensors exist as single components, with additional modules required for bias magnetic fields, signal modulation, and other functions. This setup increases system power consumption, reduces operational time, and negatively impacts measurement accuracy. However, with advancements in manufacturing processes, integrated magnetic sensors are expected to become mainstream [140]. These sensors will offer strong functionality, high precision, fast response, low power consumption, and be cost-effective for long-distance signal transmission. For example, Ref. [141] utilizes electrodeposited CPP GMR nanowires to create a magnetic field sensor with a significantly larger sensor area than its template, maximizing sensitivity. Furthermore, integrating TMR sensors on CMOS wafers with readout electronics allows for small detection probes, improving spatial resolution for applications such as industrial defect detection and internal 3D structure measurements.

E. Smart City Sensing Revolution

Historically, magnetic sensors have played an important role in smart city construction, primarily identifying metal objects through eddy current effects. However, a new trend is the use of TMR magnetic sensors to develop safety systems that do not require manual operation. As described in [126], the magnetic anomaly detection system automatically records the magnetic fingerprint of an object and can be used for security checks in small Spaces such as conference rooms. For example, [76] introduces magnetic sensors into urban traffic systems, which can still provide more accurate traffic situation awareness in complex environments. If combined with IoT and AI technologies, these systems can create a wireless security network for large-scale city monitoring, greatly enhancing smart city infrastructure.

F. AI-Enhanced Magnetic Perception

AI-driven intelligent perception will become an important development direction in the field of magnetic sensors, the core of which is to give magnetic sensors stronger data processing, feature extraction, and decision-making capabilities through artificial intelligence technologies such as machine learning and deep learning. The traditional 'sensor acquisition signal, signal modulation, back-end processing logic' is changed to sensor acquisition and edge AI processing, intelligent decision-making, and structured information output. For example, [142] can recover the drop in estimation accuracy caused by sensor position offset by machine learning using training data from moving sensor positions. Machine learning methods are up to 30 times faster than traditional methods. This research result is expected to be applied to vehicle position acquisition, human motion acquisition, and other fields to realize real-time tracking of moving people and objects based on magnetic sensing principles.

G. Combining Magnetic Techniques with Robotics

Magnetic sensors and robotics synergize to address complex challenges in automation, precision control, and human-machine interaction. In soft robotics, magnetoelastomers enable tactile sensing and force feedback by deforming under external forces, with magnetic sensors detecting field variations to quantify contact points, pressure, and directional forces. For instance, bioinspired magnetic tactile sensors integrated into robotic arms allow object recognition and texture differentiation, mimicking human Merkel cells for enhanced dexterity. Flexible magnetic sensors, such as GMR- or AMR-based electronic skins, are embedded in robotic surfaces to monitor motion states and positional data in real time, enabling adaptive grasping and safe human-robot collaboration [143]. Magnetic actuation further enhances soft robots' functionality, enabling wireless control in confined spaces. Innovations like pyramid-shaped microstructures on magnetic films improve signal-to-noise ratios and pressure sensitivity, critical for compliant human-machine interfaces [144]. Future directions include integrating flexible magnetic sensor arrays with robotic systems for multi-axis force detection and 3D spatial navigation, advancing applications in industrial automation, minimally invasive surgery, and augmented reality.

H. Combining Magnetic Techniques with Machine Learning.

Machine learning (ML) amplifies the capabilities of magnetic sensors by optimizing performance, interpreting complex data, and enabling predictive analytics. ML algorithms process raw magnetic field data to resolve ambiguities in sensor outputs, such as distinguishing multi-axis magnetic signals or compensating for environmental noise. For example, neural networks enhance force and position resolution in magnetoelastic tactile sensors, while attention-based LSTM models decode texture patterns from magnetic field changes, enabling braille recognition and fabric classification [143]. In wearable and IoT applications, ML-driven models correlate magnetic sensor data with physiological signals (e.g., muscle movements, cardiac activity) for real-time health monitoring [145]. Future integration will focus on edge computing for low-latency decision-making and federated learning frameworks to enhance sensor networks' adaptability in dynamic environments, such as smart cities or autonomous robotics.

IX. Conclusion

Magnetic sensors have proven to be indispensable in a variety of sectors, from transportation and industrial automation to healthcare and security. This survey presents various hardware and the key techniques of magnetic sensing and communication and reviews existing magnetic works based on different sensing tasks and communication scenarios, i.e., automotive systems, smart grid management, medical equipment, and security systems. We further discuss potential challenges and future directions, including trends in magnetic field sensors, toward enhanced sensing in complex environments, magnetoresistive sensing in medical technology, integrated magnetic sensors, and magnetoresistive sensors in urban safety.

TABLE VIII
List of Abbreviations

Abbreviation	Explanation
AMR	Anisotropic Magnetoresistance
AMPD	Automatic Peak Detection
AUVs	Autonomous Underwater Vehicles
BARC	Bead Array Counter
eHBC	Electric Field-based Human Body Communication
EM	Electromagnetic
EMI	Electromagnetic Interference
ECT	Eddy Current Testing
GMI	Giant Magnetoimpedance
GMR	Giant Magnetoresistance
HALL	Hall Effect
HBC	Human Body Communication
HECS	Hall-Effect Current Sensors
HTS	High-Temperature Superconducting
IPT	Inductive Power Transfer
MCG	Magnetocardiography
ME	Magnetoelectric
MEG	Magnetoencephalography
MF	Magnetic Fluid
MI	Magnetic Induction
MIMO-MI	Multiple-Input Multiple-Output Magnetic Induction
MIP	Magnetoimpedance
MOI	Magnetic Optic Imaging
MR	Magnetoresistance
MB-MI	Multi-Band Magnetic Induction
mHBC	Magnetic Human Body Communication
OPM	Optically Pumped Magnetometer
SDT	Spin-Dependent Tunneling
SNR	Signal-to-Noise Ratio
SQUID	Superconducting Quantum Interference Device
TEC	Thermoelectric Cooler
TMR	Tunneling Magnetoresistance
WPT	Wireless Power Transfer
WUSNs	Wireless Underground Sensor Networks

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REFERENCES

[1] J. E. Lenz, "A review of magnetic sensors," Proceedings of the IEEE, vol. 78, no. 6, pp. 973–989, 1990.

[2] P. Ripka and M. Janosek, "Advances in magnetic field sensors," IEEE Sensors journal, vol. 10, no. 6, pp. 1108–1116, 2010.

[3] C. Morón, C. Cabrera, A. Morón, A. García, and M. González, "Magnetic sensors based on amorphous ferromagnetic materials: A review," Sensors, vol. 15, no. 11, pp. 28 340–28 366, 2015.

[4] M. Bichurin, R. Petrov, O. Sokolov, V. Leontiev, V. Kuts, D. Kiselev, and Y. Wang, "Magnetoelectric magnetic field sensors: A review," Sensors, vol. 21, no. 18, p. 6232, 2021.

[5] M. A. Khan, J. Sun, B. Li, A. Przybysz, and J. Kosel, "Magnetic sensors-a review and recent technologies," Engineering Research Express, vol. 3, no. 2, p. 022005, 2021.

[6] N. Alberto, M. F. Domingues, C. Marques, P. André, and P. Antunes, "Optical fiber magnetic field sensors based on magnetic fluid: A review," Sensors, vol. 18, no. 12, p. 4325, 2018.

[7] J. Heremans, "Solid state magnetic field sensors and applications," Journal of Physics D: Applied Physics, vol. 26, no. 8, p. 1149, 1993.

[8] M. Melzer, D. Makarov, and O. Schmidt, "A review on stretchable magnetic field sensorics," Journal of Physics D: Applied Physics, vol. 53, no. 8, p. 083002, 2020.

[9] C. Liu, T. Shen, H.-B. Wu, Y. Feng, and J.-J. Chen, "Applications of magneto-strictive, magneto-optical, magnetic fluid materials in optical fiber current sensors and optical fiber magnetic field sensors: A review," Optical fiber technology, vol. 65, p. 102634, 2021.

[10] D. Murzin, D. J. Mapps, K. Levada, V. Belyaev, A. Omelyanchik, L. Panina, and V. Rodionova, "Ultrasensitive magnetic field sensors for biomedical applications," Sensors, vol. 20, no. 6, p. 1569, 2020.

[11] "Hall Effect Sensors: A Comprehensive Guide," https://www.monolithicpower.com/en/hall-effect-sensors-a-comprehensive-guide.

[12] "TMAG5253 — Linear Hall-effect sensors," https://www.ti.com.cn/product/cn/TMAG5253.

[13] "Datasheet: 1- and 2-Axis Magnetic Sensors HMC1001/1002/1021/1022," https://aerospace.honeywell.com/content/dam/aerobt/en/documents/learn/products/sensors/datasheet/N61-2056-000-000_MagneticSensors_HMC-ds.pdf.

[14] "DRV5057-Q1 data sheet, product information and support," https://www.ti.com/product/DRV5057-Q1.

[15] "TMAG5131-Q1 data sheet, product information and support," https://www.ti.com/product/TMAG5131-Q1.

[16] "TMAG5115 data sheet, product information and support," https://www.ti.com/product/TMAG5115.

[17] "TMAG5124-Q1 data sheet, product information and support," https://www.ti.com/product/TMAG5124-Q1.

[18] L. Jogschies, D. Klaas, R. Kruppe, J. Rittinger, P. Taptimthong, A. Wienecke, L. Rissing, and M. C. Wurz, "Recent developments of magnetoresistive sensors for industrial applications," Sensors, vol. 15, no. 11, pp. 28 665–28 689, 2015.

[19] M. Díaz-Michelena, P. Cobos, and C. Aroca, "Lock-in amplifiers for amr sensors," Sensors and Actuators A: Physical, vol. 222, pp. 149–159, 2015.

[20] Y. Guo, Y. Deng, and S. X. Wang, "Multilayer anisotropic magnetoresistive angle sensor," Sensors and Actuators A: Physical, vol. 263, pp. 159–165, 2017.

[21] N. G. Hadjigeorgiou and P. P. Sotiriadis, "Parasitic capacitances, inductive coupling, and high-frequency behavior of amr sensors," IEEE Sensors Journal, vol. 20, no. 5, pp. 2339–2347, 2019.

[22] M. Janosek, J. Vyhnanek, and P. Ripka, "Cw metal detector based on amr sensor array," in SENSORS, 2011 IEEE. IEEE, 2011, pp. 1515–1517.

[23] X. Li, R. Kang, Y. Liu, Z. Wang, X. Shu, and J. Lan, "Sensitivity online recognition of amr sensor," in The 2010 IEEE International Conference on Information and Automation. IEEE, 2010, pp. 956–959.

[24] M. H. Kang, B. W. Choi, K. C. Koh, J. H. Lee, and G. T. Park, "Experimental study of a vehicle detector with an amr sensor," Sensors and Actuators A: Physical, vol. 118, no. 2, pp. 278–284, 2005.

[25] "KMZ51,115 — DigiKey Electronics," https://www.digikey.com/en/products/detail/nxp-usa-inc/KMZ51-115/965745.

[26] V. Fúra, V. Petrucha, and A. Platil, "Construction of an amr magnetometer for car detection experiments," in IOP Conference Series: Materials Science and Engineering, vol. 108, no. 1. IOP Publishing, 2016, p. 012028.

[27] J. Köszegi, B. Schmitz, K. Alomari, O. Kugeler, and J. Knobloch, "A combined temperature and magnetic field mapping system for srf cavities," in Proceedings of 9th International Particle Accelerator Conference (IPAC'18), 2018, pp. 1228–1231.

[28] "Datasheet: 1- and 2-Axis Magnetic Sensors HMC1001/1002/1021/1022," https://aerospace.honeywell.com/content/dam/aerobt/en/documents/learn/products/sensors/datasheet/N61-2056-000-000_MagneticSensors_HMC-ds.pdf.

[29] "KMZ51 Datasheet - NXP Semiconductors," https://pdf1.alldatasheet.com/datasheet-pdf/view/17844/PHILIPS/KMZ51.html.

[30] "AFF755B MagnetoResistive Field Sensor," https://www.sensitec.com/fileadmin/sensitec/Service_and_Support/Downloads/Data_Sheets/AFF700_800/SENSITEC_AFF755B_DSE_06.pdf.

[31] M. N. Baibich, J. M. Broto, A. Fert, F. N. Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas, "Giant magnetoresistance of (001) fe/(001) cr magnetic superlattices," Physical review letters, vol. 61, no. 21, p. 2472, 1988.

[32] G. Binasch, P. Grünberg, F. Saurenbach, and W. Zinn, "Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange," Physical review B, vol. 39, no. 7, p. 4828, 1989.

[33] R. Ranchal, M. Torija, E. López, M. Sánchez, C. Aroca, and P. Sánchez, "The influence of anisotropy on the magnetoresistance of permalloy-copper-permalloy thin films," Nanotechnology, vol. 13, no. 3, p. 392, 2002.

[34] M. Mujika, S. Arana, E. Castano, M. Tijero, R. Vilares, J. Ruano-López, A. Cruz, L. Sainz, and J. Berganza, "Microsystem for the immunomagnetic detection of escherichia coli o157: H7," physica status solidi (a), vol. 205, no. 6, pp. 1478–1483, 2008.

[35] ——, "Magnetoresistive immunosensor for the detection of escherichia coli o157: H7 including a microfluidic network," Biosensors and Bioelectronics, vol. 24, no. 5, pp. 1253–1258, 2009.

[36] B. Dieny, V. S. Speriosu, S. Metin, S. S. Parkin, B. A. Gurney, P. Baumgart, and D. R. Wilhoit, "Magnetotransport properties of magnetically soft spin-valve structures," Journal of Applied Physics, vol. 69, no. 8, pp. 4774–4779, 1991.

[37] S. Parkin, R. Fontana, and A. Marley, "Low-field magnetoresistance in magnetic tunnel junctions prepared by contact masks and lithography: 25% magnetoresistance at 295 k in mega-ohm micron-sized junctions," Journal of Applied Physics, vol. 81, no. 8, pp. 5521–5521, 1997.

[38] A. Berkowitz, J. Mitchell, M. Carey, A. Young, S. Zhang, F. Spada, F. Parker, A. Hutten, and G. Thomas, "Giant magnetoresistance in heterogeneous cu-co alloys," Physical Review Letters, vol. 68, no. 25, p. 3745, 1992.

[39] "Datasheet: 3-Axis Magnetic Sensor Hybrid HMC2003," https://aerospace.honeywell.com/content/dam/aerobt/en/documents/learn/products/sensors/datasheet/3-AxisMagneticSensorHybridHMC2003_ds.pdf.

[40] "AA004-02E — DigiKey Electronics," https://www.digikey.com/en/products/detail/nve-corp-sensor-products/AA004-02E/1624606.

[41] "TLE5014," https://www.infineon.com/dgdl/Infineon-TLE5014C_P_S-DataSheet-v01_00-EN.pdf?fileId=5546d46276fb756a01771a9695b43a08.

[42] "TMR2001-Datasheet-EN-V1.0a.pdf," https://www.aecsensors.com/components/com_virtuemart/shop_image/product/Magnetic-Tunnelling-Magnetoresistive-TMR-Linear-Sensors/pdfs/TMR2001-Datasheet-EN-V1.0a.pdf.

[43] W. Miao, X. Liu, K. Lam, and P. W. Pong, "Dc-arcing detection by noise measurement with magnetic sensing by tmr sensors," IEEE Transactions on Magnetics, vol. 54, no. 11, pp. 1–5, 2018.

[44] L. Wang, J. Wu, J. Liu, R. Mao, M. Guan, D. Xian, Q. Mao, C. Wang, Z. Wang, Z. Jiang et al., "A magnetic field imaging system based on tmr sensors for banknote recognition," IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1–9, 2022.

[45] X. Liu, W. Han, C. Liu, and P. W. Pong, "Marker-free coil-misalignment detection approach using tmr sensor array for dynamic wireless charging of electric vehicles," IEEE Transactions on Magnetics, vol. 54, no. 11, pp. 1–5, 2018.

[46] H. Su, H. Li, W. Liang, C. Shen, and Z. Xu, "Non-contact current measurement for three-phase rectangular busbars using tmr sensors," Sensors, vol. 24, no. 2, p. 388, 2024.

[47] P. Ziegler, Y. Zhao, J. Haarer, J. Ruthardt, M. Fischer, and J. Roth-Stielow, "Compact design of a wide bandwidth high current sensor using tilted magnetic field sensors," IEEE Transactions on Industry Applications, 2023.

[48] "TMR2104 - Large Dynamic Range Series - Sensors - MDT - TMR2104 Large Dynamic Range Linear Magnetic Sensor," https://www.dowaytech.com/en/1800.html.

[49] H. Zhang, F. Li, H. Guo, Z. Yang, and N. Yu, "Current measurement with 3-d coreless tmr sensor array for inclined conductor," IEEE Sensors Journal, vol. 19, no. 16, pp. 6684–6690, 2019.

[50] S. Jiang, Z. Deng, L. Liang, Y. Wang, J. Liu, and H. Zhang, "Novel method to detect the speed and position of the hts maglev train by using the tmr sensor and the magnet arrays," Measurement, vol. 219, p. 113280, 2023.

[51] "TMR2301-Datasheet-EN-V1.0a.pdf," https://www.aecsensors.com/components/com_virtuemart/shop_image/product/Magnetic-Tunnelling-Magnetoresistive-TMR-Linear-Sensors/pdfs/TMR2301-Datasheet-EN-V1.0a.pdf.

[52] "TMR2701-Datasheet-EN-V1.0a.pdf," https://www.aecsensors.com/components/com_virtuemart/shop_image/product/Magnetic-Tunnelling-Magnetoresistive-TMR-Linear-Sensors/pdfs/TMR2701-Datasheet-EN-V1.0a.pdf.

[53] M. Hott, P. A. Hoeher, and S. F. Reinecke, "Magnetic communication using high-sensitivity magnetic field detectors," Sensors, vol. 19, no. 15, 2019. [Online]. Available: https://www.mdpi.com/1424-8220/19/15/3415

[54] S. Wei, X. Liao, H. Zhang, J. Pang, and Y. Zhou, "Recent progress of fluxgate magnetic sensors: Basic research and application," Sensors, vol. 21, no. 4, p. 1500, 2021.

[55] X. Guo, L. Tan, C. Gu, Y. Shu, S. He, and J. Chen, "Magwear: Vital sign monitoring based on biomagnetism sensing," IEEE Transactions on Mobile Computing, vol. 23, no. 12, pp. 14 918–14 933, 2024.

[56] J. Huang, X. Guo, C. Gu, Y. Miao, S. He, Y. Shu, and J. Chen, "Magkey: Empowering wearables with ballistocardiography-based key generation through magnetic field vibration sensing," Proc. ACM Interact. Mob. Wearable Ubiquitous Technol., vol. 9, no. 1, 2025. [Online]. Available: https://doi.org/10.1145/3712272

[57] T. Chen, Y. Yang, X. Fan, X. Guo, J. Xiong, and L. Shangguan, "Exploring the feasibility of remote cardiac auscultation using earphones," in Proceedings of the 30th Annual International Conference on Mobile Computing and Networking, ser. ACM MobiCom '24, 2024.

[58] H. Jiang, J. Zhang, X. Guo, and Y. He, "Sense me on the ride: Accurate mobile sensing over a lora backscatter channel," in Proceedings of the 19th ACM Conference on Embedded Networked Sensor Systems, 2021, p. 125–137.

[59] J. Zhang, R. Xi, Y. He, Y. Sun, X. Guo, W. Wang, X. Na, Y. Liu, Z. Shi, and T. Gu, "A survey of mmwave-based human sensing: Technology, platforms and applications," IEEE Communications Surveys & Tutorials, vol. 25, no. 4, pp. 2052–2087, 2023.

[60] Y. Chen, C. Xu, K. Li, J. Zhang, X. Guo, M. Jin, X. Zheng, and Y. He, "Wireless sensing for material identification: A survey," IEEE Communications Surveys & Tutorials, 2024.

[61] L. Xu, K. Wang, C. Gu, X. Guo, S. He, and J. Chen, "Gestureprint: Enabling user identification for mmwave-based gesture recognition systems," in Proceedings of IEEE ICDCS, 2024, pp. 1074–1085.

[62] X. Guo, Y. He, L. Shangguan, Y. Chen, C. Gu, Y. Shu, K. Jamieson, and J. Chen, "Mighty: Towards long-range and high-throughput backscatter for drones," IEEE Transactions on Mobile Computing, vol. 24, no. 3, pp. 1833–1845, 2025.

[63] B. Behera, U. P. Borole, J. Khan, H. C. Barshilia, and P. Chowdhury, "Fabrication of industrial grade gmr multilayer magnetic sensors for non-recording applications," Microelectronic Engineering, vol. 298, p. 112311, 2025.

[64] C. Mușuroi, M. Oproiu, M. Volmer, J. Neamtu, M. Avram, and E. Helerea, "Low field optimization of a non-contacting high-sensitivity gmr-based dc/ac current sensor," Sensors, vol. 21, no. 7, p. 2564, 2021.

[65] M. Crescentini, S. F. Syeda, and G. P. Gibiino, "Hall-effect current sensors: Principles of operation and implementation techniques," IEEE Sensors Journal, vol. 22, no. 11, pp. 10 137–10 151, 2021.

[66] X. Yang, H. Liu, Y. Wang, Y. Wang, G. Dong, and Z. Zhao, "A giant magneto resistive (gmr) effect based current sensor with a toroidal magnetic core as flux concentrator and closed-loop configuration," IEEE transactions on applied superconductivity, vol. 24, no. 3, pp. 1–5, 2013.

[67] C. Fan, Z. Jin, and J. Chen, "Current state of triaxial magnetoresistance sensors and their applications: a review," Sensors and Actuators A: Physical, p. 115724, 2024.

[68] M. H. Kang, B. W. Choi, K. C. Koh, J. H. Lee, and G. T. Park, "Experimental study of a vehicle detector with an amr sensor," Sensors and Actuators A: Physical, vol. 118, no. 2, pp. 278–284, 2005.

[69] Z. Zhang, M. Tao, and H. Yuan, "A parking occupancy detection algorithm based on amr sensor," IEEE Sensors Journal, vol. 15, no. 2, pp. 1261–1269, 2014.

[70] P. Ripka, J. Vyhnanek, M. Janosek, and J. Vcelak, "Amr proximity sensor with inherent demodulation," IEEE Sensors Journal, vol. 14, no. 9, pp. 3119–3123, 2014.

[71] J. J. Clark, "A magnetic field based compliance matching sensor for high resolution, high compliance tactile sensing," in Proceedings. 1988 IEEE International Conference on Robotics and Automation. IEEE, 1988, pp. 772–777.

[72] S. Somlor, R. S. Hartanto, A. Schmitz, and S. Sugano, "A novel triaxial capacitive-type skin sensor," Advanced Robotics, vol. 29, no. 21, pp. 1375–1391, 2015.

[73] C. M. Oddo, M. Controzzi, L. Beccai, C. Cipriani, and M. C. Carrozza, "Roughness encoding for discrimination of surfaces in artificial active-touch," IEEE Transactions on Robotics, vol. 27, no. 3, pp. 522–533, 2011.

[74] D. Jones, L. Wang, A. Ghanbari, V. Vardakastani, A. E. Kedgley, M. D. Gardiner, T. L. Vincent, P. R. Culmer, and A. Alazmani, "Design and evaluation of magnetic hall effect tactile sensors for use in sensorized splints," Sensors, vol. 20, no. 4, p. 1123, 2020.

[75] K. Rohrmann, M. Sandner, P. Meier, and M. Prochaska, "A novel magnetoresistive wheel speed sensor with low temperature drift and high stray field immunity," pp. 1–6, 2018.

[76] Y. F. G. M. B. C. C. L. Y. H. Z. Xu, "Magmonitor: Vehicle speed estimation and vehicle classification through a magnetic sensor," IEEE Transactions on Intelligent Transportation Systems, vol. 23, no. 2, pp. 1311–1322, 2022.

[77] J. Vyhnánek, M. Janošek, and P. Ripka, "Amr gradiometer for mine detection," Sensors and Actuators A: Physical, vol. 186, pp. 100–104, 2012.

[78] H. Citak, Y. Ege, S. Bicakci, H. Gunes, and M. Coramik, "The determination of buried magnetic material from various heights: A neural network application," IEEE Transactions on Instrumentation and Measurement, vol. 69, no. 7, pp. 4188–4199, 2019.

[79] N. V. Nair, V. R. Melapudi, H. R. Jimenez, X. Liu, Y. Deng, Z. Zeng, L. Udpa, T. J. Moran, and S. S. Udpa, "A gmr-based eddy current system for nde of aircraft structures," IEEE Transactions on Magnetics, vol. 42, no. 10, pp. 3312–3314, 2006.

[80] Z. Mao, W. Zhai, Y. Shen, S. Zhao, and J. Gao, "Advanced metal detection system based on tmr sensor array," Journal of Magnetism and Magnetic Materials, vol. 543, p. 168601, 2022.

[81] K. Sun, P. Qi, X. Tao, W. Zhao, and C. Ye, "Vector magnetic field imaging with high-resolution tmr sensor arrays for metal structure inspection," IEEE Sensors Journal, vol. 22, no. 14, pp. 14 513–14 521, 2022.

[82] J. Man, G. Chen, and J. Chen, "Recent progress of biomimetic tactile sensing technology based on magnetic sensors," Biosensors, vol. 12, no. 11, p. 1054, 2022.

[83] K. Kalyan, V. K. Chugh, and C. Anoop, "Non-invasive heart rate monitoring system using giant magneto resistance sensor," in 2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE, 2016, pp. 4873–4876.

[84] N. Ravi, G. Rizzi, S. E. Chang, P. Cheung, P. J. Utz, and S. X. Wang, "Quantification of cdna on gmr biosensor array towards point-of-care gene expression analysis," Biosensors and Bioelectronics, vol. 130, pp. 338–343, 2019.

[85] D. A. Hall, R. S. Gaster, T. Lin, S. J. Osterfeld, S. Han, B. Murmann, and S. X. Wang, "Gmr biosensor arrays: A system perspective," Biosensors and Bioelectronics, vol. 25, no. 9, pp. 2051–2057, 2010.

[86] A. Kikitsu, Y. Higashi, Y. Kurosaki, S. Shirotori, T. Nagatsuka, K. Suzuki, and Y. Terui, "Magnetic field microscope using high-sensitivity giant magneto-resistance sensor with ac field modulation," Japanese Journal of Applied Physics, vol. 62, no. SB, p. SB1007, 2022.

[87] J. Rife, M. Miller, P. Sheehan, C. Tamanaha, M. Tondra, and L. Whitman, "Design and performance of gmr sensors for the detection of magnetic microbeads in biosensors," Sensors and Actuators A: Physical, vol. 107, no. 3, pp. 209–218, 2003.

[88] C. Marquina, J. De Teresa, D. Serrate, J. Marzo, F. Cardoso, D. Saurel, S. Cardoso, P. Freitas, and M. Ibarra, "Gmr sensors and magnetic nanoparticles for immuno-chromatographic assays," Journal of Magnetism and Magnetic Materials, vol. 324, no. 21, pp. 3495–3498, 2012.

[89] X. Guo, L. Tan, T. Chen, and C. Gu, "Exploring biomagnetism for inclusive vital sign monitoring: Modeling and implementation," ACM MobiCom 2024 - Proceedings of the 30th International Conference on Mobile Computing and Networking, vol. 5, 2024.

[90] X. Guo, Y. He, Z. Yu, J. Zhang, Y. Liu, and L. Shangguan, "RF-Transformer: A unified backscatter radio hardware abstraction," in

Proceedings of ACM MobiCom, Sydney, NSW, Australia, October 17-21, 2022.

[91] X. Na, X. Guo, Z. Yu, J. Zhang, and Y. He, "Leggiero: Analog WiFi backscatter with payload transparency," in Proceedings of ACM MobiSys, Helsinki, Finland, June 18-22, 2023.

[92] W. Wang, X. Zheng, Y. He, and X. Guo, "Adacomm: Tracing channel dynamics for reliable cross-technology communication," in 2019 16th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON), 2019, pp. 1–9.

[93] X. Guo, L. Shangguan, Y. He, J. Zhang, H. Jiang, A. A. Siddiqi, and Y. Liu, "Aloba: Rethinking ON-OFF keying modulation for ambient LoRa backscatter," in Proceedings of ACM SenSys, Virtual Event Japan, November 16-19, 2020.

[94] X. Guo, L. Shangguan, Y. He, N. Jing, J. Zhang, H. Jiang, and Y. Liu, "Saiyan: Design and implementation of a low-power demodulator for LoRa backscatter systems," in Proceedings of USENIX NSDI, Renton, WA, USA, April 4-6, 2022.

[95] X. Guo, Y. He, and X. Zheng, "Wizig: Cross-technology energy communication over a noisy channel," IEEE/ACM Transactions on Networking, vol. 28, no. 6, pp. 2449–2460, 2020.

[96] D. Gao, H. Wang, Y. Chen, Q. Ye, W. Wang, X. Guo, S. Wang, Y. Liu, and T. He, "Lobee: Bidirectional communication between lora and zigbee based on physical-layer ctc," IEEE Transactions on Wireless Communications, 2025.

[97] M. Hott, P. A. Hoeher, and S. F. Reinecke, "Magnetic communication using high-sensitivity magnetic field detectors," Sensors, vol. 19, no. 15, p. 3415, 2019.

[98] J.-Y. Kim, I.-K. Cho, H. J. Lee, J. Lee, J.-I. Moon, S.-M. Kim, S.-W. Kim, S. Ahn, and K. Kim, "A novel experimental approach to the applicability of high-sensitivity giant magneto-impedance sensors in magnetic field communication," IEEE Access, vol. 8, pp. 193 091–193 101, 2020.

[99] M. Muzzammil, N. Ahmed, G. Qiao, I. Ullah, and L. Wan, "Fundamentals and advancements of magnetic-field communication for underwater wireless sensor networks," IEEE Transactions on Antennas and Propagation, vol. 68, no. 11, pp. 7555–7570, 2020.

[100] J. Park and P. P. Mercier, "Magnetic human body communication," in 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE, 2015, pp. 1841–1844.

[101] Y. Li, S. Wang, C. Jin, Y. Zhang, and T. Jiang, "A survey of underwater magnetic induction communications: Fundamental issues, recent advances, and challenges," IEEE Communications Surveys & Tutorials, vol. 21, no. 3, pp. 2466–2487, 2019.

[102] I. F. Akyildiz, P. Wang, and Z. Sun, "Realizing underwater communication through magnetic induction," IEEE Communications Magazine, vol. 53, no. 11, pp. 42–48, 2015.

[103] Z. Sun, I. F. Akyildiz, S. Kisseleff, and W. Gerstacker, "Increasing the capacity of magnetic induction communications in rf-challenged environments," IEEE Transactions on Communications, vol. 61, no. 9, pp. 3943–3952, 2013.

[104] P. Singh, R. P. Singh, Y. Singh, J. S. Chohan, S. Sharma, M. Sadeghzadeh, and A. Issakhov, "Magnetic induction technology-based wireless sensor network for underground infrastructure, monitoring soil conditions, and environmental observation applications: Challenges and future aspects," Journal of Sensors, vol. 2022, no. 1, p. 9332917, 2022.

[105] S. Kisseleff, I. F. Akyildiz, and W. H. Gerstacker, "Survey on advances in magnetic induction-based wireless underground sensor networks," IEEE Internet of Things Journal, vol. 5, no. 6, pp. 4843–4856, 2018.

[106] M. C. Domingo, "Magnetic induction for underwater wireless communication networks," IEEE transactions on antennas and propagation, vol. 60, no. 6, pp. 2929–2939, 2012.

[107] M. Masihpour and J. I. Agbinya, "Cooperative relay in near field magnetic induction: A new technology for embedded medical communication systems," in 2010 Fifth International Conference on Broadband and Biomedical Communications. IEEE, 2010, pp. 1–6.

[108] M. Muzzammil, N. Ahmed, G. Qiao, I. Ullah, and L. Wan, "Fundamentals and advancements of magnetic-field communication for underwater wireless sensor networks," IEEE Transactions on Antennas and Propagation, vol. 68, no. 11, pp. 7555–7570, 2020.

[109] S. Ryu, K. Kim, J.-Y. Kim, I.-K. Cho, H. Kim, J. Ahn, J. Choi, and S. Ahn, "Design and analysis of a magnetic field communication system using a giant magneto-impedance sensor," IEEE Access, vol. 10, pp. 56 961–56 973, 2022.

[110] ——, "Design and analysis of a magnetic field communication system using a giant magneto-impedance sensor," IEEE Access, vol. 10, pp. 56 961–56 973, 2022.

[111] M. A. Khan, J. Sun, B. Li, A. Przybysz, and J. Kosel, "Magnetic sensors-a review and recent technologies," Engineering Research Express, vol. 3, no. 2, p. 022005, 2021.

[112] A. K. Sharma, S. Yadav, S. N. Dandu, V. Kumar, J. Sengupta, S. B. Dhok, and S. Kumar, "Magnetic induction-based non-conventional media communications: A review," IEEE Sensors Journal, vol. 17, no. 4, pp. 926–940, 2016.

[113] Y. Li, S. Wang, C. Jin, Y. Zhang, and T. Jiang, "A survey of underwater magnetic induction communications: Fundamental issues, recent advances, and challenges," IEEE Communications Surveys & Tutorials, vol. 21, no. 3, pp. 2466–2487, 2019.

[114] H. Wang, J. Ge, W. Luo, T. Meng, Y. Liu, A. Chen, H. Liu, and H. Dong, "Construction and experimental verification of an integrated dual-mode overhauser magnetometer for marine magnetism survey," IEEE Sensors Journal, vol. 23, no. 21, pp. 25 854–25 863, 2023.

[115] J. Hu, K. Yang, G. Wen, and L. Hanzo, "Integrated data and energy communication network: A comprehensive survey," IEEE Communications Surveys & Tutorials, vol. 20, no. 4, pp. 3169–3219, 2018.

[116] X. Sun, Q. Huang, Y. Hou, L. Jiang, and P. W. T. Pong, "Noncontact operation-state monitoring technology based on magnetic-field sensing for overhead high-voltage transmission lines," IEEE Transactions on Power Delivery, vol. 28, no. 4, pp. 2145–2153, 2013.

[117] A. Bernieri, L. Ferrigno, M. Laracca, and A. Rasile, "An amr-based three-phase current sensor for smart grid applications," IEEE Sensors Journal, vol. 17, no. 23, pp. 7704–7712, 2017.

[118] G. Rieger, K. Ludwig, J. Hauch, and W. Clemens, "Gmr sensors for contactless position detection," Sensors and Actuators A: Physical, vol. 91, no. 1-2, pp. 7–11, 2001.

[119] P. Sreevidya, U. P. Borole, R. Kadam, J. Khan, H. C. Barshilia, and P. Chowdhury, "A novel amr based angle sensor with reduced harmonic errors for automotive applications," Sensors and Actuators A: Physical, vol. 324, p. 112573, 2021.

[120] C. Giebeler, D. Adelerhof, A. Kuiper, J. Van Zon, D. Oelgeschläger, and G. Schulz, "Robust gmr sensors for angle detection and rotation speed sensing," Sensors and Actuators A: Physical, vol. 91, no. 1-2, pp. 16–20, 2001.

[121] Z. Liu, P. Li, B. Tian, J. Zhao, Y. Hu, H. Sun, X. Yin, Z. Wang, and M. Guo, "Current and voltage measurement method based on magnetic and electric field sensors for smart grid applications," 2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2), pp. 2783–2786, 2020.

[122] V. Ramakrishnan, D. Savio A, and N. R, "Robust wireless ev charging: Misalignment sensing and auto aligning system using magnetic sensors and maximum power point tracking," IEEE Sensors Journal, vol. 24, no. 24, pp. 41 954–41 962, 2024.

[123] B. Wu, Y. Wang, X. Liu, and C. He, "A novel tmr-based mfl sensor for steel wire rope inspection using the orthogonal test method," Smart Materials and Structures, vol. 24, no. 7, p. 075007, 2015.

[124] C. Ye, Y. Wang, and Y. Tao, "High-density large-scale tmr sensor array for magnetic field imaging," IEEE Transactions on Instrumentation and measurement, vol. 68, no. 7, pp. 2594–2601, 2018.

[125] W. Zhao, X. Tao, C. Ye, and Y. Tao, "Tunnel magnetoresistance sensor with ac modulation and impedance compensation for ultra-weak magnetic field measurement," Sensors, vol. 22, no. 3, p. 1021, 2022.

[126] J. Gao, J. Wang, L. Zhang, Q. Yu, Y. Huang, and Y. Shen, "Magnetic signature analysis for smart security system based on tmr magnetic sensor array," IEEE Sensors Journal, vol. 19, no. 8, pp. 3149–3155, 2019.

[127] G. Rizzi, J.-R. Lee, P. Guldberg, M. Dufva, S. X. Wang, and M. F. Hansen, "Denaturation strategies for detection of double stranded pcr products on gmr magnetic biosensor array," Biosensors and Bioelectronics, vol. 93, pp. 155–160, 2017.

[128] Y. Gao, W. Huo, L. Zhang, J. Lian, W. Tao, C. Song, J. Tang, S. Shi, and Y. Gao, "Multiplex measurement of twelve tumor markers using a gmr multi-biomarker immunoassay biosensor," Biosensors and Bioelectronics, vol. 123, pp. 204–210, 2019.

[129] P. D. Jayanti, L. J. Mahardhika, H. P. Kusumah, H. Ardiyanti, N. A. Wibowo, N. I. Istiqomah, N. S. Asri, J. Angel, E. Suharyadi et al., "Real-time biomolecule detection using gmr chip-based sensor with green-synthesized fe3o4/rgo nanocomposites as magnetic labels," Sensors and Actuators A: Physical, vol. 375, p. 115493, 2024.

[130] M. Callejas-Cuervo, J. C. Alvarez, and D. Alvarez, "Capture and analysis of biomechanical signals with inertial and magnetic sensors as support in physical rehabilitation processes," 2016 IEEE 13th International Conference on Wearable and Implantable Body Sensor Networks (BSN), pp. 119–123, 2016.

[131] K. Y. Lim, F. Young Koon Goh, W. Dong, K. D. Nguyen, I.-M. Chen, S. H. Yeo, H. Been Lirn Duh, and C. G. Kim, "A wearable, self-calibrating, wireless sensor network for body motion processing," pp. 1017–1022, 2008.

[132] Z. Zhang, X. He, J. Huang, and H. Yuan, "Parking detection using combined magnetic sensor and pulsed coherent radar," IEEE Internet of Things Journal, vol. 9, no. 18, pp. 17 210–17 219, 2022.

[133] J. T. Vaheeda and B. George, "Tmr sensor-based detection of evs in semi-dynamic traffic for optimal charging," IEEE Transactions on Intelligent Transportation Systems, vol. 23, no. 8, pp. 13 721–13 730, 2021.

[134] H. Weitensfelder, H. Brueckl, A. Satz, and D. Suess, "Temperature dependence of noise in giant- and tunneling magnetoresistive vortex sensors," IEEE Transactions on Magnetics, vol. 55, no. 7, pp. 1–5, 2019.

[135] R. Mattheis, M. Diegel, and R. Weiss, "Giant magnetoresistance-stack optimization for current sensor application with low hysteresis and a temperature-independent sensitivity at low current," IEEE Transactions on Magnetics, vol. 52, no. 10, pp. 1–6, 2016.

[136] T. Sen, C. Anoop, and S. Sen, "Simple linearising front-end-circuit for giant magneto-resistance sensors," Electronics Letters, vol. 54, no. 2, pp. 81–83, 2018.

[137] S. Paliwal, S. Yenuganti, and M. Manuvinakurake, "Fabrication and testing of a hall effect based pressure sensor," Sensor Review, vol. 42, no. 3, pp. 354–364, 2022.

[138] L. Wang, Z. Hu, Y. Zhu, D. Xian, J. Cai, M. Guan, C. Wang, J. Duan, J. Wu, Z. Wang et al., "Electric field-tunable giant magnetoresistance (gmr) sensor with enhanced linear range," ACS applied materials & interfaces, vol. 12, no. 7, pp. 8855–8861, 2020.

[139] X. Sun, C. Lei, L. Guo, and Y. Zhou, "Separable detecting of escherichia coli o157h: H7 by a giant magneto-resistance-based bio-sensing system," Sensors and Actuators B: Chemical, vol. 234, pp. 485–492, 2016.

[140] J. Davies, J. Watts, J. Novotny, D. Huang, and P. Eames, "Magnetoresistive sensor detectivity: A comparative analysis," Applied Physics Letters, vol. 118, no. 6, 2021.

[141] B. Cox, D. Davis, and N. Crews, "Creating magnetic field sensors from gmr nanowire networks," Sensors and Actuators A: Physical, vol. 203, pp. 335–340, 2013.

[142] A.-i. Sasaki and E. Ohta, "Magnetic-field-based position sensing using machine learning," IEEE Sensors Journal, vol. 20, no. 13, pp. 7292–7302, 2020.

[143] L. Pan, Y. Xie, H. Yang, M. Li, X. Bao, J. Shang, and R.-W. Li, "Flexible magnetic sensors," Sensors, vol. 23, no. 8, p. 4083, 2023.

[144] J. Zhang, G. Chen, Z. Jin, and J. Chen, "A review on magnetic smart skin as human–machine interfaces," Advanced Electronic Materials, vol. 10, no. 5, p. 2300677, 2024.

[145] A. Elzwawy, M. Rasly, M. Morsy, H. Piskin, and M. Volmer, "Magnetic sensors: Principles, methodologies, and applications," in Handbook of Nanosensors: Materials and Technological Applications. Springer, 2024, pp. 891–928.

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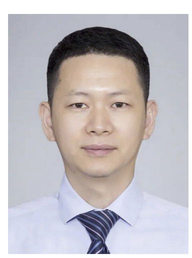

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