(REVIEW ARTICLE)

A comprehensive review of embedded systems in autonomous vehicles: Trends, challenges, and future directions

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Abstract

The integration of embedded systems in autonomous vehicles represents a transformative paradigm shift in the automotive industry, offering unprecedented opportunities for enhanced safety, efficiency, and user experience. This comprehensive review explores the current landscape of embedded systems in autonomous vehicles, delving into emerging trends, persistent challenges, and future directions that shape the trajectory of this rapidly evolving field. The review begins by examining the foundational concepts of embedded systems in the context of autonomous vehicles, elucidating the intricate interplay between hardware and software components. It surveys the state-of-the-art technologies that empower these systems, including advanced sensors, actuators, and communication protocols, highlighting their pivotal roles in perception, decision-making, and control aspects of autonomous driving. One of the prominent trends discussed in this review is the increasing reliance on artificial intelligence (AI) and machine learning algorithms within embedded systems. The incorporation of these intelligent algorithms enables vehicles to adapt and learn from real-world scenarios, enhancing their ability to navigate diverse and dynamic environments. Additionally, the review sheds light on the growing emphasis on connectivity and edge computing, illustrating how embedded systems leverage these technologies to facilitate seamless communication between vehicles and their surrounding infrastructure. Despite the promising advancements, the review critically examines the persistent challenges that impede the widespread adoption of embedded systems in autonomous vehicles. Issues such as safety concerns, cybersecurity threats, and regulatory frameworks are analyzed, providing insights into the complex ecosystem in which these technologies operate. In addressing the future directions of embedded systems in autonomous vehicles, the review envisions a trajectory marked by continuous innovation and collaboration across industries. It anticipates the evolution of embedded systems towards more robust, adaptive, and fault-tolerant architectures, paving the way for increased autonomy and widespread deployment of autonomous vehicles. This comprehensive review provides a holistic understanding of embedded systems in autonomous vehicles, encapsulating current trends, challenges, and future directions. As the automotive landscape undergoes a paradigm shift, this review serves as a valuable resource for researchers, practitioners, and policymakers seeking to navigate the dynamic terrain of autonomous vehicle technology.

Keyword: Autonomous Vehicle; Embedded Systems; Innovation; Automobile; Review

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1. Introduction

The convergence of embedded systems and autonomous vehicles represents a revolutionary nexus in the automotive landscape, ushering in a new era of mobility that promises enhanced safety, efficiency, and user experience (Allioui & Mourdi, 2023, DeNardis, 2020, Raihan, 2023). As the global automotive industry undergoes a transformative paradigm shift, the integration of advanced technologies within the intricate framework of embedded systems has become a linchpin in the development and deployment of autonomous vehicles.

This comprehensive review aims to provide a nuanced understanding of the current state of embedded systems in autonomous vehicles, offering insights into the prevailing trends, persistent challenges, and the future trajectories that shape this dynamic field. Embedded systems, comprising both hardware and software components seamlessly interwoven, play a pivotal role in the realization of autonomous driving capabilities, acting as the nerve center that facilitates perception, decision-making, and control in real-time.

Against the backdrop of rapid technological advancements, the review will delve into the foundational concepts of embedded systems in the context of autonomous vehicles, elucidating the symbiotic relationship between hardware and software that underpins their functionality. From advanced sensors powering perception to the integration of artificial intelligence and machine learning algorithms, we will explore the state-of-the-art technologies that empower embedded systems and drive the evolution of autonomous vehicles (Bathla, et. al., 2022, Fayyad, et. a., 2020, Liu, et. al., 2020).

As the automotive industry progresses, this review will analyze emerging trends that define the trajectory of embedded systems in autonomous vehicles, including the increasing reliance on artificial intelligence, connectivity, and edge computing. While these trends promise unprecedented capabilities, the review will also critically examine the persistent challenges that act as roadblocks to the widespread adoption of embedded systems in autonomous vehicles, including safety concerns, cybersecurity threats, and the regulatory landscape.

Looking ahead, the review will illuminate the potential future directions of embedded systems in autonomous vehicles, envisioning a path marked by continuous innovation, adaptive architectures, and increased fault tolerance. With a focus on collaboration and interdisciplinary approaches, this review aims to serve as a valuable resource for researchers, practitioners, and policymakers navigating the intricate landscape of embedded systems in the realm of autonomous vehicles.

1.1. Foundational Concepts of Embedded Systems in Autonomous Vehicles

As autonomous vehicles continue to advance, the seamless integration of embedded systems stands as the bedrock of their functionality. Embedded systems, comprising both hardware and software elements intricately interwoven, play a pivotal role in shaping the landscape of autonomous driving (Allioui & Mourdi, 2023, Giannaros, et. al., 2023, Zhao, et. al., 2023). This exploration delves into the foundational concepts that define embedded systems in autonomous vehicles, examining their definition, components, the intricate interplay between hardware and software, and their crucial role in perception, decision-making, and control. Embedded systems are specialized computing systems designed to perform dedicated functions within a larger system or product (Barkalov, Titarenko & Mazurkiewicz, 2019, Marwedel, 2021). In the context of autonomous vehicles, these systems are the technological nerve center that enables the vehicle to perceive its surroundings, make informed decisions, and control its movements autonomously. The components of embedded systems in autonomous vehicles encompass both hardware and software elements.

Autonomous vehicles are equipped with an array of sensors such as LiDAR, radar, cameras, and ultrasonic sensors. These sensors capture real-time data from the vehicle's surroundings, providing critical information for navigation and decision-making. These are the mechanisms responsible for translating decisions into actions. Examples include motors controlling steering, brakes, and accelerators. Actuators execute the commands generated by the embedded systems, allowing the vehicle to respond to its environment (Ayala & Mohd, 2021, Vargas, et. al., 2021, Yeong, et. al., 2021).

This software interprets the data received from sensors, processes it, and generates control commands for the actuators. It ensures the vehicle responds appropriately to its surroundings and follows a predefined trajectory. Embedded systems house sophisticated algorithms, often based on artificial intelligence and machine learning, to make complex decisions in real-time. These algorithms assess sensor data, predict potential scenarios, and determine the optimal course of action.

The efficacy of embedded systems in autonomous vehicles lies in the seamless collaboration between their hardware and software components (Damaj, Yousafzai & Mouftah, 2022, Vermesan, et. al., 2021). The hardware captures and processes data from the vehicle's environment, while the software interprets this data, makes decisions, and translates them into actionable commands. This intricate interplay is crucial for the vehicle's ability to navigate diverse and dynamic scenarios. Embedded systems demand real-time processing capabilities to analyze sensor data and make split-second decisions (Munirathinam, 2020, Voudoukis, 2019). This requires a symbiotic relationship between high-performance hardware and efficient software to ensure responsiveness and accuracy. The communication between hardware and software components is characterized by a constant exchange of information. Sensors continuously feed data to the embedded software, which, in turn, generates commands for the actuators. This bidirectional communication ensures a continuous feedback loop for autonomous decision-making (Castelo-Branco, Cruz-Jesus & Oliveira, 2019, Zhou, et. al., 2020).

Embedded systems serve as the cognitive powerhouse of autonomous vehicles, orchestrating the three key elements of perception, decision-making, and control. Sensors embedded in the vehicle act as sensory organs, perceiving the external environment. LiDAR, radar, and cameras capture data on road conditions, obstacles, and other vehicles (Himeur, et. al., 2023, Ndlovu & Ayomoh, 2023, Raj & Surianarayanan, 2020). The embedded system processes this sensory input to create a comprehensive understanding of the surroundings. The processed data is then subjected to decision-making algorithms within the embedded system. These algorithms analyze the information, predict potential scenarios, and determine the best course of action. This may involve adjusting the vehicle's speed, changing lanes, or responding to unexpected obstacles. The final stage involves translating decisions into actions through control mechanisms. Actuators, under the command of the embedded system, adjust the vehicle's steering, acceleration, and braking to execute the chosen course of action. This seamless integration of perception, decision-making, and control ensures the vehicle's ability to navigate autonomously and respond to dynamic environments.

In conclusion, the foundational concepts of embedded systems in autonomous vehicles encompass a sophisticated interplay between hardware and software components. These systems serve as the intelligence hub, enabling vehicles to perceive their environment, make informed decisions, and execute precise control actions. As technology continues to advance, the refinement of these foundational concepts will play a pivotal role in shaping the future of autonomous driving, fostering safety, efficiency, and a transformative user experience.

1.2. State-of-the-Art Technologies Empowering Embedded Systems

The rapid evolution of autonomous vehicles relies on cutting-edge technologies that empower embedded systems to perceive, decide, and act in real-time (Bathla, et. al., 2022, Biswas & Wang, 2023, Vermesan, et. al., 2021). This exploration delves into the state-of-the-art technologies shaping the landscape of embedded systems in autonomous vehicles. The discussion spans advanced sensors for perception, actuators and control mechanisms, communication protocols enhancing vehicle connectivity, and the integration of artificial intelligence (AI) and machine learning (ML) algorithms.

Perception is the cornerstone of autonomous driving, and advanced sensors play a pivotal role in enabling vehicles to interpret their surroundings accurately. These sensors provide a constant stream of real-time data, allowing the embedded systems to make informed decisions. Several key sensor technologies contribute to enhancing perception capabilities; LiDAR (Light Detection and Ranging sensors use laser beams to measure distances, creating detailed 3D maps of the vehicle's surroundings (Gupta et. al., 2021, Sun, et. al., 2023, Zhao, et. al., 2023). These high-resolution maps provide crucial information about the environment, including the precise location of obstacles, pedestrians, and other vehicles. Radar sensors use radio waves to detect objects and assess their distance and speed. They excel in adverse weather conditions and low visibility scenarios, complementing the capabilities of other sensors. Radar technology contributes to the robustness of perception systems in various driving conditions. Vision-based systems, often comprising multiple cameras, capture visual information from the environment. Advanced computer vision algorithms analyze this visual data to identify and track objects, interpret road signs, and recognize lane markings. Cameras are essential for image recognition and scene understanding.

Ultrasonic sensors use sound waves to detect objects in close proximity to the vehicle. They are particularly useful for parking assistance and obstacle detection at low speeds, enhancing the safety of autonomous vehicles during maneuvers (Obuhuma, Okoyo & McOyowo, 2019, Toa & Whitehead, 2020). Actuators and control mechanisms translate decisions made by embedded systems into physical actions, enabling the vehicle to navigate its environment autonomously. In autonomous vehicles, steer-by-wire systems eliminate the mechanical connection between the steering wheel and the wheels. Instead, electronic signals from the embedded system control the steering, allowing for precise adjustments and enhancing responsiveness. Brake-by-wire systems replace traditional hydraulic braking systems with electronic

control. This technology allows for more precise control of braking forces, contributing to enhanced safety and responsiveness. Drive-by-wire systems electronically control the vehicle's acceleration and deceleration, eliminating the need for a physical connection between the accelerator pedal and the engine. This technology enhances the vehicle's overall controllability and responsiveness.

Connectivity is a linchpin for the successful integration of autonomous vehicles into the broader transportation ecosystem. Communication protocols enable seamless data exchange between vehicles and infrastructure, fostering a connected and cooperative environment. Key communication technologies include; Vehicle-to-Vehicle (V2V) Communication allows vehicles to share real-time information with each other, such as speed, position, and traffic conditions (Abbasi & Rahmani, 2023, Singh, 2023). This enables collaborative decision-making, improving overall traffic flow and enhancing safety by preventing collisions. Vehicle-to-Infrastructure (V2I) Communication establishes a connection between vehicles and infrastructure elements, such as traffic lights and road signs. This interaction provides vehicles with real-time information about traffic signals, construction zones, and other critical updates, optimizing route planning and decision-making. The deployment of 5G networks significantly enhances data transfer speeds and reduces latency, crucial for the real-time communication demands of autonomous vehicles. High-speed connectivity enables faster and more reliable information exchange, contributing to safer and more efficient autonomous driving.

The integration of AI and ML algorithms within embedded systems marks a paradigm shift in the capabilities of autonomous vehicles. These technologies enable vehicles to adapt, learn from experience, and make complex decisions in real-time. Key aspects of this integration include; AI algorithms fuse data from multiple sensors to create a comprehensive and accurate perception of the environment (Cunneen, Mullins & Murphy, 2019, Khayyam, et. al., 2020). This holistic approach enhances the reliability of the perception system, allowing the vehicle to make more informed decisions. Machine learning algorithms analyze vast datasets to predict potential scenarios and optimize path planning. The embedded system uses this information to make decisions, adapting to dynamic environments and unforeseen obstacles. Deep learning techniques, such as convolutional neural networks (CNNs), excel in object recognition. These algorithms enable vehicles to identify and classify objects in their surroundings, distinguishing between pedestrians, vehicles, and other obstacles with high accuracy. Machine learning models can predict the behavior of other road users, anticipating their movements and intentions (Hansen, Güttel & Swart, 2019, Marwedel, 2021, Schranz, et. al., 2021). This predictive capability enhances the vehicle's ability to navigate complex traffic scenarios safely.

In conclusion, the state-of-the-art technologies empowering embedded systems in autonomous vehicles showcase a convergence of advanced sensors, actuators, communication protocols, and intelligent algorithms. As these technologies continue to evolve, they collectively contribute to the realization of safer, more efficient, and adaptive autonomous driving experiences. The ongoing integration of cutting-edge innovations positions embedded systems at the forefront of the autonomous vehicle revolution, driving the industry toward a future marked by unprecedented capabilities and transformative mobility solutions.

1.3. Emerging Trends in Embedded Systems for Autonomous Vehicles

The landscape of embedded systems in autonomous vehicles is continually evolving, marked by emerging trends that push the boundaries of innovation and redefine the capabilities of self-driving cars (Chai, Nie & Becker, 2021, Mallozzi, et. al., 2019, Zigure, 2023). This exploration delves into three prominent trends shaping the future of embedded systems in autonomous vehicles: the increasing reliance on artificial intelligence (AI) and machine learning, the integration of connectivity and edge computing, and the evolving adaptive and learning capabilities of embedded systems.

The integration of AI and machine learning stands as a pivotal trend in the evolution of embedded systems for autonomous vehicles. Traditional rule-based systems are giving way to more sophisticated and adaptive approaches, allowing vehicles to learn from data and experiences, thereby enhancing their decision-making capabilities. AI algorithms enable sensor fusion, combining data from diverse sensors such as LiDAR, radar, and cameras. This holistic approach enhances the accuracy and reliability of perception systems, allowing the vehicle to form a comprehensive understanding of its surroundings (Gill, et. al., 2022, Grigorescu, et. al., 2020, Ma, et. al., 2020).

Machine learning models are increasingly employed for path planning and decision-making. These algorithms analyze vast datasets to predict potential scenarios, optimize routes, and make decisions in real-time. The adaptability of machine learning enables vehicles to navigate complex and dynamic environments with improved efficiency. Deep learning techniques, including convolutional neural networks (CNNs), revolutionize object recognition. These algorithms enable the vehicle to distinguish and classify objects in its surroundings with unprecedented accuracy, including identifying pedestrians, other vehicles, and road signs.

Machine learning models provide predictive analytics for anticipating the behavior of other road users. By learning from historical data and real-time observations, vehicles equipped with embedded systems can predict and respond to the movements and intentions of pedestrians, cyclists, and other vehicles on the road (Abou Elassad, et. al., 2020, Mozaffari, et. al., 2020, Yin, et. al., 2021).

Connectivity and edge computing represent a transformative trend in embedded systems, enabling vehicles to communicate seamlessly with each other and with infrastructure elements. This trend is pivotal for achieving a connected and cooperative environment, fostering enhanced safety and efficiency. V2V communication facilitates the exchange of real-time information between vehicles on the road. This cooperative communication allows vehicles to share data on speed, position, and traffic conditions, contributing to collective decision-making and reducing the risk of collisions. V2I communication establishes a link between vehicles and infrastructure components such as traffic lights and road signs (Douch, et. al., 2022, Vermesan & Bacquet, 2022). This connectivity provides vehicles with up-to-date information on traffic signals, road conditions, and construction zones, optimizing route planning and decision-making. The deployment of 5G networks plays a crucial role in supporting the communication demands of autonomous vehicles. High-speed and low-latency connectivity enhance the reliability of real-time data exchange, ensuring vehicles receive timely information for decision-making. Edge computing involves processing data closer to the source, reducing latency and enhancing response times. In the context of autonomous vehicles, edge computing allows embedded systems to analyze and process data locally, enabling faster decision-making without relying solely on centralized cloud resources (Ahangar, et. al., 2021, Guevara & Auat Cheein, 2020, Hakak, et. al., 2023).

The future of embedded systems in autonomous vehicles lies in their ability to adapt, learn, and evolve over time. This trend signifies a departure from static systems to dynamic architectures capable of continuous improvement. Embedded systems are incorporating mechanisms for continuous learning, allowing vehicles to adapt to changing environments and scenarios. This adaptive learning ensures that the system becomes more proficient over time, refining its decision-making based on accumulated experience. Creating feedback loops within embedded systems enables them to learn from real-world outcomes. By analyzing the consequences of decisions and actions, the system can iteratively improve its algorithms, enhancing its ability to navigate diverse and challenging situations (Kocić, Jovičić & Drndarević, 2019, Liu, et. al., 2019). Adaptive embedded systems also extend to understanding and adapting to user preferences and behavior. These systems can tailor driving styles, comfort settings, and in-cabin experiences based on individual user habits, providing a personalized and user-centric driving experience. Building adaptive capabilities into embedded systems includes enhancing fault tolerance and self-healing mechanisms. This ensures that the system can identify and address issues in real-time, mitigating the impact of hardware or software failures without compromising safety.

In conclusion, the emerging trends in embedded systems for autonomous vehicles reflect a paradigm shift towards more intelligent, connected, and adaptive driving experiences. The increasing reliance on AI and machine learning, coupled with connectivity and edge computing, positions embedded systems at the forefront of the autonomous vehicle revolution. As these trends unfold, the adaptive and learning capabilities of embedded systems pave the way for a future where autonomous vehicles not only navigate roads but continually evolve to meet the dynamic challenges of the transportation landscape.

1.4. Persistent Challenges in Adoption

The advent of embedded systems in autonomous vehicles promises a transformative shift in the automotive industry, but this journey is not without its persistent challenges. As the technology evolves, three key hurdles continue to impede the widespread adoption of embedded systems in autonomous vehicles: safety concerns, cybersecurity threats to embedded systems, and regulatory frameworks with compliance issues. Safety is a paramount concern in the development and deployment of autonomous vehicles. The reliance on embedded systems for critical functions such as perception, decision-making, and control introduces challenges that demand rigorous evaluation and mitigation strategies (Lempp, & Siegfried, 2022, Paiva, et. al., 2021).

Autonomous vehicles heavily depend on algorithms, including those powered by artificial intelligence and machine learning, for real-time decision-making. The complexity of real-world scenarios poses challenges in ensuring that these algorithms can accurately perceive and respond to various situations, raising concerns about the robustness of safety-critical functions (Andronie, et. al., 2021, Shi, et. al., 2020, Bachute & Subhedar, 2021).

The development of embedded systems involves addressing ethical considerations related to decision-making in unforeseen scenarios. Determining how vehicles should prioritize the safety of occupants, pedestrians, and other road users in critical situations is a challenging ethical dilemma that requires careful consideration and consensus within the

industry. Embedded systems heavily rely on sensor technologies for perception. Ensuring the reliability of these sensors under diverse environmental conditions, such as adverse weather or challenging lighting, and implementing effective redundancy mechanisms are ongoing challenges in enhancing the safety of autonomous vehicles. The transition between autonomous and manual driving modes introduces challenges in designing effective human-machine interfaces. Ensuring that drivers can seamlessly take control of the vehicle and understand the system's capabilities and limitations is crucial for maintaining safety during transitions.

The increasing integration of connectivity and sophisticated software in embedded systems exposes autonomous vehicles to cybersecurity threats. Safeguarding these systems from malicious activities is a critical challenge that requires constant vigilance and proactive measures. Embedded systems are susceptible to cyber-attacks that exploit vulnerabilities in software and communication protocols. As vehicles become more connected, the potential for unauthorized access, data breaches, and manipulation of critical functions poses a significant threat to the safety and integrity of autonomous driving (Chattopadhyay, Lam & Tavva, 2020, Kim, et. al., 2021, Sun, Yu, & Zhang, 2021). The collection and transmission of large volumes of data by embedded systems raise concerns about data privacy. Protecting sensitive information, such as location data and personal preferences, from unauthorized access is a crucial aspect of building trust in autonomous vehicles. Secure Over-the-Air (OTA) Updates are essential for keeping embedded systems up-to-date with the latest software and security patches. However, ensuring the security of these updates to prevent tampering and unauthorized modifications is a persistent challenge, as compromised updates can potentially lead to system malfunctions or unauthorized control. The automotive industry faces the challenge of establishing collaborative security measures and standards to address cybersecurity threats effectively. Building a collective defense against cyber threats requires cooperation among manufacturers, technology providers, and regulatory bodies to establish robust security frameworks.

The deployment of autonomous vehicles is subject to a complex regulatory landscape that varies across regions. Achieving global regulatory alignment and ensuring compliance with existing and evolving standards pose challenges that impact the pace of adoption. The absence of unified global standards for autonomous vehicles and embedded systems creates challenges for manufacturers and developers. Divergent regulations across regions hinder the seamless deployment of autonomous vehicles, necessitating efforts to establish international standards that promote interoperability and safety. Developing comprehensive testing and certification protocols for embedded systems in autonomous vehicles is a formidable task. Establishing standardized procedures for evaluating the safety and performance of these systems is crucial for gaining regulatory approval and ensuring public confidence (Bezai, et. al., 2021, Taeihagh & Lim, 2019, Tan & Taeihagh, 2021). The introduction of autonomous vehicles raises complex questions regarding legal liability in the event of accidents or failures. Establishing clear legal frameworks and insurance policies that address liability issues associated with autonomous driving is a persistent challenge requiring collaboration between legal experts, policymakers, and the automotive industry. Regulatory challenges also extend to public perception and acceptance. Building trust in autonomous vehicles necessitates transparent communication about safety measures, data privacy, and regulatory compliance. Regulatory bodies play a role in fostering an environment where users feel confident in the safety and reliability of embedded systems in autonomous vehicles.

In conclusion, the persistent challenges in the adoption of embedded systems in autonomous vehicles revolve around safety concerns, cybersecurity threats, and regulatory frameworks. Addressing these challenges requires a multidisciplinary approach, involving collaboration between technology developers, regulatory bodies, policymakers, and the public. As the industry continues to navigate these challenges, the evolution of embedded systems in autonomous vehicles will be shaped by advancements in technology, proactive cybersecurity measures, and the establishment of robust regulatory frameworks that prioritize safety and public trust.

1.5. Addressing Challenges: Current Approaches and Solutions

The challenges surrounding the adoption of embedded systems in autonomous vehicles are met with ongoing efforts to innovate, enhance safety mechanisms, fortify cybersecurity measures, and establish comprehensive policy recommendations and regulatory frameworks. As the automotive industry continues to evolve, these current approaches serve as critical pillars for overcoming obstacles and advancing the deployment of autonomous vehicles (George, Baskar & Srikaanth, 2023, Krichen, 2023).

To address safety concerns in autonomous driving, there is a notable focus on enhancing sensor redundancy and fusion techniques. By integrating diverse sensor technologies and ensuring multiple layers of sensing capabilities, vehicles can build a more comprehensive and accurate perception of their environment. This redundancy not only improves the reliability of embedded systems but also provides fail-safes in the event of sensor malfunctions. Innovations in ADAS play a pivotal role in bridging the transition between conventional and autonomous driving. Features such as adaptive

cruise control, lane-keeping assistance, and automatic emergency braking serve as building blocks for the gradual integration of autonomous functionalities. These systems contribute to enhanced safety by assisting drivers and mitigating risks, paving the way for the broader acceptance of autonomous technologies.

The development and testing of autonomous systems involve extensive simulations and controlled environments. Simulated scenarios allow engineers to expose embedded systems to a wide range of situations, including rare and dangerous events, to validate their responses. This approach aids in refining algorithms, improving safety mechanisms, and ensuring the robustness of autonomous vehicles before real-world deployment. Enhancements in HMI design focus on creating intuitive interfaces that facilitate effective communication between the vehicle and its occupants. Clear communication of the system's intentions, status, and the ability to hand over control to the driver when necessary, contribute to building trust and ensuring safety during autonomous driving (Fremont, et. al., 2020, Rosique, et. al., 2019, Stach, et. al., 2021).

To combat cybersecurity threats, embedded systems in autonomous vehicles employ robust encryption methods and secure communication protocols. Encryption ensures that data exchanged between vehicle components and external entities remains confidential and tamper-proof, reducing the risk of unauthorized access and manipulation. Embedded systems integrate intrusion detection systems that continuously monitor network activity and behavior. These systems can detect anomalies and potential cyber threats, triggering immediate responses to prevent unauthorized access or malicious activities. Real-time monitoring contributes to the early identification and mitigation of cybersecurity risks. Emphasizing secure software development practices is crucial in mitigating vulnerabilities in embedded systems. Developers follow industry best practices, conduct thorough code reviews, and implement secure coding standards to minimize the risk of software-related security flaws. Regular software updates and patches address identified vulnerabilities promptly. The automotive industry actively engages in collaborative initiatives to address cybersecurity challenges collectively. Organizations such as the Automotive Information Sharing and Analysis Center (Auto-ISAC) facilitate information sharing among manufacturers, suppliers, and stakeholders. This collaborative approach enables the industry to stay ahead of emerging cybersecurity threats and collectively enhance the security posture of embedded systems.

Addressing regulatory challenges involves international standardization efforts to create uniform guidelines for autonomous vehicles. Organizations such as the United Nations Economic Commission for Europe (UNECE) work towards establishing a global framework for the deployment of autonomous vehicles, encompassing safety, cybersecurity, and interoperability standards. Regulatory bodies recognize the need for a gradual evolution of regulations to accommodate the advancements in autonomous technologies. Rather than imposing rigid frameworks, regulators are adopting flexible approaches that allow for continuous adaptation to technological developments while prioritizing safety and public confidence. Policies are being developed to address ethical dilemmas in autonomous driving. Establishing clear ethical guidelines for decision-making algorithms and defining accountability frameworks helps navigate complex scenarios. These guidelines ensure transparency in how autonomous systems prioritize safety and handle unforeseen situations. Building public awareness and engagement is a key aspect of addressing regulatory challenges. Governments and regulatory bodies actively communicate with the public to explain the benefits, risks, and regulatory measures surrounding autonomous vehicles. Public input and feedback contribute to the development of regulations that align with societal expectations.

In conclusion, addressing the challenges associated with embedded systems in autonomous vehicles involves a multifaceted approach encompassing innovations in safety mechanisms, robust cybersecurity measures, and the development of effective policy recommendations and regulatory frameworks. As technology continues to advance, these current approaches serve as crucial foundations for fostering the safe and responsible deployment of autonomous vehicles. Collaborative efforts between industry stakeholders, regulators, and the public are essential to navigate the complexities and ensure the successful integration of autonomous technologies into our transportation systems.

1.6. Future Directions of Embedded Systems in Autonomous Vehicles

The trajectory of embedded systems in autonomous vehicles is poised for transformative advancements, driven by the pursuit of more robust, adaptive, and fault-tolerant architectures. As the automotive industry continues to push the boundaries of innovation, the future directions of embedded systems revolve around evolving architectures, implementing fault-tolerant designs with redundancy mechanisms, and anticipating advancements that propel autonomy towards widespread deployment (Divakarla, et. al., 2019, Miller, et. al., 2023, Telli, et. al., 2023).

The future of embedded systems in autonomous vehicles is likely to witness a shift towards distributed and edge computing architectures. This evolution aims to distribute processing tasks across various components within the

vehicle and leverage edge computing capabilities. By decentralizing computation, vehicles can enhance real-time decision-making, reduce latency, and improve overall system efficiency. Future embedded systems will likely adopt modular designs, allowing for easier integration and upgradability. Modular components enable manufacturers to adapt to evolving technologies by replacing or upgrading individual modules, enhancing the overall lifespan and capabilities of autonomous vehicles. This approach facilitates seamless integration of new sensors, processors, and algorithms as they become available. The integration of advanced communication technologies, including 5G and beyond, is anticipated to play a crucial role in future embedded systems. High-speed, low-latency communication is essential for real-time data exchange between vehicles and infrastructure, enabling faster decision-making and enhancing the overall connectivity and coordination of autonomous vehicles within smart transportation ecosystems. The future of embedded systems in autonomous vehicles involves the integration of adaptive learning architectures. These architectures go beyond traditional rule-based systems, allowing vehicles to continuously learn and adapt to their operating environments. Adaptive learning facilitates improved perception, decision-making, and the ability to navigate complex and dynamic scenarios with increased efficiency.

To enhance safety and fault tolerance, future embedded systems will likely incorporate more redundant sensor systems. Redundancy in critical sensors, such as LiDAR, radar, and cameras, ensures that even if one sensor fails or provides inaccurate data, the vehicle can rely on alternative sensors for accurate perception and decision-making. Future embedded systems may prioritize decentralized decision-making to improve fault tolerance. Instead of relying on a central processing unit for all decision-making, vehicles could distribute decision-making tasks across multiple computing units. This approach reduces the impact of a single point of failure and enhances the overall robustness of the system. Predictive maintenance and failure prediction algorithms will become integral components of future embedded systems. These algorithms analyze data from various vehicle components to identify potential failures before they occur. Proactive maintenance based on predictive analytics ensures the timely replacement or repair of components, minimizing the risk of unexpected system failures.

Future embedded systems may feature advanced health monitoring capabilities to continuously assess the overall health and performance of the autonomous system. This monitoring includes self-diagnosis of embedded components, ensuring that any anomalies or deterioration in performance are detected early, allowing for preventive measures to be taken. The future of embedded systems in autonomous vehicles is expected to witness advancements towards achieving higher levels of autonomy (Abdulkarem, et. al., 2020, Anikwe, et. al., 2022, Marques, et. al., 2019). Level 4 and Level 5 autonomy, where vehicles can operate without human intervention in specific or all scenarios, respectively, are anticipated goals. Achieving these levels requires more sophisticated embedded systems capable of handling complex urban environments and diverse driving conditions. The widespread deployment of autonomous vehicles is likely to focus on urban mobility solutions. Shared autonomous fleets, ride-hailing services, and integration with public transportation systems are anticipated to play a significant role in addressing urban congestion and providing efficient, on-demand mobility solutions. The future deployment of autonomous vehicles will involve a more human-centric approach in system design. User experience, safety, and the integration of human preferences will be central considerations. Human-machine interfaces (HMIs) will evolve to ensure clear communication between the vehicle and its occupants, fostering trust and acceptance of autonomous technologies. Anticipated advancements in autonomy and widespread deployment will also rely on the development of comprehensive regulatory frameworks and industry standards. Collaboration between regulatory bodies, industry stakeholders, and policymakers will be essential to establish guidelines that ensure the safety, reliability, and ethical use of autonomous vehicles on a global scale.

In conclusion, the future directions of embedded systems in autonomous vehicles point towards the evolution of architectures for enhanced adaptability, fault-tolerant designs with redundancy mechanisms, and anticipated advancements in autonomy leading to widespread deployment. As the automotive industry continues to innovate, these directions pave the way for a future where autonomous vehicles seamlessly integrate into urban environments, prioritize user experience, and contribute to more sustainable and efficient transportation systems.

2. Recommendation and Conclusion

In the exploration of embedded systems in autonomous vehicles, our comprehensive review has unveiled critical trends, persistent challenges, and promising future directions. The foundational concepts highlighted the intricate interplay between hardware and software, emphasizing their pivotal role in perception, decision-making, and control. State-of-the-art technologies showcased the integration of advanced sensors, actuators, communication protocols, and AI algorithms, propelling the capabilities of embedded systems in autonomous driving.

We delved into the challenges, addressing safety concerns, cybersecurity threats, and regulatory frameworks. Innovations in safety mechanisms, cybersecurity measures, and evolving policy recommendations emerged as crucial

pillars in mitigating these challenges. Moreover, we examined emerging trends, such as the increasing reliance on AI, connectivity, and adaptive learning capabilities, foreseeing a future marked by more intelligent, connected, and adaptive autonomous vehicles. For researchers, this review underscores the need for continued exploration into the evolving architectures of embedded systems. The call is to deepen our understanding of adaptive learning mechanisms, fault-tolerant designs, and the integration of emerging technologies. Investigating the human-machine interaction aspects and ethical considerations in decision-making algorithms will be vital for advancing the field.

Practitioners are encouraged to adopt and contribute to the innovations discussed, prioritizing safety, security, and user-centric design. Emphasizing modular and upgradable components, as well as engaging in collaborative initiatives for cybersecurity, will be instrumental in the successful implementation of embedded systems in autonomous vehicles. Policymakers play a central role in facilitating the widespread deployment of autonomous vehicles. The review highlights the importance of flexible regulatory frameworks that evolve with technological advancements. Encouraging international collaboration and standardization efforts can create a conducive environment for the industry to thrive while ensuring the safety and ethical considerations are at the forefront.

The journey towards fully autonomous vehicles requires a collective effort from researchers, practitioners, and policymakers. Collaboration is the cornerstone for addressing challenges, sharing insights, and fostering innovation. As we stand at the intersection of technology and mobility, the call to action is clear: Researchers from diverse fields, including computer science, engineering, ethics, and law, should collaborate to tackle the multifaceted challenges of embedded systems in autonomous vehicles. A holistic approach is essential for addressing technical, ethical, and regulatory dimensions. Practitioners should engage in active knowledge exchange platforms, sharing best practices, lessons learned, and emerging technologies. This collaborative ecosystem ensures a continuous flow of innovation and accelerates the development and deployment of safe and efficient autonomous vehicles. Policymakers must work collaboratively to establish global regulatory alignment. By fostering international standards and harmonizing regulations, they can create a conducive environment that encourages innovation while ensuring a consistent and safe deployment of autonomous vehicles worldwide.

All stakeholders should prioritize transparent communication and engage with the public. Building trust and understanding the benefits and challenges of autonomous vehicles are paramount. Public input should be incorporated into the regulatory frameworks, ensuring that policies align with societal expectations. In conclusion, the comprehensive review of embedded systems in autonomous vehicles paints a vivid picture of a transformative future. By leveraging the insights, recommendations, and collaborative spirit outlined in this review, the collective efforts of researchers, practitioners, and policymakers can drive the automotive industry toward a safer, more connected, and autonomous future. The call to action is not just an invitation but a commitment to shaping a transportation landscape that is not only technologically advanced but also ethical, inclusive, and sustainable.

Compliance with ethical standards

Disclosure of conflict of interest

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Reference

[1] Abbasi, S., & Rahmani, A. M. (2023). Artificial intelligence and software modeling approaches in autonomous vehicles for safety management: A systematic review. Information, 14(10), 555.

[2] Abdulkarem, M., Samsudin, K., Rokhani, F. Z., & A Rasid, M. F. (2020). Wireless sensor network for structural health monitoring: A contemporary review of technologies, challenges, and future direction. Structural Health Monitoring, 19(3), 693-735.

[3] Abou Elassad, Z. E., Mousannif, H., Al Moatassime, H., & Karkouch, A. (2020). The application of machine learning techniques for driving behavior analysis: A conceptual framework and a systematic literature review. Engineering Applications of Artificial Intelligence, 87, 103312.

[4] Ahangar, M. N., Ahmed, Q. Z., Khan, F. A., & Hafeez, M. (2021). A survey of autonomous vehicles: Enabling communication technologies and challenges. Sensors, 21(3), 706.

[5] Allioui, H., & Mourdi, Y. (2023). Exploring the full potentials of IoT for better financial growth and stability: A comprehensive survey. Sensors, 23(19), 8015.

[6]   Andronie, M., Lăzăroiu, G., Iatagan, M., Uță, C., Ștefănescu, R., & Cocoșatu, M. (2021). Artificial intelligence-based decision-making algorithms, internet of things sensing networks, and deep learning-assisted smart process management in cyber-physical production systems. Electronics, 10(20), 2497.

[7]   Anikwe, C. V., Nweke, H. F., Ikegwu, A. C., Egwuonwu, C. A., Onu, F. U., Alo, U. R., & Teh, Y. W. (2022). Mobile and wearable sensors for data-driven health monitoring system: State-of-the-art and future prospect. Expert Systems with Applications, 202, 117362.

[8]   Ayala, R., & Mohd, T. K. (2021). Sensors in Autonomous Vehicles: A Survey. Journal of Autonomous Vehicles and Systems, 1(3), 031003.

[9]   Bachute, M. R., & Subhedar, J. M. (2021). Autonomous driving architectures: insights of machine learning and deep learning algorithms. Machine Learning with Applications, 6, 100164.

[10]   Barkalov, A., Titarenko, L., & Mazurkiewicz, M. (2019). Foundations of embedded systems (Vol. 195). Cham, Switzerland: Springer International Publishing.

[11]   Bathla, G., Bhadane, K., Singh, R. K., Kumar, R., Aluvalu, R., Krishnamurthi, R., ... & Basheer, S. (2022). Autonomous vehicles and intelligent automation: Applications, challenges, and opportunities. Mobile Information Systems, 2022.

[12]   Bezai, N. E., Medjdoub, B., Al-Habaibeh, A., Chalal, M. L., & Fadli, F. (2021). Future cities and autonomous vehicles: analysis of the barriers to full adoption. Energy and Built Environment, 2(1), 65-81.

[13]   Biswas, A., & Wang, H. C. (2023). Autonomous vehicles enabled by the integration of IoT, edge intelligence, 5G, and blockchain. Sensors, 23(4), 1963.

[14]   Castelo-Branco, I., Cruz-Jesus, F., & Oliveira, T. (2019). Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union. Computers in Industry, 107, 22-32.

[15]   Chai, Z., Nie, T., & Becker, J. (2021). Autonomous driving changes the future. Springer.

[16]   Chattopadhyay, A., Lam, K. Y., & Tavva, Y. (2020). Autonomous vehicle: Security by design. IEEE Transactions on Intelligent Transportation Systems, 22(11), 7015-7029.

[17]   Cunneen, M., Mullins, M., & Murphy, F. (2019). Autonomous vehicles and embedded artificial intelligence: The challenges of framing machine driving decisions. Applied Artificial Intelligence, 33(8), 706-731.

[18]   Damaj, I. W., Yousafzai, J. K., & Mouftah, H. T. (2022). Future trends in connected and autonomous vehicles: Enabling communications and processing technologies. IEEE Access, 10, 42334-42345.

[19]   DeNardis, L. (2020). The Internet in everything. Yale University Press.

[20]   Divakarla, K. P., Emadi, A., Razavi, S., Habibi, S., & Yan, F. (2019). A review of autonomous vehicle technology landscape. International Journal of Electric and Hybrid Vehicles, 11(4), 320-345.

[21]   Douch, S., Abid, M. R., Zine-Dine, K., Bouzidi, D., & Benhaddou, D. (2022). Edge computing technology enablers: A systematic lecture study. IEEE Access, 10, 69264-69302.

[22]   Fayyad, J., Jaradat, M. A., Gruyer, D., & Najjaran, H. (2020). Deep learning sensor fusion for autonomous vehicle perception and localization: A review. Sensors, 20(15), 4220.

[23]   Fremont, D. J., Kim, E., Pant, Y. V., Seshia, S. A., Acharya, A., Bruso, X., ... & Mehta, S. (2020, September). Formal scenario-based testing of autonomous vehicles: From simulation to the real world. In 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC) (pp. 1-8). IEEE.

[24]   George, A. S., Baskar, T., & Srikaanth, P. B. (2023). Securing the Self-Driving Future: Cybersecurity Challenges and Solutions for Autonomous Vehicles. Partners Universal Innovative Research Publication, 1(2), 137-156.

[25]   Giannaros, A., Karras, A., Theodorakopoulos, L., Karras, C., Kranias, P., Schizas, N., ... & Tsolis, D. (2023). Autonomous vehicles: Sophisticated attacks, safety issues, challenges, open topics, blockchain, and future directions. Journal of Cybersecurity and Privacy, 3(3), 493-543.

[26]   Gill, S. S., Xu, M., Ottaviani, C., Patros, P., Bahsoon, R., Shaghaghi, A., ... & Uhlig, S. (2022). AI for next generation computing: Emerging trends and future directions. Internet of Things, 19, 100514.

[27]   Grigorescu, S., Trasnea, B., Cocias, T., & Macesanu, G. (2020). A survey of deep learning techniques for autonomous driving. Journal of Field Robotics, 37(3), 362-386.

[28]   Guevara, L., & Auat Cheein, F. (2020). The role of 5G technologies: Challenges in smart cities and intelligent transportation systems. Sustainability, 12(16), 6469.

[29]   Gupta, A., Anpalagan, A., Guan, L., & Khwaja, A. S. (2021). Deep learning for object detection and scene perception in self-driving cars: Survey, challenges, and open issues. Array, 10, 100057.

[30]   Hakak, S., Gadekallu, T. R., Maddikunta, P. K. R., Ramu, S. P., Parimala, M., De Alwis, C., & Liyanage, M. (2023). Autonomous Vehicles in 5G and beyond: A Survey. Vehicular Communications, 39, 100551.

[31]   Hansen, N. K., Güttel, W. H., & Swart, J. (2019). HRM in dynamic environments: Exploitative, exploratory, and ambidextrous HR architectures. The International Journal of Human Resource Management, 30(4), 648-679.

[32]   Himeur, Y., Sayed, A., Alsalemi, A., Bensaali, F., & Amira, A. (2023). Edge AI for Internet of Energy: Challenges and perspectives. Internet of Things, 101035.

[33]   Khayyam, H., Javadi, B., Jalili, M., & Jazar, R. N. (2020). Artificial intelligence and internet of things for autonomous vehicles. Nonlinear Approaches in Engineering Applications: Automotive Applications of Engineering Problems, 39-68.

[34]   Kim, K., Kim, J. S., Jeong, S., Park, J. H., & Kim, H. K. (2021). Cybersecurity for autonomous vehicles: Review of attacks and defense. Computers & Security, 103, 102150.

[35]   Kocić, J., Jovičić, N., & Drndarević, V. (2019). An end-to-end deep neural network for autonomous driving designed for embedded automotive platforms. Sensors, 19(9), 2064.

[36]   Krichen, M. (2023). Formal methods and validation techniques for ensuring automotive systems security. Information, 14(12), 666.

[37]   Lempp, M., & Siegfried, P. (2022). Automotive Disruption and the Urban Mobility Revolution. Springer International Publishing.

[38]   Liu, L., Lu, S., Zhong, R., Wu, B., Yao, Y., Zhang, Q., & Shi, W. (2020). Computing systems for autonomous driving: State of the art and challenges. IEEE Internet of Things Journal, 8(8), 6469-6486.

[39]   Liu, S., Liu, L., Tang, J., Yu, B., Wang, Y., & Shi, W. (2019). Edge computing for autonomous driving: Opportunities and challenges. Proceedings of the IEEE, 107(8), 1697-1716.

[40]   Ma, Y., Wang, Z., Yang, H., & Yang, L. (2020). Artificial intelligence applications in the development of autonomous vehicles: A survey. IEEE/CAA Journal of Automatica Sinica, 7(2), 315-329.

[41]   Mallozzi, P., Pelliccione, P., Knauss, A., Berger, C., & Mohammadiha, N. (2019). Autonomous vehicles: state of the art, future trends, and challenges. Automotive systems and software engineering: State of the art and future trends, 347-367.

[42]   Marques, G., Pitarma, R., M. Garcia, N., & Pombo, N. (2019). Internet of things architectures, technologies, applications, challenges, and future directions for enhanced living environments and healthcare systems: a review. Electronics, 8(10), 1081.

[43]   Marwedel, P. (2021). Embedded system design: embedded systems foundations of cyber-physical systems, and the internet of things (p. 433). Springer Nature.

[44]   Miller, T., Durlik, I., Kostecka, E., Mitan-Zalewska, P., Sokołowska, S., Cembrowska-Lech, D., & Łobodzińska, A. (2023). Advancements in Artificial Intelligence Circuits and Systems (AICAS). Electronics, 13(1), 102.

[45]   Mozaffari, S., Al-Jarrah, O. Y., Dianati, M., Jennings, P., & Mouzakitis, A. (2020). Deep learning-based vehicle behavior prediction for autonomous driving applications: A review. IEEE Transactions on Intelligent Transportation Systems, 23(1), 33-47.

[46]   Munirathinam, S. (2020). Industry 4.0: Industrial internet of things (IIOT). In Advances in computers (Vol. 117, No. 1, pp. 129-164). Elsevier.

[47]   Ndlovu, B. N., & Ayomoh, M. (2023). Reliability Analysis of the Functional Capabilities of an Autonomous Vehicle. International Journal of Mathematical, Engineering and Management Sciences, 8(5), 943.

[48]   Obuhuma, J. I., Okoyo, H. O., & McOyowo, S. O. (2019). Shortcomings of Ultrasonic Obstacle Detection for Vehicle Driver Assistance and Profiling.

[49]   Paiva, S., Ahad, M. A., Tripathi, G., Feroz, N., & Casalino, G. (2021). Enabling technologies for urban smart mobility: Recent trends, opportunities and challenges. Sensors, 21(6), 2143.

[50]   Raihan, A. (2023). An overview of the implications of artificial intelligence (AI) in Sixth Generation (6G) communication network. Research Briefs on Information and Communication Technology Evolution, 9, 120-146.

[51] Raj, P., & Surianarayanan, C. (2020). Digital twin: the industry use cases. In Advances in computers (Vol. 117, No. 1, pp. 285-320). Elsevier.

[52] Rosique, F., Navarro, P. J., Fernández, C., & Padilla, A. (2019). A systematic review of perception system and simulators for autonomous vehicles research. Sensors, 19(3), 648.

[53] Schranz, M., Di Caro, G. A., Schmickl, T., Elmenreich, W., Arvin, F., Şekercioğlu, A., & Sende, M. (2021). Swarm intelligence and cyber-physical systems: concepts, challenges and future trends. Swarm and Evolutionary Computation, 60, 100762.

[54] Shi, X., Wong, Y. D., Chai, C., & Li, M. Z. F. (2020). An automated machine learning (AutoML) method of risk prediction for decision-making of autonomous vehicles. IEEE Transactions on Intelligent Transportation Systems, 22(11), 7145-7154.

[55] Singh, B. (2023). Federated learning for envision future trajectory smart transport system for climate preservation and smart green planet: Insights into global governance and SDG-9 (Industry, Innovation and Infrastructure). National Journal of Environmental Law, 6(2), 6-17.

[56] Stach, E., DeCost, B., Kusne, A. G., Hattrick-Simpers, J., Brown, K. A., Reyes, K. G., ... & Maruyama, B. (2021). Autonomous experimentation systems for materials development: A community perspective. Matter, 4(9), 2702-2726.

[57] Sun, C., Zhang, R., Lu, Y., Cui, Y., Deng, Z., Cao, D., & Khajepour, A. (2023). Toward Ensuring Safety for Autonomous Driving Perception: Standardization Progress, Research Advances, and Perspectives. IEEE Transactions on Intelligent Transportation Systems.

[58] Sun, X., Yu, F. R., & Zhang, P. (2021). A survey on cyber-security of connected and autonomous vehicles (CAVs). IEEE Transactions on Intelligent Transportation Systems, 23(7), 6240-6259.

[59] Taeihagh, A., & Lim, H. S. M. (2019). Governing autonomous vehicles: emerging responses for safety, liability, privacy, cybersecurity, and industry risks. Transport reviews, 39(1), 103-128.

[60] Tan, S. Y., & Taeihagh, A. (2021). Adaptive governance of autonomous vehicles: Accelerating the adoption of disruptive technologies in Singapore. Government Information Quarterly, 38(2), 101546.

[61] Telli, K., Kraa, O., Himeur, Y., Ouamane, A., Boumehraz, M., Atalla, S., & Mansoor, W. (2023). A comprehensive review of recent research trends on unmanned aerial vehicles (uavs). Systems, 11(8), 400.

[62] Toa, M., & Whitehead, A. (2020). Ultrasonic sensing basics. Dallas: Texas Instruments, 53-75.

[63] Vargas, J., Alsweiss, S., Toker, O., Razdan, R., & Santos, J. (2021). An overview of autonomous vehicles sensors and their vulnerability to weather conditions. Sensors, 21(16), 5397.

[64] Vermesan, O., & Bacquet, J. (Eds.). (2022). Internet of Things–The Call of the Edge: Everything Intelligent Everywhere. CRC Press.

[65] Vermesan, O., John, R., Pype, P., Daalderop, G., Kriegel, K., Mitic, G., ... & Waldhör, S. (2021). Automotive intelligence embedded in electric connected autonomous and shared vehicles technology for sustainable green mobility. Frontiers in Future Transportation, 2, 688482.

[66] Voudoukis, N. F. (2019). Arduino Based Embedded System and Remote Access Technologies of Environmental Variables Monitoring. European Journal of Electrical Engineering and Computer Science, 3(4).

[67] Yeong, D. J., Velasco-Hernandez, G., Barry, J., & Walsh, J. (2021). Sensor and sensor fusion technology in autonomous vehicles: A review. Sensors, 21(6), 2140.

[68] Yin, X., Wu, G., Wei, J., Shen, Y., Qi, H., & Yin, B. (2021). Deep learning on traffic prediction: Methods, analysis, and future directions. IEEE Transactions on Intelligent Transportation Systems, 23(6), 4927-4943.

[69] Zhao, J., Zhao, W., Deng, B., Wang, Z., Zhang, F., Zheng, W., ... & Burke, A. F. (2023). Autonomous driving system: A comprehensive survey. Expert Systems with Applications, 122836.

[70] Zhou, S., Xu, W., Wang, K., Di Renzo, M., & Alouini, M. S. (2020). Spectral and energy efficiency of IRS-assisted MISO communication with hardware impairments. IEEE wireless communications letters, 9(9), 1366-1369.

[71] Zigure, S. (2023). Towards a framework for the study of ongoing socio-technical transitions: explored through the UK self-driving car paradigm (Doctoral dissertation, Manchester Metropolitan University).