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New Horizons of Microelectromechanical Systems in the Automotive Industry

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Abstract

Microelectromechanical Systems (MEMS) are the integration of mechanical components, sensors, actuators, and electronic devices on a silicon substrate using microchip fabrication technology to realize System on Chip (SoC). With technological advancements, there is a growing need for more precise measurement tools to improve the quantity and quality of devices like automobiles. This demand has driven advancements in microchip manufacturing technology and led to the emergence of MEMS technology with higher precision, smaller sizes, and lower costs. The application of these devices in practical fields such as accelerometers, manifold pressure sensors, gyroscopes, micro-optic sensors, automotive airbags, inertial navigation, guidance and control systems, and motion control systems has resulted in enhanced reliability and safety. MEMS enable the creation of small, efficient, and multifunctional devices for simultaneous monitoring of parameters such as temperature and pressure. In the context of smart, autonomous, and Electric Vehicles (EV), the focus is on pressure sensors, accelerometers, and gyroscopes. This article examines the capability of MEMS accelerometers to measure the parameters of vibration in various vehicle locations, considering the dynamic functions of cars. It also reviews the Tire Pressure Monitoring System (TPMS) and Motor Air Pressure (MAP) sensors.

Keywords: Microelectromechanical inertial sensors, Micro accelerometer, Microelectromechanical systems, Pressure sensor, Acceleration sensor.

1 | Introduction

With the advancement of technology today, the need for more precise measuring instruments and sensors in the automotive industry and other sciences is felt more than ever. Integrating micro-scale mechanical components, sensors, actuators, and electronic devices on a single chip is the fundamental operational principle of Microelectromechanical Systems (MEMS). In this context, MEMS with high functional accuracy and small dimensions, combining electrical and mechanical components, are employed in practical fields such as accelerometers and pressure sensors to perform various functions, including sensing, control, and

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activation on a microscale [1]. In their simplest form, these sensors gather environmental information by measuring thermal, mechanical, chemical, biological, magnetic, and optical phenomena.

Processing this information triggers actuators to respond with actions such as movement, displacement, adjustment, pumping, and filtering to guide the environment toward desired outcomes [2], [3].

The commercial attractions of this technology lie in its ability to reduce production costs with high-volume manufacturing, its inherently small dimensions at the micro-scale, low mass and power consumption, and its robustness combined with accuracy [4]–[6]. These factors have made this technology highly practical in various fields, especially the automotive industry. In this sector, MEMS sensors are used as single-purpose or multifunctional sensors for measuring temperature, pressure, position, speed, and flow. They help achieve goals like Electronic Stability Control (ESP), rollover and slip detection, engine component management, pressure monitoring, and security [7]. MEMS sensors are essential for enhancing engine performance, monitoring tire pressure, ensuring vehicle safety, and controlling pollution [8]–[10].

Large-scale integrated MEMS include micro transducers (Actuators/sensors and innovative structures), radiative energy devices (Antennas), optical devices, processors and memories, interconnect networks (Communication buses), input-output devices, and more. These devices are produced through micromachining processes, whereby parts of a wafer are removed, or new layers are added, depending on the application. While MEMS are not limited to silicon substrates, silicon is often preferred due to its excellent properties, making it ideal for high-quality applications. For instance, the strength-to-weight ratio of silicon is higher than that of many other engineering materials, allowing for the creation of mechanical devices with a wide bandwidth [3], [4].

Some examples of MEMS technology applications in science and engineering include Micro-systems for Polymerase Chain Reaction (PCR) to amplify and identify DNA, Scanning Tunneling Microscopes (STM) manufactured through machining processes, and Biochips for detecting hazardous chemical and biological agents, Micro-systems for rapid drug screening and selection, Instruments for determining product quality, Micro-bio-electromechanical systems for high-performance artificial neural elements or lenses, and tools for genomic data analysis and clinical diagnostics [8], [11], [12].

MEMS devices in medicine are used for measuring internal body fluid flow, dialysis, blood pressure, gas masks, respiratory capacity, and pacemakers. For example, based on piezoelectric properties, the Medical Pressure device is a disposable item in hospitals. In the aerospace industry, MEMS sensors and actuators are used in cockpit indicators, flaps, emergency jump tools, wind tunnel measurement devices, and microsatellites. Radio Frequency Microelectromechanical Systems (RFMEMS) are extensively used in the communications industry, especially in mobile phone manufacturing. The advancement of RFMEMS technology has led to cheaper and smaller mobile phones. Micro-Opto-Electro-Mechanical Systems (MOEMS) take advantage of the massless nature of photons and the speed of light, making them suitable for use in filters, modulators, and antennas [4], [6], [12].

This study first provides a general view of this innovative technology and examines the design and manufacturing methods for one of its common applications in pressure sensors and micro accelerometers. These devices are used in various fields such as manifold pressure measurement systems, automotive airbags, inertial navigation, guidance and control systems, and motion control systems. In the second part, the focus will be on the construction and design of MEMS systems. The third section will explore the global market and technical applications of MEMS. The application of MEMS technology in the automotive industry will be discussed in the fourth section, and the conclusion will be presented in the fifth section.

2 | Methods of Manufacturing Microelectromechanical Systems

As shown in *Fig. 1*, the traditional materials used for manufacturing MEMS devices include gold, silver, platinum, titanium, aluminum, nickel, copper, chromium, and tungsten. The chosen strategies for fabricating these materials typically involve electroplating and sputtering [13]. Polymers have recently been utilized in fabricating these devices; however, silicon remains the most commonly used material in MEMS manufacturing. Silicon is not only economically viable but also possesses unique characteristics. It does not exhibit hysteresis or energy loss when deformed, and it has a very high fatigue resistance, enduring up to several billion operating cycles [3], [14].

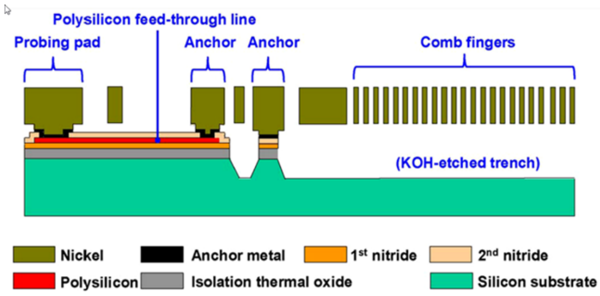

Fig. 1. Using different materials to make microelectromechanical systems [3].

Fig. 2 illustrates the integration of micromachining with Complementary Metal-Oxide-Semiconductor (CMOS) device fabrication processes in creating a System on Chip (SoC). The three fundamental processes in MEMS manufacturing are:

I. Deposition: This process involves creating a thin film of materials through chemical or physical interactions. These thin films are subsequently used in etching processes.

II. Etching: This process can be performed using wet etching (Immersing layers in chemical solvents) and dry etching (Using reactive ions or various vapors).

III. Lithography: This process transfers a pattern onto a light-sensitive material by exposing it to light, causing the properties of the exposed areas to differ from those of the unexposed parts [15]–[17].

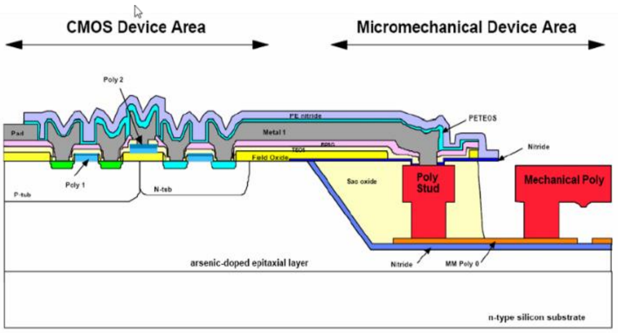

Fig. 2. Integration of silicon microelectronic and microelectromechanical systems devices [15].

The three general methods for fabricating MEMS are surface micromachining, bulk micromachining, and LIGA. As shown in *Fig. 3*, in Surface Micromachining, most of the substrate remains intact, and only the surface material is coated or etched through a series of specific processes. This technique is suitable for creating thin, surface-level structures [18]. The bulk micromachining method, illustrated in *Fig. 4*, is used for structures with significant height and length.

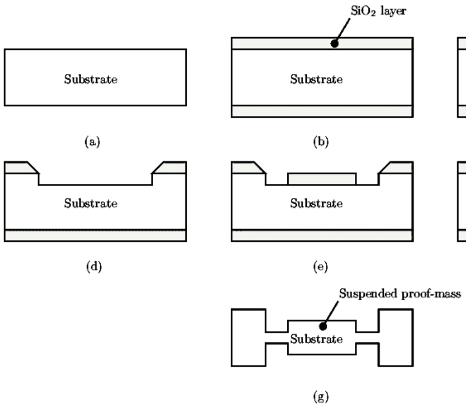

Fig. 3. Microelectromechanical systems manufacturing by surface micromachining method [18].

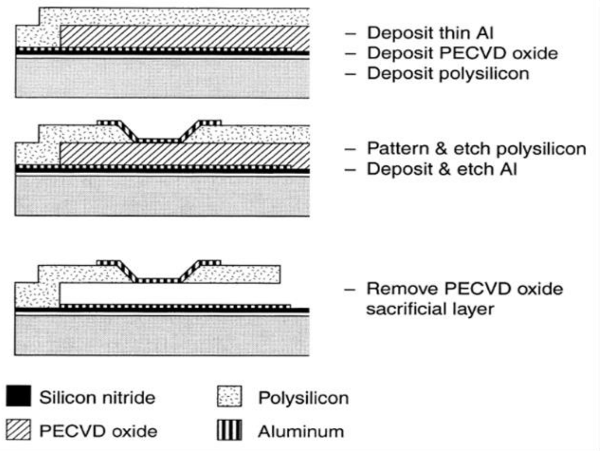

Fig. 4. Microelectromechanical systems manufacturing by bulk micromachining method [19].

Bulk micromachining uses thick substrate layers and removes substrate in large volumes to shape structures, which is crucial for MEMS devices in photonic switching (Optical and wireless devices) [19]. The LIGA process creates three-dimensional molds, which can be final products or filled with materials like metals and plastics to form diverse MEMS structures [20].

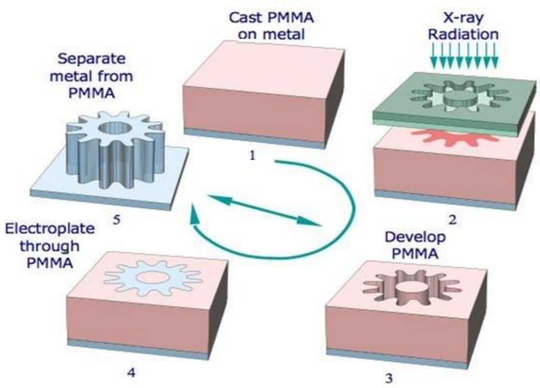

Fig. 5. Fabrication of microelectromechanical systems by LIGA method [20].

3 | Microelectromechanical Systems Market

In MEMS technology, batch fabrication is used to increase yield and reliability, and to reduce size, weight, and cost. These advantages are illustrated in *Fig. 6*. MEMS technology enables the production of products that cannot be manufactured by other methods [21]. With its diverse applications, MEMS technology could become more widespread than IC microchips. It merges complex mechanical systems with IC electronic circuits. While sensors and actuators are typically costly and unreliable, MEMS enables their production with integrated fabrication techniques, achieving reliability comparable to IC precision [22].

MEMS technology has extensive applications in various industries, including the automotive, chip manufacturing, and military sectors. Countries like Japan and South Korea, which have been pioneers in developing this technology globally, now have significant production in automotive industries and microtechnology products [22], [23]. The MEMS technology market exceeded $11 billion in 2011. From 2019 to 2023, the global MEMS sensor market grew at a Compound Annual Growth Rate (CAGR) of about 15%, reaching 13.9 billion RMB in 2023.

This trend aligns with the automotive sector, where the global market for automotive sensors reached $22.5 billion in 2016. Major suppliers of MEMS for automotive use are primarily large companies from the United States, Europe, Japan, and others, which monopolize international markets. Examples include Sensata in the United States, Bosch in Germany, and Toshiba in Japan [9], [24].

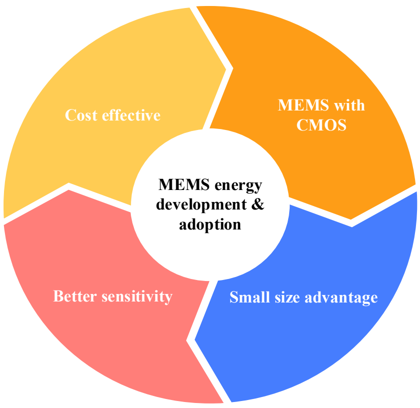

Fig. 6. Advantages of microelectromechanical systems technology [21].

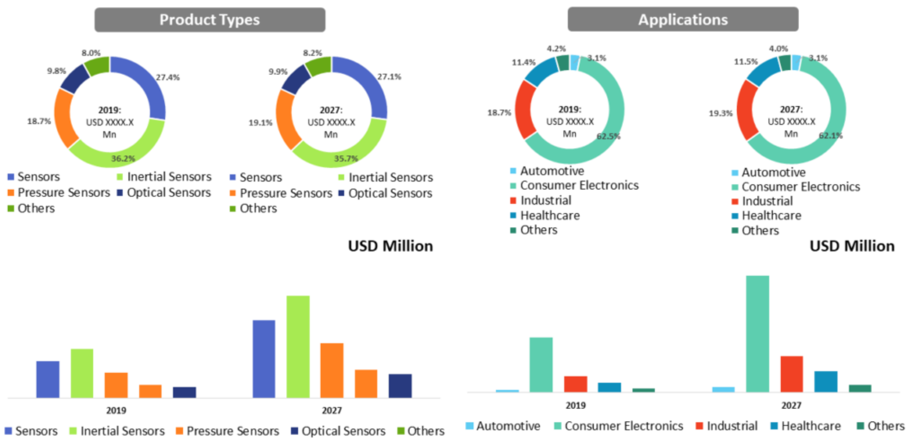

Fig. 7. Global market share of microelectromechanical systems products[1].

[1] https://dataintelo.com/report/digital-fitness-market

4 | Microelectromechanical Systems Technology in the Automotive Industry

MEMS significantly enhances vehicle precision and safety. In automobiles, MEMS sensors are widely used in various systems, including the Electronic Stability Program (ESP), Electric Parking Brake (EPB), Anti-lock Braking System (ABS), Hill Start Assist (HAS), Electronically Controlled Suspension (ECS), Tire Pressure Monitoring System (TPMS), engine stabilizers, angle measurement, driver heartbeat detection, and adaptive navigation systems [4], [6], [9].

For example, [25] describes a sensor design using gold and tin oxide electrodes featuring a gas concentration detection circuit. The n-type semiconductor with a rutile structure enhances sensitivity, and a sol-gel SnO_2 coating is applied. The sensor has 20 finger electrodes on a ceramic substrate and a heater on the bottom layer for environmental interaction.

A temperature sensor can detect the engine temperature in real time and protect the engine from overheating. MEMS sensors used in the automotive industry include various types of MEMS gyroscopes, MEMS accelerometers, MEMS pressure sensors, MEMS inertial sensors, and Motor Air Pressure (MAP) sensors. *Fig. 8* illustrates the relationship between MEMS and micro-sensors, micro-actuators, microstructures, and microelectronic computational circuits. These sensors and actuators enhance the vehicle's safety and performance by providing accurate and real-time data essential for the efficient functioning of advanced automotive systems [5], [9], [13].

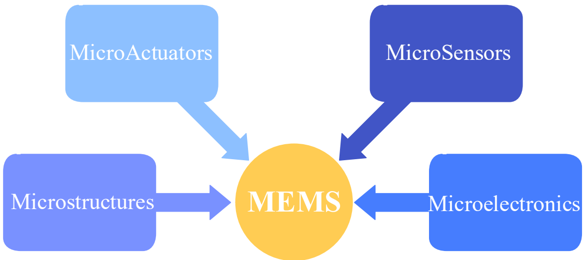

Fig. 8. Connection of circuit components with microelectromechanical systems.

Microelectromechanical systems accelerometers

An accelerometer is an electromechanical device that measures static (Gravity) and dynamic (Vibration or motion) acceleration. MEMS accelerometers are classified into piezoelectric, capacitive, and thermal. Among these, capacitive micro-accelerometers are widely used due to their high sensitivity, low-temperature effect, and simple structure. The main structure of this sensor is capacitive, consisting of a fixed electrode and a mass block etched on the surface of a silicon-integrated circuit. Acceleration causes the mass block to displace, changing the overlap area or distance between the capacitors. The output signal from the capacitor is amplified and processed, then converted into a DC voltage [9]. MEMS accelerometers are commonly used in automotive safety systems such as wheel and automatic brake operations, smart airbag deployment systems, ESP, and ABSs. They are also employed to monitor vibrations in vehicles. These accelerometers ensure the accurate and real-time detection of various physical phenomena, contributing to the overall safety and performance of the car [8], [26].

Microelectromechanical systems gyroscope

A MEMS gyroscope is a sensor with an oscillating component that measures angular velocity and acceleration, enabling the detection of changes in direction. This element is divided into two types: Vibrating and rotary. A vibrating Gyroscope uses a vibrating mass made of single-crystal silicon or polycrystalline silicon to detect angular velocity through the Coriolis effect. In a rotary Gyroscope, the rotor is made of polycrystalline silicon and angular velocity is measured using a balance ring. These types of gyroscopes are integral in various applications, providing precise measurements of angular motion [3], [9].

MEMS gyroscopes are used in navigation, vehicle dynamic control, and rollover detection. They produce a signal proportional to the vehicle's rotational movement for the centrifugal force or traction control system. If unsafe conditions are detected, the control system sends a signal to the ABS to prevent a rollover. Data is collected to compare the performance of accelerometers at different locations in the vehicle (Such as on the hood above the engine, hood above the radiator fan, exhaust pipe, and dashboard) [8], [10]. *Fig. 9* shows several examples of gyroscopes used by BOSCH.

One of the important applications of the MEMS gyroscope sensor is the ESP. ESP is an active safety system that collects rotation information through environmental sensors. To ensure vehicle stability and safety, the processor sends hydraulic brake instructions for proper execution of lateral slip. The working principle of the ESP system involves multiple accelerometers and gyroscope sensors simultaneously monitoring the vehicle's body status. When the vehicle encounters an obstacle and needs to turn in an emergency, it can easily rotate its rear. The gyroscope sensor and accelerometer continuously detect the vehicle's acceleration and angular velocity. Through these real-time measurements, the ESP system can make precise adjustments to the vehicle's dynamics, preventing skidding and maintaining control during critical maneuvers, thereby enhancing overall driving safety.

Sensors that can detect two or more parameters or characteristics are called multifunctional sensors. Their use leads to a reduction in the number of sensors in a vehicle, improved system reliability, and reduced occupied space. For example, a MEMS inertial sensor combines MEMS gyroscopes and accelerometers. These sensors detect changes in an object's inertia and convert this force into a measurable signal [2], [27]. By integrating multiple sensing capabilities into a single device, multifunctional sensors streamline the vehicle's sensor array, enhancing overall efficiency and performance. This integration is particularly valuable in modern vehicles, where space is premium and system reliability is paramount.

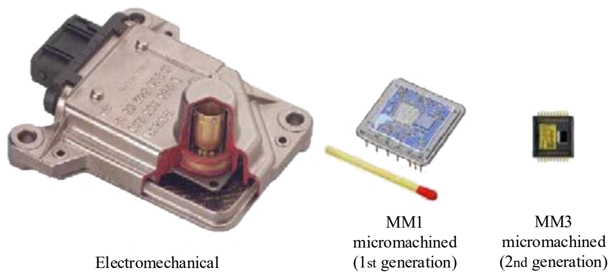

Fig. 9. Some examples of gyroscopes used in the automotive industry [28].

Microelectromechanical systems pressure sensor

MEMS pressure sensors, widely used in automobiles to measure liquid and gas pressure, come in various forms, such as piezoresistive, capacitive, differential transformer, and Surface Acoustic Wave (SAW) [14]. In capacitive sensors, pressure on the upper barrier moves it downward, changing the distance between electrodes and altering electrical capacitance. In [29], using carbon nanotubes, an ultra-precise pressure sensor capable of detection at the zeptogram level has been designed, and an Instrumentation Amplifier (IA) is used to reduce noise effects. This amplifier is also designed using Carbon Nanotube Field-Effect Transistor (CNTFET) technology.

Also, In [30], a novel two-stage Operational Transconductance Amplifier (Gm or OTA) is introduced, which addresses the requirements for low power consumption, high gain, and low noise. This design utilizes the g_m/I_D technique with the bulk-driven method. Notably, due to the inherent limitations of CMOS technology, CNFET technology is employed for the circuit designs.

One of automobiles' latest MEMS pressure sensors is the TPMS, which operates wirelessly. It includes a transmitter module inside the car tire and a receiver module near the car wheel. It provides alerts when one or more tires are significantly underinflated. Additionally, if a wheel spins faster than expected, the ECU detects the tire is underinflated and warns the driver accordingly [9]. *Fig. 10* shows the TPMS sensor. This system enhances vehicle safety by ensuring that tire pressure is always at optimal levels, preventing potential accidents caused by underinflated tires.

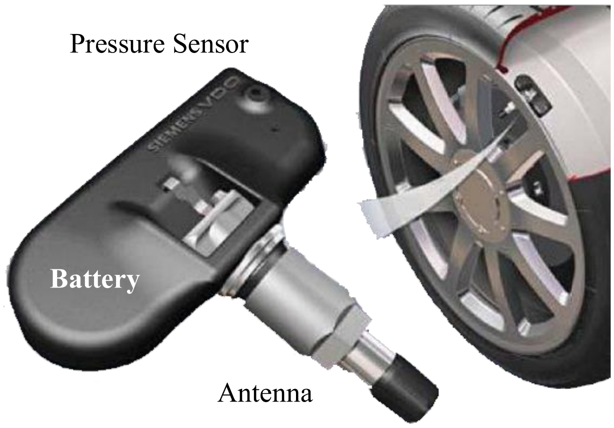

Fig. 10. Tire pressure monitoring sensor.

Engine air intake pressure management sensor

The MEMS sensors utilized in engine management include MAP and airflow sensors. The pressure sensor is adept at detecting the negative pressure within the cylinder, thereby regulating fuel injection and combustion. Based on the data provided by these sensors, the engine management system delivers the optimal fuel-air mixture to the combustion engine. This ensures efficient operation regardless of whether the vehicle navigates coastal roads or mountainous terrain, thereby preventing increased fuel consumption and environmental pollution [7], [9]. Subsequently, this file is transformed by another virtual device into a polynomial approximation of the sensor's output characteristics. This virtual device also autonomously determines the polynomial order based on the user-specified error tolerance. This file is then converted into a polynomial approximation of the sensor's output characteristics by another virtual device. This virtual device also automatically selects the polynomial order based on the error specified by the user. The program uses correction factors to create a real-time compensated pressure chart. These sophisticated calibration and compensation techniques ensure that the pressure sensors provide accurate and reliable measurements crucial for efficient engine performance and reduced emissions. By optimizing the air-fuel mixture, these sensors help maintain engine efficiency and comply with environmental standards [31], [32].

Future of microelectromechanical systems design in the automotive industry

The development of autonomous vehicles is facilitated by the integration of the Global Positioning System (GPS) and the Inertial Navigation System (INS) [33]. A significant challenge in the integrated INS/GPS is the presence of high-level random noise and uncertainties in INS sensors and the complexity of real noise data models. To mitigate these issues, a noise reduction technique based on Empirical Mode Decomposition (EMD) is employed to enhance the accuracy of INS sensor outputs and improve generalization capabilities. Furthermore, an optimized interval Type-2 fuzzy neural network is utilized to model and manage high uncertainty levels and estimate the positioning error of INS sensors when GPS signals are unavailable [34]. This approach ensures more precise INS sensor outputs and better generalization capabilities while effectively handling uncertainties and estimating positioning errors during GPS signal blockages.

For instance, [35] discusses CMOS-based MEMS resonators actuated electrostatically. It is important to note that electrostatic actuators are favored over other types in the design of microresonators due to their lower manufacturing costs, reduced losses, and enhanced controllability. Reference [36] introduces an innovative and efficient method for integrating Fiber Bragg Grating (FBG) with Artificial Neural Network (ANN) techniques to measure temperature and strain simultaneously. In [37], the temperature characteristics of fiber optic MEMS pressure sensors are examined, and a wavelength conversion temperature compensation method is proposed. The study investigates the impact of target temperature and data point selection on the compensation effect, verifying the method's effectiveness by compensating the sensor temperature before and after aging. Reference [38] details the application of the Levenberg-Marquardt Backpropagation (LMBP) algorithm in ANNs for the self-calibration of a CO gas sensor.

Investigating fault tolerance electronic systems in cars

In the drive systems of EV, the three main components (Motors, inverters, and sensors) are the most affected by faults. Induction motor faults are Stator and rotor winding faults. Stator faults include insulation failure, short circuits between windings, and ground faults. Rotor winding faults, however, are mainly mechanical failures like bearing breakage or issues in the magnetic circuit. In the process of converting Direct Current (DC) to Alternating Current (AC), Inverter faults can involve failures in the Insulated-Gate Bipolar Transistor (IGBT), which may manifest as an open circuit or a short circuit. Sensor faults involve speed and position sensor faults and current and voltage sensor faults [39]–[41].

Fault-tolerant methods are divided into two main categories: passive and active. Passive strategies are designed based on robust control techniques to withstand specific faults, while active methods dynamically respond to faults by reconfiguring the system and control settings. Active methods operate based on fault detection, isolation, and compensation and are further divided into two subgroups: Post-fault control adjustments and system reconfiguration. Fault tolerance refers to the ability of a system to continue functioning correctly even in the presence of a fault or failure in one of its components. This concept is typically implemented through system redundancy [41]–[43].

Three key factors have made fault tolerance a practical solution in vehicles, especially in Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV):

I. Integration of various control units in vehicles: For example, motor and gearbox control units have been integrated into one unit, reducing costs and increasing system redundancy [44].

II. Advances in semiconductor technology: These advances have enabled the implementation of electronic chips with fault detection capabilities. For instance, processors with self-test features can be used to ensure the correct operation of systems [43], [44].

III. Natural system redundancy: For example, an ABS wheel has an independent sensor and actuator. This natural redundancy allows the system to continue functioning even if one of the sensors or actuators fails.

A key element of fault-tolerant electronic systems is microcontrollers with self-testing and fault-detection capabilities. Fault-tolerant microcontrollers typically consist of two independent processors working in parallel, so if one fails, the other can continue operating. In Triple Modular Redundancy (TMR) architecture, three processors perform identical tasks in parallel. In the event of a failure in one, the other two can make the correct decisions with the help of a voter. In software redundancy, instead of using extra hardware components, mathematical models and observers are used to replace the signals from faulty sensors. This method can significantly reduce the weight and cost of the system but requires high accuracy in the mathematical models [41], [43], [44].

5 | Conclusion

In this article, MEMS have been studied and initially analyzed. Given their small size, lightweight, low cost, high efficiency, and high reliability with excellent yield, their use in the automotive industry is very suitable. MEMS significantly enhances vehicle safety and quality and reduces energy consumption, particularly in smart, electric, and autonomous vehicles. This approach ensures improved performance and reliability in integrated navigation systems, crucial for advancing autonomous vehicle technologies.

Conflicts of Interest

The authors have not explicitly declared any conflicts of interest in the document.

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