Automobile Fault Diagnosis and Management System: A Review and Future Directions

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Abstract
The increasing complexity of modern automobiles necessitates sophisticated fault diagnosis and management systems to ensure safety, reliability, and optimal performance. The software functionality of modern automobiles continues to increase dramatically, this growing functionality leads directly to a higher complexity in development and configuration. Additionally, advanced driver assistance systems (ADAS) and autonomous functionality, such as highly and fully automated driving or parking will be introduced. Many of these new functions require access to different communication domains within the automobile, which increases system complexity. AUTOSAR, the software architecture established as a standard in the automobile domain, provides no methodologies to reduce this kind of complexity and to master new challenges. These fast changing systems also increase the complexity of automobile fault diagnosis and management systems. This article reviews the current state-of-the-art technologies in gasoline powered automobile fault diagnosis and management systems, encompassing various diagnosis techniques, data acquisition methods, and system architectures. We discuss the challenges and limitations of existing systems and explore promising future directions, including the integration of artificial intelligence and machine learning for enhanced fault diagnosis and predictive maintenance.

Keywords: *Automobile, Expert System, Fault Diagnosis, Electronic Control Units (ECUs), Automobile Fault Diagnosis and Management Systems, On-Board Diagnostics (OBD).*

1. Introduction

The automobile industry has witnessed significant advancements in technology over the years, resulting in the development of more complex and sophisticated automobiles, with intricate systems integrating numerous electronic control units (ECUs), sensors and actuators that monitor various aspects of the automobile's performance, such as engine temperature, speed, and fuel consumption. While these systems have improved the overall efficiency and safety of automobiles, they have also made it more challenging to detect and manage faults when they occur. Automobile faults can be caused by a variety of factors, including mechanical issues, electrical problems, and software glitches. Detecting and diagnosing these faults in a timely manner is essential to prevent potential safety hazards and costly repairs. Expert systems have emerged as a valuable tool for automakers and technicians to effectively detect and manage faults in automobiles. These systems utilize artificial intelligence algorithms and knowledge-based rules to analyze data from sensors and diagnose potential issues in real-time.

Malfunctions in any component can compromise safety, performance, and fuel efficiency. Also the future use of software in electric vehicles and how the automobile ICT architecture will evolve in years to come clearly shows the importance of ICT to the future of the automobile industry. Information and communication technology (ICT) has made significant innovations in automobile construction possible: from the anti-lock braking system in 1978 to electronic stability control in 1995 and emergency brake assist in 2010. Accordingly, ICT, and especially its software, has expanded significantly, from about 100 lines of code (LOC) in the 1970s to as much as over ten million LOC presently. All these significant improvements and advances in the automobile industry technologies are architectural changes to satisfy the three essential capabilities: zero accidents, Plug & Play and always-on. This article provides a comprehensive overview of Fault Diagnosis and Management System, examining existing technologies, challenges, and future trends.

2. Diagnostic Techniques

Fault Diagnosis and Management System employ various diagnostic techniques to detect faults, some include:

i. **Model-Based Diagnosis:** This approach uses a mathematical model of the vehicle system to identify inconsistencies between predicted and measured values. Discrepancies indicate potential faults (Isermann, 2011).

ii. **Signal-Based Diagnosis:** This technique analyzes sensor signals and actuator responses to detect anomalies indicative of faults. Methods include statistical process control (SPC) and spectral analysis (Patton, Frank, & Clark, 2019).

iii. **Knowledge-Based Diagnosis:** This approach utilizes expert knowledge and rules to diagnose faults based on observed symptoms. Expert systems and rule-based systems are commonly used (Genesereth, 1982). An Expert System can be defined as an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solutions. (Zealot, 2016) once proposed the following features of an Expert System:

   a. Expert system provides the high-quality performance which solves difficult programs in a domain as good as or better than human experts.
   b. Expert System possesses vast quantities of domain specific knowledge to the minute details.
   c. Expert systems apply heuristics to guide the reasoning and thus reduce the search area for a solution.
   d. A unique feature of an expert system is its explanation capability. It enables the expert system to review its own reasoning and explain its decisions.
   e. Expert systems employ symbolic reasoning when solving a problem. Symbols are used to represent different types of knowledge such as facts, concepts and rules.
   f. Expert system can advise, modify, update, expand and deal with uncertain and irrelevant data.

iv. **Data-Driven Diagnosis:** This emerging approach leverages machine learning techniques, such as neural networks and support vector machines, to learn patterns from large datasets of vehicle sensor data and diagnose faults based on learned patterns (He, 2017).

3. Architecture of an Expert System

An expert system tool, or shell, is a software development environment containing the basic components of expert systems. The core components of expert systems are the knowledge base and the reasoning engine. Figure 1, shows the architecture of an Expert System as adopted by Bharati et al (2011):

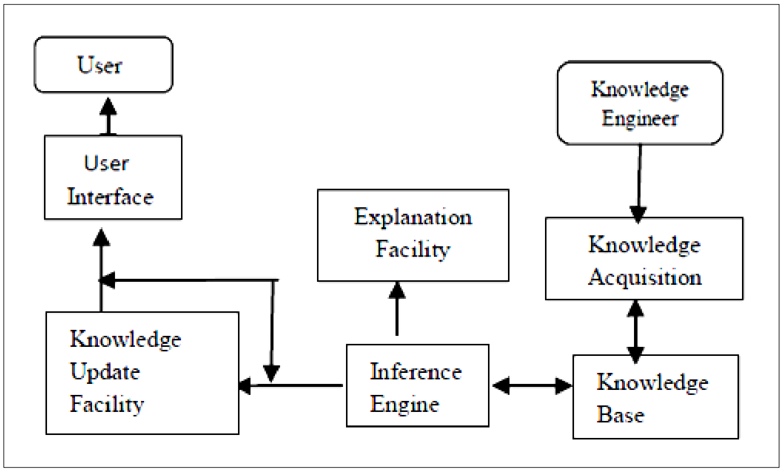

Figure 1: Architecture of an Expert System
(Source: Bharati et al, 2011)

i. **Knowledge-Base:** From figure 1, the knowledge-base contains the knowledge necessary for understanding, formulating and for solving problems. It is a warehouse of the domain specific knowledge captured from the human expert via the knowledge acquisition module. To represent the knowledge production rules, frames, logic, semantic net etc. is used. The knowledge base of expert system contains both factual and heuristic knowledge. Factual knowledge is that knowledge of the task domain that is widely shared, typically found in textbooks or journals. Heuristic knowledge is the less rigorous, more experiential, more judgmental knowledge of performance, rarely discussed, and is largely individualistic. It is the knowledge of good practice, good judgment, and plausible reasoning in the field. (Abraham, 2011)

ii. **Inference Engine:** Inference Engine is a brain of expert system. It uses the control structure (rule interpreter) and provides methodology for reasoning. It acts as an interpreter which analyzes and processes the rules. It is used to perform the task of matching antecedents from the responses given by the users and firing rules. The major task of inference engine is to trace its way through a forest of rules to arrive at a conclusion. (Akuwanne, 2017)

iii. **Knowledge Acquisition:** Knowledge acquisition is the accumulation, transfer and transformation of problem-solving expertise from experts and or documented knowledge sources to a computer program for constructing or expanding the knowledge base. It is a subsystem which helps experts to build knowledge bases. For knowledge acquisition, techniques used are protocol analysis, interviews, and observation. (Williams, 2013)

iv. **Explanation Facility:** It is a subsystem that explains the system's actions. The explanation can range from how the final or intermediate solutions were arrived at to justifying the need for additional data. Here user would like to ask the basic questions why and how and serves as a tutor in sharing the system's knowledge with the user. (Barrejo, 2016)

v. **User Interface:** It is a means of communication with the user. It provides facilities such as menus, graphical interface etc. to make the dialog user friendly. Responsibility of user interface is to convert the rules from its internal representation (which user may not understand) to the user understandable form. (Winfried, 2013)

To build the expert system is known as Knowledge Engineering. Personnel involved in expert system development are domain expert, user, the knowledge engineer and the system maintenance personnel. Domain expert has special knowledge, judgment, experience and methods to give advice and solve problems. It provides knowledge about task performance. Knowledge engineer is involved in the development of the inference engine, structure of the knowledge base and user interface. According to (Abubakar et al, 2019), the development of the Expert System on Automobile Engine Troubleshooting is based on the methodology that has been adopted from several existing methodologies for different applications especially in the field of computer science, software engineering, knowledge engineering and multimedia, since this expert system will be an integration of these technologies. The expert and knowledge engineer should anticipate user's need while designing an expert system (Ojoto, 2013).

3. Data Acquisition and Communication

Efficient data acquisition and communication are essential for effective Fault Diagnosis and Management System. According to (Zaw, 2008); data is correlated from a variety of sources during diagnosis. Most approaches to correlation that involves matching have gathered data with known patterns or models of faults. He also proposed the following questions alongside his theories: at what level should data be correlated (depth) and how much data should be correlated? Secondly, he also pointed to the fact that data is received at different times, and data from some sources may be incomplete or completely missing. Modern automobiles utilize various communication protocols, including CAN (Controller Area Network), LIN (Local Interconnect Network), and FlexRay, to exchange data between ECUs (Robert Bosch GmbH, 2012). Sensors throughout the automobile collect data on various parameters, such as engine speed, temperature, pressure, and emissions. This data is then processed by the Fault Diagnosis and Management System to detect anomalies.

The working principles of an expert system for automobile fault diagnosis involve the following steps:

i. **Data Acquisition:** The expert system collects data from various sensors in the automobile, such as the engine control unit, transmission control unit, and body control module. This data includes information about the automobile's performance, such as speed, temperature, fuel consumption, and exhaust emissions.

ii. **Data Preprocessing:** The raw data collected from the sensors is preprocessed to remove noise and irrelevant information. This step involves cleaning, filtering, and transforming the data into a format that can be used by the inference engine.

iii. **Pattern Recognition:** The inference engine analyzes the preprocessed data using pattern recognition algorithms to identify patterns and anomalies that may indicate potential faults in the automobile. These patterns are compared against the rules and heuristics stored in the knowledge base to generate hypotheses about the cause of the issue.

iv. **Diagnosis and Recommendation:** Based on the analysis of the data and the rules in the knowledge base, the expert system generates a diagnosis of the fault and recommends appropriate actions to be taken to rectify the issue. The diagnostic results are displayed to the user through the user interface, along with an explanation of the reasoning process.

v. **Feedback and Learning:** The user can provide feedback on the diagnostic results, such as confirming or rejecting the diagnosis and suggesting alternative courses of action. This feedback is used by the learning module to update the knowledge base and improve the system's accuracy in detecting faults in future instances.

4. System Architectures

Fault Diagnosis and Management System architectures vary depending on the automobile's complexity and the specific requirements, but basically the system architecture needs to provide capabilities to guarantee extra functional properties for resource utilization, safety and security. This high complexity and the distribution of software functions over many different ECUs and bus systems leads to high cost for developing and testing functionality. This complexity is additionally increased by the introduction of technology like X-by-wire driven by the demands to realize highly and fully automated driving functionality. There is also a computer system called On-Board Diagnostics (OBD) that can discover and diagnose problems with the data reported by the ECUs. Automobile Fault Diagnosis and Management Systems play a crucial role in identifying, diagnosing, and managing these faults, thereby enhancing vehicle reliability and driver safety (Bosch, 2017). Automobile electronic systems can be broken down into four main categories [1]'Powertrain Drive' consisting of electronic engine management, electronic transmission and electronic networks; [2]'Safety systems' such as Antilock Brake systems, air bag triggering, anti–theft, suspension, steering and skid systems; [3]'Comfort body systems' such as Air conditioner, seat adjusting and dashboard displays; [4]'Communication systems' such as Global positioning system, radio reception and information systems. Each of these systems requires Electronic Control Unit (ECU) for efficient performance. A complete automobile ECU can control all aspects of the automobile including engine management, transmission system, ABS, traction, and suspension control all in one ECU. But the electronic system becomes extremely complex making it less feasible. So in reality, many ECUs communicate with each other using controller area network (CAN) data bus, which uses multiplex wiring system.

Fiber optics used for multiplexed data bus will make the system resistant to electromagnetic interference. Serial port communication can be used for diagnosis, while networking can be used for diagnosis from remote centers. 'Electronic Engine Management' is the science of electronically equipping, controlling and calibrating an engine to maintain top performance and fuel economy while achieving cleanest possible exhaust stream, and continuously diagnosing system faults. Due to the requirement of lower emissions, together with the need for better performance, Electronic systems form an important part of Engine management. The design of Engine management ECU would require the use of both analog and digital hardware. Digital Hardware design is used to obtain optimum results. Microcontroller with on-chip RAM, Flash EEPROM is used for control and calculation of various parameters, along with other interfacing circuits for both analog and digital hardware. Inputs from sensors are converted by an analog to digital circuit module (ADC) into digital signals used by the microcontroller to calculate various parameters. Common architectures of Fault Diagnosis and Management System include:

1. **Centralized Architecture:** A centralized ECU is used along with a centralized fault accommodation manager; (Blanke et al. 2006). Figure 2, shows the ECU is responsible for processing data from all systems/sensors and diagnosing faults. All data gathering, processing, and decision-making functions occur at a single central ECU; this design typically means that the automobile systems or sensors simply forward their data to one main location where the Fault Diagnosis and Management System software processes the inputs. However, this creates extra dependencies which increase the complexity and thus this approach is non-modular and scales badly with the size of the system. See Figure 2.

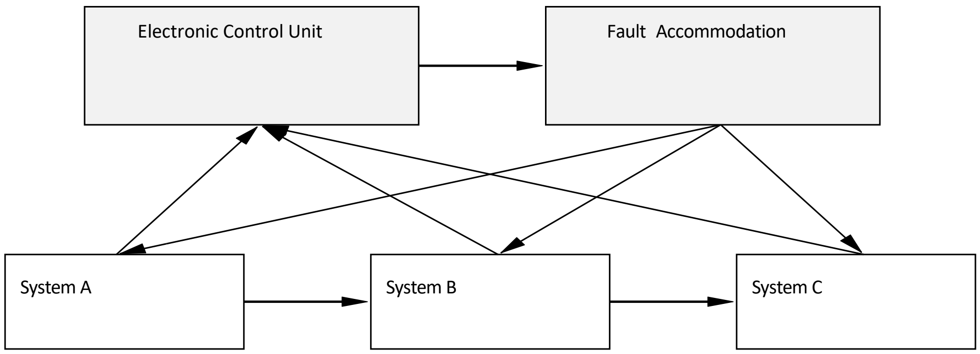

Figure 2: Centralized Architecture.

Advantages:

i. Simplified Management: Centralized control makes it easier to implement uniform security policies, system updates, and overall system maintenance.
ii. Data Consistency: With all processing occurring in one place, it's easier to ensure data uniformity and apply consistent fault-diagnosis algorithms.
iii. Lower Complexity in Design: The architecture's structure is straightforward, which can simplify system design and troubleshooting.

Disadvantages:

i. Single Point of Failure: If the central node fails or experiences downtime, the entire system's fault diagnosis and management capabilities can be compromised.
ii. Scalability Issues: As data volumes or the number of connected devices increases, the central server may become a bottleneck, impacting performance.
iii. Latency and Bandwidth Challenges: Transmitting large volumes of data from remote sensors to a central location can introduce delays and increase network load.

2. **Distributed Architecture:** Multiple ECUs share the diagnostic tasks, improving fault tolerance and reducing computational load on individual ECUs. This spreads the data processing and decision-making functions across multiple ECUs that are logically separated. In this architecture, ECUs may perform preliminary processing or fault diagnosis locally before forwarding refined information to other ECUs or a central controller when necessary. Therefore, for large scale automotive systems with functionality distributed over several ECUs, decentralized or distributed fault accommodation may be more appropriate in order to handle the inherent complexity and making the fault accommodation problem more tractable. (Nyberg

and Svärd 2010 a and b). Using this approach, the ECU, as well as the fault accommodation, is performed locally in a distributed manner, see Figure 3.

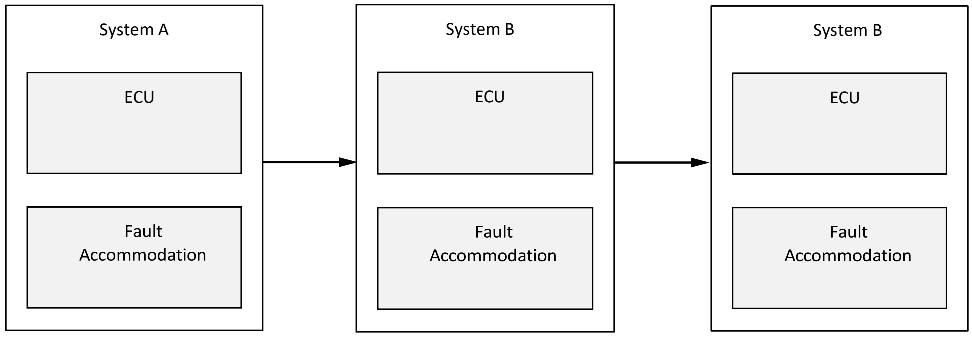

Figure 3: Distributed Architecture

Advantages:

i. Enhanced Fault Tolerance: With multiple nodes sharing the processing load, failure of one node has less impact on overall system functionality.
ii. Improved Scalability: Additional nodes can be added to handle an increased data load, which improves system responsiveness under high volume.
iii. Reduced Latency: Processing data near its source can provide faster responses to emerging faults, which is critical in time-sensitive environments.

Disadvantages:

i. Increased System Complexity: Coordinating and synchronizing data across multiple nodes requires robust communication protocols and can complicate system design.
ii. Data Consistency Challenges: Ensuring that all nodes maintain a synchronized and accurate view of the system may require complex consensus or replication strategies.
iii. Security and Maintenance Overhead: A distributed model often involves managing more endpoints, which can increase the challenge of securing and maintaining the entire network.

Summary Comparison

i. **Management & Control:**
Centralized: Easier to manage and update from one location.
Distributed: More flexible but requires complex coordination.
ii. **Fault Tolerance & Scalability:**
Centralized: Prone to bottlenecks and single points of failure.
Distributed: More resilient and scalable but demands sophisticated data consistency methods.
iii. **Performance & Latency:**
Centralized: May incur latency due to remote data transfers.
Distributed: Offers faster, localized responses to faults.

The above summary comparison shows the best choice depends on the specific requirements of the Fault Diagnosis and Management System application, including factors such as expected data volume, required response time, network reliability, and available management resources. For environments where reliability and real-time processing are critical (such as in safety-critical systems), a distributed approach may be favored despite its higher complexity, while simpler or smaller-scale applications might benefit from a centralized design.

5. On – Board Diagnostics (OBD)

The On-Board Diagnostics (OBD) is a computer system that can discover and diagnose problems with the data reported by the ECUs. If a problem occurs, the OBD system generates a trouble code that makes it possible for a service engineer to identify and fix the problem. Trouble codes and other diagnostic information can be accessed by plugging an OBD scan tool into the OBD interface in the automobile. (Abubakar et al, 2019). The different tools used in diagnosis are multimeter, oscilloscopes and engine analysers Diagnosis tools such as dedicated equipment that can break into the ECU wiring can be used. A further development could be the use of on-board diagnosis, with self-diagnosis circuits. The ECU monitors its inputs and outputs. This is done by both hardware circuits specially designed for diagnosis and programs for operating on the hardware signals. Signal ranges or values are allocated to all operating states of the sensors and actuators. If the signals deviate from normal, the ECU store's standard fault codes for both serious and minor faults. In case of serious fault, a warning lamp will also be illuminated to alert the driver.

Fault reading and erasing:

Faults can be read as two digit numbers by shorting the diagnosis wire to earth for more than 2.5 seconds but less than 10 seconds. Earthing the wire for more than 10 secs will erase the fault memory, as does removing of the battery. These codes can be read out and the test procedure corresponding to that code be followed for faultfinding. Often, if the fault is not detected again for 50 starts of engine, the ECU erases the code automatically.

Emergency / Default mode:

In case of certain system failure fault detected by hardware circuit, there will be an emergency mode, in which missing information is substituted with preprogrammed default values for safe operation.

6. Challenges and Limitations

Existing Fault Diagnosis and Management Systems face several challenges:

i. **High dimensionality of data:** The large number of sensors and parameters makes data processing and analysis complex.

ii. **Fault masking:** One fault can mask the symptoms of another, making diagnosis difficult.

iii. **Real-time constraints:** Diagnosis must be performed in real-time to ensure timely intervention.

iv. **Data security and privacy:** Protecting automobile data from unauthorized access is crucial.

7. Future Directions

Future Fault Diagnosis and Management Systems will likely incorporate advanced technologies, integrating these technologies will improve on the functionalities of Fault Diagnosis and Management Systems, some of these technologies include:

i. **Artificial Intelligence (AI) and Machine Learning (ML):** AI is revolutionizing the way computers process and analyze data. AI enables machines to learn, reason, and make decisions, mimicking human intelligence. It has applications in various fields, including finance, healthcare, manufacturing, and transportation, among others. AI systems can process vast amounts of data and identify patterns and anomalies, making them valuable tools for decision-making and problem-solving. AI technologies like machine learning and deep learning are enabling computers to perform tasks that were once thought to be the exclusive domain of humans, such as natural language processing, object recognition, and decision-making. AI is already being used in a wide range of applications, from self-driving cars to personalized marketing campaigns. AI and ML algorithms can improve fault diagnosis accuracy, enable predictive maintenance, and facilitate autonomous fault recovery.

ii. **Cloud-based diagnostics:** Cloud computing is a method of delivering computing services over the internet, providing on-demand access to a shared pool of configurable resources. With cloud computing, users can access applications, storage, and processing power without having to invest in expensive hardware and infrastructure. This technology has played a significant role in driving digital transformation, cloud computing can provide enhanced data storage, processing, and analysis capabilities. Cloud computing has made computing resources more accessible, flexible, and cost-effective. Its potential applications are vast, from data storage and backup to software development and testing. As cloud computing services continue to advance, we can expect businesses and individuals to rely on it more heavily in the future.

iii. **Integration with advanced driver-assistance systems (ADAS):** Fault Diagnosis and Management System can be integrated with ADAS to improve safety and enhance driver awareness. This will also improve the quality and accuracy of diagnostic information.

iv. **Internet of Things (IoT):** This is a technology that is changing the way we interact with devices. IoT refers to a network of physical devices, such as home appliances, vehicles, and wearables, connected to the internet and able to communicate with each other. It has the potential to transform how we live and work, enabling us to control and monitor our surroundings remotely. IoT has practical applications in energy conservation, healthcare, and transportation, making our lives more convenient and efficient. Integrating IoT with Fault Diagnosis and Management Systems, also like Artificial Intelligence and Machine Learning will improve diagnosis accuracy, enable predictive maintenance, and facilitate autonomous fault recovery.

8. Conclusion

Automobile Fault Diagnosis and Management System are critical for ensuring automobile safety, reliability, and performance. While significant advancements have been made, challenges remain in handling high-dimensional data, addressing fault masking, and meeting real-time constraints. The integration of AI, ML, and cloud computing holds immense potential for enhancing the capabilities of future Fault Diagnosis And Management System, leading to more accurate, proactive, and intelligent fault diagnosis and management.

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RACE: A Centralized Platform Computer Based Architecture for Automotive Applications Stephan Sommer∗, Alexander Camek∗, Klaus Becker∗, Christian Buckl∗, Andreas Zirkler‡ Ludger Fiege‡, Michael Armbruster‡, Gernot Spiegelberg‡, Alois Knoll† ∗fortiss

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