A Systematic Investigation of Hardware and Software in Electric Vehicular Platform

Kun Suo
Kennesaw State University
Marietta, Georgia, USA
ksuo@kennesaw.edu

Long Vu, Md Romyull Islam, Nobel Dhar
Kennesaw State University
Marietta, Georgia, USA
{lvu6,mislam22,ndhar}@students.kennesaw.edu

Tu N. Nguyen, Selena He
Kennesaw State University
Marietta, Georgia, USA
{tu.nguyen,she4}@kennesaw.edu

Xiaofeng Wu
City University of Macau
Macau, Macau, China
xiaofengwu@cityu.edu.mo

ABSTRACT

In recent years, computing has been moving rapidly from the centralized cloud to various edges. For instance, electric vehicles (EVs), one of the next-generation computing platforms, have grown in popularity as a sustainable alternative to conventional vehicles. Compared with traditional ones, EVs have many unique advantages, such as less environmental pollution, high energy utilization efficiency, simple structure, and convenient maintenance etc. Meanwhile, it is also currently facing lots of challenges, including short cruising range, long charging time, inadequate supporting facilities, cyber security risks, etc. Nevertheless, electric vehicles are still developing as a future industry, and the number of users keeps growing, with governments and companies around the world continuously investing in promoting EV-related supply chains. As an emerging and important computing platform, we comprehensively study electric vehicular systems and state-of-the-art EV-related technologies. Specifically, this paper outlines electric vehicles' history, major architecture and components in hardware and software, current state-of-the-art technologies, and anticipated future developments to reduce drawbacks and difficulties.

CCS CONCEPTS

• **Hardware** → **Electronic design automation**; • **Software and its engineering**; • **Applied computing** → **Computers in other domains**;

KEYWORDS

Electric Vehicle, Hardware, Software, System

ACM Reference Format:
Kun Suo, Long Vu, Md Romyull Islam, Nobel Dhar, Tu N. Nguyen, Selena He, and Xiaofeng Wu. 2024. A Systematic Investigation of Hardware and Software in Electric Vehicular Platform. In *2024 ACM Southeast Conference (ACMSE 2024), April 18–20, 2024, Marietta, GA, USA*. ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3603287.3651203

ACMSE 2024, April 18–20, 2024, Marietta, GA, USA

ACM ISBN 979-8-4007-0237-2/24/04.
https://doi.org/10.1145/3603287.3651203

1 INTRODUCTION

Background. Cloud computing is the third wave of innovation after the personal computer (PC) and the Internet over the last two decades. It fundamentally changes the way computing resources are used. In recent years, with the advent of the Internet of Everything and the era of 5G high-bandwidth and low latency, the electrification and intelligence of automobiles have become unstoppable. The computing power of hardware chips and the scale and complexity of software codes are growing rapidly. For example, electronics accounted for only 5% of the total cost of a car in 1970 but are expected to account for more than 50% of the total cost by 2030 [1]. As shown in Figure 1, cloud computing platforms and smart electric vehicles (EV) systems have many similarities. More people expect smart EVs to become another computing platform and innovation stage after the cloud. Policies and laws are also an important driving force for the development of electric vehicles. For instance, the US government in 2022 proposed to invest hundreds of billions of dollars in EV infrastructure and manufacturing around the country [5]. In addition, as more people pay attention to energy and environmental issues, more countries and consumers are starting to adopt electric vehicles with various power sources, including fuel cells, hybrid vehicles, and others. In the first half of 2022, 4.3 million new battery-powered electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) were sold globally, up by 37% and 75% compared to 2021. Additionally, sales of various types of EVs are expected to continue climbing, with sales expected to increase by 57% to 10.6 million in 2022 [3].

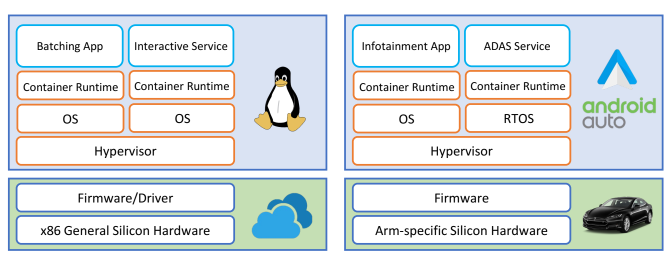

Figure 1: Similarity between the Modern Cloud Platform and Electronic Vehicle Infrastructure

Motivation. However, despite being a rapidly developing computing platform, research and analysis related to EVs remain insufficient, particularly within academia. Firstly, with the exponential growth of computing power in hardware chips and software complexity within the automotive industry, investigating EV hardware and software has become crucial to keeping pace with technological advancements and innovations. Secondly, as EVs gain popularity, there is a pressing need to explore the hardware and software of EV platforms to support their development and integration into the next-generation transportation ecosystem. Thirdly, EVs confront numerous challenges, such as limited cruising range, extended charging times, inadequate supporting infrastructure, network security risks, etc. Understanding these challenges can motivate the exploration of solutions and innovations in EV technology. In this article, we analyze the current state of EV technology development, focusing on the global EV market and its trends. We delve into the hardware systems of EVs, encompassing various energy subsystems, charging infrastructure, high-efficiency control subsystems, powertrain subsystems, power electronics, and chip technology. Additionally, we examine numerous mainstream EV software architectures, technologies, developments, and applications. Furthermore, we address the limitations and challenges of current EV platforms that necessitate improvement in future EV technologies.

To summarize, this paper has made the following contributions:

- We systematically examined EV systems, encompassing the historical evolution of EVs, primary architectures, modules, technologies, developments, and applications in both hardware and software. Additionally, we scrutinized the most advanced technologies currently in use.
- We analyze the constraints and obstacles encountered by existing EV platforms and explore avenues for enhancing future EV technology development.
- We aim to draw attention from scholars in this domain toward the advancement of vehicle computing. Meanwhile, we hope this work can better shed light on further research on electric vehicle platforms and related technologies.

The rest of the paper is organized as follows. Section 2 briefly describes the electric vehicle's history and its current development status. Section 3 studies the existing key components and techniques in hardware, such as the energy subsystem, control subsystem, sensors, etc. The EV software technology is covered in Section 4, including virtualization, hypervisor, OS, auto applications, etc. Section 5 investigates the current limitations of electric vehicles and provides our insights and potential future research directions. Section 6 summarizes this paper with a conclusion.

2 HISTORY OF EV AND CURRENT STATUS

The electric vehicles (EVs) has more than 100 years history. In 1873, British chemist Robert Davidson built the world's first practical electric car. The end of the 19th century to the 1920s was the first golden period for the development of electric vehicles. Because then the early internal combustion engines have many significant drawbacks, including short mileage, high failure rates, difficult maintenance, high vibration, and noise [28]. After the 1920s, electric vehicles were gradually surpassed by the popularity of gasoline vehicles and the lack of technology until recent years. After entering the 21st century, technological advances such as vehicle batteries, motors, and control systems have greatly promoted the marketization of electric vehicles. The number of EVs is growing rapidly as more traditional vehicles use non-renewable conventional fuel, leading to energy and environmental concerns [26]. With a series of carbon reduction policies, such as carbon peaking and carbon neutralization in various countries, the penetration rate of electric vehicles has significantly accelerated. In 2021, more than 6 million EVs were sold, and the global market share of EVs was around 10%, significantly up from 2% in 2019 [7].

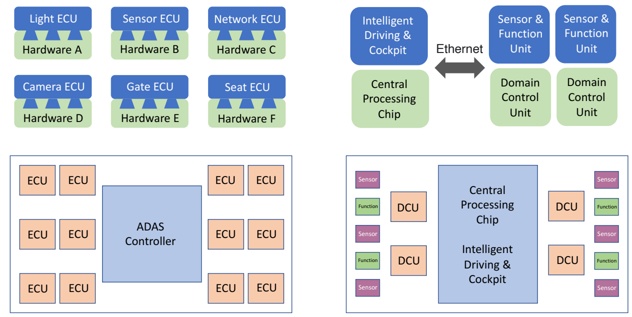

Figure 2: Comparison of Distributed Electrical/Electronic Architecture in Traditional Vehicles and Centralized Computing Architecture for Electric Vehicles

Specific to Georgia, electric vehicles and related industries have also developed rapidly in recent years. Especially after the establishment of the Georgia Electric Mobility and Innovation Alliance (EMIA) in July 2021 [6], school bus manufacturers Blue Bird [2], Rivian [8], Hyundai Motor Group [4] and others have increased investment in the electric vehicle industry and related supply chains in different counties in Georgia. Also, Georgia leads all U.S. states with 27,817 newly announced electric vehicle manufacturing jobs, including car and battery plants and electric vehicle charging stations, according to the Southern Alliance for Clean Energy.

Electric vehicles have many unique advantages compared to those traditional fossil fuel-powered vehicles. First, they are more environmentally friendly by not emitting exhaust pollutants like carbon dioxide or nitrogen dioxide into the air. Compared to the transmission in traditional cars, an electric vehicle makes almost negligible noise. In addition, the number of engine components in electric vehicles is significantly reduced with fewer and simpler components, resulting in much lower maintenance costs. However, despite the above advantages, compared with traditional vehicles, electric vehicles still have many shortcomings, including short cruising range, long charging time, and imperfect supporting infrastructure facilities [26].

3 EV HARDWARE

Compared with the IT industry, the development and update of the automotive industry are much slower. Traditional automobiles are based on a distributed electrical architecture with multiple electronic control units (ECU) and are bound by limited computing power, low communication efficiency, and complex wiring harness links. However, with the advent of the Internet-of-Everything

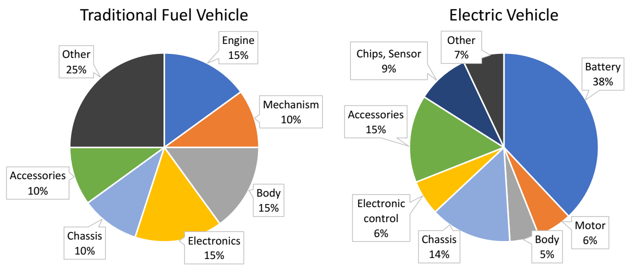

Figure 3: Hardware Cost Composition of Fuel Vehicles and Electric Vehicles

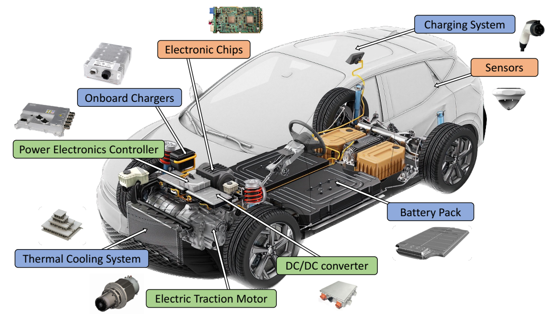

Figure 4: Key Hardware Components in EV Platforms

and 5G, the electrification and intellectualization of automobiles have become unstoppable, and the computing power of hardware chips and the scale and complexity of software code are all growing rapidly. Recently, the automotive electronic and electrical (EE) hardware architecture has been changing from a traditional distributed architecture to a central and domain-specific computing architecture. Under the traditional architecture, ECUs are developed by different suppliers, and the framework cannot be reused or unified. Nevertheless, with the development of smart vehicles, the number of ECUs installed inside the vehicle has increased rapidly, and a centralized hardware architecture has become increasingly necessary [11], as depicted in Figure 2. Moreover, in order to support software-defined vehicles, centralized hardware architecture is also an essential and important foundation.

The hardware of electric vehicles is the basis of the whole system. Taking the Tesla Model 3 as an example, the key components of electric vehicles include a battery system, central control system, thermal management system, circuit system, intelligent driving chip, various sensors, body structure, tires, and so on. The hardware cost of traditional fuel vehicles varies differently from electric vehicles. As shown in Figure 3, the mechanics, body, chassis, etc. account for most of the cost in traditional fuel vehicles, while the expenditure in smart electric vehicles is mainly used in battery, electric motor, controller, and various electronic equipments [36]. In this session, we classify and discuss the components, including energy-related hardware (blue part), control-related hardware (green part), and others (orange part), as depicted in Figure 4.

3.1 Energy Subsystem

Charging System. There are various charging systems for EV batteries, including alternating current (AC) charging, direct current (DC) charging, AC-DC charging, and wireless charging [24, 28]. Generally, the EV charging system is divided into three levels: ① Level one (120 volts) charging, usually works at home with a charging speed of 3 to 5 miles per hour; ② Level two (208 to 240 volts) charging has a speed of 28 to 80 miles per hour and must be installed particularly in residences, public charging lots or any workplace. Typically, level one and level two charging adopt AC power; ③ Level three or DC fast charging or superchargers (400 to 900 volts) [14] are fast charging stations that charge between 3 and 20 miles per minute, such as Tesla v3 chargers. Recently, ABB company launched Terra 360 degrees, the world's fastest onboard charger capable of charging an electric vehicle in less than 15 minutes or a range of 100 kilometers in less than 3 minutes. In comparison, the wireless charging system is currently less common. It consists of floor and car mats, which convert alternating current into a magnetic field and transmit power through the air. The first wireless charging station is provided by Plugless Power, which offers a charging speed of 20 to 25 miles per hour.

Battery Pack. Electric vehicles primarily rely on batteries as their main energy source. The inverter plays a critical role by converting the battery's DC power into AC power, which in turn powers the motor and moves the vehicle forward [16, 27]. Currently, the market offers various types of EV batteries, each with its own set of characteristics and applications. ① Lead-acid batteries: These batteries are known for their affordability and decent performance in low temperatures. However, they suffer from drawbacks such as low energy density, short lifespan, large size, and safety concerns. Consequently, they are typically used in low-speed vehicles [21, 28]. ② Ni-MH batteries: These batteries boast advantages such as cost-effectiveness, established technology, longevity, and superior performance compared to traditional lead-acid batteries. Nevertheless, they still struggle with issues like low energy density, bulkiness, and low voltage, making them suitable mainly for small vehicles. ③ Lithium iron phosphate batteries: Lithium iron phosphate batteries have become the preferred choice for most electric vehicles today [15]. They offer good thermal stability, high safety standards, reasonable cost, and extended lifespan. However, they exhibit average cruising range and encounter challenges such as low energy density, diminished performance in cold conditions, and slower charging rates. ④ Ternary lithium batteries: Known for their high energy density and prolonged cycle life, ternary lithium batteries excel in cold weather conditions. However, their premium price tags restrict their adoption of high-end electric vehicles. Additionally, there's ongoing research into sodium-ion batteries, which are expected to debut in recent years [9]. These batteries promise enhanced safety, cost-effectiveness, high capacity retention, and reduced fire risk compared to lithium-ion batteries. However, they come with drawbacks, such as significantly higher weight and insufficient energy capacity.

Onboard Charger. The onboard charger is for charging the battery on an electric vehicle, which can convert the alternating current into direct current. The output power of the onboard charger varies according to the electric vehicle battery specification, usually between 3.7 kW and 22 kW. For example, Tesla's onboard charger is

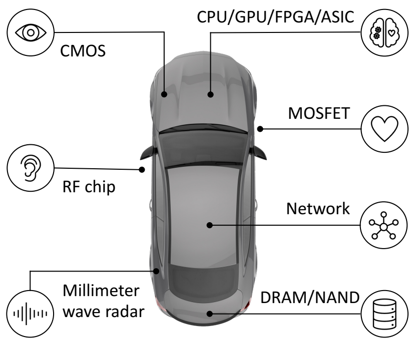

Figure 5: Electric Vehicle Chips and Their Applications

11.5 kW, while the Chevrolet's volts are 7.2 kW. The input voltage of the onboard charger of various electric vehicles is also different. The onboard charger accepts 110 to 260 volts AC in a single-phase connection and 360 to 440 volts when using three phase connector. The output voltage of the battery is between 450 and 850 volts.

Thermal Cooling System. The cooling system is an essential part of the entire electric vehicle. On the one hand, it enables key components such as the engine system to work within a suitable temperature range, preventing performance degradation or even damage due to unexpected temperatures. On the other hand, the cooling system also affects the energy utilization of the vehicle. For electric vehicles, there is no waste heat from conventional engines to utilize. In addition, heating the battery pack, electronic devices, water pumps, etc., will consume some of the electric energy, affecting the vehicle's driving range. Therefore, it is of great significance for electric vehicles to rationally optimize the configuration of the cooling system to ensure thermal performance and consume less energy. Generally, the cooling system of electric vehicles includes the cooling of the power motor, the battery, and the electronic units. A well-designed cooling system needs to consider more from the energy point of view through the use of motor waste heat and battery temperature classification control, etc., to optimize energy utilization and thermal performance.

3.2 Control Subsystem

Power Electronics Controller. A controller unit is an inverter and converter combination that recharges an EV's battery pack while braking. A controller unit works in tandem with the converter-inverter combinations to control energy flow to and from the battery. The frequency of inverters decreases when the brake sends a signal to the controller to decelerate. When the accelerator sends the signal to the controller to change the conversion frequency in inverters, the inverter converts DC to AC to make it compatible with running an electric transaction motor. Recently, multi-level inverters have been introduced, providing greater efficiency, higher power density, better waveform quality, and inherent fault tolerance. For example, the silicon carbide inverter in the Tesla Model S is a variation of a multi-level inverter. Besides the benefits, multi-level inverters also introduce the control system's complexity, cost, and computation time [25].

DC/DC Converter. The DC/DC converter can convert received DC power into DC power of different voltages and provide a stable voltage source for connected components [38]. In electric vehicles, DC/DC converter is responsible for converting the energy of high-voltage battery packs into low-voltage power for 12 to 48 volts low-voltage equipment such as air conditioners, lights, wipers, audio, and navigation. The inverter receives direct current from a DC/DC converter and converts to alternating current to power electric traction motors. Also, it is bidirectional, which is especially useful under regenerative braking conditions when EVs travel long distances. With increasing demand, the efficiency, stability, and power capacity of DC/DC converters have greatly improved over the years. In the near future, how to use high-efficiency converters to output the correct voltage and stably convert the high voltage to low voltage between different power sources will be the key research topic for the next generation of DC/DC converters in electric vehicle systems.

Electric Traction Motor. The electric traction motor converts alternating current (AC) power into mechanical power for the wheels. DC motors, permanent brushless DC motors (BLDC), induction motors, permanent magnet synchronous motors (PMSM), and switched reluctance motors (SM) are the most common types of electric traction motors. Tesla Model S is powered by a three-phase induction motor, while Model 3 is equipped with an internal permanent magnet-switched reluctance motor. SM is cost-effective but difficult to implement due to severe torque ripple and noise [35]. Permanent magnet synchronous motors are extremely efficient, have high torque, and provide the best mileage performance but are costly. The best EV motor in use is a three-phase alternating current induction motor, which is also used in Tesla S and X models for high efficiency, performance, and cost-efficiency. Also, three-phase alternating current induction motors do not require maintenance and are less expensive than DC and BLDC motors.

3.3 Automotive Semiconductors and Sensors

Electronic Chips. Automotive chips are at the core of helping vehicles enter the smart era. Currently, as shown in Figure 5, each vehicle contains an average of 1,400 semiconductors provided by manufacturers, including Infineon, NXP Semiconductors, Texas Instruments, etc. [1], which control everything inside the vehicles, from airbags to engines. According to their application fields, automotive chips can be divided into categories, including system-on-chip (SoC), power semiconductors, sensors, power management, etc. From the application perspective, the SoC chip is the brain of a smart EV and usually integrates CPU, GPU, FPGA, and other modules for control and autonomous driving AI calculations. Tesla's Full Self-Driving (FSD) chip revolves around a SOC that combines industry-standard components such as an ISP and GPU with a custom neural network accelerator, as shown in Figure 6. When fully utilized, the FSD chip can process up to 2,300 frames per second, which is around 21× improvement over its previous hardware and brings a new level of safety and autonomy on the road. Tesla vehicles have eight exterior cameras and 12 ultrasonic sensors around the body. The powerful onboard computer then processes the data collected by these components for autonomous driving and other functions.

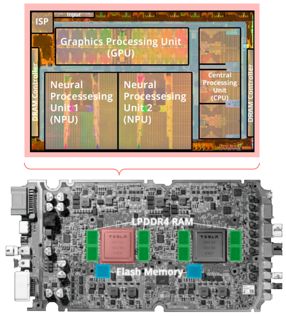

Figure 6: Tesla FSD Chips and Its Components

Power semiconductors, such as metal–oxide–semiconductor field-effect transistors (MOSFET), are another category of auto chips which are mainly used in the acceleration and braking of automobile engines and steering control. With the development of electrification, informatization, intelligence, and vehicle networking ability, auto data storage increased from GB to TB. For example, L4 level sensors need to store 2TB of scene recording data every two hours due to the increase in quantity and resolution requirements. Therefore, memory chips have also become indispensable in today's electric vehicle systems.

Sensors. With the rapid development of the Internet of Things (IoT) and intelligent terminals, modern electric vehicles are equipped with more sensors than before. Vehicle sensors can be categorized as environmental perception sensors, body perception sensors, and interior sensors. The environmental perception sensor enables the vehicle to obtain information from the outside world, including nearby vehicles, road conditions, pedestrians, and other objects. They realize essential functions such as distance measurement and calculation and provide decision-making for autonomous driving. The primary environmental perception sensors include cameras, ultrasonic radars, laser radars, millimeter-wave radars, etc. The body perception sensors realize the vehicle's perception of its state, such as position, driving speed, etc. The body perception sensors include position sensors, pressure sensors, temperature sensors, etc. In-vehicle sensors, as the name suggests, are mainly used to monitor the internal environment in the vehicle and provide a better user experience. For instance, air quality sensors can monitor the real-time air quality and pollution inside electric vehicles.

In addition, EV hardware also includes body, tires, chassis, safety systems, etc., which are not discussed in this paper.

4 EV SOFTWARE

Besides the hardware, it is widely accepted that the role of software in the automotive industry, such as connectivity, autonomous driving, etc., will grow exponentially. Over the past few years, we have also witnessed an increase in automotive components and software complexity [13]. Currently, as depicted in Figure 7, the automotive system design is based on modular control systems, with software subsystems distributed across multiple control units [12]. However, it is widely believed that the future of the automotive industry will move towards a more centralized vehicle architecture.

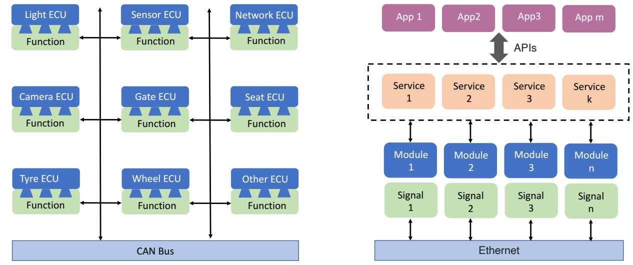

Figure 7: Comparison of Software Architecture in Traditional Vehicles and Service-Oriented Architecture (SOA) for EVs

For manufacturers, the centralized architecture can effectively increase the reusability of basic software, reduce development costs, and use various services. At the same time, it can accelerate the software iteration speed, increase the convenience of OTA upgrades, and improve the user experience of the entire vehicle life cycle. For developers, this architecture can also help develop lower-layer module interfaces and attract application developers to build a smart vehicle ecosystem. For consumers, it's possible to personalize and expand their vehicles through different levels of automotive software integration.

Additionally, in-vehicle virtualization has emerged as a technology capable of handling upcoming innovations, increasing complexity, and demand for computing power [18]. It is a concept that has been introduced previously to bring virtualization to the automotive field. This technology has been used in the cloud field for decades to ensure the flexible customization and integration of heterogeneous subsystems without interference [19, 20, 22, 23, 29–34, 37]. As the automotive industry increasingly uses more customized heterogeneous multi-core chips and systems become more complex, the scope for vehicle virtualization implementation is also growing. This section introduces vehicle software stack, including virtualization, hypervisor, operating system, applications, and automotive electronics software standards, such as AUTOSAR, etc.

4.1 Virtualization

In the past two decades, virtualization has been the underlying cornerstone of the rapid development of cloud computing. However, there are still significant differences between embedded vehicle virtualization and traditional cloud computing virtualization. First, cloud virtualization focuses on elastic resource allocation on demand and flexible management. In comparison, vehicle virtualization focuses more on real-time performance and functional safety. Second, there are more resources in the cloud, while the in-vehicle system is more demanding on the utilization of resources. Therefore, vehicle virtualization requires higher standards for the utilization of resources. Finally, virtualization in the cloud is often a hierarchy structure and different layers interact through a unified interface. Instead, hardware and software in vehicle virtualization are often highly bounded and have closer coupling.

In modern automotive electronic and electrical systems, various ECU hardware provides different services with different priorities and requirements for the system. For example, automotive instrumentation is closely related to the engine system, requiring high

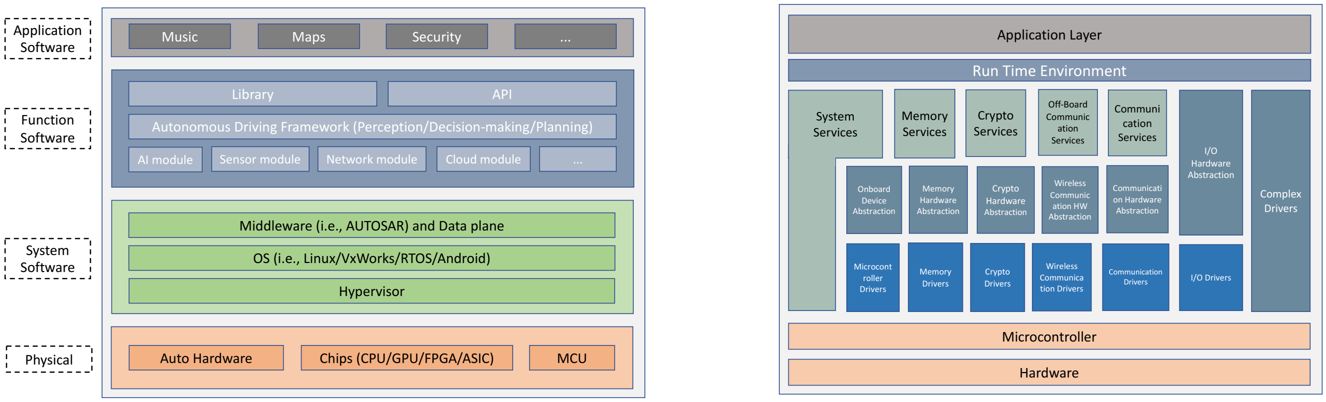

Figure 8: EV Software Architecture and AUTOSAR Stack

real-time performance, reliability, and security, and using the QNX system. Meanwhile, the infotainment system mainly provides a control interface for human-computer interaction in the car for a variety of applications and services. These systems are mainly built on Linux or Android. The virtualization solution provides the ability and flexibility to host heterogeneous systems on the same hardware platform and realizes high reliability to ensure isolation between real-time trusted applications and general services. In addition, it also achieves an integration of onboard computing units and computing resource sharing.

4.2 Hypervisor

The hypervisor provides a software environment in which different programs or entire operating systems can run simultaneously as they would directly on hardware [10, 17]. Thus, the hypervisor acts as an abstraction layer between the virtual machines and the hardware, and multiple virtual machines can run almost transparently on a single hardware platform. For different types of operating systems (OSes) and applications, the hypervisor provides resource sharing and high flexibility on the same hardware while achieving good reliability to ensure security isolation between mission-critical, hard real-time services and general-purpose, untrusted applications. Currently, Wind River Systems, Green Hills Software, Continental AG, Mentor Graphics, Blackberry, and Sasken Technologies are among the leading automotive hypervisor manufacturers.

Wind River Hypervisor is an industry-leading embedded hypervisor with a small footprint, low latency, and optimized performance. It provides safe and secure partitioning, which helps isolate and separate applications with different degrees of importance. In addition, Wind River Hypervisor also allows applications to maintain real-time determinism while providing innovation and differentiation. Unlike Wind River, Green Hills provides a hypervisor with hardware integration of a multivisor processor based on ARM Cortex-A9. Incorporates certified real-time microkernel is capable of hosting one or more guest operating systems (i.e., Android) using para-virtualization. Green Hills's u-visor also has scalable and efficient architecture, ensuring that various operating systems can run on the same CPU and do not interfere with each other. With hardware-enforced separation, the virtual machine and its operating system can achieve their best performance in the vehicle environment. In contrast with the above commercial products, Blackberry's QNX hypervisor is currently the most widely used open-source virtualization platform. It is the industry standard for vehicles that run multiple operating systems. QNX is built with a microkernel architecture to ensure functional safety and complex real-time requirements for instrument clusters and vehicle controls, and it currently has the largest market share for digital instrument clusters in the RTOS space. The vehicle companies currently using the QNX hypervisor include BMW, Bosch, Ford, GM, Honda, Mercedes-Benz, Toyota, and Volkswagen, etc.

4.3 Operating System

The operating system (OS) is an important software platform in the automotive industry, which is responsible for managing and scheduling the vehicle hardware and software resources and providing interfaces for developers or other software to use. A vehicle has hundreds of controllers, including a motor, battery, central screen, lane assist, etc. The hardware has different requirements for real-time performance, and two operating systems are usually required: Real-Time Operating System (RTOS) and Time-sharing Operating System (TSOS). Since equipment like airbag controllers is critical for safety, a small timing error (either too early or too late) can have catastrophic consequences and even lead to loss of life. Therefore, it has been managed and controlled by RTOS. For UI terminals, users may need to make a phone call while performing navigation, so the multiplexing TSOS is used for this scenario. Next, we discuss major automotive operating systems in the current market.

Android Automotive OS (AAOS) is one of the most popular infotainment platforms automakers integrate into their EVs. Many cars use Android Automotive OS, such as the 2021 Volvo XC40 P8, 2020 Polestar 2, GMC Hummer EV 2022, etc. Drivers can download compatible apps directly into the car without a phone and use an interface designed for the vehicle screen. Android's common framework, language, and APIs enable the reuse of the development expertise and complete software of hundreds of thousands of Android developers worldwide, contributing to its scale and popularity. QNX Neutrino is another recognized leader in operating system platforms for electronic vehicles. QNX Neutrino is a real-time automotive operating system that automakers use to ensure that all processes and operations are completed successfully and safely. QNX Neutrino has worked with about 40 automakers, including Ford, Acura, Volkswagen, BMW, and Audi. VxWorks is a real-time vehicle operating system compliant with the ISO-26262 security standard. Wind River creates VxWorks to provide IoT software for safety-critical areas such as automobiles. This vehicle operating system enables automakers and OEMs to deploy safe and reliable autonomous platforms, which Toshiba widely uses, Bosch, BMW, Ford, Volkswagen, and other automakers. While NVIDIA is not leading the automotive OS race, the chipmaker whose GPUs are the processing engines at the heart of many self-driving cars cannot be underestimated. NVIDIA launched DriveWorks Alpha 1, its operating system for self-driving cars, in 2016 and constantly iterated in recent years. DriveWorks is now used by 370 automakers, Tier 1 suppliers, developers, and researchers worldwide, including Tesla, Volkswagen, Mercedes-Benz, Audi, Veoneer, and Bosch. Finally, Automotive Grade Linux (AGL) is a collaborative open-source software stack widely used by auto manufacturers. For instance, Tesla's operating system is built on a modified Linux version of a Debian or Ubuntu distribution.

4.4 Applications

In this section, we discuss the ecology of applications on EV platforms. First, energy-related applications are indispensable for EV users. Many applications are available to identify charging stations and track EV charging efficiency, including ZapMap, PlugShare, ChargePoint, etc. The ZapMap app helps drivers find charging stations and plan longer electric trips, and its vast database lists more than 25,000 charging stations and 47,000 connectors. The PlugShare app finds public charging stations around the world. More than 533,000 charging stations are available on most major networks worldwide, including North America, Europe, and elsewhere. With over 100,000 charging points, the ChargePoint app currently has the largest network of EV charging stations in North America and Europe. It displays information about site location, cost (some are free), available speed (in kilowatts), and usage. Secondly, navigation is a significant and mandatory application for every vehicle. A Best Enroute Planner is one of the top apps for creating electric vehicle routes. The latest Google and Apple maps can also provide optimal navigation experiences for electric vehicles. Finally, there are many popular EV service-related applications exist. For example, JustPark connects cars to parking spaces. Whether you are looking for parking slots or renting out your space, it provides real-time space availability information and booking and payment processing. The Caura app helps to set up and manage parking, tolls, road tax, car insurance, congestion, and clean air zone charges. Thus, this app relieves all vehicle-related administrative burdens and expenses. While this software is not designed specifically for EV drivers, it is essential for the development of the automotive app ecosystem.

4.5 Automotive Open System Architecture

Many automotive electronic software standards are in the market, including AUTOSAR, OSEK/VDX, etc. Among them, the AUTOSAR standard has been developed over a decade and has become the mainstream of vehicle control operating systems. It has already formed a complex technical system and development ecology, as Figure 8 shows. AUTOSAR aims to define more unified middleware and services to facilitate the separation of hardware and software and reduce development costs and system complexity. Large vehicle companies like Toyota, BMW, Volkswagen, Ford, Daimler, General Motors, Bosch, and PSA are among its founders. The architecture of AUTOSAR is conducive to the exchange and update of vehicle electronic system software. It provides a basis for the efficient management of increasingly complex vehicle electronic and software systems. In addition, AUTOSAR improves cost efficiency while ensuring product and service quality. In the field of electric vehicles, we expect that AUTOSAR will still play an indispensable role, bringing about the collaboration and development of different manufacturers.

4.6 Autonomous Driving

The swift evolution of autonomous driving technology has instigated profound transformations in the automobile industry, fostering the amalgamation and inventive progression of various sectors, including computing, the automotive industry, artificial intelligence, the Internet, and next-generation transportation. Viewed from a systemic standpoint, autonomous driving constitutes an intricate system necessitating the collaboration of software and hardware. Broadly speaking, an autonomous driving system comprises three pivotal modules. Firstly, the environment perception module. Self-driving vehicles employ an array of sensors such as cameras, lidar, and millimeter-wave radar to perceive environmental cues. For instance, Tesla's Full Self-Driving (FSD) primarily relies on cameras coupled with computer vision to discern lanes, pedestrians, road conditions, and obstacles. Secondly, the behavioral decision-making module. Self-driving vehicles make real-time driving decisions grounded in road network information, the surrounding traffic environment, and their own operational status. Lastly, the motion control module. The vehicle generates control commands for power, brakes, and steering based on the planned driving trajectory, current position, and speed. Recently, the rapid strides in artificial intelligence have played a pivotal role in integrating and analyzing multi-source data, including information from maps, vehicle sensors, and real-time road conditions, which enables a profound understanding and better prediction of autonomous driving scenarios. By harnessing the power of artificial intelligence, the next generation of autonomous driving systems can significantly enhance the safety, stability, and intelligence of the driving experience.

5 CURRENT LIMITATIONS AND RESEARCH DIRECTIONS

In addition to advantages, electric vehicles also face disadvantages and difficulties nowadays. These shortcomings are also essential directions for the development of electric vehicles in the near future. Some current problems and deficiencies that need to be solved are listed below.

Energy & Power Supply. Most existing electric vehicles will only have a range of around 200 miles per charge. In everyday life, there are far fewer charging stations than regular gas stations unless you have a dedicated one currently in significantly short supply. In addition, electric vehicles take a much longer time to charge than gas vehicles. For example, charging electric vehicles generally takes about 8 hours at home, which needs 1 hour even under quick chargers.

Price & Cost. While less maintenance is required compared to traditional vehicles and charging costs are lower than gasoline in many areas, EVs still have higher one-time purchase prices. Also, battery packs in EVs are more expensive to replace than parts in gasoline-powered vehicles. For example, a complete replacement can cost up to tens of thousands of dollars, limiting the popularity and use of EVs.

Safety & Security. Under the new trend of software-defined vehicles, intelligent functions such as remote car control, digital keys, adaptive cruise, assisted driving, remote diagnosis, and OTA upgrades also bring some safety threats. As different components inside the EVs significantly depend on each other, it might introduce the paralysis of the vehicle and further endanger the driver and passengers' safety once a certain component fails. In addition, EV systems contain large amounts of personal data. Many cybersecurity risks can arise when connecting an EV to a charging station or connecting an EV via USB or WiFi. Besides, vulnerabilities in chips or software may also cause risks when driving EVs.

G2V & V2G. Ensuring the grid load balance is the key goal of Grid-to-Vehicle (G2V) charging dispatch and power grid energy management. The uncoordinated charging behavior and uneven load distribution of EV chargings will bring serious risks to the grid system, such as overloaded networks, power loss, voltage deviation, etc. Vehicle-to-Grid (V2G) is an energy storage technology, which allows two-way power flow between the vehicle battery and the grid. Electric vehicles are expected to become an important part of the future smart grid if managed properly. However, due to the uncertainties on the power supply side and load side, it is not easy to realize the full potential of V2G today.

Intelligence & Autonomous Driving. Autonomous electric vehicles need to acquire road information through various sensors and processes on their computing system. Therefore, their reliability and stability directly affect user safety. With more advanced intelligent functions integrated, the system complexity increases, and the proportion of automatic driving accidents also gradually increases. How to effectively assess and control the negative impact of intelligent vehicles and autonomous driving on road order and public safety is also a challenging research topic.

6 CONCLUSIONS

As the electric vehicle becomes increasingly popular, it has emerged as the next-generation computing platform and an important arena for innovation. Compared with traditional cars, electric vehicles have many unique advantages, such as superior performance, fewer maintenance requirements, environmental friendliness, and better driving experience while simultaneously facing great challenges. We analyze the current state of EV technology development and future trends. We summarize the hardware systems and existing technologies of EV platforms, including energy subsystems, powertrain subsystems, electronics, chip technologies, etc., as well as many mainstream EV software architectures, technologies, developments, and applications. In addition, we also discuss the current environment, challenges, and possible future technological advances for electric vehicles. Although many policy, regulatory, technical, and commercial challenges still need to be resolved, we hope that this research survey can guide more scholars in the field to focus on the development of electric vehicle platforms and help them further explore. In our future research, we plan to investigate designing and implementing a combination of software and hardware approaches to help build next-generation smart, efficient, and safe EV platforms and infrastructures.

ACKNOWLEDGMENTS

We are grateful to the anonymous reviewers for their comments and suggestions on this paper. This work was supported in part by U.S. NSF grants CPS-2103459, SHF-2210744, 2244450, AMPS-2229073, and CNS-2103405.

REFERENCES

[1] [n. d.]. *Automotive Electronics Cost as a Percentage of Worldwide From 1970 To 2030.* https://www.statista.com/statistics/277931/automotive-electronics-cost-as-a-share-of-total-car-cost-worldwide/.
[2] [n. d.]. *Blue Bird Corporation.* https://www.blue-bird.com/.
[3] [n. d.]. *Electric Vehicles: The 3 Main Factors Holding Back Sales.* https://www.weforum.org/agenda/2022/10/ev-sales-charging-infrastructure-transport-sector-sustainable/.
[4] [n. d.]. *EV - Hyundai Motor Group.* https://www.hyundaimotorgroup.com/tech/824.
[5] [n. d.]. *Fact Sheet: President Biden's Economic Plan Drives America's Electric Vehicle Manufacturing Boom.* https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/14/fact-sheet-president-bidens-economic-plan-drives-americas-electric-vehicle-manufacturing-boom/.
[6] [n. d.]. *Georgia Electric Mobility and Innovation Alliance.* https://www.georgia.org/EMIA.
[7] [n. d.]. *Global EV Outlook 2022.* https://www.iea.org/reports/global-ev-outlook-2022.
[8] [n. d.]. *Rivian - Electric Adventure Vehicles.* https://rivian.com/.
[9] [n. d.]. *Will Sodium-ion Battery Cells Be A Game-changer for Electric Vehicle and Energy Storage Markets?* https://www.woodmac.com/news/opinion/will-sodium-ion-battery-cells-be-a-game-changer-for-electric-vehicle-and-energy-storage-markets/.
[10] Hadi Askaripoor, Morteza Hashemi Farzaneh, and Alois Knoll. 2022. E/E Architecture Synthesis: Challenges and Technologies. *Electronics* (2022).
[11] Victor Bandur, Gehan Selim, Vera Pantelic, and Mark Lawford. 2021. Making the Case for Centralized Automotive E/E Architectures. *IEEE Transactions on Vehicular Technology* (2021).
[12] Manfred Broy, Sascha Kirstan, Helmut Krcmar, and Bernhard Schätz. 2012. What Is the Benefit of a Model-Based Design of Embedded Software Systems In the Car Industry? In *Emerging Technologies for The Evolution and Maintenance of Software Models.* IGI global.
[13] Samarjit Chakraborty, Martin Lukasiewycz, Christian Buckl, Suhaib Fahmy, Naehyuck Chang, Sangyoung Park, Younghyun Kim, Patrick Leteinturier, and Hans Adlkofer. 2012. Embedded Systems And Software Challenges in Electric Vehicles. In *Design, Automation & Test in Europe Conference.* IEEE, Dresden, Germany.
[14] Cagla Dericioglu, Emrak YiriK, Erdem Unal, Mehmet Ugras Cuma, Burak Onur, and Mehmet Tumay. 2018. A Review of Charging Technologies for Commercial Electric Vehicles. *Journal of Advances on Automotive and Technology* (2018).
[15] Jian Duan, Xuan Tang, Haifeng Dai, Ying Yang, Wangyan Wu, Xuezhe Wei, and Yunhui Huang. 2020. Building Safe Lithium-ion Batteries For Electric Vehicles: a Review. *Electrochemical Energy Reviews* 3, 1 (2020), 1–42.
[16] Mulugeta Gebrehiwot and Alex Van den Bossche. 2015. Range Extenders for Electric Vehicles. *Editorial Board* (2015).
[17] Marco Haeberle, Florian Heimgaertner, Hans Loehr, Naresh Nayak, Dennis Grewe, Sebastian Schildt, and Michael Menth. 2020. Softwarization of Automotive E/e Architectures: A Software-defined Networking Approach. In *2020 IEEE Vehicular Networking Conference (VNC).* IEEE, 1–8.
[18] Peter Hank, Steffen Müller, Ovidiu Vermesan, and Jeroen Van Den Keybus. 2013. Automotive Ethernet: In-vehicle Networking and Smart Mobility. In *Design,*

Automation & Test in Europe Conference & Exhibition (DATE). IEEE, Grenoble, France.

[19] Hang Huang, Jia Rao, Song Wu, Hai Jin, Kun Suo, and Xiaofeng Wu. 2019. Adaptive Resource Views for Containers. In *Proceedings of the 28th International Symposium on High-Performance Parallel and Distributed Computing (HPDC)*. Phoenix, USA.

[20] Hang Huang, Yuqing Zhao, Jia Rao, Song Wu, Hai Jin, Duoqiang Wang, Kun Suo, and Lisong Pan. 2022. Adapt Burstable Containers to Variable CPU Resources. In *IEEE Transactions on Computers (TC)*.

[21] Leszek Kasprzyk. 2017. Modelling and Analysis of Dynamic States of the Lead-acid Batteries in Electric Vehicles. *Eksploatacja i Niezawodność* 19, 2 (2017).

[22] Jiaxin Lei, Manish Munikar, Kun Suo, Hui Lu, and Jia Rao. 2021. Parallelizing Packet Processing in Container Overlay Networks. In *Proceedings of the Sixteenth European Conference on Computer Systems (EuroSys)*.

[23] Jiaxin Lei, Kun Suo, Hui Lu, and Jia Rao. 2019. Tackling Parallelization Challenges of Kernel Network Stack For Container Overlay Networks. In *11th USENIX Workshop on Hot Topics in Cloud Computing (HotCloud)*. Renton, WA, USA.

[24] Sadeq Ali Qasem Mohammed and Jin-Woo Jung. 2021. A Comprehensive State-of-the-art Review Of Wired/wireless Charging Technologies For Battery Electric Vehicles: Classification/common Topologies/future Research Issues. *IEEE Access* (2021).

[25] Amirreza Poorfakhraei, Mehdi Narimani, and Ali Emadi. 2021. A Review of Multilevel Inverter Topologies in Electric Vehicles: Current Status and Future Trends. *IEEE Open Journal of Power Electronics* 2 (2021), 155–170.

[26] Julio A Sanguesa, Vicente Torres-Sanz, Piedad Garrido, Francisco J Martinez, and Johann M Marquez-Barja. 2021. A Review on Electric Vehicles: Technologies and Challenges. *Smart Cities* 4, 1 (2021), 372–404.

[27] George Suciu and Adrian Pasat. 2017. Challenges and Opportunities for Batteries of Electric Vehicles. In *International Symposium On Advanced Topics In Electrical Engineering*. IEEE, Bucharest, Romania.

[28] Xiaoli Sun, Zhengguo Li, Xiaolin Wang, and Chengjiang Li. 2019. Technology Development of Electric Vehicles: A Review. *Energies* 13, 1 (2019), 90.

[29] Kun Suo, Jia Rao, Luwei Cheng, and Francis CM Lau. 2016. Time Capsule: Tracing Packet Latency Across Different Layers in Virtualized Systems. In *Proceedings of the 7th ACM SIGOPS Asia-Pacific Workshop on Systems (APSys)*. Hong Kong, China.

[30] Kun Suo, Jia Rao, Hong Jiang, and Witawas Srisa-an. 2018. Characterizing and Optimizing Hotspot Parallel Garbage Collection on Multicore Systems. In *Proceedings of the Thirteenth EuroSys Conference (EuroSys)*. Porto, Portugal.

[31] Kun Suo, Junggab Son, Dazhao Cheng, Wei Chen, and Sabur Baidya. 2021. Tackling Cold Start of Serverless Applications by Efficient and Adaptive Container Runtime Reusing. In *Proceedings of IEEE International Conference on Cluster Computing (CLUSTER)*.

[32] Kun Suo, Yong Zhao, Wei Chen, and Jia Rao. 2018. An Analysis and Empirical Study of Container Networks. In *Proceedings of IEEE International Conference on Computer Communications (INFOCOM)*. Honolulu, HI, USA.

[33] Kun Suo, Yong Zhao, Wei Chen, and Jia Rao. 2018. vNetTracer: Efficient and Programmable Packet Tracing in Virtualized Networks. In *Proceedings of International Conference on Distributed Computing Systems (ICDCS)*. Vienna, Austria.

[34] Kun Suo, Yong Zhao, Jia Rao, Luwei Cheng, Xiaobo Zhou, and Francis CM Lau. 2017. Preserving I/O Prioritization in Virtualized OSes. In *Proceedings of the Symposium on Cloud Computing (SoCC)*. Santa Clara, California.

[35] Zhikun Wang, Tze Wood Ching, Shaojia Huang, Hongtao Wang, and Tao Xu. 2020. Challenges Faced by Electric Vehicle Motors and Their Solutions. *IEEE Access* (2020).

[36] Geng Wu, Alessandro Inderbitzin, and Catharina Bening. 2015. Total Cost of Ownership of Electric Vehicles Compared to Conventional Vehicles: A Probabilistic Analysis and Projection across Market Segments. *Energy Policy* (2015).

[37] Yong Zhao, Kun Suo, Xiaofeng Wu, Jia Rao, Song Wu, and Hai Jin. 2019. Preemptive Multi-queue Fair Queuing. In *Proceedings of the 28th International Symposium on High-Performance Parallel and Distributed Computing (HPDC)*. Phoenix, USA.

[38] Xiang Zhou, Bo Sheng, Wenbo Liu, Yang Chen, Laili Wang, Yan-Fei Liu, and Paresh C Sen. 2021. A High-efficiency High-power-density on-board Low-voltage DC-DC Converter for Electric Vehicles Application. *IEEE Transactions on Power Electronics* (2021).