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Magnetoresistive Sensor Development Roadmap (non-recording applications)

Abstract— **Magnetoresistive (MR) sensors have been identified as promising candidates for the development of high-performance magnetometers due to their high sensitivity, low cost, low power consumption, and small size. The rapid advance of MR sensor technology has opened up a variety of MR sensor applications. These applications are in different areas that require MR sensors with different properties. Future MR sensor development in each of these areas requires an overview and a strategic guide. A MR sensor roadmap (non-recording applications) was therefore developed and made public by the Technical Committee of The IEEE Magnetics Society with the aim to provide an R&D guide for MR sensors intended to be used by industry, government, and academia. The roadmap was developed over a three-year period and coordinated by an international effort of 22 taskforce members from 10 countries and 17 organizations, including universities, research institutes, and sensor companies. In this paper, the current status of MR sensors for non-recording applications was identified by analyzing the patent and publication statistics. As a result, timescales for MR sensor development were established and critical milestones for sensor parameters were extracted in order to gain insight into potential MR sensor applications (non-recording). Five application areas were identified, and five MR sensor roadmaps were established. These include biomedical applications, flexible electronics, position sensing (PS) and human-computer interactions (HCI), non-destructive evaluation and monitoring (NDEM), and navigation and transportation. Each roadmap was analyzed using a logistic growth model, and new opportunities were predicted based on the extrapolated curve, forecasted milestones, and professional judgement of the taskforce members. This paper provides a framework for MR sensor technology (non-recording applications) to be used for public and private R&D planning, in order to provide guidance into likely MR sensor applications, products, and services expected in the next 15 years and beyond.**

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***Keywords*—magnetoresistive sensor, R&D guide, roadmap, smart living, Internet of Things.**

ACRONYMS

AHRS	Attitude and heading reference system
AMR	Anisotropic magnetoresistive
AOB	All-organic-based
APB	All-polymeric-based
AR	Augmented reality
CTC	Circulating tumor cells
DOF	Degree-of-freedom
EPO	European Patent Office
FDA	Food and drug administration
GMR	Giant magnetoresistive
HCI	Human-computer interaction
HPV	Human Papillomavirus
IoT	Internet-of-Things
MTJ	Magnetic tunnel junction
MFC	Magnetic flux concentrator
MEMS	Micro-electro-mechanical system
MR	Magnetoresistive
MCG	Magnetocardiography
MEG	Magnetoencephalography
NASA	National Aeronautics and Space Administration
NDEM	Non-destructive evaluation and monitoring
PS	Position sensing
POC	Point-of-care
SQUID	Superconducting quantum interference device
STPO	State Intellectual Property Office of China
TMR	Tunnelling magnetoresistive
TIPO	Taiwan Intellectual Property Office
TRL	Technology readiness levels
TLC	Technological life cycle
R&D	Research and development
UAV	Unmanned aerial vehicle
USPTO	United States Patent and Trademark Office
UUV	Unmanned underwater vehicle
VR	Virtual reality

I. INTRODUCTION

In the field of magnetic field sensing, magnetoresistive (MR) [1-4] sensors have attracted much interest owing to their high sensitivity, low cost, low power consumption, and small size [5-13]. The technological progress of MR sensors has resulted in a wide range of sensor applications, products, and services. These application areas require MR sensors with diverse properties, from high sensitivity and detectivity for biomedical applications[14-63], high mechanical flexibility and compactness for wearable/portable electronics [64-87], low power consumption and small physical dimension for position sensing (PS) [88-91] and human-computer interaction (HCI) [92-101], low cost and mass manufacturability for large-scale non-destructive evaluation and monitoring (NDEM) systems [102-122], to high accuracy and stability for navigation and transportation systems [123-141]. However, there is a lack of both an overview of the development of MR sensor applications and a strategic guide for future implementation of MR sensor technologies. These issues are resolved in this roadmap with the main scientific and technological objectives as follows:

1. To forecast MR sensor technology for the next 15 years and beyond so as to provide an R&D guide for industry, government, and academia.

2. To provide a framework for public and private MR sensor research and development (R&D) planning.

3. To use our expertise to predict opportunities for using MR sensors to serve society in innovative ways in the next 15 years and beyond.

The paper is structured as follows. In Section II, the roadmap development methodology is described. In Section III, the current status of MR sensors is identified, and the MR sensors development trend is summarized. In Section IV, critical sensor parameters are identified and their timelines are established, in order to gain insight into different possible sensor applications. In Section V, possible future MR sensor applications are identified, and five roadmaps are developed according to the corresponding application areas. These areas include biomedical applications, flexible electronics, PS and HCI, NDEM, and navigation and transportation. Finally, Section VI predicts the most likely future MR sensor applications.

II. ROADMAP DEVELOPMENT METHODOLOGY

In order to have a strategic guideline to follow, a 5-stage methodology for the roadmap development was established, as illustrated in Figure 1.

In Stage 1, the roadmap taskforce was commissioned by the Technical Committee of The IEEE Magnetic Society at the IEEE International Magnetics Conference (Intermag) 2014, in Dresden, Germany. Recruitment of taskforce members commenced.

In Stage 2, the roadmap taskforce discussed the objective and purpose of the roadmap during the 1st taskforce meeting at the Intermag 2015, in Beijing, China. The scope and objective of the roadmap were defined, and more taskforce members were recruited.

In Stage 3, statistics of patents and publications related to MR sensors (non-recording) were analyzed. The publication data were collected from the Web of Science by keyword search. The search fields were applied only in the Title and Abstract of publications in order to exclude unrelated topics. The related patent data were obtained from four patent databases compiled by the European Patent Office (EPO), United States Patent and

Trademark Office (USPTO), State Intellectual Property Office of China (STPO), and Taiwan Intellectual Property Office (TIPO). Based on the patent and publication data, a professional assessment of relevant MR sensor parameters was made during the 2nd taskforce meeting at the Joint Magnetism and Magnetic Materials (MMM)/Intermag 2016, in San Diego, USA. The current status of MR sensor applications was then discussed, and critical sensor parameters for non-recording applications were identified.

In Stage 4, published articles and filed patents related to fundamental MR sensor research were reviewed. A professional assessment of critical milestones for selected sensor parameters was made during the 3rd taskforce meeting at MMM 2016, in New Orleans, USA. Timelines for MR sensor development and for critical milestones of the sensor parameters were established and forecasted.

In Stage 5, publications related to MR sensor applications were analyzed. A professional assessment of future MR sensor applications was made according to the forecasted critical milestones for sensor parameters during the 4th taskforce meeting at Intermag 2017, in Dublin, Ireland. Finally, a review and prediction of likely MR sensor applications, products, and services was then performed, and five roadmaps for MR sensor applications were developed.

The maturity levels of MR sensor applications, products and services were gauged by the technology readiness levels (TRL) [142]. In this paper, the classification of TRL defined by National Aeronautics and Space Administration (NASA) was adopted [143]. The TRL values of the historical MR sensor applications were analyzed using the logistic model [144, 145]. As a commonly-used growth trend curve, the logistic model has been widely utilized to describe the S-shaped feature of the technological life cycle (TLC) [142, 146, 147], which typically comprises four phases: emergence, growth, maturity, and saturation, as exhibited in Figure 2. The formula of the logistic growth curve is

$$Y = \frac{L}{1 + ae^{-bt}} \tag{1}$$

where Y represents the indicator related to the TRL, t represents the development time, the constants a, b, and L are the fitting parameters. In the technology emergence phase (TRL 1-2), fundamental investigation and basic research are conducted. In the technology growth phase (TRL 3-4), researches are carried out to prove the feasibility of the technology. In the technology maturity phase (TRL 5-6), model/sub-model and full-scale tests are demonstrated. In the final saturation phase (TRL 7-9), systems are validated and related products are deployed into market. In this review, we first fitted the logistic model with the TRL levels of the historical MR sensor applications so that the future trends could be predicted by extending the fitting curves beyond 2018. New opportunities were predicted by utilizing the extrapolated curve, forecasted milestones, and professional judgements on critical sensor parameters. The global vision of new MR sensor (non-recording) applications, products and services was launched out through the next 15 years and beyond.

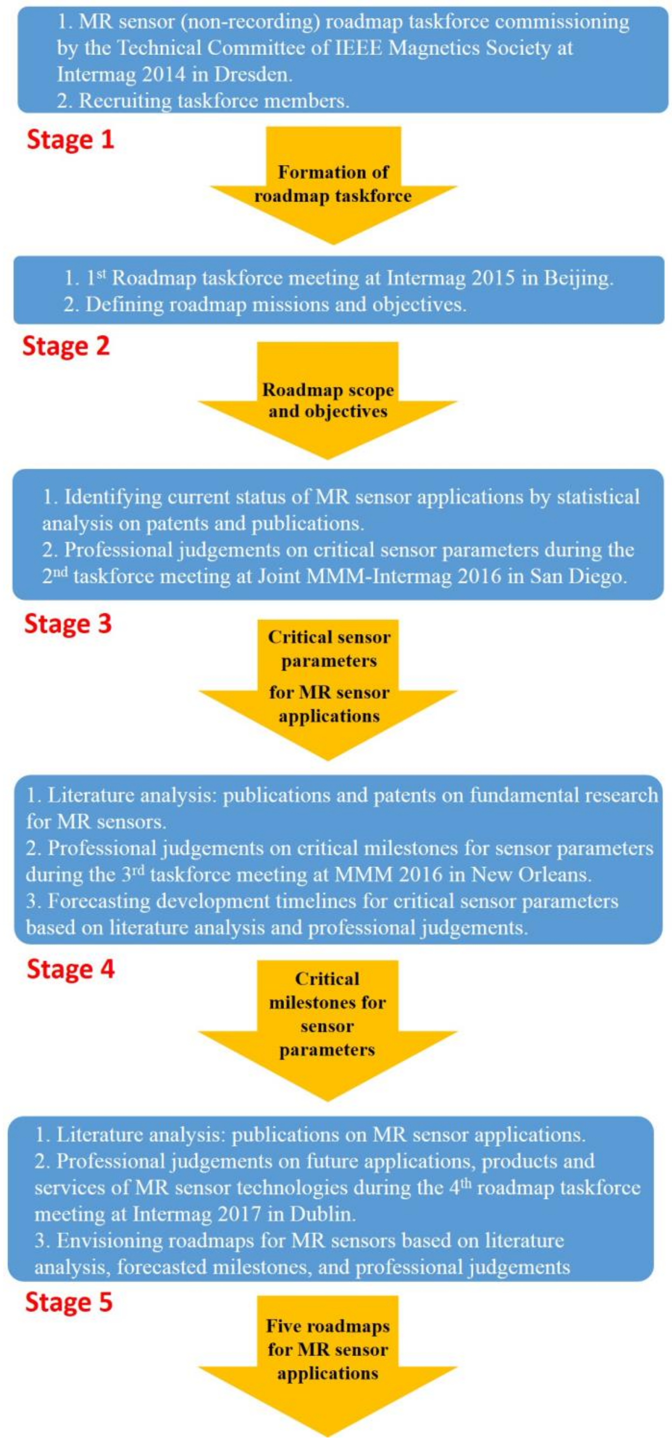

Fig. 1. Methodology for the roadmap development.

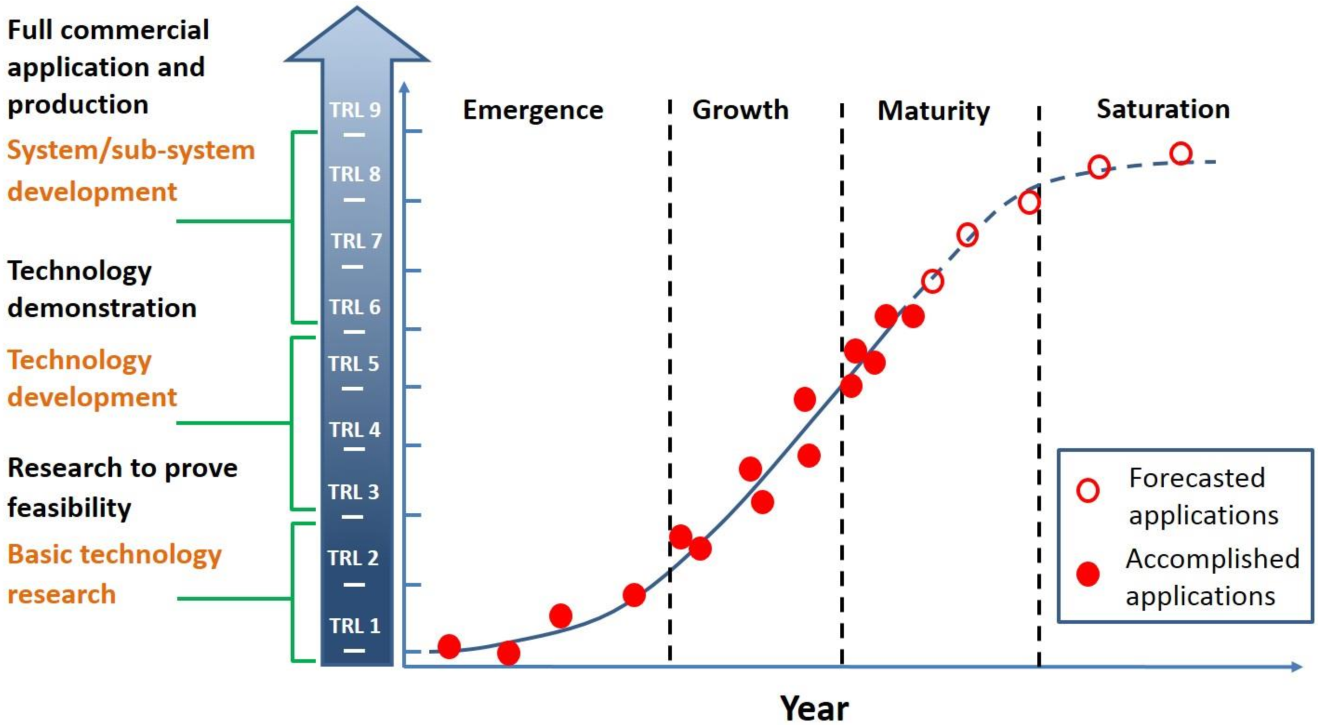

Fig. 2. Technological life cycle fitted with the logistic growth model to forecast future technological development.

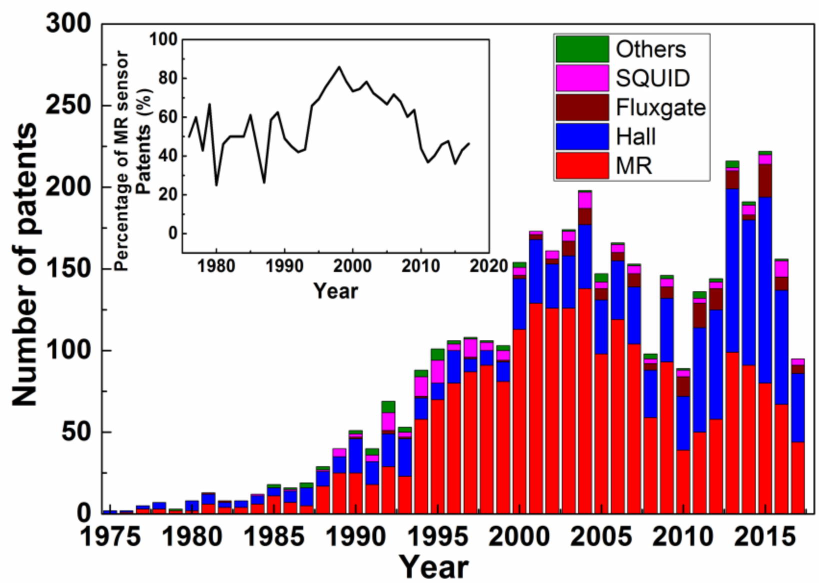

Fig. 3. Statistics of common magnetic sensors from 1975 to 2017 in the selected patent databases compiled by EPO, USPTO, STPO, and TIPO. Inset is the percentage of MR sensor patents among all types of magnetic field sensors. The list of keyword search queries for patent statistics is shown in Table I.

III. Current status of MR sensor applications

Magnetic field detection has tremendous impact on a large variety of applications and industries [8, 9, 11-13, 148-152], which exploit a wide range of physical phenomena and principles [7, 153-167]. To obtain an overview of magnetic field sensing techniques, an analysis of statistics of common magnetic sensors from 1975 to 2017 in the selected patent databases is shown in Figure 3. To rule out any unrelated applications, the search queries were applied only in the Title and Abstract. The list of search keywords for patents statistics of magnetic field sensors is shown in Table I. Typical magnetic sensors [13, 148, 149, 168] were taken into account, including MR sensors [7, 11, 157, 169], Hall effect sensors [26, 155, 170-172], fluxgates [173-177], superconducting quantum interference devices (SQUID) [156, 178-181], magneto-optical sensors [161, 182-186], search coils [187-191], magneto-inductive sensors [160, 192-195], magneto-impedance sensors [160, 196-199], magneto-diodes [153, 200-203], magneto-transistors [154, 204-207], and optically pumped magnetometers [158, 208-211]. As one of the most commonly-used magnetic sensors, MR sensors cover a relatively large portion of patent applications [5, 7, 10-13, 149, 169], especially during the period from 1988 to 2008, as illustrated in Figure 3. In general, MR sensors cover over 50% of the patent applications. The patent statistics trend of MR sensors (Figure 3) is well matched with the publication statistics curve (Figure 4). The list of search keywords for publication statistics of parallel and perpendicular anisotropic magnetoresistive (AMR), giant magnetoresistive (GMR), and tunnelling magnetoresistive (TMR) sensors is shown in Table II. Here, the perpendicular AMR refers to the planar Hall magnetoresistance/resistance effect [212-218]. The number of publications of GMR sensors exhibits an explosive growth after the discovery of GMR effect in 1988 [1, 2]. After 1995, the number of publications related to TMR sensors dramatically increases and starts to exceed that of GMR sensors in 2000. The total number of publications of MR sensors reaches a peak in 2004-2006 and then shows a slight decrease (Figure 4), which is consistent with the patent trend (Figure 3).

TABLE I KEYWORD SEARCH QUERIES FOR PATENT STATISTICS OF MAGNETIC FIELD SENSORS

Magnetic field sensor	Keyword
MR sensor	(1) "magnetoresistive" AND "magnetic" AND "sensor" (2) "magnetoresistance" AND "magnetic" AND "sensor"
Hall sensor	(1) "Hall" AND "magnetic" AND "sensor"; (2) "Hall effect" AND "magnetic" AND "sensor";
Fluxgate	"fluxgate" AND "magnetic" AND "sensor"
Magneto-optical sensor	(1) "magneto-optical" AND "magnetic" AND "sensor" (2) "magnetic-optic" AND "magnetic" AND "sensor"
Superconducting quantum interference devices	(1) "superconducting quantum interference device" AND "magnetic" AND "sensor" (2) "SQUID" AND "magnetic" AND "sensor"
Search coil	"search coil" AND "magnetic" AND "sensor"
Magneto-inductive sensor	(1) "magneto-inductive" AND "magnetic" AND "sensor" (2) "magnetic-inductantance" AND "magnetic" AND "sensor"
Magneto-impedance sensor	(1) "magneto-impeditive" AND "magnetic" AND "sensor" (2) "magnetic-impedance" AND "magnetic" AND "sensor"
Magneto-diode	"magneto-diode" AND "magnetic" AND "sensor"
Magneto-transistor	"magneto-transistor" AND "magnetic" AND "sensor"
Optically pumped sensor	"optically pumped" AND "magnetic" AND "sensor"

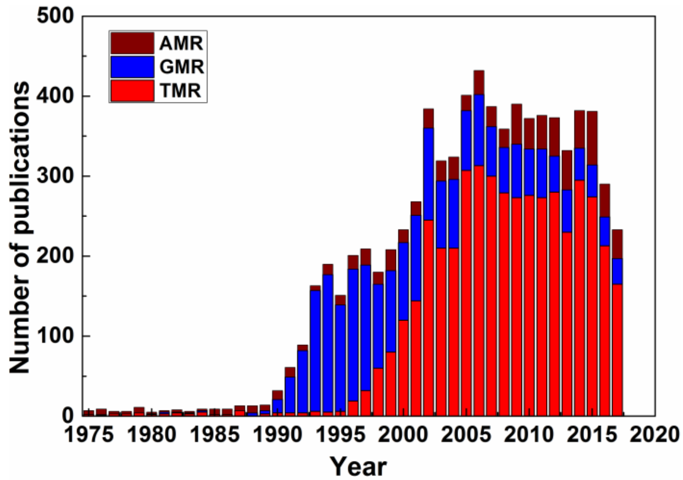

Fig. 4. Publication statistics of AMR, GMR, and TMR sensors from 1975 to 2017 in the Web of Science. The list of search keyword queries for publication statistics of AMR, GMR, and TMR sensors is shown in Table II.

TABLE II KEYWORD SEARCH QUERIES FOR PUBLICATION STATISTICS OF MR SENSORS

Magnetic field sensor	Keyword
AMR sensor	(1) "anisotropic" AND "magnetoresistive" AND "sensor" (2) "anisotropic" AND "magnetoresistance" AND "sensor" (3) "planar Hall" AND "magnetoresistive" AND "sensor" (4) "planar Hall" AND "magnetoresistance" AND "sensor" (5) "planar Hall resistance" AND "sensor"
TMR sensor	(1) "tunnel" AND "magnetoresistive" AND "sensor" (2) "tunnel" AND "magnetoresistance" AND "sensor" (3) "tunneling" AND "magnetoresistive" AND "sensor" (4) "tunneling" AND "magnetoresistance" AND "sensor" (5) "tunnelling" AND "magnetoresistive" AND "sensor" (5) "tunnelling" AND "magnetoresistance" AND "sensor"
GMR sensor	(1) "giant" AND "magnetoresistive" AND "sensor" (2) "giant" AND "magnetoresistance" AND "sensor"

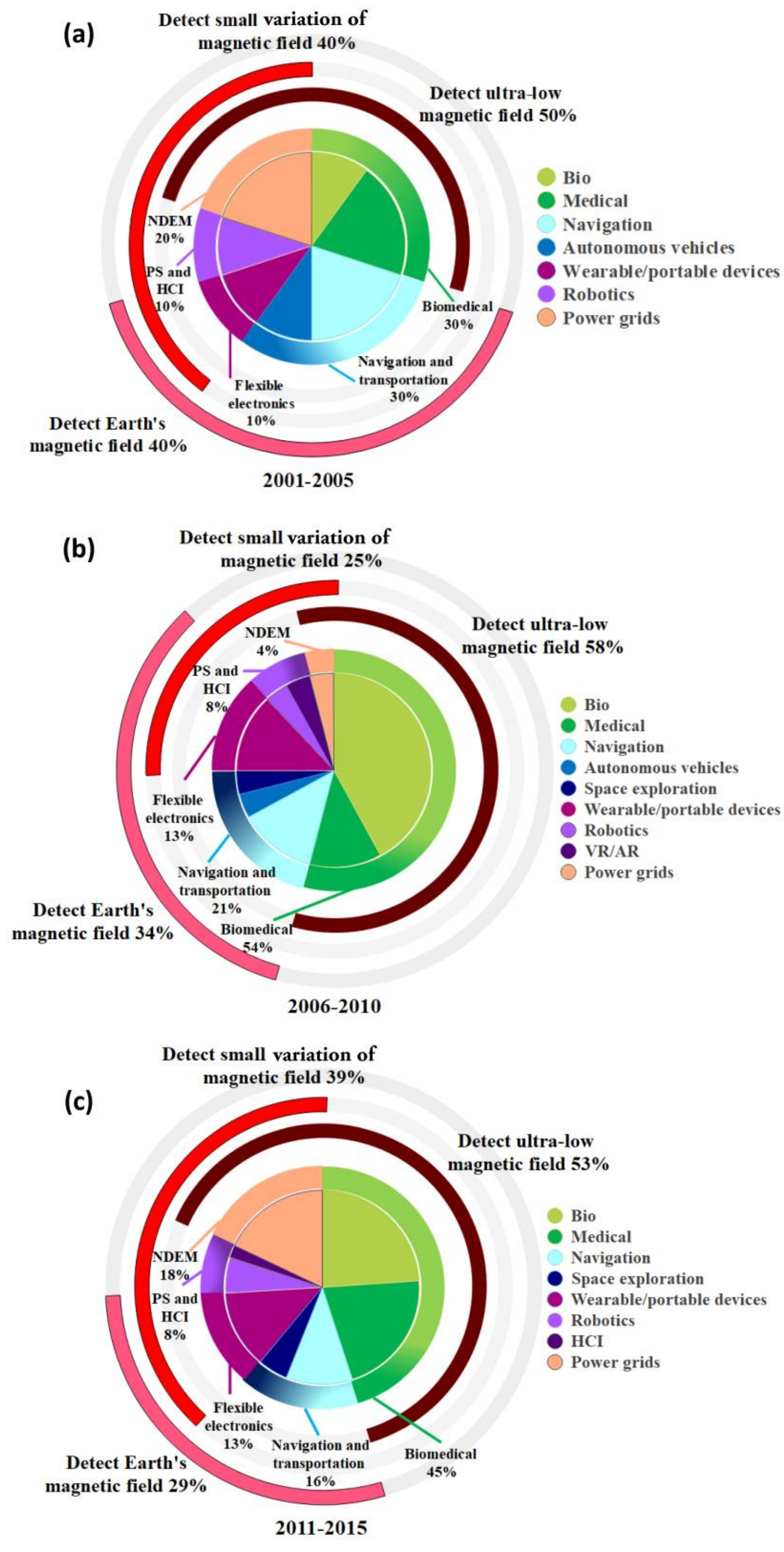

Fig. 5. Distribution of publications on MR sensor applications including biomedical applications, flexible devices, position sensing (PS) and human-computer interactions (HCI), non-destructive evaluation and monitoring (NDEM), and navigation and transportation in the periods of (a) 2001-2005, (b) 2006-2010, and (c) 2011-2015.

Continuous endeavors from scientists and engineers have opened up various applications of MR sensor techniques [29-31, 33, 34, 37-46, 48, 50, 51, 53-55, 78, 97, 109, 120, 219-223] as shown in Figure 5. According to the strength of the measured field, MR sensor applications can be divided into three major categories: 1) measuring the Earth's magnetic field (~μT) [123-

125, 129-139, 224-233], 2) measuring small variations of magnetic field (from ~µT to ~nT) [107, 108, 110, 111, 113, 114, 116-121, 234], and 3) measuring ultralow magnetic field (lower than ~nT) [16, 18-21, 23-31, 33-35, 37-40, 42-44, 46, 48, 50, 51, 53-56, 222, 235].

In the earlier applications in the period of 2001-2005 (Figure 5(a)), MR sensors were frequently used as magnetic compasses to detect Earth's magnetic field in navigation and transportation (30%) [129, 130, 236, 237], among which 10% were incorporated into autonomous vehicles, [126, 238] and wearable/portable devices (10%) [239, 240] as well. On the other hand, MR sensors were applied for non-destructive power-grid monitoring (20%) [157, 241] and were utilized as sensitive magnetic probes to detect ultra-low magnetic field in biomedical applications (30%) [18, 20, 21, 24, 27, 29].

In the period of 2006-2010 (Figure 5(b)), more MR sensors (58%) were used to detect ultralow magnetic field owing to the improvement of their sensing performance (*e.g.*, sensitivity, detectivity). Especially, more biomedical applications with MR sensors were explored (increased from 30% in 2001-2005 to 54% in 2006-2011) [34-40, 42, 222]. With the development of flexible sensor substrates, a growing number of MR sensors with high tolerable tensile strain [70, 73, 75] were integrated into wearable/portable devices [96] (increased from 10% in 2001-2005 to 13% in 2006-2010) to detect Earth's magnetic field and small variations of magnetic field. A series of satellites were equipped with MR sensors for space exploration (4%) [134, 231, 232] by virtue of their reduced size and power consumption [242-245]. MR sensors also exhibited their great compatibility with emerging technologies, such as PS and HCI (8%) in virtual reality/augmented reality (VR/AR) [96, 246] and robotics [247].

In the period of 2011-2015 (Figure 5(c)), MR sensors continued to be widely used in the field of biomedical applications (45%) [48, 50, 51, 53-57]. Motivated by the concept of a smart grid, more MR sensors were implemented in power grid monitoring [110, 113, 116, 119] (increased from 4% in 2006-2010 to 18% in 2011-2015) in order to detect small variations of the magnetic field and the magnetic field generated by the currents of power cables. In order to push forward and realize MR sensor applications with existing and emerging technologies, further enhancement of MR sensor performance reflected by the critical parameters is required. Next session explores the impact of these parameters on the (1) sensitivity, (2) detectivity, (3) power consumption, (4) mechanical flexibility, and (5) robustness.

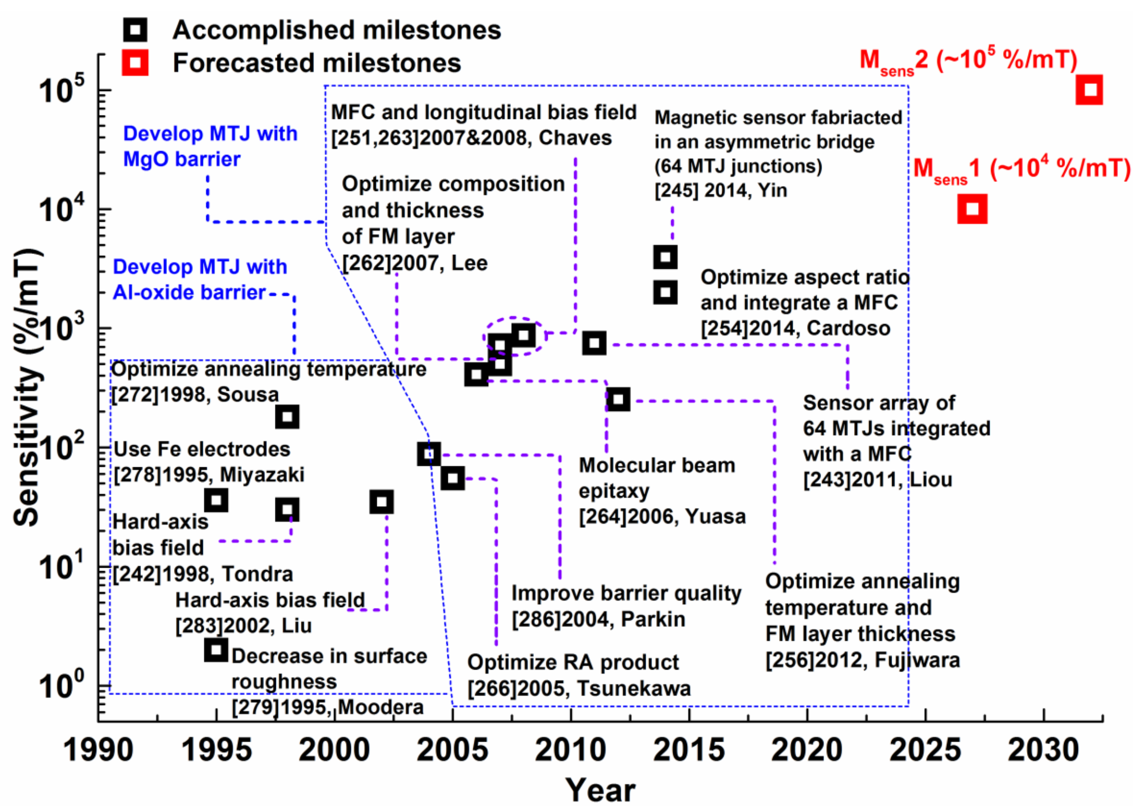

Fig. 6. Development trend for the sensitivity of MR sensors at room temperature from 1995 to 2032.

IV. DEVELOPMENT TIMELINES FOR CRITICAL MR SENSOR PARAMETERS

In order to gain deep insights into the technological evolution, MR sensor development timescales were established. Timelines of key sensor performance parameters including sensitivity, detectivity, power consumption, mechanical flexibility, and robustness were investigated and illustrated. Past achievements of these performance parameters were identified and their driving forces for sensor applications were discussed. Forthcoming milestones were predicted based on both the historical trends and fitted curves.

A. Sensitivity

As one of the most fundamental and critical performance parameters of MR sensors, sensitivity has exhibited a considerable growth in the last two decades [223, 243, 245, 248-266], as shown in Figure 6. The sensitivity [250, 254] of MR sensors is defined in the linear operation range of the magnetic transfer curve as

$$S = \frac{MR}{2\mu_0 H_{sat}} \tag{2}$$

where MR and H_{sat} represent the MR ratio and saturation field, respectively. Both increased MR ratio and reduced saturation field give rise to an improved sensitivity. Large MR ratio can be obtained by selecting the thin-film materials [262, 267-271], optimizing the fabrication process [256, 272-274], and device geometry including layer thicknesses [257, 275-277]. Suppression of saturation field can be achieved by incorporating the sensors with magnetic flux concentrators (MFCs) [249, 251, 254, 263], utilizing soft ferromagnetic materials with low saturation field [262], and modifying sensor geometry [257] as well. Due to relatively high MR ratio of TMR sensors (Figure 7), researchers and engineers favor the use of TMR elements for applications requiring highly sensitive MR sensors. For the TMR sensors with an AlO_x barrier during the period of 1995-2002, TMR sensors with sensitivity from several %/mT to almost two hundred %/mT were fabricated [242, 269, 278-284]. After replacing the AlO_x barrier with the crystalline MgO barrier, a rapid increase of MR ratio was accomplished (Figure 7) [269, 270, 285-287], resulting in a notable enhancement of sensitivity to 300-1000 %/mT (Figure 6) [245, 250, 251, 253, 255]. By integrating MFCs into the TMR sensors, the saturation field was greatly diminished and thus the sensitivity was significantly increased [249-251, 254, 263]. Another major improvement of sensitivity was achieved by designing a sensor array with 64 MTJ junctions and incorporating the sensor array with a MFC [245]. Sensitivity as high as 3944 %/mT was obtained by utilizing this strategy [245]. To further improve MR sensitivity to $>10^4$ %/mT, two technological challenges (TC) will need to be solved:

TC 1.1: accomplishment of >1000% MR ratio at room temperature.

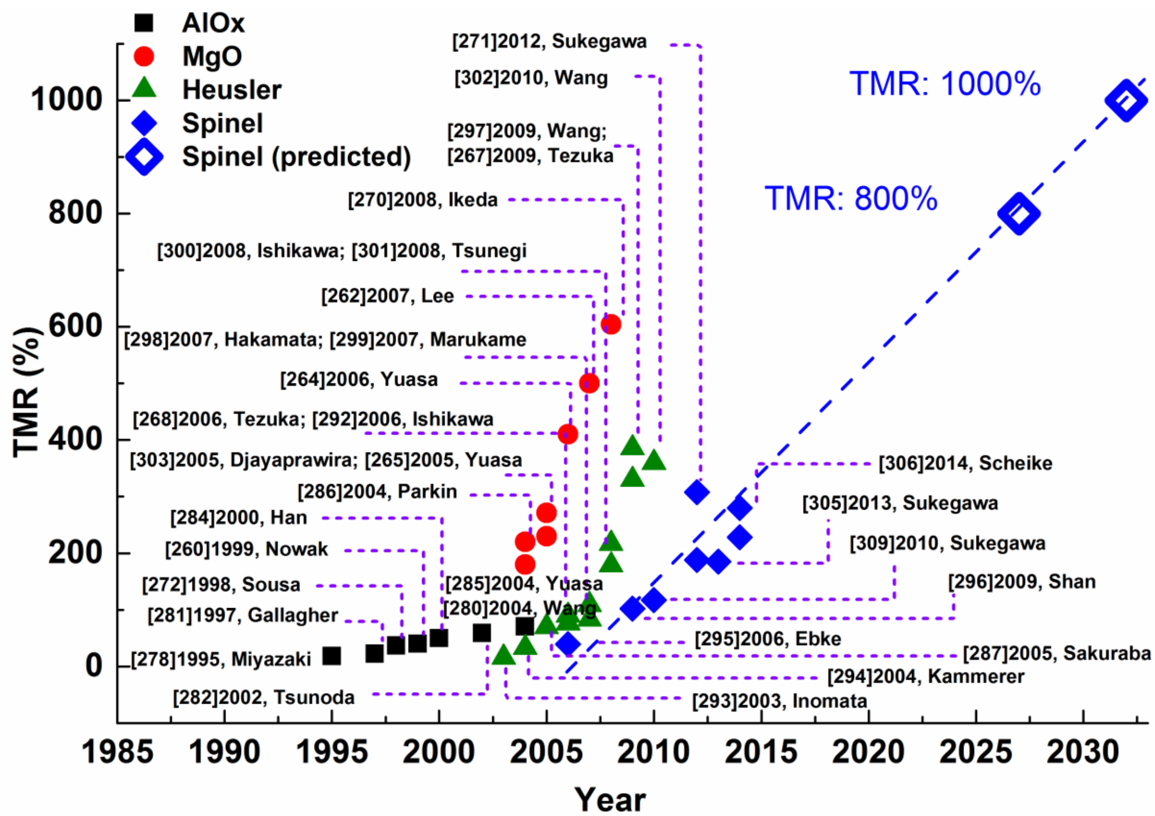

Fig. 7. Development trend of TMR ratio at room temperature for MTJs from 1995 to 2032.

TC 1.2: accomplishment of <0.1 mT saturation field $2\mu_0 H_{sat}$ at room temperature.

For TC 1.1, the half-metallic Heusler alloy is an attractive choice of material due to high spin polarization [288-296]. As shown in Figure 7, MgO-based magnetic tunnel junction (MTJ) with Heusler alloy electrodes achieved comparable TMR ratio [267, 292, 297-302] as those MTJs with conventional ferromagnetic electrodes [264, 270, 303]. However, further enhancement of TMR was limited by the relatively large lattice mismatch between the MgO barrier [286] and Heusler alloy electrodes [304, 305]. This issue was resolved by replacing the MgO barrier with a spinel $MgAl_2O_4$ barrier [271, 305-308]. Compared to the MgO barrier, smaller lattice spacing of the $MgAl_2O_4$ barrier resulted in a much better lattice match of the barrier/ferromagnetic layer interface [306, 307, 309]. Furthermore, a perfectly dislocation-free interface was obtained by utilizing the cation-disorder spinel (Mg-Al-O) barrier [271, 305] where its lattice spacing was tunable through modifying the Mg-Al compositions [305]. Therefore, a significantly enhanced TMR ratio can be expected through utilizing the lattice-tuned Mg-Al-O barrier and optimizing the Heusler alloy electrodes. To estimate the forthcoming milestone, the historical data was fitted with a linear line and the future trend was forecasted by extrapolating the fitted line. Based on the fitting curve using the data points of spinel-based MTJs in Figure 7, 800% TMR may be reached by ~2027, and finally 1000% TMR may be accomplished by ~2032. For TC 1.2, the saturation field $2\mu_0 H_{sat}$ around 0.08 mT was demonstrated by combining the sensor with a Conetic MFC (gain: ~77 times) in 2011 [243]. In 2015, a factor of 400 times MFC was reported for an MTJ bridge [315]. In 2017, Valadeiro *et al*. reported a high gain (~400 times) MFC with a double layer architecture [310]. By using this type of MFC, the authors believe that the saturation field will be further reduced from ~0.08 mT to ~0.01 mT in the near future. With the accomplishment of both TC 1.1 and TC 1.2, one can expect high-performance TMR sensor with sensitivity approaching ~10^4 %/mT (1st milestone of sensitivity: $M_{sens}1$) by ~2027 and ~10^5 %/mT (2nd milestone of sensitivity: $M_{sens}2$) by ~2032 (see the forecasted milestones in Figure 6).

It is worth mentioning that although the linear extrapolation of MR ratio over time in Figure 7 might be optimistic, the milestone of sensitivity mentioned above can still be possibly achieved by advancing the progress of TC 1.2. At present, many experimental demonstrations already show gains of hundreds for MFCs. In fact, larger magnetic field amplification (~1000 or even higher) can be possibly achieved by implementing the sensors inside tailor-made MFCs with their shape, dimensions and geometry (e.g., aspect ratio, the ratio of outer to inner width), material (e.g., high-permeability material) and the gap length optimized [311, 312]. As such, the final goal combining $M_{sens}1$ and $M_{sens}2$ is still expected.

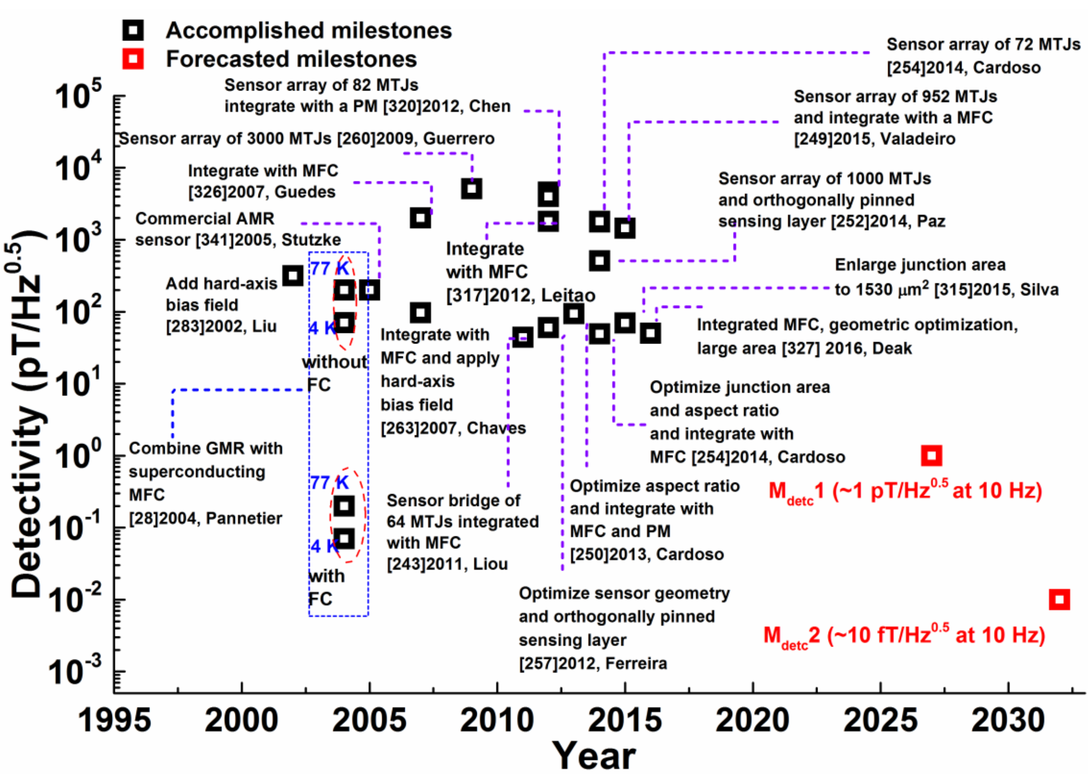

Fig. 8. Development trend of the detectivity of MR sensors at room temperature from 1995 to 2032.

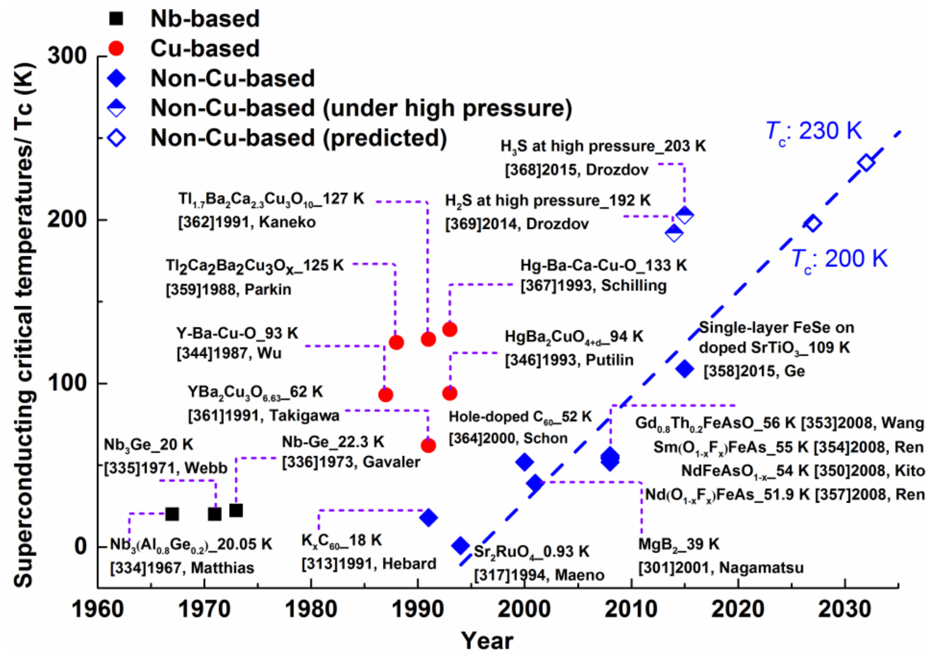

Fig. 9. Development trend of the superconducting critical temperature (T_c) of superconductors from 1967 to 2032.

It is also worth mentioning that the noise level of a TMR sensor (S_B) is correlated with its MR ratios. The total field noise power of a TMR sensor is given by [313]

$$S_B = \left(\frac{dB}{dV}\right)^2\left[S_v^{Amp} + S_V^{shot} + S_v^{elec.1/f}\right] + S_B^{therm.mag.} + S_B^{mag.1/f} \tag{3}$$

$$\frac{dV}{dB} = \frac{\Delta R}{R}\frac{NV_J}{2B_{sat}} \tag{4}$$

where $\frac{\Delta R}{R}$ is the MR ratio, N is the number of MTJs per leg, V_J is the voltage drop across each MTJ, B_{sat} is the free-layer saturation field, $S_v^{Amp}, S_V^{shot}, S_v^{elec.1/f}, S_B^{therm.mag.}$ and $S_B^{mag.1/f}$ are amplifier noise voltage power, shot-noise voltage power, electronic *1/f* noise, thermal magnetic noise, and magnetic *1/f* noise magnetization power respectively. The overall noise level of MR sensor can be reduced by increasing MR ratio because the amplifier noise voltage power, shot-noise voltage power, and electronic 1/f noise can be suppressed by a larger MR ratio ($\frac{\Delta R}{R}$ in Eq. (4)); however, the thermal magnetic noise and magnetic 1/f noise magnetization power do not change with the MR ratio ($\frac{\Delta R}{R}$ in Eq. (4)). Further discussion on noise and detectivity can be found in the next section.

B. Detectivity

To fabricate high-performance MR sensors for measuring ultra-low magnetic field, researchers endeavor not only to boost their sensitivity but also to improve their detectivity which determines the smallest magnetic signal a sensor can detect [50, 222, 223, 243, 249-255, 257-260, 314-326], as shown in Figure 8. The detectivity [250] of an MR sensor is associated with its sensitivity and noise level, as expressed by

$$D = \frac{1}{S}\sqrt{\frac{S_V}{V^2}} \tag{5}$$

where *D* is the detectivity, *S* is the sensitivity, *V* is the applied bias voltage and S_V/V^2 is the normalized noise level. From Eq. 5, both improvement of the sensitivity and suppression of the sensor noise can enhance the detectivity. As discussed in Section A, incorporation of the MR sensor array with MFCs can dramatically improve its sensitivity [245, 252], leading to a considerable increase of the sensor detectivity. On the other hand, the sensor detectivity can be greatly enhanced by reducing the sensor noise through optimization of sensor fabrication, such as enlarging the sensor area [250, 315], modifying the annealing process [243, 258, 323], and soft-pinning the sensing layer [249, 257]. Defect-free MR sensors with relatively large sensing area can greatly reduce the 1/*f* noise and a sensor detectivity of ~60 pT/Hz$^{0.5}$ has been successfully demonstrated at 10 Hz [257]. Applying hard-axis bias field [263, 283] or orthogonally soft-pinning the sensing layer [249, 257] are effective techniques to stabilize the magnetization of the sensing layer and suppress the sensor noise. MultiDimension Technology released its highly-sensitive TMR sensors (TMR9001/9002) with detectivities of ~50 pT/Hz$^{0.5}$ at 10 Hz in a commercial product, and ~20 pT/Hz$^{0.5}$ at 10 Hz in a larger prototype device [327]. Owing to unremitting research efforts, pT detectivities [243, 249, 252, 254, 257] has been achieved at room temperature and fT detectivities has been demonstrated at low temperature (77 K) by using superconductor MFCs [28, 222]. There are other methods for reducing the low-frequency noise in MR sensors. In the modulation technique, MFCs are deposited on micro-electro-mechanical systems (MEMS) flaps which are driven to oscillate at very high frequencies [328]. The advantage of modulation can only be achieved when the sensor element is responsible for most of 1/f noise, not the other parts of the sensor system. Moreover, it is challenging to design a successful fabrication route to combine the MEMS technology

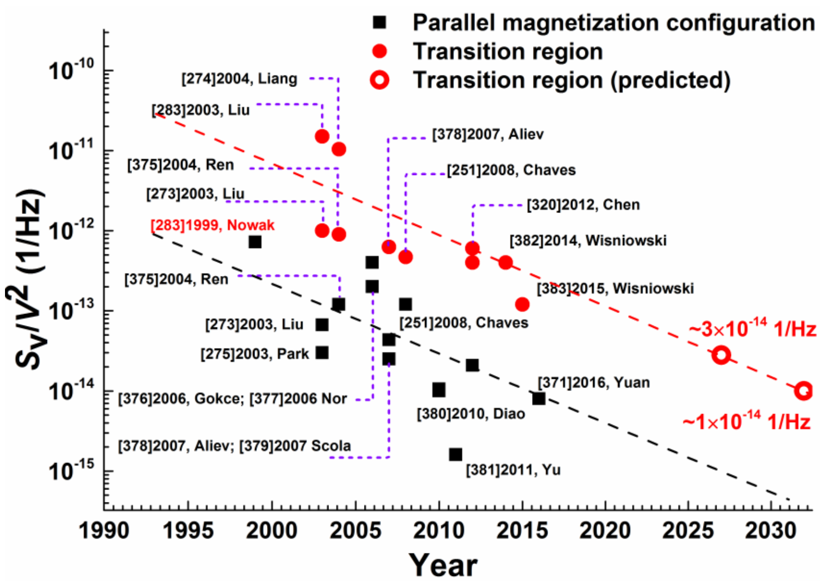

Fig. 10. Noise reduction trend at room temperature in both the magnetization-transition region and parallel magnetization configuration from 1990 to 2032.

and magnetic sensor. Though the modulation based on MEMS was presented, and several prototypes were fabricated with electro-static combs, torsionators, and cantilevers, the modulation efficiency is low [329]. In the chopping technique, chopper switches are designed for the output of MR sensors [330]. The noise characteristics of the chopper switches are dependent on charge leakage, parasitic capacitance, IC substrate coupling noise, voltage stability of the drive signal, and the external electric field sensitive electrodes [331]. All these factors need to be considered and optimized in order to suppress the noise. The methods of modulation and chopping still require research efforts to overcome these technical challenges.

To accomplish fT/Hz$^{0.5}$ detectivity at/near room temperature, two technological challenges (TC) have been identified:

TC 2.1: development of high-gain (>1000) MFC at/near room temperature.

TC 2.2: accomplishment of ~10^{-14} 1/Hz normalized noise level in low frequency range (typically <100 Hz) at/near room temperature.

Regarding TC 2.1, high-temperature superconductor MFCs are required to be developed. Comparing superconducting MFCs and SQUIDs, the SQUIDs have two disadvantages. Firstly, the Josephson junction of SQUIDs is short-lived and complicated to fabricate because of poor reproducibility and low yield, and thus they are expensive [332]. Secondly, though SQUIDs comprised of ceramic HTS materials could alleviate the size, weight and power requirements, they have been found to be difficult to work with because of anisotropic electrical properties and intrinsic noise [333]. Compared to the conventional MFCs using soft ferromagnetic materials [249, 250, 254, 317, 326], superconductor MFCs exhibit a much higher gain (100-1000), as reported in [28, 222]. However, the application of superconductor MFC is restricted by its relatively low superconducting critical temperature (T_c) [28, 222, 223, 334-366], which is far below the room temperature, as shown in Figure 9. The highest known T_c values in the Cu-based and non-Cu-based superconductors are 133 K [367] and 109 K [358] at ambient pressure, respectively. Under high pressures, T_c values of certain superconducting materials can be notably increased [368-370] and even room-temperature superconductor MFCs can be realized. When high pressure is applied, the T_c values around 200 K for non-Cu-based superconductors have been achieved [368, 369], which is much higher than their Cu-based superconductor contenders (T_c~164 K). To predict higher T_c values, a linear curve was fitted with the past data for the non-Cu-based superconductors in Figure 9. From the extrapolated curve, one expects the emergence of non-Cu-based superconductors with higher T_c than their Cu-based superconductor contenders by ~2022. The T_c value can possibly reach ~210 K by ~2027 and exceed ~245 K by ~2032, which is approaching room temperature.

Regarding TC 2.2, suppression of the noise in the magnetization-transition region is the primary task because the sensor noise mainly originates from the magnetization fluctuations during operation and its magnitude is considerably larger than that of the electrically originated noise (as exhibited in the parallel magnetization configuration) [255, 273, 371-383], as shown in Figure 10. Since operation region of MR sensors is where the magnetization of the sensing layer undergoes a transition, we predict the noise reduction trend by fitting and extrapolating the noise data for the magnetization-transition region with a linear line. Normalized noise level around ~3×10^{-14} 1/Hz can be expected by ~2027 and one can estimate noise level to go down to the order of ~1×10^{-15} 1/Hz in approximately 15 years (*i.e.*, ~2032). Considering the forecasted accomplishments for both sensitivity and noise level in the following 15 years, one expects that a detectivity of ~1 pT/Hz$^{0.5}$ (1st Milestone of detectivity: M_{detc} 1) can be achieved by ~2027. Incorporating MR sensors with near-room-temperature superconductor MFC (gain: ~1000 times), a detectivity of ~10 fT/Hz$^{0.5}$ (2nd Milestone of detectivity: M_{detc} 2) is expected by ~2032 (see the forecasted milestones in Figure 8).

It should be noted that the expected detectivity may not be achievable without the deployment of magnetic shielding because the external background magnetic field noise may render the low-field detectivity useless. Magnetic shielding can effectively eliminate background field noise and facilitate low-field detection [384-395]. Magnetic shielding with high shielding effectiveness can be fabricated with soft magnetic materials such as Conetic alloy [395, 396] and multi-layered structures [397-399]. The field reduction exceeded 25dB for combined active and passive shields in 2003 [400]. In 2007, a shielding factor of 6×10^6 was measured in a nested set of three shields, and a shielding factor of up to 10^{13} was predicted when five shields were used [401]. In the work of Komack's group [402], a magnetometer with single-channel sensitivity of 0.75 ft/Hz$^{0.5}$ was demonstrated by using a ferrite shield, limited only by the magnetization noise of ferrite and photon shot noise. In the high-temperature superconducting area, shielding factors as high as 95% were observed for three-layer hybrid shielding structures in 2016 [403]. A group reported that 98% attenuation of the magnetic field was achieved by more than five layers of the coated conductor tape wound with the same orientation and angle to cover the gaps of an inner layer achieves in 2018 [385]. Some researchers are now making use of computational intelligence to optimize a series of shielding parameters such as material, shape, thickness, and the number of layers for a higher shielding effectiveness [404-406].

Besides, it is worth mentioning that the influence of MR ratio and noise are discussed separately in Section IV(A) and (B), respectively. The discussion in Section IV(A) on sensitivity and MR ratio is purely based on %/mT as derived from Eq. 2 which does not take into account the noise. The detailed discussion on noise is provided in Section IV(B) which elaborates on detectivity from the point of view of noise level (T/Hz$^{0.5}$). In fact, a good MR sensor needs both good MR ratio and low noise level. Now the researchers are working on the realization of the ultra-sensitive and high-resolution MR sensors by reducing their intrinsic noise without sacrificing MR ratios. The authors in Ref. [407] worked on a TMR device with CoFeB-MgO-CoFeB structures with MR ratios up to 600% at room temperature. They showed that the voltage-induced magnetic anisotropy modulation could be used to control and reduce magnetic noise in TMR sensors with perpendicular anisotropy. The magnetic noise was reduced by around one order of magnitude. In Ref. [320], the yoke-shaped TMR sensors based on MgO-barrier MTJs were designed. Their field sensitivity was up to 27%/mT, while the field detectivity reached 3.6 nT/Hz$^{0.5}$ at 10 Hz and 460 pT/Hz$^{0.5}$ at 1k Hz through designing a nearly-perpendicular configuration of two ferromagnetic electrodes. The TMR sensors fabricated with electron-beam evaporated MgO barriers can provide about an order of magnitude improvement in their signal-to-noise ratio compared to the conventional sputtered MgO tunnel barriers [380]. Frequency noise was investigated in MgO double-barrier MTJs with TMR ratios up to 250% at room temperature, and the research disclosed that the double-barrier MTJs were useful for improving the signal-to-noise ratio compared to single-barrier MTJs under low bias. These methods are critical for the overall improvement in the field detectivity of MR-sensor devices and their applications.

C. Operational performance (power consumption, mechanical flexibility, robustness)

In addition to high-performance sensing, MR sensors have other desirable capabilities, including low power consumption [242-245], high mechanical flexibility [83, 85], and high robustness [127, 128, 134, 135], as shown in Figure 11.

Power consumption is critical in certain applications where power supply is limited, such as MR elements used in spacecrafts [226, 229], MR sensors integrated into portable devices [96, 98, 99], and also MR sensors for the Internet-of-Things (IoT) [408, 409]. As exhibited in Figure 11(a), an MR sensor with power consumption of 0.1 mW was demonstrated in 1998 [242]. After more than 10 years of development, a sensitive 64-element MTJ sensor was fabricated by Liou *et al*. in 2011 and each MTJ element only dissipated ~16 μW of power [243]. The power consumption of MR sensors was then further reduced to ~3 μW by Yin *et al*. in 2014 [245]. In the same year (2014), Honeywell released two nano-powered MR sensors (SM353LT, SM351LT) in which power consumptions were as low as ~510 nW and ~590 nW, respectively [244]. By fitting the historical development over the last two decades with a linear line, one can expect MR sensors with ultralow power consumption of ~1 nW (Milestone of power consumption: M_{pow}) in ~2022.

Another operational parameter is the mechanical flexibility of MR sensors [64-87], which is crucial for MR sensors installed in flexible devices or for MR sensors sustaining mechanical strains. The development trend of the mechanical flexibility of MR sensor can be divided into three levels, namely, moderately flexible (fabricated on a planar substrate), highly flexible (bendable or able to be elongated), and extremely flexible (twistable) in Figure 11(b). In "Moderately flexible" level, MR sensors deposited on/in different flexible

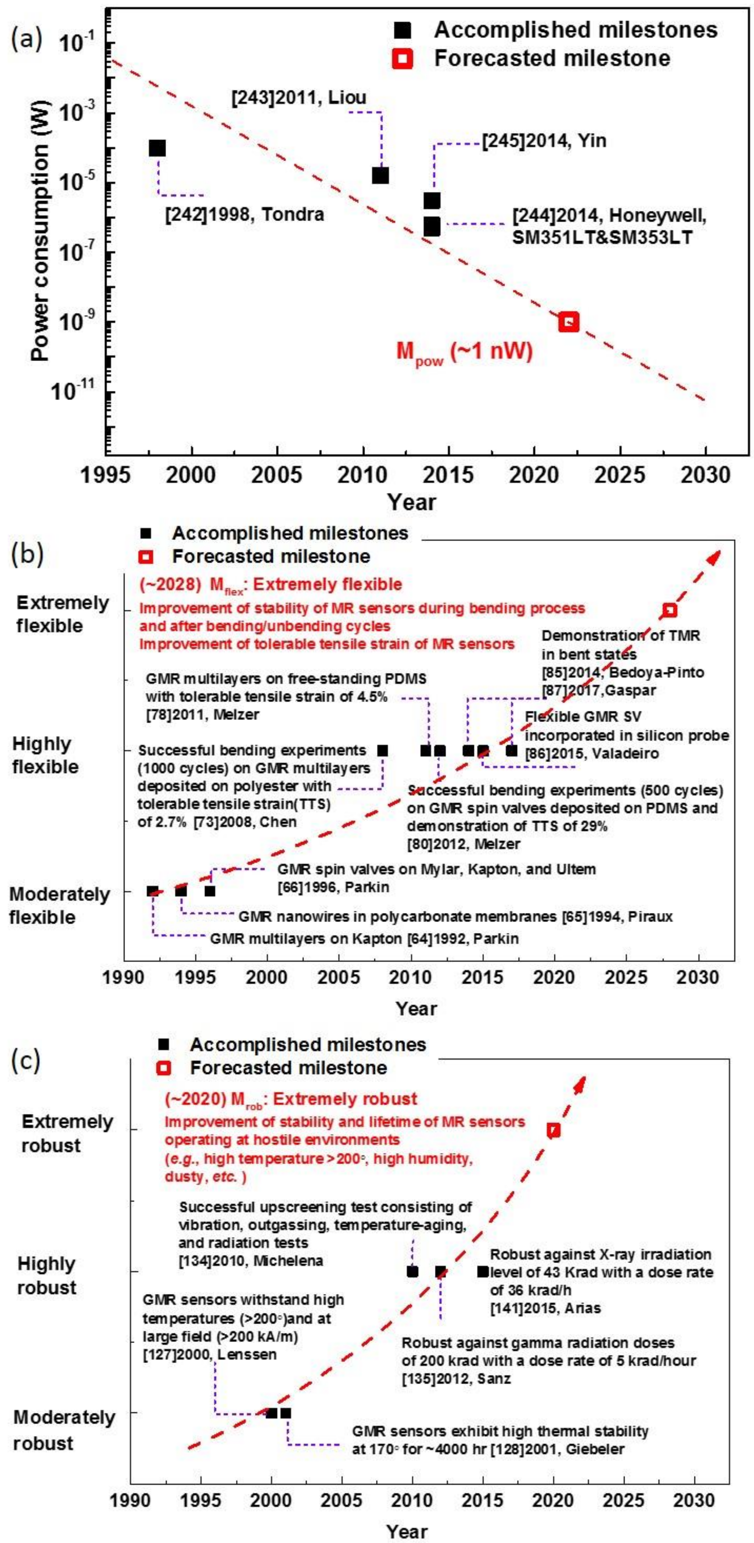

Fig. 11. Development trend of (a) power consumption, (b) mechanical flexibility, and (c) robustness of MR sensors from 1990 to 2032. PDMS represents poly(dimethylsiloxane) membranes.

materials in a planar substrate were fabricated [64-66, 68, 70]. Parkin *et al*. fabricated the first flexible GMR multilayer sensor on a kapton substrate in 1992 [64]. In 1994, growth of GMR nanowires in etched polycarbonate membranes were reported. Since then, MR sensors grown on a variety of planar substrates were realized, such as mylar, kapton, ultem, polypropylene sulfide, polystyrene, and poly (2-vinyl pyridine) [65, 66, 68, 70]. After these achievements, mechanical flexibility of MR sensors was tested and characterized through bending and elongation in the period of 2008 to 2017 (highly flexible) [73, 78, 80, 85-87]. MR sensors with tolerable tensile strains of 2.7%, 4.5%, 29% were recorded in 2008 [73], 2011 [78], and 2012 [80], respectively. Bending experiments were performed on both multilayer (1000 bending/unbending cycles) and spin-valve (500 bending/unbending cycles) GMR sensors [73, 80]. The GMR sensors exhibited no changes in both resistance and MR ratio after bending/unbending tests. In 2014, Bedoya-Pinto *et al*. fabricated flexible TMR sensors on kapton substrates and obtained TMR ratio of 12% in bent state [85]. In 2015, Freitas' group incorporated MR sensors into micromachined silicon probes, which exhibited constant MR ratio and no significant changes in their noise level under a continuous tensile stress [86]. In 2017, the same group fabricated high-performance MTJ sensing devices (TMR above 150%) on flexible polyimide substrates [87]. Under controlled mechanical stress conditions, TMR value showed subtle variation (~1%) and sensitivity changed by 7.5% when the curvature radius of the device was reduced down to 5 mm upon bending. These works unambiguously demonstrated the mechanical flexibility of MR sensors, elevating the mechanical flexibility level from "Moderately flexible" to "Highly flexible". From Figure 11(b), it requires around 10 years to develop MR sensors from "Moderately flexible" to "Highly flexible" and each stage lasts for around 10 years. We therefore expect that the future milestone of mechanical flexibility (M_{flex}: "Extremely flexible") will be reached in ~2028 with further improvements on stability of flexible MR sensors and their tolerable tensile strain. In this stage, the MR sensors are expected to maintain the MR ratio even after twisting, and thus can be made into almost any shape [66, 410]. This extremely flexible performance of MR sensors will allow many future use of organic electronics for bio-applications by forming the MR sensors on organic substrate [53].

In addition to the mentioned operational parameters, the robustness of MR sensors is one of the paramount issues, especially for sensors operating in hostile environments. Similarly, the development trend of the robustness of MR sensors is summarized into three levels, namely, moderately robust (only thermal endurance), highly robust (multi-degree environment endurance such as temperature, irradiation, and vibration), and extremely robust (high endurance in multi-degree environment) in Figure 11(c). In "moderately robust" level during the period of 2000 to 2001, basic tests on robustness of MR sensors were conducted on their thermal stability. In 2000, Lenssen *et al*. tested the thermal and magnetic stability of GMR sensors at high temperatures (>200°C) and large magnetic field (>200 kA/m) [127]. In 2001, GMR sensors operating with high stability at 170°C for ~4000 h were reported [128]. In "highly robust" level, the robustness of MR sensors was systematically validated in multi-degree environments. For example, the application of MR sensors was validated in aerospace by performing the up-screening tests and irradiation tests in 2010 [134]. The up-screening tests included a series of tests, such as vibration, outgassing, and temperature-aging.

In another published work in 2012, a systematic gamma irradiation test of MR sensors was carried out [135]. AMR sensors were tested to be robust against radiation doses of 200 krad with a dose rate of 5 krad/h. In 2015, X-Ray irradiation test of TMR sensors was performed by Freitas' group under total dose level of 43 krad with a much higher dose rate of 36 krad/h [141]. The device sensitivity exhibited a slight reduction during the irradiation and recovered afterwards. From Figure 11(c), since there has been steady progress in robustness level in the past two decades (from "Moderately robust" in 2000 to "Highly robust" in 2010), we can expect MR sensors will be demonstrated to be extremely robust (Milestone of robustness: M_{rob}) by ~2020. The achievement of M_{rob} will enable advanced applications that critically rely on sensor robustness (*e.g.*, MR sensor with high stability and long lifetime operating in hostile environments).

These achievements indicate that MR sensors are promising candidates for a wide range of applications where power saving, mechanical flexibility, and robustness are of significant importance.

V. MR Sensor applications and future directions

Continuous research and engineering efforts on MR sensors have remarkably improved their sensitivity, detectivity, mechanical flexibility, power consumption, and robustness as discussed in Section IV, opening up a wide range of applications [29-31, 33, 34, 37-46, 48, 50, 51, 53-55, 78, 97, 109, 120, 219-223] as shown in Figure 5. Main MR sensor applications can be categorized into five areas, including biomedical applications, flexible electronics, PS and HCI, NDEM, navigation and transportation. To shed light on the future directions of MR sensor applications, five roadmaps for these five application areas were developed. The historical data from literature analysis was fitted with the logistic growth model to obtain the fitted trend curve. The fitted curve was then further adjusted and fine-tuned based on the critical milestones for sensor parameters developed in Section IV and the consensus of the professional judgements reached during the taskforce meetings and subsequent communications. Roadmaps predicting new opportunities for MR sensor technology in different application areas were created based on these extrapolated trend curves. Speculations about new MR applications, products, and services were presented for the next 15 years and beyond.

A. Biomedical applications

Regarding MR sensor applications in the biomedical field, the detectivity of MR sensors is a paramount issue because the generated biomagnetic signals are usually rather small, ranging from nT to fT [14-46, 48-58, 222]. The roadmap is shown in Figure 12. Biomedical applications for MR sensor technology can be categorized into two scenarios (S_{biomed}):

S_{biomed}1. MR sensors to detect magnetic signals generated from bio-functionalized nanoparticles/nanostructures

$S_{biomed}2$. MR sensors to directly detect magnetic signals generated from human organs (*e.g.*, brain, heart, muscles, *etc*.)

In $S_{biomed}1$, as MR sensor technology improved and matured after the basic technology research stage (TRL 1-2) from 1975 to 1990, the feasibility of applying MR sensors in biomedical research was investigated during the period from 1990 to 2004 [16, 18-21, 23, 24, 26, 27]. In 1998, the measurements of intermolecular forces between DNA-DNA, antibody-antigen, or ligand-receptor pairs were demonstrated by using GMR sensors [16]. In 2001, the detection of DNA hybridization was achieved by using GMR sensor arrays [18]. The feasibility of adopting MR sensors in biomedical applications was preliminarily proved and TRL reached 3.

This technology was then further developed by several groups. In 2002, a group from the Instituto de Engenharia de Sistemas e Computadores and Instituto Superior Tecnico introduced a method to control the movement of nano/micro-sized magnetic labels and demonstrated the detection of single microspheres bonded with biomolecules [19]. In addition, AMR sensors were used to detect micro-sized nanoparticles and an AMR-based bio-sensor prototype was proposed in 2002 [21]. In 2003, the biological binding of single streptavidin functionalized magnetic microspheres on the surface of GMR sensors was detected by Graham *et al*. from INESC-MN (former INESC) and IST [23]. In the same year, Wang's group in Stanford successfully detected the presence of magnetic particles (Dynabead, 2.8 μm in diameter) with micro-scaled spin-valve GMR sensors [60]. All these works laid the groundwork and revealed the feasibility of adopting MR sensors in biomedical research and indicated that MR sensors can be utilized to develop biomedical technology (TRL 3-4).

After 2004, further development of biomedical technology with MR sensors then proceeded and focused on detecting magnetic signals generated from biofunctionalized magnetic nanoparticles/nanostructures [29-31, 33, 34, 37-39, 41-46, 48, 51, 53-55, 191, 222].

In the period of 2005 to 2008, the detection of bio-functionalized nanoparticles/nanostructures with MR sensors was demonstrated in both *in-vitro* and *in-vivo* conditions [29-31, 33, 34]. In 2005, cystic fibrosis related DNAs were successfully detected with spin-valve GMR sensors by using an AC magnetic field focusing technique [29, 30]. Grancharov *et al*. successfully detected protein-functionalized and DNA-functionalized monodisperse nanoparticles with a TMR bio-sensor [31]. These results suggested that MR bio-sensors were validated in laboratory environment and TRL 5 was achieved.

Since then, bio-sensing applications with MR sensors were developed in relevant environments [35-37, 39, 42, 43, 48, 51, 55]. At the 29th IEEE Engineering in Medicine and Biology Society conference in 2007, an AMR-based biomagnetic prototype was demonstrated to evaluate the gastric activity contractions and *in-vivo* tests were performed [35, 36]. In 2008, a portable bio-sensing prototype was developed and the detection of magnetic nanoparticles was demonstrated [37]. In the same year, Wang's group developed a GMR-based biochip

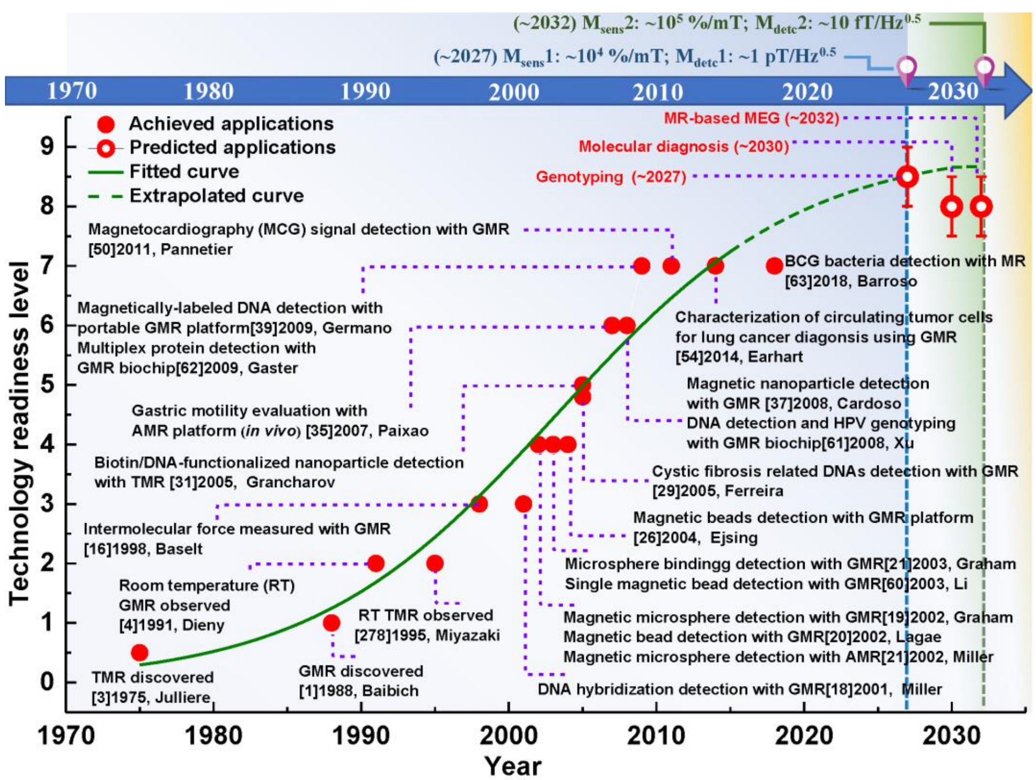

Fig. 12. Roadmap for MR sensors in biomedical applications from 1970 to 2032.

for DNA detection and human papillomavirus (HPV) genotyping [61]. Their work also showed real-time signal responses of multiple DNA fragments, which demonstrated the multiplex detection capability of the GMR-based biochip. These works revealed that MR-based bio-sensing prototypes were tested and implemented in practical environment and TRL 6 was reached.

After 2008, bio-sensing chips/systems with MR sensors were developed and thus MR sensor-based biomedical technology was elevated to a higher level. In 2009, a portable GMR platform was demonstrated to detect magnetically-labelled DNA by Germano *et al*. [39]. Furthermore, Wang's group developed a multiplex GMR-based bio-sensing platform for protein detection in blood and cell lysates [62]. The developed platform exhibited an extensive linear dynamic range over six orders of magnitude and a protein detecting resolution down to attomolar level. In 2014, the detection and characterization of circulating tumor cells (CTCs) were conducted with a GMR-based biochip and CTCs were detected in the blood samples from lung cancer patients [54]. In 2018, the detection of Bacillus Calmette-Guérin bacteria was also carried out with an MR-based bio-sensing platform for tuberculosis diagnosis [63]. These works elevated the laboratory achievements of MR bio-sensor technology to the clinical/near-clinical level (TRL ~7).

Compared to MR sensor applications in $S_{biomed}1$, the requirements of MR detectivity is much higher in $S_{biomed}2$, which is attributed to the fact that the generated magnetic signals from human organs are merely in the range of pT (*e.g.*, magnetic field produced by heart) to fT (*e.g.*, magnetic field produced by brain) [14]. For the biomagnetic signals produced from human organs, two most-investigated signals are generated from the heart and brain. These signals contain valuable information and lead to two application areas, magnetocardiography (MCG) [17, 22, 50] and magnetoencephalography (MEG) [14], respectively. Seven years after the detectivity of pT range was reached in 2004 [28], MCG biomagnetic signals from healthy volunteers were recorded and a magnetocardiography MCG signal distribution was mapped with a highly sensitive (pT) GMR sensor in 2011 [50]. These technology demonstrations indicated that bio-sensing subsystems/systems with MR sensors were validated in operational environments, and TRL 7 was achieved.

To predict and outline the future biomedical applications, the above historical biomedical developments summarized from the published literature were analyzed using the logistic growth model and the extrapolated trend curve was established (Figure 12). Adjustment of the curve was then performed based on the critical milestones for sensitivity and detectivity derived in Sections IV(A) and IV(B) and the professional assessment consensed by the roadmap taskforce. Likely biomedical applications with MR sensors were then predicted and their TRL levels were estimated.

Synthesis of DNA-functionalized or even DNA-bases-functionalized nanoparticles will possibly enable commercialized genotyping applications [49] with MR sensor technologies. With the achievement of $M_{sens}1$ (~10^4 %/mT) and $M_{detc}1$ (~1 pT/Hz$^{0.5}$) in ~2027, MR sensors can be used to accurately detect the real-time magnetic signals from magnetically-labeled DNA fragments or entities. After improving the multiplexing features [41, 45, 61] and localized detection ability of MR sensors [34], we expect that commercialized genotyping products with MR sensors will be released and the corresponding TRL of level 8-9 will be achieved.

The development of genotyping applications with MR sensors will promisingly facilitate the diagnosis and treatment of genetic diseases. Continuous efforts on synthesis of various bio-functionalized magnetic nanoparticles or nanostructures [23, 31, 40] will stimulate the application of highly-sensitive MR sensors in molecular diagnosis [15, 25]. However, the MR-based molecular diagnosis systems are required to be validated and their commercialization requires Food and Drug Administration (FDA) clearance from the government of the targeting market. We therefore expect that MR-based molecular diagnosis products or services will be commercially available a few years later than genotyping and its maturity will reach a slightly lower TRL of level ~8 in 2030. This accomplishment can promisingly offer personalized diagnosis and possibly lead to optimized therapies for individual patients.

On the other hand, a more challenging category of application, MR-sensor-based MEG requires fT range detectivity and therefore will be developed after the achievement of $M_{sens}1$ (~10^4 %/mT) and $M_{detc}1$ (~1 pT/Hz$^{0.5}$) in ~2027. Through further improvement of sensitivity and detectivity towards $M_{sens}2$ (~10^5 %/mT) and $M_{detc}2$ (~10 fT/Hz$^{0.5}$) respectively, one can expect the implementation of MR-sensor-based MEG applications (TRL~8) with elaboration on clinical level around or after 2032.

Apart from MR sensing elements, the other key factors such as magnetic labels, surface chemistry, microfluidic systems and electronics setup are critical to achieve high-performance, automated, portable point-of-care bioanalytical assays [411]. The size of the MR sensing element and the bio-molecule binding capacity of the magnetic particles need to be carefully designed [9]. A reliable biochip platform needs a fine control of the surface chemistry in order to achieve immobilization efficiency and specificity and avoid corrosive effect. A microfluidic system is required to establish mechanism for sample delivery protocol and controlled washing [411]. Last but not the least, the system miniaturization of signal processing and system automation will be implemented with electronics microsystems for building point-of-care devices [412, 413].

B. *Mechanically flexible electronics*

Flexible electronic devices have gained increasing interest due to the promising potential applications offered by their pliable surface geometries [78, 81, 83, 85]. MR-based devices have been implemented on various types of flexible substrates, such as stretchable and deformable polymeric materials [64, 70, 75, 78, 81, 85], and even papers [79, 83]. This roadmap is shown in Figure 13.

The flexible MR sensors are required to be robust against mechanical bending or stretching and withstand many cycles of deformations without the degradation of sensing performance. The emergence and growth of the flexible MR sensor technology took place in the period of 1992-2007 [64-72]. In 1992, Parkin *et al*. investigated the GMR effect in Co/Cu multilayers deposited on a Kapton polyimide substrate by magnetron sputtering [64]. In 1994, growth of GMR nanowires in etched polycarbonate membranes were reported by Piraux *et al*. [65]. Two years later (1996), Parkin successfully fabricated spin-valve GMR sensors on other flexible organic films (mylar, a transparent film, and ultem polyimide) [66]. These works built the foundation and proved the feasibility of manufacturing flexible MR sensors, pushing the TRL of the flexible MR sensor technology towards level 3.

This technology was then further developed by several groups. In 2002, Yan *et al*. deposited GMR multilayers on flexible polypyrrole films [68]. The mechanical flexibility of the prepared GMR film was tested by cutting it into various shapes. In 2006, Uhrmann *et al*. reported the mechanical flexibility of GMR spin valves grown on polyimide substrates and the sensors were elastic up to an elongation of 3% [70]. These studies further proved the feasibility of flexible MR sensor technology and TRL 4 was reached.

After 2006, the mechanical flexibility of MR sensors was tested through the bending and strain experiments [73, 78, 80, 85]. In 2008, tensile strain measurement was carried out on the GMR sensors on polyester substrates and the stress was applied to the GMR sensors by performing in-plane elongation [73]. The sensors exhibited great stability and withstood 1000 bending/unbending cycles with no degradation of GMR ratio. In 2011, multilayer GMR sensors on free-standing polydimethylsiloxane membranes revealed a high GMR of 50% and the GMR effect was preserved with tensile strain up to 4.5% [78]. These works demonstrated the mechanical flexibility of MR sensors and pushed the TRL towards level ~5.

The mechanical flexibility of MR sensor was then further enhanced. In 2012, the tolerable tensile strain as high as 29% was achieved by depositing spin valves on pre-stretched and pre-wrinkled polydimethylsiloxane substrates [80]. In 2014, Bedoya-Pinto *et al*. successfully deposited TMR sensors on

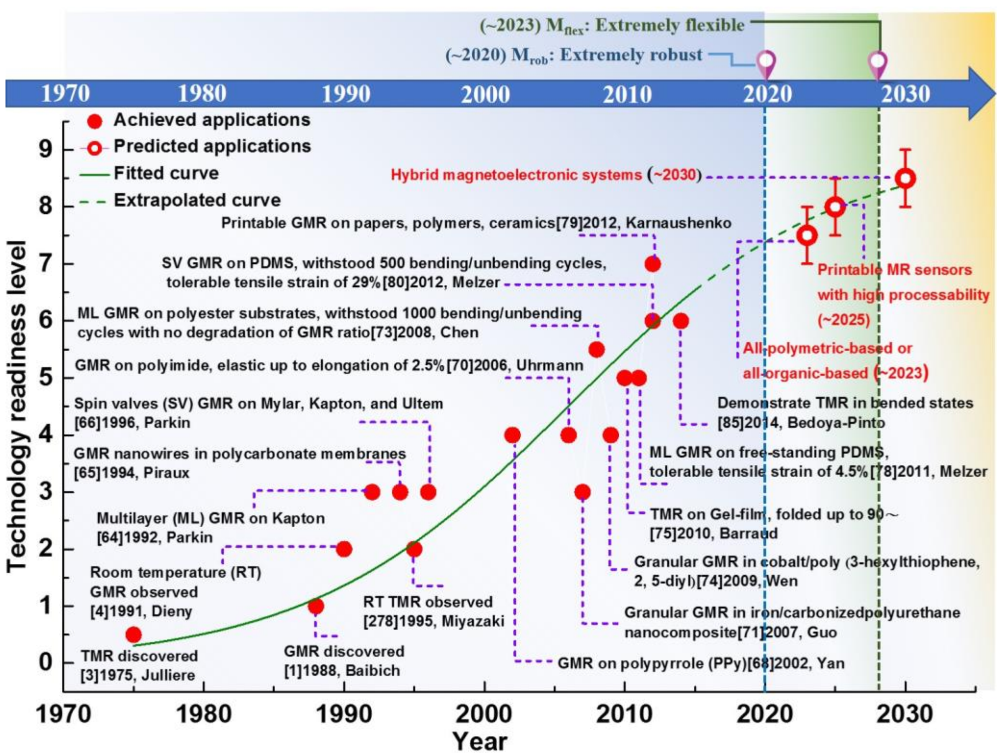

Fig. 13. Roadmap for MR sensor applications in flexible electronics from 1970 to 2032.

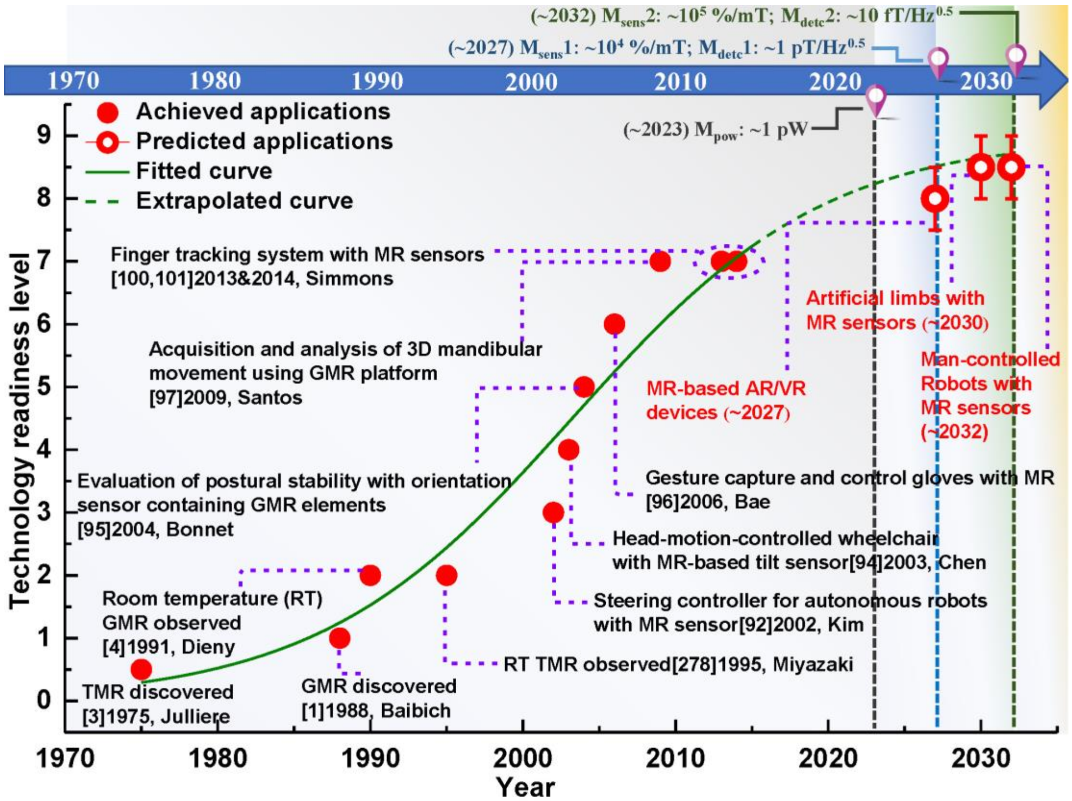

Fig. 14. Roadmap for MR sensor applications in PS and HCI from 1970 to 2032.

kapton substrates and demonstrated the preservation of TMR effect in bent states [85]. Also, flexible MR sensors prepared with printable magneto-sensitive inks were reported by Karnaushenko *et al*. [79]. The printable MR inks were prepared by a process including magnetron sputtering, rinsing, ball milling, and mixing. The prepared inks were then painted on various substrates (*e.g.*, papers, polymers, and ceramics) and the fabricated sensors with GMR response up to 8% were demonstrated. This fabricated GMR sensor was integrated into a paper-based electronic circuit and acted as a magnetic switch of the whole circuit, which confirmed the functionality of flexible sensing systems/subsystems with MR sensors. These works revealed that the mechanical flexibility of MR sensors was validated in practical environments and TRL reached level 6 and approached early stage of level 7.

The enhancement of mechanical flexibility will enable the applications of MR sensors in wearable and portable electronics. Most of the reported flexible MR sensors were composed of a flexible polymeric substrate and a conventional MR multilayer structure [53, 64, 66, 68, 70-73, 75, 78, 80, 84, 85]. Although the polymeric substrate was robust against mechanical deformations, the MR response of the multilayer tended to degrade after many bending cycles [73], which essentially limited its sensing performance. To resolve this issue, all-polymeric-based (APB) or all-organic-based (AOB) MR devices are required to be developed, which is a promising pathway toward highly deformable and bendable MR sensors. An important step forward for the APB or AOB MR devices was the demonstration of MR effect in an organic spin valve where the organic $V[TCNE]_x$ (x ~ 2, TCNE: tetracyanoethylene) served as ferromagnetic layers and the rubrene ($C_{42}H_{28}$) was used as the insulating barrier [77]. After the achievement of M_{rob} (extremely robust) in ~2020 and the development of sensor mechanical flexibility towards M_{flex} (extremely flexible) in ~2028, one can expect the realization of APB or AOB MR system (TRL 7-8) in ~2023 with higher mechanical flexibility as well as better robustness through performing necessary deformation and bending evaluations.

The implementation of APB or AOB MR sensors will lead to the achievement of fabricating MR sensors with higher mechanical flexibility as well as better robustness, promoting the application of MR sensors in wearable, portable, and printable electronics. Particularly, the printable MR sensors will revolutionize the field of magnetoelectronics offering low-cost and large-scale production in manufacturing processes. Through research efforts on the synthesis and optimization of MR inks, paints, and pastes, we expect that the printable MR sensors with high processability (TRL~8) can be accomplished in a short period (in ~2025).

Then hybrid magnetoelectronic devices can be developed by integrating printed MR sensors in a purpose-designed electronic circuit (*e.g.*, authorization, monitoring, data recording, *etc*.). The integrated MR sensor can serve as a magnetic-information acquisition element or a magnetically-manipulable option in the hybrid magnetoelectronic devices. However, the implementation of actual hybrid magnetoelectronic systems (TRL-9) will be expected within five years (in ~2030) after the demonstration of the high processability of printable MR sensors. The development of printable MR sensors can promisingly reduce the fabrication cost, weight, and physical dimension of MR sensors by replacing conventional substrates (Si) with standard printing materials (paper, polymer, ceramics), promoting the high-volume production of printable magnetoelectronics.

C. Position sensing (PS) and human-computer interaction (HCI)

Owing to the high sensitivity, low power consumption and small physical dimension, MR sensors have been considered as promising magnetic sensors embedded in PS applications [88-91] and HCI systems [94-101, 414]. This roadmap is shown in Figure 14.

In PS applications, MR-based linear and angular sensors are used to acquire incremental or absolute scale data from magnetic linear rulers, code wheels, and human body [88-91, 94, 96, 97, 100, 101]. Through software development and integration of computer interface, the obtained information can be processed and further utilized in HCI implementations.

In the period of 2002 to 2003, the feasibility of integrating MR sensors into PS and HCI was investigated [92-94]. In 2002, an MR-sensor-based steering controller for outdoor mobile robot was designed [92]. A computer simulation was performed to verify the performance of the controller. In 2003, Chen *et al.* proposed a head-motion-controlled wheelchair with an MR-based tilt sensor integrated into the headgear [94]. The comfortability and safety of the developed wheelchair were tested and verified. Basic biomechanical motions were captured and processed in these works, which proved the feasibility of integrating MR sensors into PS and HCI and raised the corresponding TRL to 3-4.

This technology was further investigated and the acquisition and analysis of more complicated biomechanical motions and postures were carried out [95-101, 414]. In 2004, Bonnet *et al*. introduced a novel method to evaluate the postural stability with an orientation sensor containing GMR magnetometers and accelerometers [95]. By virtue of the high sensitivity of the orientation sensor, subtle postural variations were captured and could be utilized in clinical balance assessments. In 2006, Bae *et al*. were able to track the wrist gestures and control the movements of the robot with GMR-based wearable gloves [96]. These works demonstrated the operation of HCI prototypes with MR sensors and boosted the TRL to 5-6.

The HCI systems/subsystems were then developed and the TRL was elevated to a higher level. In 2009, the acquisition of three-dimensional mandibular movements was realized by using a GMR-based device by Santos *et al*. [97]. A computer application was developed to analyze the movements and generate diagnosis reports. In the period of 2013 to 2014, a 3 degree-of-freedom (DOF) finger tracking system was demonstrated by using a commercially available 3-axis MR sensor [100, 101]. Both finger joint position and finger movement configurations (stationary joint, flexing joint, etc.)

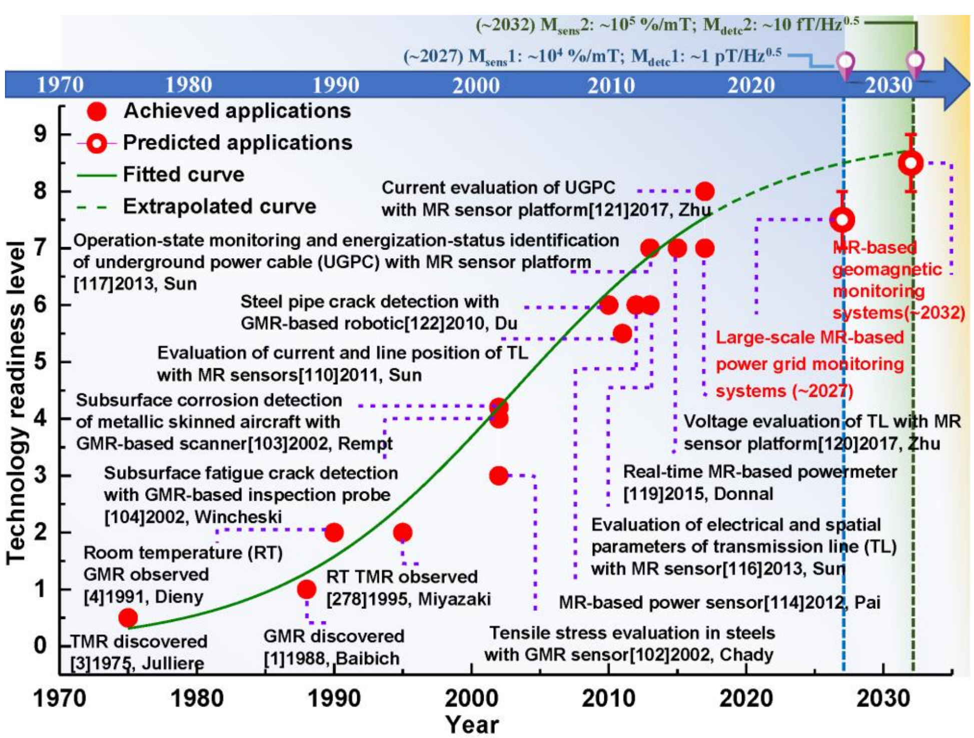

Fig. 15. Roadmap for MR sensor applications in NDEM from 1970 to 2032.

were captured and evaluated. These works validated the operational performance of the MR-sensor-based HCI systems/subsystems and suggested that the TRL entered level 7.

Based on past developments and professional consensus of the roadmap taskforce members, the future potential MR-based HCI applications were predicted. As demonstrated in the reported HCI systems with MR sensor description, biomechanical movements of various body parts can be effectively captured and recorded by processing and analyzing the acquired magnetic data. This type of biomechanical data will likely be used in the field of AR and VR. With the achievement of enhanced sensitivity ($M_{sens}1$, ~10^4 %/mT) and detectivity ($M_{detc}1$, ~1 pT/$Hz^{0.5}$) in ~2027, one can expect that AR/VR devices integrated with high-performance MR sensors (TRL ~8) will be available.

Commonly-used joysticks will then be replaced by wearable MR-based controllers to realize uncumbersome HCI interfaces. MR sensors can also be integrated into artificial limbs of disabilities and the obtained biomechanical signals can be processed to assist their desired movements.

Further improvement of sensitivity and detectivity will enable accurate detection of biomechanical signals and reduction of power consumption (M_{pow}, ~1 pW) will extend the lifetime of the artificial limbs with MR sensors, which will push forward its maturity level to 8-9 in around 2028. Furthermore, the implementation of MR-based man-controlled robots will be possibly realized by collecting and processing all the biomechanical movements. However, such technology will require a tremendous amount of tests and assessments and further improvement of MR sensor performance ($M_{sens}2$, ~10^5 %/mT; M_{detc2}, ~10 fT/$Hz^{0.5}$). We therefore estimate that the full maturity (*i.e.*, TRL 8-9) of the MR-based man-controlled robots will be accomplished around 2032.

D. *Non-destructive evaluation and monitoring (NDEM)*

Compared to destructive sensing devices, NDEM with MR sensors can be easily installed and accessed by end users, enabling effective acquisition of magnetic or magnetic-related information from the subsystems/systems under monitoring [102-104, 107, 108, 110, 111, 113, 114, 116-122]. This roadmap is shown in Figure 15.

The feasibility of utilizing MR sensors in NDEM was first tested by several groups in 2002. The MR-sensor-based NDEM of subsurface mechanical and chemical damages in metallic or magnetic components was introduced, especially, to investigate the components used in high-standard products (*e.g.*, aircrafts) [102-104]. A GMR-based inspection probe was developed to detect the subsurface fatigue cracks and holes under airframe fasteners [104]. The functionality of the developed probe was studied by both finite-element-method simulation and experiment. In the same year, a GMR-based gradiometer was introduced to measure the tensile stress of the SS400 steels [102]. Ray Rempt from the Boeing company also proposed an 8-element MR scanner for inspecting the subsurface corrosion of the airframe [103]. The stress damages in the steels were evaluated and visualized by interpreting the sensor data with a signal processing algorithm. These results suggested that the feasibility of NDEM technique with MR

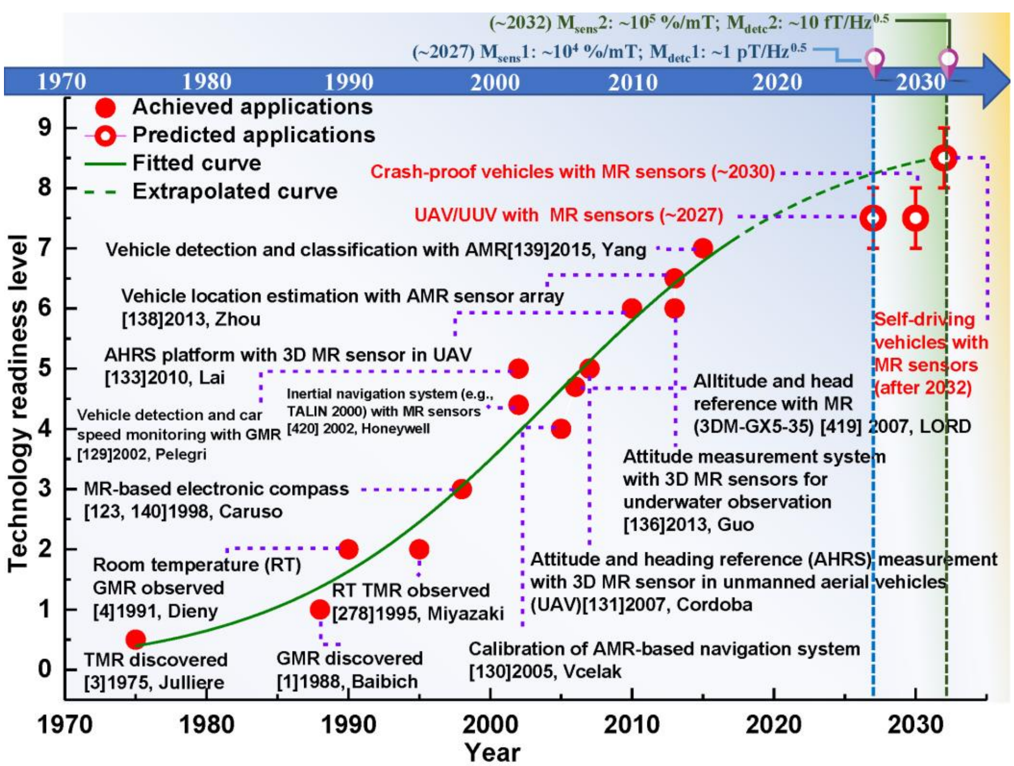

Fig. 16. Roadmap for MR sensor applications in navigation and transportation from 1970 to 2032.

components/breadboards was validated in practical conditions. The maturity of NDEM with MR sensors reached TRL 3-4.

Another promising application of the non-destructive MR sensors is the evaluation and monitoring of the power grids. Abundant studies demonstrated the feasibility of using MR sensors for monitoring both the high-voltage overhead transmission lines and underground power cables [106, 110, 111, 113, 114, 116-121]. In 2011, a proof-of-concept laboratory setup was constructed to determine the phase current and line position of transmission lines by Sun *et al*. [110]. In 2012, Pai *et al*. introduced an MR-based power meter to measure near-field voltage and current waveforms of a power cord [114]. Accuracy of power measurement better than 5% was accomplished. These works demonstrated the operation performance of NDEM prototype with MR sensors and indicated the achievement of TRL 5-6.

Further studies were performed to establish MR-sensor-based NDEM systems/subsystems. Pong's group proposed and developed several novel MR-based platforms to monitor the loading voltages and currents of power lines [111, 116-118, 120, 121]. The MR-based monitoring platforms were able to characterize the fault location [111] and operation state of the power lines by extracting the loading current data [116]. Utilizing the capacitive-coupling between the power lines and induction bars, the voltages of the power lines were accurately evaluated and the ability of high-frequency transient measurement was demonstrated [120]. The phase current of the power line was reconstructed by analyzing the magnetic field from the power lines. The feasibility and accuracy of the proposed method were verified by a scaled laboratory platform and then validated by performing an on-site experiment in a substation [121]. The MR-assisted voltage monitoring system was validated with a scaled testbed [234]. These achievements demonstrated that the validation of MR-sensor-based NDEM systems in practical environment and marked the maturity of NDEM technology with MR sensors (TRL 7-8).

Continuous efforts on improving sensing performance of MR sensors will promote the development of MR-based NDEM systems. The maturity of this application will enable large-scale evaluation of key parameters of power grids, such as current [106, 113, 114, 116], voltage [114, 119, 120], phase [110, 116, 117], power flow [114, 119], power quality [119], load [117, 119], transmission and distribution line conditions [111, 116, 117, 120]. By analyzing and processing the power grid parameters, the real-time state of power grids can be evaluated, enabling the prompt determination and response of power faults or abnormal conditions in a wide area. After the achievement of $M_{sens}1$ (~10^4 %/mT) and $M_{detc}1$ (~1 pT/$Hz^{0.5}$) in ~2027, the implementation of the large-scale power grid monitoring systems with MR sensors (TRL 7-8) will be expected. The full establishment of these systems (TRL 8-9) will require a large quantity of supporting facilities (e.g., energy harvesting for outdoor sensors [415, 416], and a common time source for synchronized measurements [417, 418]), and therefore will be realized in a long-term period (after ~2027).

With the further improvement of MR sensor sensitivity and detectivity to $M_{sens}2$ (~10^5 %/mT) and $M_{detc}2$ (~10 fT/$Hz^{0.5}$) in ~2032, another promising field of application is a large-scale geomagnetic monitoring system, which will be utilized to monitor subtle geomagnetic disturbances related to some geomagnetic hazards, such as seismic activities [109]. MR sensors can be installed on a large seismically-active zone to monitor abnormal geomagnetic changes that are associated with seismic activities. With the assistance of a reference permanent magnet, MR sensors can also be used as displacement sensors to detect the abnormal disturbances related to foreshock patterns or plate dynamics [109]. However, the implementation of a reliable geomagnetic monitoring system with MR sensors (TRL 8-9) requires a long-term investigation of geomagnetism and cooperation between geological and magnetic societies, which will take more time to progress and will be realized around 2032.

E. Navigation and transportation

MR-based magnetometers have been widely used in navigation and transportation systems as well [123-126, 129-133, 136-139]. This roadmap is shown in Figure 16.

In the period of 1997 to 2005, the feasibility of applying MR sensors in navigation and transportation was investigated. In 1997, MR sensors provided a solid-state solution for building compass navigation systems for their high sensitivity, good repeatability and small size [123]. In 1998, an electronic compass with MR sensor was introduced [140]. The compass reading was tilt compensated and the disturbance from nearby ferrous materials was corrected. In 2005, an AMR-based navigation system was proposed [130]. With calibration of sensor's triplet deviation, the introduced navigation system provided information about actual azimuth, roll and pitch with improved accuracy. In 2005, a dead-reckoning navigation system was developed for pedestrians with an array of accelerometers and MR sensors. MR sensors became capable of collecting more informative data by virtue of the development and commercialization of 3-axis/3D MR-based magnetometers [131, 133, 136]. Commercial dead-reckoning and inertial navigation systems using MR sensors have also been developed. For example, the Lord Sensing introduced attitude and head reference systems (e.g. Lord MicroStrain 3DM-GX5-35) with MR sensors to provide attitude and navigation solutions [419]. The Honeywell introduced inertial navigation system (e.g. TALIN 2000) with MR sensors to provide navigation, pointing and weapon stabilization [420]. All these works proved the feasibility of applying MR sensors in the fields of navigation and transportation (TRL 3-4).

The technology was further developed and demonstrated from 2007 to 2010. In 2007, by integrating the 3-axis MR sensor with accelerometers and gyroscopes, a real-time attitude and heading reference system (AHRS) was reported by Cordoba *et al*. [131]. The constructed system was equipped in unmanned aerial vehicles (UAVs) and accurate attitude angle measurements were performed for the UAVs operating in both accelerated and non-accelerated conditions. To validate the AHRS in various dynamic conditions, Lai *et al*. designed and constructed a 3-axis rotating platform in 2010 [133], which was able to simulate dynamic conditions in the operation of different unmanned vehicles (unmanned underwater vehicles (UUVs), UAVs, self-driving vehicles). Another promising application of MR-based magnetometers is the vehicle detection and monitoring [129, 132, 138, 139], which makes use of the local magnetic field disturbance caused by moving vehicles. In 2002, a GMR-based vehicle detection and monitoring module was introduced [129]. The local magnetic field disturbance was successfully detected and the speed of the car was measured on site. These works demonstrated the implementation of MR sensors in navigation and transportation systems in relevant conditions and the accomplishment of TRL 5-6.

With the enhancement of the sensing ability of MR sensors, the functionalization and performance of the MR-based vehicle detection systems were remarkably improved [137-139]. In 2013, Zhou *et al*. reported the real-time location estimation of vehicles by utilizing an AMR array [138]. In 2015, the classification of various types of vehicles was achieved by analyzing the characteristics of the detected field disturbance signals [139]. These works demonstrated the possibility of achieving high-level autonomous vehicles with MR sensors, such as UUVs, UAVs, crash-proof vehicles, and self-driving vehicles, which marked the later stage of TRL 6 for navigation and transportation systems with MR sensor technology.

Considering that the AHRS with MR sensors has already been validated in several operating conditions [131], one can expect the integration of AHRS with MR sensors (TRL 7-8) into UUVs and UAVs by ~2027 with the achievement of $M_{sens}1$ (~10^4 %mT), $M_{detc}1$ (~1 pT/$Hz^{0.5}$). However, the implementation of crash-proof and self-driving vehicles with MR sensors would be much more difficult. MR sensors equipped in these vehicles are required to possess ultra-high sensing performance. The detected magnetic disturbance from all the surrounding vehicles and objects are required to be considered and analysed to avoid possible risks. Therefore, one can expect that the realization of crash-proof and self-driving vehicles with MR sensors (TRL 7-9) around or after 2032 with the achievement of $M_{sens}2$ (~10^5 %/mT), $M_{detc}2$ (~10 fT/$Hz^{0.5}$). Since the complexity of crash-proof vehicles is lower and technologically less complicated than that of self-driving vehicles, the authors believe that the crash-proof vehicles with MR sensors will be implemented a few years earlier than self-driving vehicles in ~2030.

VI. Outlook and Perspectives

The field of MR sensors is now rapidly evolving from science to technology. The proliferation of MR devices with high operational and sensing performance is opening up a

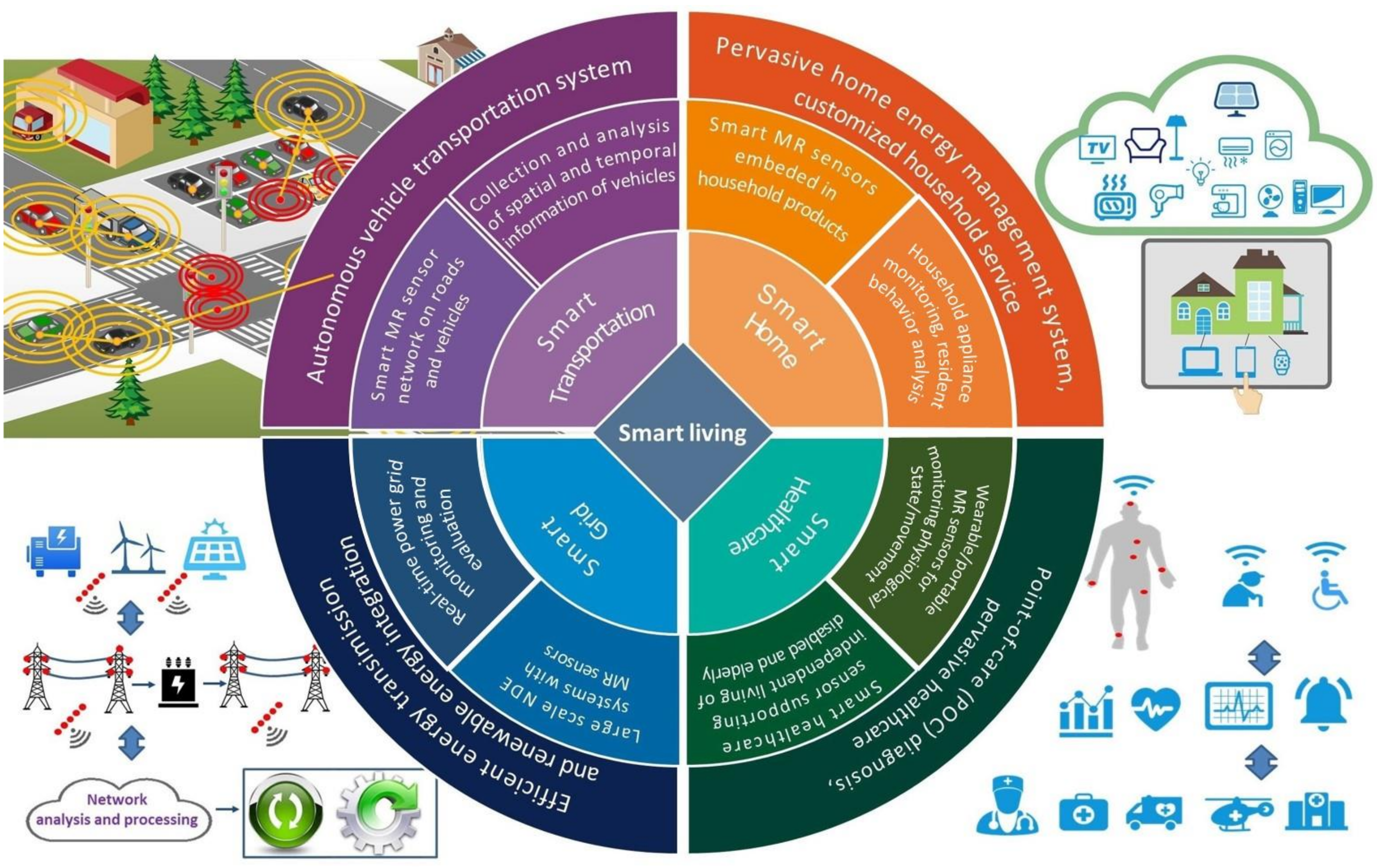

Fig. 17. Contribution and impact of MR sensor technology in the concept of smart living, including smart home, smart healthcare, smart grid, and smart

variety of applications based on MR technologies, such as biomedical applications, flexible electronics, PS and HCI, NDEM, and navigation and transportation. The widespread utilization of MR sensors will also offer more data and information (magnetic or magnetic-related) to the Internet of Things (IoT) [421-424], enriching and upgrading the context of smart living [425-428], such as smart home [427, 429-431], smart healthcare [425, 432-434], smart grid [105-108, 118], and smart transportation [435-438], as shown in Figure 17. One of the key supporting features of smart living is the acquisition and utilization of sufficient data and information from the "Things", which requires a large amount of networked sensors for information collection and processing [430]. Therefore, the robust MR sensors with low cost, low power consumption, small physical dimension, and superb sensing performance can be excellent candidates as networked sensors in each aspect of smart living.

A smart home is a residence equipped with sensor and communication technologies that monitor the household appliances/resident behavior and provide proactive services [425, 433]. Pervasive MR sensors can be embedded in household products, monitoring the states (*e.g.*, on, off, standby) of household products [119]. The evaluated data can also be stored in the cloud and accessible to the residents on their smartphones, personal computers, and wearable devices. The wasteful usage of each household appliance can then be identified and avoided via adaptive control or remote control by residents. With the integration of IoT platform, a pervasive home energy management system will be developed and implemented. Furthermore, the acquired usage data of household products and residents' behavior can be analyzed and used to learn the life pattern of the resident. Customized household services (*e.g.*, personalized household appliance automation) can therefore be delivered to the residents.

MR devices can also be used as smart-healthcare sensors to support independent living of the disabled and elderly, as well as to relieve the workload from family caregivers. Real-time physiological state or movement will be monitored with wearable/portable MR sensors [94-97, 100, 101]. Abnormal situations will be immediately alerted so that necessary assistance can be provided in time. With the development of MR-based MCG or MEG sensors [50], they can be attached on the bodies of patients with cardiac or encephalic diseases. Timely warning can be sent to the corresponding server when a cardiac or encephalic event is detected. Medical assistances and actions can then be taken by doctors and therapists. Also, low-cost, small-size, and highly wearable/portable MR biomedical sensors can be integrated into point-of-care (POC) devices [51], which can be widely distributed in hospitals, homes, and in outdoor areas. Immediate clinical services can be delivered to patients when diagnosis is completed using these POC devices. With the help of the POC technology and IoT platform, patients' past and present healthcare data will be monitored and recorded. These healthcare data will be accessible to clinicians or authorized entities. Based on the analysis and evaluation of the data, healthcare products and services can be provided in time whenever/wherever they are needed, facilitating the implementation of pervasive healthcare.

Regarding the smart grid, MR sensors can be deployed in large-scale for monitoring transmission and distribution networks. MR sensors or sensor arrays are used to monitor the real-time power grid parameters, such as current [106, 113, 114, 116], voltage [114, 119, 120], phase [110, 116, 117], power flow [114, 119], power quality [119], load [117, 119], transmission and distribution line conditions [111, 116, 117, 120]. Power grid abnormal conditions (*e.g.*, fault, sagging, overload, and imbalance) can be evaluated and pinpointed based on analysis of measured power grid parameters [111, 116, 117]. Necessary actions can then be performed by operation staff and predictive decisions can be made for ensuring efficient and reliable transmission and distribution of power in smart cities. The establishment of the large-scale MR-based NDEM power-grid monitoring system will provide more dynamic and pervasive monitoring information. This is critical for systematic evaluation of the existing power grid system and makes the integration of renewable energy possible.

For the smart transportation aspect, smart sensor networks with a large amount of MR sensors can be deployed on roads and vehicles and integrated into a wireless sensor network. The spatial and temporal distribution of vehicles correlates with magnetic field and can be collected by MR sensors, because a vehicle induces perturbation in the local Earth's magnetic field as it passes by a sensor [129, 138, 139]. As such, dynamic traffic information including vehicle speed [129], vehicle location [138], occupancy rate [129, 139], and traffic flow volume [129, 139] can be obtained and processed by the server. The traffic data can then be analyzed by a traffic management center and utilized to establish a large-scale traffic monitoring and management system. With the improvement of stability and efficiency of this type of system, crash-proof and self-driving vehicles can be further developed, promoting the development of autonomous vehicle transportation systems.

Through establishment of international standards as well as cooperation across institutions, more revolutionary MR-related products and technologies may be developed and sustainable MR industries can be established, which will in turn enrich and upgrade the content of smart living in the coming 15 years and beyond.

VII. CONCLUSION AND FUTURE WORK

The roadmap of MR sensors (non-recording) was developed in this paper. The past and current statuses of MR sensors were identified by analyzing the patent and publication statistics, and the timescales of MR sensors were established and predicted. MR devices are expected to proliferate with high sensing and operational performance in the area of biomedical applications, flexible electronics, PS and HCI, NDEM, and navigation and transportation. However, more investment on MR sensors is needed to reduce their costs in order to compete with Hall-effect sensors. Tens of millions of Hall effect devices are made each year, making the price of Hall-effect sensors lower than the MR sensors due to economy of scale [439]. The cost of MR sensor will continue to decrease as the sales volume increases. At high market volume of MR sensors, the cost difference between Hall sensor and MR sensors would be very small. In addition, MR sensors can provide unique performance that Hall elements cannot, which makes MR sensor more suitable for widespread use in the future.

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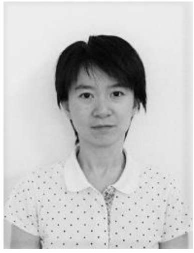

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