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Application of Intelligent Sensing Technology in Automotive Parts

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ABSTRACT
As a key technology in the intelligent transformation of the automotive industry, intelligent sensing technology plays an important role in the precise control, performance optimization and safety improvement of automotive parts. This paper systematically describes the definition, classification system and technology evolution path of intelligent sensing technology, and focuses on analyzing its application in the fields of powertrain optimization, safety system upgrade and body control system. At the same time, it prospectively discusses the advanced development trends such as the fusion of smart materials and sensing and the extended application of digital twin, which provides theoretical reference and practical guidance for the further application of intelligent sensing technology in automotive parts.

KEYWORDS
intelligent sensing technology; automotive parts; precise control

With the rapid development of the automobile industry in the direction of intelligence, electrification and connectivity, intelligent sensing technology, as an important basis for realizing the intelligent function of vehicles, is increasingly widely used in automotive parts. From the precise control of the powertrain to the real-time monitoring of the safety system, and then to the intelligent management of the body system, intelligent sensing technology has become a key driving force to improve the overall performance and technical level of the vehicle. This paper aims to systematically analyze the application status of intelligent sensing technology in automotive parts, explore its technology evolution path, and conduct prospective research on its future development trend, so as to provide theoretical support for industry development and technological innovation.

1 Overview of Intelligent Sensing Technology

1.1 Technical Definition and classification System

As the core enabling technology of modern automotive engineering, intelligent sensing technology is essentially to achieve accurate capture and intelligent analysis of environmental information through interdisciplinary. Its technical definition includes three elements: an integrated sensing system with physical signal capture, edge computing and data communication, intelligent features with self-calibration and self-diagnosis functions, and meeting the engineering requirements of vehicle reliability throughout the life cycle. The construction of the technical classification system follows two dimensions. The dimension of sensing objects can be divided into physical quantity sensors (covering the detection of mechanical parameters such as pressure, vibration and torque), chemical quantity sensors (such as the monitoring of proton exchange membrane of hydrogen fuel cells), and biological quantity sensors (identification of driver' physical signs). The dimension of system integration is divided into three types: discrete (suitable for traditional mechanical parts), embedded (conformal packaging with lightweight materials), and distributed (multi-sensor coordination of Internet of vehicles). Among them, embedded sensors show significant advantages in the application of composite materials. For example, the implantation process of fiber optic sensors in carbon fiber preforms, which can improve the strain measurement accuracy to ±0.3με, and has a 5-fold increase in spatial resolution compared to traditional surface mount technology. The technical system follows the ISO 23125:2015, and in the automotive field, it must comply with the AEC-Q100 reliability verification standard, with special emphasis on the ability to maintain the signal stability under a wide temperature range of -40℃~150℃ [1].

1.2 Technology Evolution Path

The evolution of intelligent sensing technology presents a three-stage development of "perceptual dimension expansion - integration density improvement - function ubiquitous extension". The first stage (1980-2000) is dominated by discrete sensors. One of the typical representations is the first mass-produced MAP sensor developed by Bosch, which uses the piezoresistive principle to measure the intake manifold pressure with an accuracy of ±1.5kPa [2]. In the second stage (2000-2015), with the breakthrough of MEMS technology, the sensor size is reduced to the millimeter level, and the TPMS chip produced by Texas Instruments realizes the fusion detection of pressure, temperature and acceleration. The current stage (2015 to date) presents three major trends. The first is the innovation of material interface technology. For example, flexible electronic printing technology makes the sensor thickness break through the threshold of 0.1mm, to achieve seamless coextrusion with SMC materials. The second is the improvement of the multi-mode perception capability. The third-generation environmental perception module developed by Continental integrates the information of millimeter wave radars, LiDAR and vision sensors, and its target recognition accuracy is 99.97%. The third is the deep integration of edge intelligence. Sensor nodes supported by NXP S32G processors have local decision-making capabilities, and the delay is reduced by 80% compared with traditional architectures [3]. The examples in the automotive industry include a thermal runaway warning network of 240 temperature sensors embedded in the Tesla 4680 battery pack, and a 32-channel fiber optic sensing system embedded in the BMW i3 carbon fiber body for real-time diagnosis of structural health.

2 Automotive Parts Application Scenario Analysis

2.1 Powertrain Optimization

Intelligent sensing technology significantly improves the operating efficiency of the powertrain through high-precision signal acquisition and dynamic closed-loop control. In the field of internal-combustion engine, the fuel-injection pressure sensor realizes real-time monitoring of common rail pressure based on piezoresistive effect, its operating range covers 0 to 300MPa, and the repeatability error is controlled within 0.05% of the full scale, thus ensuring the air-fuel ratio optimization of sub millisecond. In the new energy drive system, the distributed optical fiber sensor of the temperature control network of the battery pack realizes the fully covered thermal field monitoring through the principle of Raman scattering, and the single module integrates 128 measurement points, and the axial temperature gradient detection sensitivity reaches 0.1℃/m. The motor drive system relies on the Hall effect sensor and resolver to construct the redundant Angle detection system, and the angular resolution is better than 0.01 degree. It can effectively suppress the electromagnetic torque ripple combined with the space vector modulation algorithm.

2.2 Security System Upgrade

Multi-source sensor data fusion technology has promoted a new paradigm of active safety system. The millimeter-wave radar array realizes the four-dimensional point cloud reconstruction based on the MIMO architecture. The theoretical ranging accuracy reaches centimeter level, and the azimuth resolution is improved to less than 0.5 deg., which meets the target identification requirements of ISO 21434 for emergency braking systems. The body safety domain controller integrates strain gauge load cell and capacitive biometric module. The former adopts the Wheatstone bridge structure to achieve 1kg load resolution, and the latter realizes occupant physical sign classification through subcutaneous tissue dielectric constant detection. The tension monitoring unit of the intelligent seat belt system is developed based on the counter-magnetostriction effect. The sensitivity factor of the magnetoelastic sensor after heat treatment reaches 12mV/N, and it can trigger the classification early warning strategy within 50ms [4].

2.3 Body Control System

The construction of car body sensing network realizes the deep coupling of mechanical structure and electronic system. The intelligent seat pressure distribution sensing system adopts the optical fiber braid layer, and inverts the support force distribution through the light intensity attenuation model. A single seat cushion integrates 1024 detection nodes, and can generate 14 standard support modes with the pneumatic actuator. A combination scheme of magnetorheological fluid damper and giant magneto resistance sensor is introduced into the window anti-pinch module. The detection resolution of magnetic field intensity reaches 0.1mT, and the nonlinear clamping force suppression mechanism is formed by combining the fuzzy PID control algorithm. The chassis system is equipped with a six-dimensional force sensor array, decoupling the three-dimensional force and torque components based on the strain analysis of the elastomer structure, and the range covers ±5000N and ±300Nm. The integration of the hub bearing and the vibration acceleration detection unit can identify the characteristics of the impact load of the road surface above 0.5g.

2.4 Integrated Monitoring of Lightweight Materials

The structural health monitoring of carbon fiber-reinforced polymer (CFRP) relies on the fiber Bragg grating (FBG) sensor network. The adaptability of it minimum curvature radius is increased to 5mm, and the resolution of wavelength demodulator is 1pm, which can realize the distributed detection of interlaminar shear strain of the composite material. In sheet molding compound (SMC) process, the viscosity-time function relationship of the curing kinetic model is established by the complex impedance spectrum analysis of dielectric sensor array under alternative electric fields, and the phase change determination error is controlled within 3 minutes. The surface acoustic wave (SAW) sensor is embedded in the surface modified layer of magnesium alloy die-casting parts. The thickness of piezoelectric substrate is optimized to 50μm, and the resonant frequency stability fluctuates no more than 0.03% at 200℃, thus realizing the online reconstruction of the residual stress field. The carbon fiber drive shaft system of BMW i8 is implanted with an 8-channel optical fiber sensor group, and the spatial coordinates of the damaged area are located based on the optical time domain reflectometer. The fracture toughness evaluation error is less than 5% of the nominal value.

3 Outlook on the Development Trend of Intelligent Sensing Technology

3.1 Intelligent Materials and Sensing Fusion

3.1.1 Self-powered piezoelectric composites

The development of self-powered piezoelectric composites marks a major breakthrough in energy-independent sensing technology. This kind of materials realizes the direct conversion of mechanical stress and electrical signal through the micro-structure design of piezoelectric ceramics and flexible substrates, the essence of which is to embed the energy conversion function in the intrinsic properties of the material. Typical application scenarios include vibration energy recovery for automotive suspension systems. When a vehicle passes through an uneven road, the electric charge generated by lattice deformation inside the composite material can be used to power the on-board sensors through an energy management circuit to form a closed-loop self-sustaining sensing network. In the field of lightweight structural health monitoring, the carbon fiber reinforced piezoelectric composite laminates can simultaneously output strain distribution and energy collection signals under the bending load by optimizing the layer, thus effectively solving the energy supply problem of traditional embedded sensors. The technical challenge focuses on the control of piezoelectric performance degradation in long-term service, and charge output stability needs to be maintained through interface modification and polarization process optimization. Future research will focus on multi-physics coupling mechanisms, such as the regulation law of piezoelectric response by temperature-stress synergies to expand its applicability in extreme environments.

3.1.2 Self-regulation of Shape Memory Polymer Strain

The combination of shape memory polymers with sensing technology opens up a new dimension of adaptive structures. This kind of material can restore the preset form triggered by external stimuli (such as temperature and electric field), and its strain response mechanism is deeply integrated with the resistance/capacitance sensing unit to form an intelligent system with self-feedback ability. In the automotive sector, this technology is applied to the shape control of active aerodynamics packages, which can monitor the spoiler deformation through embedded strain sensors in real time, and dynamically adjust the windward angle based on the shape memory effect to optimize the aerodynamic performance. Another innovative direction is the development of self-healing sealing components. When sensors detect micro-cracks in rubber parts, local heating activates the shape memory function and drives material flow to fill the defect. The core scientific problem is the matching design of the material phase transition temperature and the sensing signal threshold, which needs to balance the response speed and energy efficiency. The prospective study explores photoresponsive shape memory polymers, which use optical fibers to achieve both stimulus delivery and deformation monitoring, and make the unwired intelligent structure possible.

3.2 Extend Application of Digital Twin

3.2.1 Prediction Model of Material Damage Evolution

Through multi-scale modeling and real-time data assimilation, digital twin technology is reconstructing the research methods of material damage evolution. Aiming at the progressive damage such as composite delamination and metal fatigue crack, the twin model integrates the microscopic defect evolution equation with the macro-mechanics constitutive relation, and establishes the cross-scale mapping rules from atomic bond breaking to component failure. In the health management of automotive lightweight parts, the model dynamically modifies the damage expansion rate equation by receiving the strain and acoustic emission signals of embedded sensors, and realizes the online probabilistic prediction of the remaining life. Key technological breakthroughs are reflected in the optimization of multi-physics coupling algorithms, such as the incorporation of thermal-mechanical-chemical coupling effect into the finite element iterative process to significantly improve the simulation accuracy of material property degradation in corrosive environments. The industry is trying to combine crystallographic theory with machine learning to accelerate damage pattern recognition through deep learning, thus shortening the prediction cycle by several orders of magnitude.

3.2.2 Application of Virtual Calibration Technology

Virtual calibration technology is driving a paradigm change in sensor manufacturing processes. By constructing digital twins containing material characteristics, process deviation and environmental disturbance, the technology simulates the response characteristics of the sensor under all working conditions in virtual space, which replaces the complicated experiments in traditional physical calibration. For automotive MEMS sensors, the model needs to accurately reproduce the nonlinear deformation behavior of silicon microstructure under the inertial load and the effect of temperature drift on the piezoresistive coefficient. The key technologies include the development of rapid simulation framework based on the reduced order model and the design of closed-loop optimization algorithm for calibration data and measured results. Application cases include multi-sensor collaborative calibration of the steering-by-wire system. The virtual environment can synchronously simulate the coupling effect of steering wheel torque, wheel steering angle and tire-road friction coefficient, and complete the overall optimization of control parameters at one time. The future development direction is to establish a digital thread covering the whole life cycle of sensors, seamlessly connect data at all stages of design, manufacturing and service, and realizes forward-looking compensation for performance degradation.

4 Conclusion

The application of intelligent sensing technology in automotive parts has significantly promoted the technological innovation and intelligent transformation of the automotive industry, and it has shown excellent technical value in precise control, performance optimization and safety improvement. Through the in-depth application of power system optimization, safety system upgrade and body control system, intelligent sensing technology not only improves the operating efficiency and reliability of automotive parts, but also provides a solid foundation for the realization of intelligent functions. It is expected that with the deep integration of intelligent materials and sensing technology and the extended application of digital twin technology in the future, intelligent sensing technology will further break through the traditional limitations and show greater application potential in the fields of self-powered sensors, material damage prediction and virtual calibration.

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