Electrical Systems in Autonomous Vehicles: A Comprehensive Study

[1]**Mohaimen Q. Algburi,** [2]**Ayman N. Muhi,** [3]*****Mustafa Ghanim**

[1,2,3]College of Communication Engineering, University of Technology- Iraq
*Corresponding Author's E-mail: mustafa.g.rzooki@uotechnology.edu.iq

Abstract - **Technological advancements and the adoption of innovative ideas have simplified our lives. We have witnessed this development in all sectors, including transportation, manufacturing, and technology. The entire transportation network is evolving towards artificial intelligence. One of the most important components of future smart cities is intelligent mobility for autonomous vehicles. This emerging topic has attracted significant attention, but it is still in its early stages and requires careful research and solutions to potential problems and possibilities. This research paper addresses the present state of two major parts of an autonomous vehicle system: (1) electrical and electromechanical systems; and (2) smart vehicle sensors. Such systems include a broad spectrum of technologies, including high-resolution sensors (LiDAR, radar, and cameras, etc), high-performance computing platforms to make real-time decisions, and accurate electromechanical actuators to steer, brake, and propel. Moreover, the electrification of self-driving cars introduces new issues of power management, energy efficiency, and thermal control, especially as computing demands are increasing. Electrical systems are a critical research and development area because well-coordinated interaction among sensing, computing, and actuation is critical to the realization of robust autonomy. This paper provides a systematic review of the current electrical systems in autonomous vehicles, discusses how they are integrated into the overall vehicle architecture, and identifies some of the emerging trends that will shape the future of autonomous mobility.**

Keywords: Autonomous vehicles; Sensors; Electrical systems; LiDAR; vehicle-to-everything (V2X).

I. INTRODUCTION

The future of transportation and mobility has been transformed by autonomous vehicles (AVs), which have quickly moved out of the realm of science fiction and into prototypes. Their development can be generally divided into six levels (0–5) of driving automation, which are established by the Society of Automotive Engineers (SAE) [1], as illustrated in Figure.1 The simplest driver-assist systems were

adaptive cruise control, lane-keeping assistance, and parking aids, which were included in vehicles at the earliest stages. Gradually, more advanced systems were developed, which could conduct conditional automation in a certain environment, leading to the development of fully autonomous vehicles that do not need any human control. This change is motivated by the development of sensing technologies, computing power, and artificial intelligence, but fundamentally, autonomy is made possible by the smooth combination of electro systems, complex systems of electronic, electrical, and electromechanical components that process perception, decision-making, and actuation [2]. Table 1 Details of the levels of driving automation.
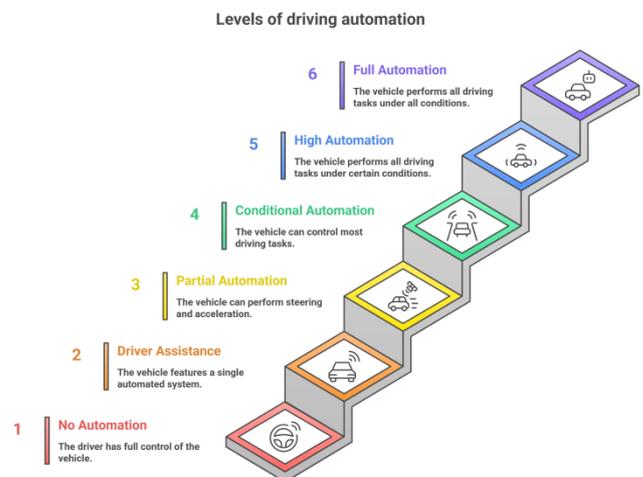

Figure 1: The levels of driving automation

AVs rely on electro-systems to provide the foundation of autonomy through the connection of the physical and digital worlds of the vehicle. In the awareness layer, a lot of sensors, such as LiDAR, radar, and high-resolution cameras, gather a lot of real-time data about the environment [3, 4]. This lets the car see things, understand how traffic is moving, and guess how other people will act. These sensors should be synergistic in operation using sensor fusion methods to deliver reliable and redundant data to support safety-critical functions. After the data is collected, the information is processed with the help of powerful electronic control units (ECUs) and high-

performance computing platforms, utilizing advanced algorithms, such as deep neural networks, to recognize objects and plan trajectories [5]. The results of decision-making are further converted into accurate actuation commands through electric steering, braking, and propulsion systems. These fundamental functions are supported by modules of energy management that provide sufficient power to both high-computation processors and electromechanical actuators with efficiency and thermal stability [6].

Electromechanical systems are not only significant in their fundamental operation, but also in their facilitating reliability, safety and scalability. One such area is the drive-by-wire systems, where mechanical links are substituted by hybrid electronic signals, which are quicker and permit more flexible vehicle designs [7]. Similarly, distributed electrical networks may be designed to accommodate redundancy and fault tolerance, such that autonomous functions may be maintained even in the case of hardware failures. The industry is moving to fully electric and autonomous vehicles, which is putting more strain on electro-systems, requiring higher bandwidth communications, higher computing density, and more efficient power distribution. Future technologies such as domain controllers, solid state LiDAR, neuromorphic computers, and vehicle-to-everything (V2X) communication are transforming the manner in which electromechanical systems are interconnected and constructed [8].

The purpose of this review paper is to offer a detailed analysis of electrical systems in autonomous vehicles, their current status, integration issues, and new developments. It starts by examining the architecture of such systems, pointing out the technologies that enable perception, computation and actuation. It then talks about power management and communication systems that facilitate dependable autonomous operation. Furthermore, the article discusses the latest developments and areas of study that will shape the next generation of electrical systems. It focuses on making autonomous transportation safer, more efficient, and more sustainable. This review can be used by researchers, engineers, and policymakers to achieve safe and intelligent autonomous transportation by consolidating the developments in these areas.

Table 1: Shows the levels of driving automation in detail

Level	Name	Controls	Automation Scope	Driver Role
0	No Automation	Human driver only	No automation	Full control of steering, braking, etc.
1	Driver Assistance	Human driver + single assist	Assists with either steering or acceleration/braking	Must monitor and stay engaged
2	Partial Automation	Human + vehicle combined	Controls steering and speed simultaneously	Must keep hands on wheel & monitor road
3	Conditional Automation	Vehicle in limited conditions	Handles driving in specific scenarios (e.g. highway)	Must be ready to take over if needed
4	High Automation	Vehicle mostly	Fully drives itself in geo-fenced or controlled areas	No driver needed in these areas
5	Full Automation	Vehicle always	Drives everywhere under all conditions	No driver required at all

II. RELATED WORKS

The electrical systems of self-driving cars have been the subject of numerous reports recently due to advanced technology and new ideas that help make them smarter and more efficient. The author in [9] examines the overlap between Artificial Intelligence (AI) and AV safety, and it performs a systematic literature review synthesizing the results of 59 studies. This in-depth discussion shows how AI is central to the safety of AVs by making better decisions and interpreting the environment. Nevertheless, it also highlights the risks that are inherent in the malfunctioning systems, which is why continuous research is necessary to reduce the possible risks. The topic of increasing scientific understanding of autonomous driving technologies is covered in [10]. By using a multidisciplinary strategy to uncover and synthesize latent information across wide study domains, this issue is resolved. The suggested approach offers a succinct and thorough summary of the conceptual organization of the

autonomous vehicle (AV) research area by combining subject modeling techniques with citation-based community finding methods. The authors in [11] make contributions to the literature by addressing the verification and validation (V&V) of Self-driving Autonomous Vehicles (SAVs). Their coverage-based testing approaches systematic review shows that the industry is paying more attention to safety assurance and consumer confidence in SAV technology.

The published works provide a broad and varied perspective of autonomous electric vehicle systems, which are innovative in design, advanced algorithms, and commitment to sustainability. These articles contribute to our knowledge of the issues and opportunities in this area, which will lead to additional research and development of autonomous transportation systems. Further literature related to autonomous vehicles is illustrated in Table 2.

Table 2: Comparison of the latest published literature on autonomous vehicles

Ref. no	Year	Contribution	Challenges/Limitations
[12]	2020	Analyzed AV accident/disengagement reports; categorized safety causes and reviewed mitigation strategies.	Majority of accidents are still in autonomous mode; limited reaction to unexpected human-driven behaviors.
[13]	2021	Reviewed AV-enabling communication technologies across ranges (Bluetooth, DSRC, 5G, etc.) with latency, range, and application scope.	Integration challenges due to variable latency and coverage; lack of unified communication standards; security vulnerabilities.
[14]	2021	Quantified weather effects on major AV sensors (LiDAR, radar, camera, GNSS); proposed simulation models for realistic perception testing.	High error rates in dense fog, snow, and rain; lack of universal models for sensor degradation under diverse conditions.
[15]	2023	Comprehensive review on perception enhancement, sensor fusion, and weather classification under adverse weather for AVs.	Sensor degradation in rain/fog; lack of diverse training datasets; limited robustness of 1550 nm LiDARs.
[16]	2024	Surveyed the emerging challenge of SOTIF in AVs, emphasizing validation strategies, ISO 21448, and functional insufficiencies.	Uncertainty in AI decisions, poor interpretability, lack of verification tools for unknown unsafe conditions.
[17]	2025	Proposed a transformer-enhanced federated learning-based ID with dynamic feature fusion and adaptive model weighting for CAN bus security.	Heterogeneity in node data distributions; need for low-resource deployment; challenges of real-time model adaptation.
[18]	2025	Systematic review of FDD, risk assessment, and resilience frameworks; suggested future solutions like verifiable ML and digital twins.	Scarcity of cross-layer fault modeling and scenario-driven datasets; lack of formal methods for ML verification.
[19]	2025	Developed a VR-based multimodal interface for AV teleoperation with haptic feedback to enhance safety and human trust.	Latency, operator cognitive overload, and scalability of the system across heterogeneous vehicle platforms.
[20]	2025	Enhanced ROS-based ADS with adaptive PID and metaheuristic path planning validated in chicane scenarios.	Real-time integration issues for optimization algorithms; dependency on fine-tuned sensor calibration.

III. SYSTEMS IN AUTONOMOUS VEHICLES

There are two systems in autonomous vehicles:

3.1 Electromechanical Systems in Autonomous Vehicles

AVs rely on electromechanical systems to enable the vehicle to communicate with the physical world. These systems combine electrical control and mechanical motion to allow fine control of many components necessary to achieve autonomy [22]. AVs involve the use of electromechanical systems to substitute or supplement the conventional human-operated systems. As an example, electric power steering (EPS) removes the mechanical steering column, and instead software can control the steering of

the vehicle using sensor feedback. Similarity, electronic brake-by-wire systems substitute hydraulic connections with electronically managed actuators, which allow smooth, adaptive braking in reaction to real-time traffic situations [23].

On the other hand, advanced AVs are based on electromechanical sensors and actuators to control their motion. The central controller is fed with data by LIDAR, radar, and ultrasonic sensors and directs actuators to perform such tasks as lane-keeping, obstacle avoidance, and adaptive cruise control. Also, active suspension systems can change the ride height and damping according to the road conditions, enhancing the safety and comfort of the passengers [24]. The replacement of conventional mechanical systems with electromechanical solutions has many benefits, such as reduced weight, higher reliability, and packaging flexibility, enabling their integration with more sophisticated control algorithms and AI-based decision-making technologies that are needed to operate fully autonomously. Moreover, the electromechanical systems are simpler to monitor and maintain by diagnostics and predictive maintenance, enhancing long-term safety and efficiency [25]. Wiring technologies remove a lot of the failure-pronecomponents, allow redundancy, and are increasingly compatible with digital control architectures, which makes them a pillar of autonomous mobility.

3.2 Electrical Systems in Autonomous Vehicles

The electrical systems of AVs are the nervous system, which powers, connects and coordinates all subsystems required to operate autonomously [26]. They provide the necessary power to the onboard electronics, sensors, computing platforms and communication modules, which are integrated without any issues. It focuses on high-voltage power distribution systems, which are usually based on advanced battery packs or hybrid powertrains [27]. This system delivers energy to electric propulsion systems, drive-by-wire systems and other modules on board. In addition, the peripheral devices, infotainment, and redundant safety circuits are powered by the low-voltage systems (12V/48V). A sensor suite of an AV Lidar, radar, cameras, and ultrasonic sensors is highly sensitive to a stable and noise-free electrical supply [28, 29]. These sensors are constantly feeding information to the central electronic control unit (ECU) or high-performance domain controllers that run machine learning algorithms to do perception, decision-making, and control. Also, electrical redundancy and fail-safe systems are significant in AVs to provide reliability. To provide backup in case of primary system failure, backup power supplies are used to power critical functions e.g. braking or steering [30]. Thermal management systems also make sure that batteries and processors are not overheated and are at the correct temperatures [31].Table 3. shows a comparison of the main differences between electrical and electromechanical systems in AVs:

Table 3: Comparison of electromechanical and electrical systems in Avs

Aspect	Electromechanical Systems in AVs	Electrical Systems in AVs
Primary Function	Convert electrical signals into mechanical motion (actuation)	Provide power, communication, and control for all vehicle electronics
Examples	Steering actuators, brake-by-wire, active suspension, drivetrain mechanisms	Battery packs, power distribution, ECUs, communication networks
Interaction	Directly interacts with the physical environment (steering, braking, moving parts)	Supports all electronic components and data processing
Control Input	Controlled by electronic signals from the AV's central controller	Supplies energy and signals to sensors, controllers, and actuators
Main Components	Motors, actuators, servos, gears, linkages	Wiring harnesses, battery management systems, power converters
Role in Autonomy	Executes physical actions based on AI decisions (e.g., lane change, braking)	Ensures seamless power and data flow for perception, planning, and control
Dependency	Depends on electrical power and signals to function	Independent from mechanical parts but essential for their operation
Failure Impact	Directly affects vehicle mobility (e.g., loss of steering or braking)	Can lead to total system failure, affecting both sensors and actuators
Integration with AI	Executes AI-driven decisions physically	Enables AI processing by powering computing platforms and sensors

IV. SENSING TECHNOLOGY IN AUTONOMOUS VEHICLES

Sensor technologies are the eyes and ears of AVs as they are used to sense and interpret the surrounding environment with high precision. The role of sensors in electrical AVs is twofold: they provide environmental awareness of autonomous driving and safety and efficiency of the inner systems of the vehicle. The main sensors include:

4.1 LiDAR Systems

One of the most significant sensors of autonomous vehicles is LiDAR (Light Detection and Ranging) which gives high-resolution 3D mapping of the surrounding environment. Mechanical LiDAR involves rotating mirrors or assemblies to send laser pulses, which record millions of data points in a second to form precise point clouds [32]. Mechanical LiDARs are bulky, costly, and wear out easily, although they are very accurate. Solid-state LiDAR, however, removes moving parts, and instead uses microelectromechanical systems (MEMS) or optical phased arrays, making them smaller, less expensive, and more durable [33]. LiDAR works best for finding objects at a distance and in poor light. It works well with cameras and radar. But it is not effective during heavy rain, fog, or snow, when laser signals may scatter. Future trends are hybrid LiDARs that have a longer range, use less power, and have noise filtering through AI to better detect and classify objects [34].

4.2 Radar Systems

Radar (Radio Detection and Ranging) systems are also important in AVs because they are more reliable in poor weather conditions. They work on different frequencies (usually 24 GHz or 77 GHz) and distances short-range radars are used to monitor blind spots and parking assistance, medium-range radars are used to adaptive cruise control, collision avoidance, and cross-traffic alerts, and long-range radars are used to monitor blind spots and parking assistance. The benefit of radar is that it can measure the velocity of objects by measuring the Doppler shifts, and thus it is suitable for tracking moving cars and people. Nevertheless, radar data is spatially less resolved than LiDAR and cameras, and this makes it difficult to differentiate between objects that are close to each other. This limitation is being overcome with advanced imaging radars and 4D radar technologies that offer near-LiDAR-like resolution and still offer the weather resilience of radar [35]. Radar perception is being improved in the next-generation autonomous driving systems through integration with AI-based signal processing.

4.3 Camera Systems

Cameras are the most flexible and affordable sensors in AVs that offer rich color and texture data that is vital in lane detection, traffic sign recognition, and object classification [36]. Monocular cameras offer one perspective, which is suitable in forward-looking vision, whereas stereo cameras have two lenses to approximate depth. Fisheye cameras provide a large field of view to have 360-degree situational awareness. Cameras are also good at picking up semantic information such as road markings and signals that radar and LiDAR can not easily interpret. They are, however, very sensitive to lighting conditions, glare, and weather, and need sophisticated image enhancement and deep learning models to perceive robustly. The vision systems of modern AVs are based on AI, including convolutional neural networks, and are used to perform tasks, including object recognition, semantic segmentation, and scene understanding. Although cameras are advantageous, they cannot be used as a reliable distance measurement tool on their own, and thus are best used in a sensor fusion architecture with LiDAR and radar to provide redundancy and better reliability [37].

4.4 Ultrasonic Sensors

Ultrasonic sensors are a basic but critical part of autonomous vehicles, especially when it comes to low-speed, near-field detection. They produce sound waves of high frequency, which bounce off the surrounding objects, and the time-of-flight is measured to determine distance. These sensors are cheap, small, and very dependable in sensing obstacles in a few meters and are therefore suitable in parking assistance, blind-spot detection, and automated docking maneuvers. In contrast to cameras or LiDAR, ultrasonic sensors are not sensitive to weather and work well in darkness. But they have a very narrow range and their resolution is not enough to classify objects in detail. They also have difficulties with soft or angled surfaces, which reflect sound waves poorly [38]. They are usually in arrays around the vehicle in fully autonomous vehicles to provide 360-degree near-field coverage, enhancing safety in low-speed urban and confined operations. Table 4 shows a comparison of sensors used in autonomous vehicles, and Figure 2 illustrates the sensors used in autonomous vehicles.

Table 4: Comparison of sensors used in autonomous vehicles

Feature	LiDAR Systems	Radar Systems	Camera Systems
Primary Function	Measures distance with laser pulses to create 3D maps	Uses radio waves to detect object distance, speed, and movement	Captures visual images for recognition and classification
Detection Range	(100–250 m) Medium to long	(10–250 m) short to long range	(50–150 m) (depends on lens)
Accuracy & Resolution	Very high spatial resolution, accurate depth perception	Moderate resolution, excellent velocity detection	High resolution for visual features like color and text
Strengths	Precise 3D mapping, works in low light, accurate obstacle detection	Performs well in all weather, detects fast-moving objects	Low cost, good for lane detection and traffic signs
Limitations	High cost, affected by rain, fog, or snow	Lower spatial resolution, cannot capture detailed shapes	Poor performance in low light, glare, fog, or heavy rain
Applications	Environment mapping, localization, obstacle detection	Adaptive cruise control, collision avoidance, blind-spot detection	Lane detection, traffic sign recognition, pedestrian tracking

Figure 2: Main sensors used in autonomous vehicles

V. ACTUATION SYSTEMS IN AUTONOMOUS VEHICLES

5.1 Electric Steering (Steer-by-Wire)

Steer-by-wire technology is a technology that substitutes the mechanical connection between the steering wheel and the front wheels with an electronic control system. It employs sensors to sense driver input, electronic control units (ECUs) to process signals and electric actuators to change wheel angles. This method allows more accurate steering, better responsiveness and adjustable steering feel depending on the driving conditions [39]. Steer-by-wire in autonomous vehicles enables the control system to smoothly assume steering without mechanical limitations, and make advanced maneuvers such as automated lane changes and tight-space navigation. This also saves weight and increases the design flexibility, enabling new cabin layouts, since there are no mechanical parts. Nevertheless, steer-by-wire needs redundant systems, fail-safe systems, and high adherence to functional safety standards (e.g., ISO 26262) [40]. Future trends are the combination of steer-by-wire with AI-based control algorithms, fault tolerance, and user experience in shared and autonomous mobility solutions.

5.2 Electric Braking (Brake-by-Wire)

Brake-by-wire is an electronic control of braking systems that substitute hydraulic braking systems. Brake pedal input or automated braking commands are sensed and electronic control units control brake actuators on each wheel. This enables more precise and immediate braking action, enhanced compatibility with regenerative braking in electric cars and enhanced stability

control [41]. Brake-by-wire in autonomous vehicles allows the coordination of braking, steering and propulsion to be smoother and safer in automated maneuvers. It also facilitates the more advanced torque vectoring and automated emergency braking. The system removes hydraulic lines, which makes it lighter and easier to design the vehicle. But it is important that redundancy, reliability and constant braking force be ensured in all conditions and this necessitates dual electronic circuits and fail-operational modes. The next trend is brake-by-wire systems, which are combined with AI-based predictive braking, which uses sensor fusion data to maximize stopping distances, passenger comfort, and safety in complex traffic situations [42].

5.3 Electric Propulsion

The core of autonomous electric vehicles is electric propulsion systems that include electric motors, inverters, and regenerative braking systems [43]. Electric motors with high efficiency allow accurate control of torque needed to achieve smooth autonomous driving. Inverters change DC power of the battery to AC power to operate the motor, allowing variable speed and torque control. Regenerative braking captures the kinetic energy when braking and increases the overall energy efficiency. In the case of autonomous vehicles, accurate propulsion control is essential to low-speed driving, stop-and-go traffic, and predictive driving using sensor data. The combination of propulsion and braking and steering systems improves vehicle dynamics and energy optimization. Nevertheless, the ability to handle high thermal loads and reliability in continuous autonomous operation is a challenge [44]. Future developments are on small, high-power-density motors, silicon carbide (SiC) inverters to increase efficiency, and sophisticated regenerative strategies that respond to traffic conditions. These systems, coupled with AI-powered energy management, increase the range, efficiency and performance of autonomous mobility [45].

5.4 Adaptive Chassis and Suspension Control

Adaptive chassis and suspension control improves ride comfort, stability and safety of autonomous vehicles by varying suspension stiffness and damping in response to road conditions, vehicle speed and passenger load [46. The system can be used to soften the suspension to provide comfort or stiffen it to improve handling using electronic dampers, actuators and real-time sensor feedback]. Adaptive chassis control plays an important role in autonomous driving to ensure passenger comfort when automated maneuvers are performed, e.g., sudden braking, lane change, or driving on rough roads. It also enhances safety by minimizing body roll, pitch, and vibrations, which increases sensor stability to improve the accuracy of perception. Adaptive suspension will be integrated with steering and brake-by-wire systems in the next few years to offer integrated vehicle dynamics control [47]. This will make autonomous driving more efficient, smooth, and safe Table 5 illustrates a comparison of actuation systems, and Figure 3 shows the main actuators system in Avs.
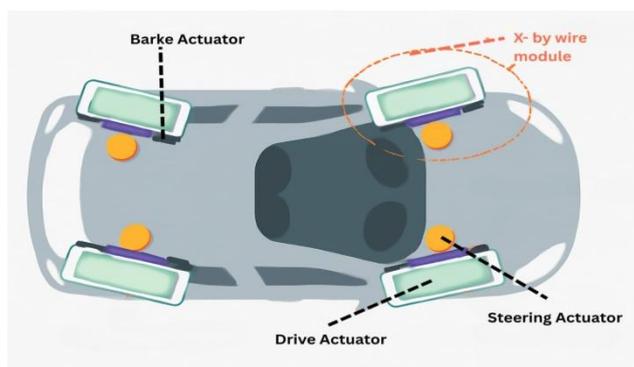

Figure 3: The main actuators in autonomous vehicles

Table 5: Comparison of actuation systems used in AVs

Actuation System	Advantages	Limitations	Typical Uses
Steer-by-Wire	Precise steering control, customizable steering feel, reduces weight, enables new cabin layouts	Requires redundant systems for safety, sensitive to electronic failures	Automated lane changes, tight parking maneuvers, autonomous path following
Brake-by-Wire	Instantaneous braking response, integrates regenerative braking, supports torque vectoring	Needs fail-operational safety, must ensure consistent braking force	Automated emergency braking, adaptive cruise control, smooth deceleration

Electric Propulsion	High torque accuracy, efficient energy use, supports regenerative braking	Thermal management challenges, high computing demands	Low-speed autonomous maneuvers, stop-and-go traffic, energy-optimized driving
Adaptive Chassis & Suspension	Improves ride comfort & stability, predictive road handling, enhances sensor stability	Higher cost, requires complex integration with other systems	Passenger comfort in AVs, proactive bump/pothole response, stable perception platform

VI. ENERGY MANAGEMENT IN AUTONOMOUS VEHICLES

Energy management is a significant aspect of AVs, since they use significantly more energy than conventional vehicles due to the high computational and sensing demands [48]. Besides propulsion, AVs are required to operate LiDAR, radar, cameras, ultrasonic sensors, and high-performance computing platforms continuously, which add to the electrical system load. The architecture of smart energy management should be provided to guarantee reliability, efficiency, and safety [49].On the other hand, Battery management systems (BMS) are the most important part of battery health, state of charge (SoC), and state of health (SoH) monitoring and optimization [50]. Autonomous vehicles use a Smart BMS that uses forecasting algorithms to regulate the energy flow between the propulsion and auxiliary systems. This increases the battery life and the range of the vehicle. Meanwhile, regenerative energy systems capture kinetic energy when braking or decelerating, which lowers net energy use and increases efficiency. AVs also have to support high computational loads in power distribution networks because the constant processing of sensor data and AI-based decision-making needs powerful ECUs and GPUs [51]. In addition, AVs are also being developed with modular, high-voltage systems that can accommodate propulsion and advanced electronics without any issues.

Apart from the intrinsic characteristics of the vehicles, the vehicle-to-grid (V2G) systems are the other significant trend in the automotive industry. AV can be used as a mobile energy storage system or, in other words, supply surplus energy to the electric network during extreme demands. Quite on the contrary, they are able to store the surplus renewable energy during the periods when the resources are abundant, such as sunny days [52]. Not only do the two-fold features supplement the sustainability of the fleet of autonomous vehicles, but they also bear a renewed business model of shared mobility services. Using an example, there is opportunity where the fleet operators can receive profits by selling energy in the energy markets, which is the mere selling of the battery capacity of the fleets. This is not only the best utilization of benefits but also will allow diluting to a greener as well as more stable energy future, which will finally affect the consumers as well as the environment. The AI-based predictive energy optimization, the next-generation solid-state batteries, and the ultra-fast charging infrastructures will be the next few years in the AV energy management and will provide autonomous vehicles with efficiency, reliability, and energy stability [53]. Table 6 describes the principal elements of energy control in AV.

Table 6: Comparison of the main components of electric vehicle energy management

Component	Function	Advantages	Challenges	Typical Use
Battery Management System (BMS)	Monitors and controls battery health, charge, and safety	Extends battery life, improves safety, optimizes power delivery	Requires complex algorithms, adds cost and integration complexity	Ensures stable power for propulsion, sensors, and computing
Regenerative Braking System	Recovers kinetic energy during deceleration	Improves energy efficiency, increases vehicle range	Limited recovery efficiency, dependent on driving conditions	Converts braking energy into stored battery power
Power Distribution Network	Routes energy to propulsion, sensors, and computing units	Balances loads, prevents power bottlenecks, supports redundancy	Needs robust architecture for high-demand electronics	Supplies continuous power to AV control and perception systems
Vehicle-to-Grid (V2G) Integration	Allows energy exchange between vehicle and power grid	Enhances sustainability, enables energy cost savings	Requires smart grid infrastructure, bidirectional chargers	Shared AV fleets acting as mobile energy storage units

VII. FUTURE TRENDS

With the autonomous vehicle industry growing at an unprecedented rate, the future of electrical components will alter the way these intelligent machines perceive, process, and communicate with their surroundings radically. The transition to solid-state LiDAR technology and low-cost sensing, to replace large, expensive mechanical LIDARs with small, rugged devices that can generate high-resolution 3D maps, is one of the most important developments [54]. These are the new-generation sensors that are more efficient and have fewer moving parts and thus they can be mass produced and used in sleek vehicle designs. In parallel to this evolution is the application of domain controller-based architectures, where distributed electronic control units are incorporated into high-performance centralized control units that concurrently control multiple subsystems steering, braking, propulsion, and infotainment [55]. This simplifies the transfer of data, simplifies the wiring, improves the efficiency of the system and makes vehicles more flexible and adaptable to software updates and new features. In the meantime, the increased focus on energy efficiency and sustainability has given rise to electrification strategies and modular propulsion systems, allowing the creation of vehicle platforms that can more readily accommodate the new propulsion technologies, such as hybrid, plug-in hybrid, and fully electric.

Autonomous vehicles are also turning to AI-based predictive control systems to optimize performance in real time based on large volumes of sensor data to make dynamic driving decisions. These systems use machine learning and self-learning algorithms to figure out how other cars on the road will behave and what the road conditions will be like [56]. They then change their driving techniques to make them safer and more efficient. Quantum computing and neuromorphic processors will change the world in the future. Their huge processing capacity and brain-like processing skills will be needed to make ultra-fast sensor fusion, situational awareness, and decision-making in uncertain situations possible.. Such technologies may enable self-driving cars to drive in congested urban areas with almost human intelligence [57].

To achieve high efficiency, safety, and coordination of future urban mobility, the full integration of autonomous vehicles into the current and future Intelligent Transport Systems (ITS) infrastructure is necessary [58]. Self-driving cars can interact with other vehicles, road infrastructure, and pedestrians through this type of integration, which includes connecting to traffic control systems and smart junctions, as well as utilizing V2X technology. This complex interaction helps to make the urban transport system more efficient, safer, and coordinated, which leads to better traffic flow, less congestion, and traffic safety of all road users. This will ensure that the use of public transport in urban areas is safer, more efficient and more organized. The autonomous cars will not be in a remote area, but they will be a part of a bigger and more connected system that will share information, learn, and improve together. Future self-driving cars will change the design, construction, and optimization of electrical systems through the use of solid-state sensors, centralized systems, AI-enhanced control, and city-wide networking [59].

VIII. TECHNICAL CHALLENGES

Although the progress is rapid, the development and implementation of electrical systems in autonomous vehicles (AVs) have major technical issues that need to be resolved to achieve safe, scalable, and sustainable adoption [60]. The cost, scalability, and reliability of sensors are one of the most important issues. LiDAR and radar are still costly and hard to scale to mass production, particularly in consumer-grade AVs. Moreover, the reliability issue of maintaining the same performance of the sensors in different weather, lighting, and road conditions is also a major concern [61]. The other significant issue is the heat dissipation and power efficiency of high-performance computing units that need to process huge volumes of sensor data in real-time [62]. With the growing AI workloads, cooling and energy management solutions that do not affect vehicle performance or battery life require innovative solutions to manage thermal stress [63].

It is also necessary to ensure the redundancy of safety-critical electrical systems. Fail-operational redundancies should be incorporated into drive-by-wire, brake-by-wire, and sensor fusion systems to ensure that a malfunctioning component does not cause a catastrophic failure [64]. A significant engineering challenge is developing such systems cost-effectively and simply integrating them. In addition, there is no standardization and interoperability between AV platforms. Various producers utilize their own sensor combinations, communication protocols, and control architecture, which makes it harder to integrate, test, and get regulatory permission for systems. It will be important to come up with industry standards that will enable modular, upgradable electrical systems across vehicle models and brands. Lastly, there are ethical and regulatory issues [65, 66]. Electrical systems must not only be technically correct but also must meet high safety and legal requirements. The liability of system failures, questions of decision-making in critical situations, and data privacy of sensor feeds are still active research and policy questions. The future work should be aimed at the development of transparent, verifiable, and ethically aligned systems that users and regulators can trust. The future of autonomous vehicle technologies is determined by the way these problems are solved holistically.

IX. CONCLUSION

This paper provides a detailed and extensive overview of AVs and the underlying systems that constitute this new technology. AVs are based on electrical systems that allow them to sense, compute, and actuate in real-time and accurately. Advances in LiDAR, radar, electric drive systems and power management have brought AVs to the verge of autonomy. The future performance, safety, and scalability will be improved by the innovations of solid-state sensors, AI-based control, and domain-based architecture. The next-generation mobility will also be defined by integration with smart infrastructure and energy-efficient platforms. Electrical systems will be central to the achievement of intelligent, connected, and sustainable autonomous transportation ecosystems as research progresses to overcome the difficulties of cost, reliability, and standardization. Such profound knowledge of the underlying technologies will certainly assist new researchers and engineers in exploring this promising area with confidence and making their contribution to the creation of new solutions. Additionally, enhance AVs and provide a helpful manual for recognizing the present drawbacks and difficulties of this technology, as well as recommendations for reducing the likelihood of collisions and injuries brought on by AVs.

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AUTHORS BIOGRAPHY

Mohaimen Q. Algburi is an Iraqi researcher specializing in advanced communication systems. He earned his B.Sc. degree in Systems Engineering from the University of Technology, Baghdad, Iraq, in 2013. In 2019, he was awarded a scholarship to pursue his Master's studies in Turkey, where he obtained a Master's degree in Electrical and Computer Engineering from Altınbaş University. Since 2023, he has been working as a lecturer at the University of Technology- Iraq. His research interests encompass the design and simulation of wireless power transfer, wearable antennas, body area networks, smart antennas, electromagnetic wave scattering by complex objects, 5G/6G technologies, and beyond. Fiber optic communications systems, the Internet of Things, and artificial intelligence are a part of his interests.

Ayman N. Muhi is an Iraqi researcher. He earned his BSc and MSc degrees in Electronics and Communications Engineering from Al-Nahrain University, Baghdad, Iraq, in 2012 and 2016, respectively. During his MSc degree, he worked on a CubeSat communications design project. He has over 11 years of professional experience working with leading mobile communications equipment providers, such as Ericsson and Huawei. In 2023, he joined the University of Technology in Iraq as a lecturer. His research interests include the design and simulation of satellite communications systems, antenna design and modeling, fiber optic communications, 5G networks, and beyond. He also has extensive experience in the telecommunications sector, with proven expertise in microwave equipment, optical transmission, and their embedded systems.

Mustafa Ghanim received his B.Sc. degree in Computer Communication Engineering from Al-Rafidain University College, Baghdad, Iraq, in 2012. He obtained his M.Eng. degree in 2015 and his Ph.D. degree in Electrical Engineering in 2019 from Universiti Teknologi Malaysia (UTM), Johor, Malaysia. In 2021, he was a lecturer at the Department of Medical Instrumentation Engineering, Ashur University College. In 2023, he joined the College of Communication Engineering at the University of Technology- Iraq. His research interests include radio wave propagation, energy harvesting antennas, fifth-generation (5G) communications, satellite propagation, antennas and propagation, as well as the design and simulation of wireless communication systems, optical transmission, The IoT and AI applications are among his interests.

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