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Innovations in Electronic Control Units: Enhancing Performance and Reliability with AI (Revision-1)

Aravind Ravi, Chirag Vinalbhai Shah
Control Engineer
Sr Vehicle Integration Engineer GM,, United States,

Abstract
As the automobile industry moves toward greater efficiency, safety, and autonomous operation, the demand for Electronic Control Units (ECUs) - the microprocessors controlling everything from engine functions to infotainment systems - has exploded globally. Currently, there are more than 200 million ECUs in the world, and that number is expected to rise to 700 million by 2030, necessitating enhanced ECU performance, reliability, and safety. However, the growing complexity of ECUs has ironically led to increased false alarms and failures, which in some cases have endangered user safety and privacy, causing heavy penalties for manufacturers. Although artificial intelligence (AI) and machine learning (ML) are showing promise in addressing ECU-related issues, existing methods remain insufficient. Manufacturers need to employ AI-driven, end-to-end, standardized solutions that help design, train, test, and deploy models without deep AI expertise and allow real-time runtime monitoring and retraining of the ECUs.Drawing on decades of experience in the electronics and automotive industries, as well as a track record of successfully deploying AI-based solutions in safety-critical systems like avionics and diesel engine control, a comprehensive method is proposed. It includes an array of novel functionalities that increase transparency, reliability, and safety while keeping development times low. Central to the method is a feature that creates an environment-sensitive digital twin of the ECU by assimilating data from ECUs and the vehicle, thus improving model fidelity and monitoring for unforeseen edge cases. The proposal is based on co-design and training of AI-based perception and prediction models, which can monitor the relevant environmental parameters both on-board and in the cloud. The on-board model is lightweight yet deterministic and can trigger warnings in case of model uncertainty and prediction errors, while the corrective action is taken by the re-licensed cloud-based model. A dataset of more than 33 million kilometers of driving from passenger vehicles in Northern Europe with SaaStronic and Focus models has been provided, using compute-efficient methods for interpretation and simplification of AI-based models.

Keywords: Electronic Control Units (ECUs),Artificial Intelligence (AI),Performance Enhancement,Reliability Improvement,Automotive Electronics,Advanced Control Systems,Predictive Maintenance,Machine Learning Algorithms,Real-time Data Processing,Fault Detection and Diagnosis,Adaptive Control Strategies,Embedded AI Solutions,System Optimization,Smart Sensors Integration,Data-Driven Decision Making,Automation in ECUs,Robustness in Electronic Systems,AI-driven Performance Tuning,Self-learning Control Units,Next-Generation ECU Technology.

1. Introduction

Amidst the growing complexity in automotive systems driven by ongoing electronic innovations and the continuous increase in vehicle data volume, the Electronic Control Unit (ECU) stands out due to several key features, including its high reliability, designed structure, and ability to operate within specified conditions. The importance of ECU reliability is emphasized by year-long expectations of correct functioning when vehicles are on the road, often subjecting control strategies to a wide range of operating situations.On the other hand, with recent developments in Artificial Intelligence (AI) hardware architectures and the growing need for real-time performance due to the increase in vehicle computing units, new applications are possible to fulfill. For instance, the demand for more advanced driver assistance systems (ADAS) applications comes from the High-Performance Computer (HPC) implementing those systems with the "one brain" architecture. Applications including neural networks trained with perception data (cameras, radars, and lidar) need to be analyzed for their impact on ECU reliability. Furthermore, new initiatives from manufacturers and the road safety community aim to integrate Deep Learning (DL) models into safety-critical systems. This leads to a growing need for deep awareness of the risks related to a possible malfunction of DL systems, and the mitigation means to ensure reliability.

To investigate the possibility of detecting faulty events in systems based on fully connected Artificial Neural Networks (ANNs), which can rationally isolate malfunctioning components (weights and biases), a framework to facilitate this understanding and to develop anomaly detection methodologies is proposed. On the other side, the unintentional misuse of Information Technology (IT) in automobiles shall also be analyzed. Attacks frequently target the cybersecurity aspects as software is hackable and sensitive to corruption. However, with the increased use of data-based knowledge in road safety methods such as automotive control and ML/DL applications, the detection of data attacks aims to ensure the validity of the acquired knowledge. This is especially relevant with the upcoming introduction of Ethernet for real-time data transmission between components and additionally a reduced number of wire connections that increase bus vulnerability. As data logic can lead to hazards during networking operations in the wrong use case, this task intends to ensure the integrity of data assets in data-bus-based attack approaches. The oncoming use of the FLEXRAY bus in this respect is also analyzed.

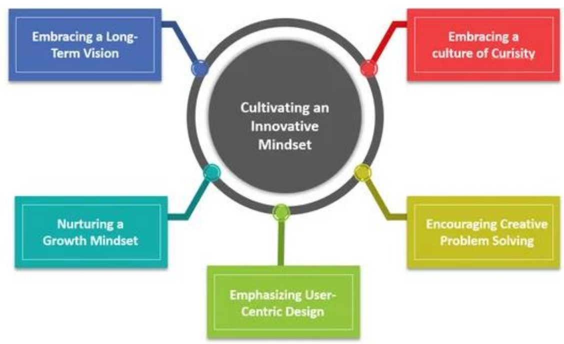

Fig 1 :Principles of cultivating an innovative mindset

1.1. Background and Significance

Innovations in electronic control units (ECUs) have become a focal point for researchers and engineers seeking to enhance the performance and reliability of vehicles equipped with diverse and complex computerized systems. Modern cars can hold more than 100 ECUs, which control safety-critical systems such as electronic stability programs, airbag deployments, and advanced brake control systems. By 2022, the number of ECUs in vehicles has reached an average of 126 units in Europe and is expected to increase to 170 by 2030. The growing number of ECUs also represents a growing number of controllers, sensors, and actuators, which are increasingly interconnected, leading to complex networked control systems.

As networked control systems (NCS) are designed and built to take advantage of numerous benefits like the reduced need for wiring and weight reduction, the number of potential threats is large and growing. For instance, complex ECUs take hours to develop their software, and sensors and communication links within the NCS development and design phases can either be faulty or behave unpredictably. Furthermore, as controller hardware in a loop (CHIL) systems are deployed, the artificial nature of the system can reveal other weaknesses, such as environmental sensitivity and cybersecurity. Cyber threats increasingly threaten control loops, as large amounts of data are sent over communication links. The availability of sophisticated tools for modeling, monitoring, and control enables parties with specific interests to manipulate the data flow in the NCS. If so, cyber threats may exploit the data links and gain potential control over the overall system, affecting safety-critical ECUs.Current legislation continues to increase vehicle regulation and safety standards. Consequently, the development of on-board electronic systems for vehicles has become time-consuming and costly. As autonomous driving continues to emerge, vehicles need to become safer and more reliable. Modern vehicles hold safety-critical computer-based systems that have a great deal of influence over the safety of the companions. A computationally enhanced unreliable ECU may lead to catastrophic events, causing fatalities and injuries. Consequently, there is a growing need for reliability in ECUs. Methods to promote reliability are desired to be embedded within the standard development lifecycle of software systems to be efficient.

1.2. Research Aim and Objectives

Electronic control units (ECUs), the "brains" of today's automobiles, receive inputs from various sensors, adjust the settings of associated actuators, as well as exchange information with other ECUs via internal communication buses. The increasing complexity of autos is the driving force behind the rapid growth in the number of ECUs and vehicle communication networks. However, despite the advantages offered by the use of multiple ECUs and the twin technologies of distributed computing and control, there exist significant drawbacks to these approaches. There are limits to the safety and reliability that can be attained by plural redundant ECUs, while a continued increase in the number of ECUs and data exchange transfers can lead to the saturation of communication buses. On the other hand, the success of global methods depends on the prior knowledge and the precise mathematical modeling of complex engine control units. Metamodeling methods possess the flexibility needed to model complex engine processes, which involve a large number of non-linear and always-changing partial differential equations with time-varying parameters. Artificial Intelligence is useful in modeling, validating, and estimating the effects of ignition, and can even be superior to explicit models in ferromagnetic hysteresis.

The overall aim of this research is to develop new techniques and applicable routines that will enable the use of advanced artificial intelligence methods for the optimization and control of complex Engine Control Units in the automotive industry. More specifically, the objectives of the proposed research are: to analyze why the traditional approaches of minimum or maximum control have proved to be incapable of handling the optimization and control of complex Engine Control Units; to identify the characteristics of optimal or near-optimal behavior and control in generic systems modeling like physical, biological, as well as man-made; to determine the most appropriate Artificial Intelligence methodology and technology for on-line adaptive modeling, optimization, and control of complex Engine Control Units; to develop new methods and applicable routines using advanced Artificial Intelligence techniques; and to demonstrate the viability and capabilities of the new approaches on a catalytic converter application of Toyota's Engine Control Unit.

2. Electronic Control Units (ECUs): Overview and Evolution

Electronic Control Units (ECUs) are key components in automotive and various industries that serve as the brain of a vehicle. They are designed to control various systems in a vehicle and ensure that these systems operate efficiently, reliably, and safely. With the rise of electric and autonomous vehicles, ECUs are gaining increasing importance, and their functionality is also rapidly evolving.

The increasing vehicle complexity, advancement of connected and automated driving, vehicle electrification, and the rise of new mobility concepts enable tremendous opportunities along with huge challenges for automotive manufacturers. Vehicles in the future will be controlled by a considerably larger number of Electronic Control Units (ECUs) that ensure safety, comfort, efficiency, connectivity, and real-time communication with other components and vehicles. They may also be equipped with more intelligent, highly sensitive, and accurate sensor systems mounted either on the vehicle or its environment. Such changes will make vehicles over one hundred times more complex than present vehicle generations. The most sophisticated vehicle functions will rely on numerous ECUs processing and communicating huge amounts of sensor data in real time; hence, the automotive electrical/electronic (E/E) architecture will be fundamentally redesigned. More and more vehicle functions require sensors and controllers for safety, comfort, and system enhancements, which leads to a steadily growing number of ECUs in vehicles. Additionally, safety and reliability requirements for these ECUs increase in parallel due to growing interdependencies of the system and safety-oriented functions on vehicle dynamics, such as the integration of braking and steering systems. The ongoing trend of mechatronic development is to control multiple functions with one common ECU. The evolution of ECUs in the automotive industry has tended towards centralized architectures with powerful computer units controlling various subsystems within the vehicle. This trend is faced with a dilemma: Emerging vehicle safety-related functions require systems on chip with high computational performance but at the same time high reliability, while recent technical developments allow for such computational units but have severe implications on system safety.The automotive industry is witnessing a significant transformation in Electronic Control Units (ECUs), driven by the complexities of modern vehicles and the advent of electric and autonomous technologies. As vehicles become more advanced, the number of ECUs is expected to increase dramatically, with future vehicles potentially containing hundreds of these units. This surge in ECUs is a response to the need for enhanced safety, comfort, efficiency, and connectivity, driven by sophisticated sensor systems and real-time data processing requirements. However, this evolution presents a complex challenge: while centralized architectures with high-performance computing units promise to streamline vehicle control by managing multiple subsystems, they also raise critical concerns about system safety and reliability. The integration of safety-critical functions, such as braking and steering, demands not only robust computational capabilities but also exceptional reliability, leading to a delicate balance between performance and safety. As the automotive sector continues to push the boundaries of mechatronic development, addressing these challenges will be crucial in shaping the future of vehicle E/E architectures.

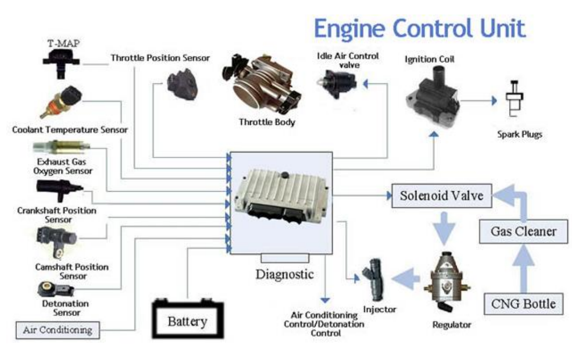

Fig 2 : Electronic Control Unit (ECU)

2.1. Definition and Functionality

Electronic Control Units (ECUs), the backbone of modern automobiles, comprise embedded systems designed to perform specific control functions.

These computerized devices play a pivotal role in various automotive systems, including engine control, transmission control, and driver assistance systems. The widespread adoption of ECUs in cars can be attributed to their ability to ensure efficient vehicle operation and enhance safety. Initially, single-function ECUs powered by 8-bit microcontrollers operated basic components such as Electronic Throttle Control (ETC) systems and Anti-lock Braking Systems (ABS). However, with the increasing demand for safety and comfort features, the automotive industry saw a surge in the number of ECUs, leading to the advent of multi-functional ECUs to optimize space and costs.

To meet the growing complexity of vehicle systems and ensure reliable operation amidst changing operating conditions, the development of more powerful microcontrollers became essential. Various functional blocks, subsystems, and peripherals were integrated into a single chip, giving birth to System on Chips (SoCs). The integration of ECUs reduced the number of external components, minimized communication latency, and enhanced the reliability of the design. Over the years, the automotive industry has witnessed continuous development and enhancement of ECUs to ensure the performance and safety of various automotive systems.The components of an ECU include Input/Output (I/O) interfaces, a central processing unit (CPU), memory, communication bus, power supply, and case. The software architecture of an ECU comprises the operating system and application software running on it. Input/output interfaces encompass sensors that collect information, such as temperature, speed, position, etc., affecting the control process. This information subsequently influences the corresponding actuators, such as valves and solenoids. With the increase in the number and complexity of ECUs in vehicles, protocols like CAN, LIN, and FlexRay have been developed to enable communication between different ECUs. A complex application, such as riding stability control, can be partitioned into several portions running on different ECUs. Furthermore, components like Integrated Circuit (IC) packaging technology have been developed to support high performance, reliability, and cost. The case protects sensitive parts from moisture, shocks, vibrations, dirt, and other harmful factors. ECUs play a crucial role in jungled space vehicle networks where mechanical deformations and temperature variations are severe.

2.2.Evolution of ECUs in the Automotive Industry

Originally designed to support their functions, control units were standalone devices with dedicated inputs and outputs. Each control unit controlled a dedicated vehicle function, such as the engine, transmission, brakes, or on-board network. With the growth of vehicle functions to be controlled, this one-function-one ECU concept led to the rise in the number of control units in a vehicle, which resulted in an overall overhead of multiple devices on the vehicle's architecture. These ECUs grew rapidly in complexity, combining a sizable computational capability with advanced software, becoming the most sophisticated devices of a vehicle, outnumbering in several aspects classic automotive devices, such as hydraulic systems, sensors, and actuators. The automotive industry was challenged to migrate these control units out of a broken paradigm assuming the hybrid cohabitation of electrical, electronic, and mechanical technologies and heavily depending on the mechanical dynamics of the chassis for a substantial proportion of driving tasks. This general context gave rise to the need for an evolution toward new types of electronic control units that would suit the most demanding use cases of autonomous driving.The evolution of automobiles is occurring in three complementary ways: an increase in vehicle functionality and served vehicle applications per vehicle; an increase in driving automation levels; and a shift from the conventional realm of driving up to partially and fully autonomous driving. ECUs ideally were envisioned in a multi-purpose design encompassing several vehicle functions and applications together with several processing cores integrated on a common chip. It was foreseen that early generations of such ECUs would support the vehicle's applications in safety-related and critical control late in the autonomous driving evolution path. A newer conception of ECUs, anticipated to be fully functional in the vehicle architecture, became multi-purpose units that controlled several safety-inherent vehicle functions and were also expected to support future vehicle applications in the domain of assisted and highly automated driving. Newer generations of ECUs were deemed inevitable, complementary to conventional ECUs, for pedestrian safety applications and low-speed driving tasks. As highly sophisticated and complex multi-sensor ECUs, these control units significantly differed from any legacy control unit, embodying a paradigm shift in the automotive industry.

3. Integration of Artificial Intelligence (AI) in ECUs

Integration of Artificial Intelligence (AI) in ECUs
Overview of AI in Automotive Systems
The automotive industry is undergoing a paradigm shift in vehicle architecture. The conventional paradigm embeds functionalities in several individual hardware distributed units, wiring nodes connected to a bus. Since ECUs are still hardware, they have limitations on cost, weight, and processing capabilities. Therefore, to cope with increasing functional complexity, higher computing power needs to be fitted into the existing architecture. The goal is to satisfy the pile-up of applications and safety constraints at affordable costs. Alternatively, centralizing processing in a single unit significantly reduces the overall system complexity and increases performance and reliability. However, complex algorithms cannot be run on the existing central units because of their limitations in terms of safety and performance. ECUs automating complex tasks are taking safety-critical decisions that require high reliability. ECUs play a key role in modern automotive systems, supporting advanced functionalities like assisted driving. With increasing complexity and demand for new features, middleware-based decoupling and a combination of model-based design and reuse architectures and application programming interfaces (APIs) can make it feasible to develop reshaping systems with future-proof safety architectures and high reuse capabilities. On the other hand, there is a growing interest in innovative engineering solutions, which combine novel computing architectures so that over-the-air updates are enabled.Integrating AI in ECUs transforms the ecosystem towards a new level of performance and enables smarter automated vehicles and mobility concepts responsive to stringent requirements on user comfort, safety, and sustainability. AI can enable enhanced perception and situational awareness with novel sensing concepts. Lateral control will go beyond the vehicle path following motion and will develop new intelligent integrated concepts that consider the broader context. Longitudinal and lateral control tasks will evolve jointly with new concepts. Exploiting the full potential of AI in vehicles involves developing novel approaches, concepts, and technologies to ensure that AI is safe, robust, reliable, explainable, transparent, and energy-efficient.

Benefits and Challenges of AI Integration in ECUs
To understand current trends and challenges with AI usage in automotive ECUs and actively shape tomorrow's technology, an automotive mindset is imperative. Essential investigative parameters are emerging new applications, the required accuracy of AI-based solutions, whether solutions for assistance or automation are intended, and the range of investigation. Model-based approaches might be pursued with processed sensor data or with raw sensor data. The acceptance of data-driven solutions greater than Level 2 automation might be difficult due to safety norms and liability reasons confined by complex transfer functions for MIMO systems.Safety becomes a growing issue with the

increased usage of AI-based solutions in ECUs because traditional safety concepts do not apply to AI. Reliability is paramount for the acceptance of AI-based solutions in ECUs and concerns on bias and discrimination are growing with increased reliance on AI inside ECUs. Clarity and explanation of AI's actions and decisions are fundamental for trustworthiness from a human acceptance perspective and must be addressed for the usage of AI inside ECUs. AI-based solutions usually require enormous training efforts depending on the complexity of the design space that must be explored and from huge amounts of training data the majority of which must be evaluated with processing resources.

3.1. Overview of AI in Automotive Systems

Artificial intelligence (AI), and its subset machine learning (ML), have begun to permeate everyday life. Up until now, AI has primarily made inroads in the consumer market. Voice recognition systems/devices like Amazon's Alexa and Google's smart speakers, video recommendation systems on platforms like YouTube, Netflix, and Hulu, graphical recognition systems on social media like Facebook and Instagram, and real-time translation devices like Apple's Siri have gained popularity. Other high technology-focused areas like the automotive sector are cognizant of the potential of AI, and major companies have invested in AI research and development.

The automotive sector has huge amounts of data that have been collected over decades through research and development jobs, mileage tests, production processes, warranty claims, and connected vehicles. Data-driven technologies have been leveraging these data through digital twin or metaverse concepts, including AI, ML, data analytics, and the Internet of Things (IoT), to enhance the productivity, performance, and reliability of both design, validation, manufacturing, and post-manufacturing processes.The expansion of AI/ML/IoT/big-data/data-hub technologies/infrastructure is dominating the broader economic sectors, but it permeated Economics-1 (Economics of Algorithm and Data) only a decade ago. However, the automotive sector has huge implications for this Economics (Economics-2), where automobiles, trucks, and SUVs would generate huge amounts of data. Moreover, many of the advanced operations of vehicles would be conducted automatically through sensors and controllers, which in turn would send huge amounts of data to the data hub (cloud/edge network).Thus, the aim of an AI/ML/electronic control unit (ECU) is to enhance either the design & development, validation, manufacturing, or after-manufacturing processes. ECUs are hardware components that can process data, previously designed to sense and control mechanisms (actuators, motors) through data communication with other ECUs and units (sensors). Later, the fuzzy-logic, neural-networks-based AI was implemented, which analyzed past data for decision-making, controlling mechanisms, etc. In the recent past, deep learning (DL) based AI, and its algorithms with huge data requirements are being implemented.

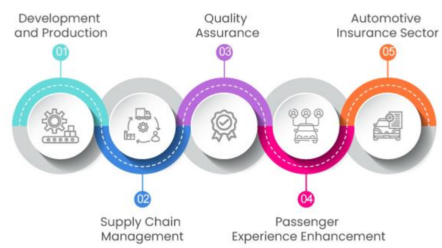

Fig 3 : AI in the Automotive Industry

3.2. Benefits and Challenges of AI Integration in ECUs

Embedding artificial intelligence (AI) components into electronic control units (ECUs) is making automotive systems more intelligent, responsive, and proactive to driver behavior. The complexity of evaluating different aspects of road conditions, drivers, accidents, and miscellaneous environmental issues including weather—while controlling vehicle functions such as steering, acceleration, and braking—calls for innovative ways to handle these challenges. These challenges can be implemented using AI components for ECUs, in addition to the traditionally followed rule-based expert systems (RES). Various AI approaches are being actively researched for use in driving assistance systems and with applications in the automotive domain. The main aim of these AI approaches is to augment the intelligence of the driving assistance system so that the vehicle is planted more securely on the road with improved performance and at the same time ensuring enhanced safety for the driver and his fellow passengers.Due to their proven performance, implementation feasibility, and robustness, techniques based on artificial neural networks (ANN) and fuzzy logic (FL) have become widely popular and are actively researched methods of AI, especially for applications in the automotive domain. Descriptions of these two AI approaches are provided, both as individual entities and in hybrid combinations. These hybrid combinations are seen to have the advantages of reducing computational costs and improving efficiencies over the conventional approach of using ANNs or FL individually. Research issues that must be addressed to broaden the area of application of this approach are also discussed.The integration of artificial intelligence (AI) techniques into traditional vehicular architectures, such as electronic control units (ECUs), enables next-generation advanced driver assistance systems (ADASs). These onboard AI techniques allow ECUs to sense, interpret, and react proactively to diverse driving situations and conditions. Developing such intelligence systems significantly augments vehicle safety, improves road traffic control, and enhances the vehicle driving experience. In addition, such intelligence systems may lead to the popularization of a new type of vehicle: autonomously propelled vehicles, which drive without any intervention from a human.

4. Innovative Applications of AI in ECUs

As electronic control units (ECUs) proliferate in vehicles, so do their related issues, including more frequent and severe failures. One promising approach to addressing these problems is the use of artificial intelligence (AI) for innovation, which can create value for the companies that adopt it and reduce their vehicle failures. Several applications of AI can enhance the performance of ECUs, thereby increasing their reliability. However, there is a need to review the recent innovative applications of AI in ECUs.

Many researchers have been examining how to enhance the performance of ECUs through various innovative applications of AI. As a result, a lot of AI applications have been developed in recent years. However, there are still some novel areas where the use of AI applications can enhance performance that have not been studied by others. AI can be applied to ECUs in both hardware and software aspects. First, considering the hardware aspect, the application of AI in ECUs regarding fault detection within the safety-critical areas. Second, considering the software aspect, several novel applications of AI in subdomains such as fault tolerance, predictive maintenance, and secure communication of ECUs have been discussed.

Various faults arise in ECUs due to the complexity of ECUs associated with advanced vehicle applications, the use of cheaper components, increased temperature, and increased chance of electromagnetic interference. As the number of ECUs in vehicles increases, the cost incurred for repairing faulty ECUs increases. So, several methods have been developed to detect faults in ECUs. Many of them are based on historical data, and this may not be enough to detect faults. New methods for detecting faults have been developed and are based on new knowledge. These innovative applications of cutting-edge AI techniques concerning the safety-critical areas of vehicles enhance fault detection and performance improvement. ECUs play an important role in autonomous driving systems for vehicles, and they are responsible for strengthening the computing and communication capabilities of vehicles.

Roads are becoming increasingly congested and dangerous. Thus, new solutions are needed to relieve traffic and improve security. Self-driving vehicles are evolving technologies that may provide new solutions to such problems. Several prominent companies have been investing in self-driving vehicles and their solutions. In autonomous driving systems, many cutting-edge AI techniques have been developed to detect surrounding objects accurately. Often a combination of several approaches is used to achieve the highest perception of quality, especially in complex environments. AI techniques such as deep learning and neural networks have attracted extensive attention. These intelligent techniques enhance perception performance while reducing computing resources dramatically. ECUs play vital roles in interpreting the data from various sensors, communicating with other ECUs, controlling the actuation, and ensuring the safety of the overall systems in autonomous vehicles.

4.1. AI for Predictive Maintenance

Artificial intelligence (AI) has become an indispensable tool for unlocking the full potential of Industry 4.0. With its promise to ensure reliable performance, increased revenue, and reduced costs, AI systems are becoming commonplace across numerous industries. In particular, AI-based predictive maintenance solutions have gained traction as a means of maximizing the potential of Condition Monitoring (CM) systems implemented in plants by addressing their main limitations, such as noise sensitivity, reliance on expert knowledge, and the need for plant shutdowns before predictive maintenance actions. The advancements of smart sensors in electronic control units (ECUs) are a step towards improved device reliability.

The ongoing CityPeg Project aims to widen the utilization of AI-based predictive maintenance solutions for ECUs. A proposal for an all-in-one predictive maintenance solution is presented, which includes regression-based remaining useful life predictions, fault classification, and clustering approaches to support knowledge augmentation with the main objective of improved reliability of the ECUs considered in electric drives for rail traction. A first step towards such a solution is made by implementing remaining useful life (RUL) predictions applied to an imperfectly mounted strain gauge sensor in ECUs using Auto-Encoders and Long Short-Term Memory Neural Networks. A proposal for the integration of the predictions within ECU applications for decision-making is presented and demonstrates the growing ability of AI-based solutions beyond the domain of data scientists.An exploratory analysis of CM data is performed to illustrate how clustering can support the augmentation of operational knowledge. The intelligent use of condition monitoring (CM) data from ECUs resulting from new vehicle generations equipped with smart sensors offers an opportunity for improved reliability predictions. Three research topics are tackled to cover the main challenges of utilizing AI approaches with a focus on exploring opportunities regarding reliability improvements of ECUs. The topics cover non-expert-friendly AI-based monitoring methods to support low-cost implementation of CM systems by vehicle manufacturers, real-time interpretable model implementations for ECU applications, and opportunities for predicting design faults or weaknesses based on CM data from ECUs of multiple vehicle generations.

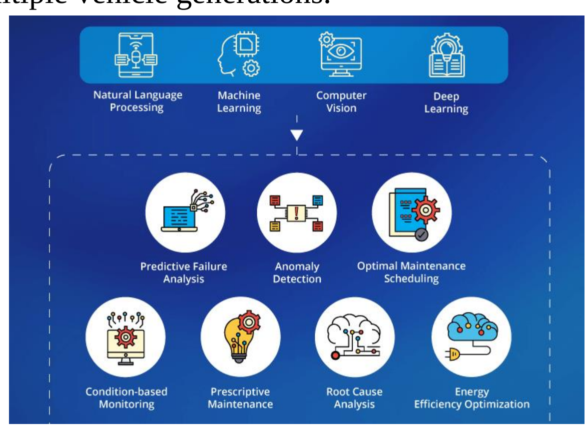

Fig 4 : AI in predictive maintenance

4.2.AI for Autonomous Driving Systems

In the pursuit of developing fully autonomous vehicles, OEMs and system integrators are deploying advanced features for high-level automation. Several of these features rely on machine learning-based perception algorithms, which rely on sensor data and are executed in high-performance electronic control units (ECUs). As a result, a new class of vehicles is emerging: smart vehicles with a high-capacity data backbone, cloud connectivity, and a growing number of networked systems of sensors and ECUs. This trend introduces new possibilities and challenges in terms of performance, cost, and cybersecurity risk for automotive embedded networks. Enhancing and possibly hardening the deployment and execution of data-intensive, machine-learning-based applications in a smart vehicle's electronic architecture is critical.

Machine learning (ML) techniques, especially deep learning (DL), have gained considerable traction in recent years and are becoming the dominant approach for processing sensory data in situations where the availability of physical models is highly limited. However, automotive ECUs traditionally rely on programmable logic arrays (PLAs) for the deployment of safety-oriented, deterministic, and hard real-time SP applications. Unfortunately, automotive-grade silicon architectures do not support the effective deployment of ML-based algorithms due to a significant mismatch between the desired and provided computational capabilities.

In this context, the challenge of driving the evolution of smart vehicle architectures is examined by addressing all relevant aspects of the application, data routing, and ECU hardware level, and outlining a small vehicle sensory and ECU configuration. State-of-the-art automotive-grade ECUs are asked to deploy data-intensive, classifier-based, machine-learning-driven, intelligent driving applications. A methodology is proposed to explore the architectural requirements and bounds on the performance of the application and the viability/sustainability of the vehicle sensory/ECU topology. The performance of sample ML-based ECUs is analyzed and categorized into the following: dominantly off-vehicle driven; additive latency; complex topology; disruptive; and unacceptable risk. Finally, there are noteworthy implications at the application, network, and ECU hardware level that drive the evolution of the smart vehicle electronic architecture.

5. Case Studies and Examples

Electronic Control Units (ECUs), the intelligence behind automotive systems, have evolved from simple mechanical controllers into complex digital microcontroller-based devices. With the growing desire for safety, comfort, and autonomous capability, automotive manufacturers have started to implement more advanced and computationally demanding applications, relying on ECUs and onboard system connectivity. However, the increasing number of ECUs can lead to unwanted complexity and undesired electronic system behavior, hence the design challenge is fueled by the competing requirements of increasing capabilities, declining costs, and the assurance of the ECUs' safety and robustness. This is especially relevant for systems involving an increasing number of safety-critical and real-time applications, such as Advanced Driver Assistance Systems (ADAS) and automated driving.Artificial Intelligence (AI) refers to either the imitation of human methods of thought, behavior, and learning or the development of methods that simulate human capabilities on a machine. In the automotive domain, the fields of AI of interest concern either the simulation of human perception, cognition, or driving actions—typically on very complex on-board simulation systems—or the attempt to imitate human capabilities in the development of the control laws to govern safety-critical functions by control laws typically on-board on the vehicle (e.g., automated speed adaptation, lane keep assist).The deployment of onboard AI in vehicles is currently enabled by the introduction of new powerful Auxiliary Processing Units (APUs) (e.g., NVIDIA Orin and Pegasus), enabling the execution of complex AI functionality on a low latency basis. However, complying with automotive safety standards—such as the umbrella standard ISO26262—is still an open challenge for deploying AI methodologies on board. The main challenge is the establishment of a systematic approach for the rigorous safety assessment of these methods.

On-board AI has been successfully deployed in non-safety-critical applications such as enhanced user experience (e.g., fraud detection, CCTV audio detection) or vehicle optimization (e.g., traffic outlier detection, predictive navigation). Safety-relevant applications have also been presented, but they are using off-board AI methods, which typically imply a less stringent safety approach (e.g., retraining the model based on driving data collected offline), consider reduced geographical and temporal horizons (i.e., evaluated on a reduced number of miles post-deployment), or assume less catastrophic consequences of a wrong decision (e.g., at most a safety of life detrimental consequence).

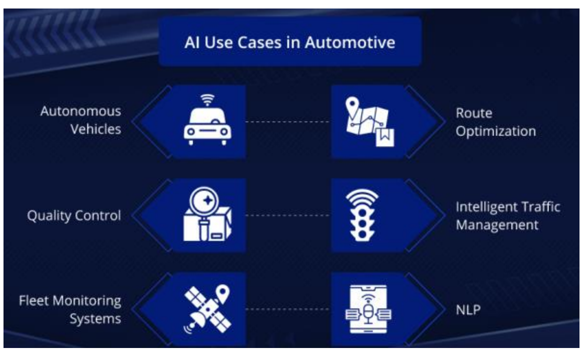

Fig 5 : AI in automotive: cases, technologies

5.1.Real-world Implementations of AI in ECUs

The merging of artificial intelligence (AI) with advanced automotive Electric Control Units (ECUs) is one of the pioneering trajectories of automotive architecture. There is a rising trend to deploy advanced AI models, such as deep learning techniques, that facilitate the extraction of information from unlabelled data. This allows for the identification of complex and non-linear relationships in sensor data, which may lead to performance and reliability enhancement. Conversely, those approaches lack the traditional signal processing model interpretability. As a result, explanatory capabilities for its decisions are often missing. In this domain, the reader will learn about two real-world examples of AI-based applications in automotive ECUs following different methodologies for data post-processing/model extrapolation.

AI in Engine Management Systems: Closing the Loop

The development of a signal model-based residual generator that determines the health indicators of an automotive air-fuel ratio (AFR) sensor is presented. This component is used in the on-board diagnosis of automotive engine management systems. The functionality is validated in a hardware-in-the-loop (HIL) setup for a turbocharged diesel engine. The ongoing operation point of the engine is subjected to real-world variations, such as load transients, road load disturbances, and noise from the actuators. Nevertheless, the closed-loop regulation of ECU-controlled manipulated variables is ensured with an output feedback controller. In these scenarios, the performance of a state-of-the-art machine learning-based residual generator is compared to the signal model-based approach to check the explainability and robustness of both methods against driver-induced events. Preliminary results show that the signal model-based solution can determine a meaningful health indicator of the AFR sensor under closing-the-loop conditions, while the signal-free approach collapses during transients.AI in Automotive Data Assessment: Fitting the Data-Driven-Machine Learning Model

A data-driven methodology using AI-based techniques to evaluate and classify real-world trips collected on vehicles is proposed. The novel approach deploys data clustering algorithms applied to the variables available in the analysis at different maturity levels of data post-processing. Further assessment of the clusters is performed by applying self-organizing maps (SOMs) that facilitate the identification of the most relevant data and the indication of reasons behind misbehavior or undesired effects of the ECUs. Robustness and detailed insight into the assessment results are guaranteed with a predefined workflow that includes several automatics and supervisory analyses. Moreover, the developed strategies for the automatic analysis of the data allow for on-demand assessments of large batches of trips. The combination of the developed classification algorithms with outlier detection strategies alleviates the burden of dedicated online personnel.

The application of AI-based data clustering techniques on raw data acquired from the vehicle was successful and revealed meaningful information about the trips or driving patterns under consideration. That approach can be used in data analysis for various purposes, such as specifying requirements for model validation extensively or PCA for data characterization with a mathematical basis. In the latter case, the identification of the most relevant variables for the analysis arises as a byproduct.

6. Conclusion

The increasing complexity and capabilities of automotive applications and the growing demand for electric vehicles (EVs) offer new avenues for innovation. In this context, artificial intelligence (AI) has gained prominence as an enabler for innovative functions and applications. Broadly, AI comprises several methods that combine data knowledge with real-time computation. Its architecture typically includes multiple sensors for "perception," control algorithms and actuators for "decision," and feedback loops for "learned improvement." Crucially, reliable data—preferably high-quality and diverse, consistent in time and space, and preferably linked to physical models—is key to successful AI integration.

Automotive control includes various domains, with electronics playing a pivotal role, spearheaded by Engine Control Units (ECUs). Vehicle ECUs are typically distributed across the vehicle, comprising millions of lines of software and dense physical wiring. Conventional development, verification, and qualification efforts focused on hardware, software, and reliability have proven effective for existing functions but are less suited to upcoming safety-critical functions leveraging AI. Notably, this refers to the combination of even slightly modified functions and deployment in safety-critical domains, such as autonomous driving or automotive power management. AI-type ECUs would filter sensor data such as camera and lidar but would need to be highly reliable, deterministic, and responsive, posing engineering design challenges similar to those faced by existing safety-critical functions.In the coming years, it is expected that automotive electronics will assure freedom from interference in safety-critical domains to ensure performance and reliability. Innovation potential is enormous, with opportunities encompassing the entire design stack, from sensors to algorithms and hardware. High-quality data sets derived from physical models, filters, and multiple sensor types would provide the groundwork for AI-based functions. In terms of algorithms, on-vehicle complementarity of AI and engineering models, explainable AI, and rigorous assurance methods can be envisioned, with applicable algorithms hitherto largely unexplored. Remarkably, using novel hardware approaches such as new architectures, high-performance components, and new processing designs, hopes are harbored for extensive changes in functionality and performance beyond mere AI integration.The increasing complexity of automotive applications and the surge in demand for electric vehicles (EVs) are driving significant innovation, with artificial intelligence (AI) emerging as a key enabler of advanced functionalities. AI integrates various methods to enhance vehicle performance, involving multiple sensors for perception, control algorithms for decision-making, and feedback loops for continuous improvement. The successful integration of AI hinges on the availability of reliable, high-quality, and diverse data that is consistent over time and space, ideally linked to physical models. As automotive control evolves, traditional Engine Control Units (ECUs) are being challenged by new safety-critical functions that leverage AI, such as autonomous driving and advanced power management. These AI-driven ECUs must filter complex sensor data like camera and lidar inputs while maintaining high reliability and responsiveness. This shift necessitates a transformation in the development and assurance processes, extending beyond conventional hardware and software approaches. Future innovations will likely span the entire design stack, from sensors and algorithms to novel hardware architectures, with a focus on integrating AI with engineering models, developing explainable AI, and exploring new processing designs to enhance vehicle functionality and performance.

6.1. Future Trends

Innovation and advancement in Electronic Control Unit (ECU) technology have progressed hand-in-hand with the development of vehicles for over four decades. This has taken place alongside the growth in electrical/electronics architecture, driveline complexity, functional requirements, and quality expectations. In this constantly changing landscape of vehicle electronics and all of its components, the ECU is very much central to the entire construction of a vehicle. For almost all vehicle functions, the ECU either contains or supports an associated hardware or software component. In recent years, the arrival of new vehicle technologies and requirements has posed multiple challenges for ECU vendors and manufacturers, who must continuously adapt and respond. Such complexity has implications across the entire production chain, from design to manufacturing and testing to supply chain and after-market. Innovations in the design and production phase (e.g., system integration, hardware/software co-design, EDA/CAM tools) as well as in the after-market (e.g., maintenance, diagnostics, repair) have been and still are required to improve competitiveness and ensure achievement of state-of-the-art products. A recent trend in this context is the use of Artificial Intelligence (AI) in various ECU-related activities, such as software generation, architecture design, pattern recognition, data analysis, knowledge representation, etc.The future trends in ECU innovations are influenced by the evolution of vehicles and vehicle electronics. The major upcoming trends, many already foreseen today, are acknowledged. The drastic evolution of vehicle electronics in every aspect will continue for at least two decades. Architects, designers, and engineers will have to develop new vehicle/ECU concepts that take full advantage of this development, especially regarding the introduction of new technologies such as ASICs. The potential arrival of completely electric or hybrid vehicles would cause a paradigm shift in the overall ECU approach, moving the focus from single dedicated electronics to distributed heterogeneous ECUs/supervisors. Furthermore, the spiral progression of complex cyber-physical systems will continue with intelligent vehicles, and vehicles with Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I).The high level of electronics and the vast number of ECUs imply the need for stringent safeguarding against erroneous behavior due to malfunctioning software, hardware, or sensors. This is further complicated by the use of wireless services. Current approaches mainly focus on safety, but there is an upcoming need to develop security measures as well to counter hidden/stealthy malfunctioning or attacks that can assure access to control the vehicle. Implementing secure ECUs will be a major challenge for both the OEMs, as well as for the software and hardware companies. At the same time, the embedded software of automotive ECUs is increasingly being developed concerning certain safety standards. Modern automotive safety standards define high-level safety goal objectives that have to be met using a concept of safety 'hurdles' of increasing safety integrity levels. Safety requirements need to be allocated to the system using safety techniques and mechanisms. This results in costly system re-design and increases the difficulty and cost of verifying the correct implementation and effectiveness. Although the allocation of safety requirements to the system is critical in ensuring safety, it is not specified or addressed in the existing standards.

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