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The Emergence of Vehicle Computing

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Connected and autonomous vehicles (CAVs) are poised to revolutionize the conventional transportation industry. In this article, we first introduce the vision of vehicle computing in the autonomous driving era and highlight that CAVs are the perfect computation platforms, so connected devices/things with limited computation capacities may rely on surrounding CAVs to perform complex computational tasks. Next, we depict several reasons why vehicle computing is essential and emerging, followed by four case studies, including in-vehicle delivery, in-vehicle meeting, in-vehicle entertainment, and in-vehicle augmented reality, to further illustrate vehicle computing. Finally, we conclude this article by listing several technical challenges related to vehicular communication, open APIs, computation hardware, energy consumption, computation offloading, as well as security and privacy.

CONNECTED AND AUTONOMOUS VEHICLES: FROM PRESENT TO FUTURE

The proliferation of communication and edge computing[1] has pushed the horizon of autonomous driving. Although technical obstacles, exorbitant costs, and social acceptability have still hindered large-scale production of connected and autonomous vehicles (CAVs), there has been an acceleration in the research and development (R&D) efforts to bring the idea of CAVs to fruition. For example, automakers spend more than 100 billion worldwide on R&D with around 5000 patents granted each year. Based on the recent considerable progress and disruptive technologies, optimists predict that by 2030, CAVs will be sufficiently reliable and commercially affordable to replace human driving.

This article envisions the next paradigm of future CAVs whose functionality will not only be limited to driving efficiently and safely in complex scenes. Instead, the future fully CAVs are expected to be universal computing platforms supporting daily life applications by providing efficient onboard computation for connected infrastructures. In this article, we introduce the concept of vehicle computing. We start from the analysis of why we need vehicle computing. Several case studies including in-vehicle delivery, in-vehicle meeting, in-vehicle entertainment, and in-vehicle augmented reality (AR) are introduced to further explain vehicle computing, followed by technical challenges waiting to address for the arrival of fully CAVs. We hope this article will gain attention from the automotive communities and inspire more research in vehicle computing.

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VEHICLE COMPUTING

In this section, we give our definition and understanding of vehicle computing, and then we list several reasons why vehicle computing is important in the postautonomous driving era.

What is Vehicle Computing

Vehicle computing refers to the enabling technologies allowing computation to be performed on CAVs, which will serve as a computing platform for multiple CAV-related services. Different from vehicular networking,[2] which serves as the communication enabler for a myriad of applications related to vehicles and transportation, vehicle computing focuses on the computation functionality of CAVs and highlights that CAVs are the perfect computation platforms helping to analyze real-time data from in-vehicle sensors, and most importantly, from the surrounding connected devices/things, even when the vehicle is in the parking mode.

More specifically, the concept of vehicle computing is inspired by the fact that future CAVs will be equipped with powerful computing capability; therefore, connected devices/things with limited computation capacities can rely on nearby CAVs to perform complex computational tasks and deliver related results back to the end-users. For example, suppose a law enforcement officer equipped with a body-worn camera is on duty. The body-worn camera is collecting and sending video data to the surrounding law enforcement vehicle for latency-sensitive analytical applications, such as object detection. A warning will be sent by the vehicle when the officer is in a potentially dangerous situation. In this example, the law enforcement vehicle serves as the efficient computing platform based on the received data from the connected devices/things (i.e., body-worn camera) so that computing resources can be reasonably and effectively utilized, and the computation tasks can be completed on time.

Drawing from the definition of vehicle computing, we further introduce the future vehicle computing paradigm in Figure 1, which is driven by the communication of vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V), and potentially vehicle-to-everything (V2X). V2X not only enables CAVs to communicate with the components of the traffic system (e.g., road-side units, cellular towers, traffic cameras, drones, scooters, and even cyclists or pedestrians), but also allows CAVs to communicate with external systems, i.e., elements of the surrounding environment (e.g., smart home sensors, industry IoT devices, health sensors, and edge servers).

Why Do We Need Vehicle Computing

Push to Clouds and Edge Servers

CAVs are equipped with enormous sensors, which could produce around one gigabyte of data per second and generate more than 11 TB of privacy-sensitive data on a daily basis. The quantity of data generated on CAVs is still growing, and the speed of data transportation is becoming the bottleneck when pushing data to clouds or edge servers for data analysis, which poses a significant challenge to provide latency-sensitive services. Besides, even if data are compressed in the CAVs before being sent out, the original sensitive data might be exposed, and it may create a potential threat of privacy leakage. Therefore, the bandwidth limitations, latency bottlenecks, and privacy concerns, in turn, calls for vehicle computing, a new computing paradigm to put the computing at the proximity of data. Previous work also demonstrated the potential benefits (such as the significant response time and energy reduction) by moving computing from the cloud to the data source.[3]

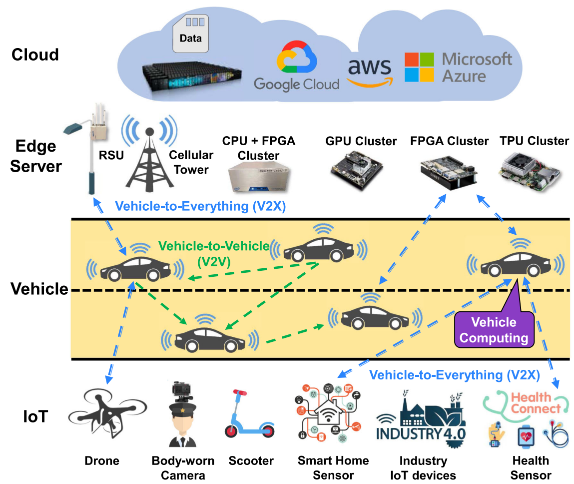

FIGURE 1. Vehicle computing paradigm.

Pull From IoT Devices

Nearly all types of electrical devices will become components of IoT and play the role of both data producers and consumers, such as body-worn cameras, scooters, and even Internet-connected bicycles. According to Cisco, the number of IoT worldwide devices will be around 500 billion by 2030. Such huge amounts of IoT devices will definitely produce enormous data, which hinders the execution of deep learning algorithms on the resource-constrained IoT devices. However, simply relying on traditional cloud computing cannot guarantee efficient data processing to handle all these generated data. In this context, we infer that IoT devices with limited computation capabilities will leverage the surrounding CAVs equipped with strong computing power to perform data processing on time, and we envision that vehicle computing will have big impact on automotive and IoT communities.

CASE STUDY

In this section, we introduce several promising case studies where vehicle computing could shine to further illustrate our vision of future CAVs.

In-Vehicle Delivery

We opine that the widespread of CAVs will be a key component of smart homes to assist people's daily life. For example, CAVs can provide a new, convenient, and secure in-vehicle delivery service when the customer are away from home. Today, Amazon, the world's largest online retailer, is taking the obvious next step by cooperating with mainstream automakers and launching early in-vehicle delivery services. Once the delivery driver reaches the vehicle parked in a publicly accessible place, the driver will send a request to remotely unlock the vehicle for delivery. After placing packages in cargo area or cabin, the driver will send a remote command to lock the vehicle again, and the customer will receive a final notification. Following this way, customers can receive packages safely even when they are not home.

In-Vehicle Meeting

In addition, since a fully CAV could achieve safe and reliable navigation by itself, there is no driver needed to focus on driving anymore. In this context, future CAVs are expected to provide other intelligent services such as providing efficient and smooth online meeting experiences in vehicles. Specifically, as the rapid development of wireless and sensor technologies enables secure and interoperable communications among vehicles, clouds, and devices/things (such as passengers' personal communication devices), we envision that the future CAVs are able to support in-vehicle meetings allowing people to share information and data without being physically present at home or office. Besides, people will be able to seamlessly attend the same meeting at home, in the vehicle, and in the office without being bothered by the repeated logout and login process, which really improves work efficiency and saves working time.

In-Vehicle Entertainment

Similarly, future CAVs have the potential to transform the way people travel by providing audio and video entertainment to enhance people's ride experience. MarketsandMarkets predicts that the in-vehicle entertainment market is estimated to reach USD 30.47 billion by 2022. Besides, starting in 2023, millions of Ford and Lincoln vehicles will be powered by Google's Android operating system to provide drivers with embedded Google applications and services. This evolution indicates that in-vehicle entertainment is on the rise. We envision in the era of fully autonomous driving that the passengers can select a variety of extended reality (XR) gaming via an interface and fully immerse themselves in the gaming experience. These XR games can provide real-time physical vehicle feedback, such as the driver's accelerating, stopping, and steering; therefore, each game experience is unique. Besides, thanks to V2V communication, passengers of different CAVs can play in-vehicle games together on the road, which will further increase the diversity of in-vehicle entertainment.

In-Vehicle AR

Moreover, we envision that AR technologies will be able to turn CAVs' windshields into movie screens, which will make the dreary journey be more interesting and secure by delivering passengers full-color graphics about their environment with a wide-viewing angle. Today, Civil Maps, a software provider for 3D maps, has revealed an AR experience for passengers, which can show passengers how a CAV equipped with AR displays navigates in the complex driving environment. Besides, Alibaba has invested $18 million in WayRay, a head-up display (HUD) company that released NAVION, the first holographic AR vehicle navigation system that can display travel details without wearing an AR helmet or glasses. When fully CAVs will come out, we opine that AR-enabled HUDs will be replaced by AR-enabled windshields, which can respond to voice commands and hand gestures.

TECHNICAL CHALLENGES

We have described four potential applications of vehicle computing in the previous section. To realize the vision of vehicle computing, we argue that the systems, algorithms, and network community need to work together. In this section, we will further summarize technical challenges in detail.

Vehicular Communication

It is estimated that by 2025, there will be 470 million CAVs on highways worldwide, generating 280 petabytes of data. Besides, when the CAV is driving in the urban area at a speed of 40 kilometers per hour, the execution time of each real-time task should be less than 100 milliseconds. However, performing efficient computation based on such a big amount of data is challenging as it requires ultrareliable and low-latency communications (URLLC) to accommodate multiple services.

The recent proliferation in communication mechanisms, such as dedicated short range communication (DSRC), long-term evolution (LTE), cellular-vehicle-to-everything (C-V2X), and WiFi, has enabled CAVs to obtain information from other vehicles, clouds, and connected devices/things.[4] Particularly, with decades of development history, DSRC has been widely deployed, but it has issues like small coverage and low throughput. In contrast, WiFi and LTE provide more bandwidth but perform poorly in the mobile environment. With the recently developed access technology, C-V2X could tackle communication issues due to high mobility and vehicular density scenarios. However, C-V2X is not affordable and widely deployed compared with DSRC. Therefore, the development of communication mechanisms still has a long way to go.

Open APIs

Machine learning-based applications are vastly utilized by CAVs. Unfortunately, there are very limited public computing platforms that support vehicular data analytic and processing. Except for Baidu's Apollo, many companies, such as Ford and General Motors, are working on their proprietary platforms. Moreover, although Apollo is open-source, it is neither scalable nor suitable for future CAVs with plenty of third-party services.

In contrast to the proprietary platform, the open-source platforms that offer free APIs and real-field vehicle data to the researchers and developers are needed, as the open APIs allow communities to deploy and evaluate applications in the real environment. Recently, BlackBerry and AWS are joining forces to develop BlackBerry IVY, a scalable, cloud-connected software platform that will allow automakers to improve operations of CAVs with new BlackBerry QNX and AWS technology. Besides, researchers proposed Open Vehicular Data Analytics Platform (OpenVDAP),[5] which is a full-stack hardware/software platform providing a public edge-aware application library. More open APIs are needed for CAVs to push the development of the third-party services.

Computation Hardware

Nowadays, representative automotive-grade computation hardware of CAVs is being designed based on graphic processor unit (GPU), field programmable gate arrays (FPGA), digital signal processor (DSP), and application-specific integrated circuit (ASIC) with improved processing speed and energy efficiency, such as NVIDIA DRIVE AGX and Texas Instruments' TDA.

However, to design a hardware system for vehicle computing scenarios, there are several open problems waiting to be addressed. First, it is important to figure out the maximum speed that the hardware can achieve with limited processing power. Second, how to efficiently manage heterogeneous computation resources and dynamically schedule applications has deserved researchers' attention. Besides, it is also essential to evaluate how suitable a hardware system is for a specific application scenario. Moreover, a level 4 CAV may cost up to 300,000 dollars, in which the sensors and computing platform cost almost two-thirds of the total price. Therefore, it is also necessary to design a reasonably priced hardware system.

Energy Consumption

With enormous sensors and complex algorithms implemented on CAVs, energy consumption has become a big problem for CAVs. Take the NVIDIA Drive PX Pegasus as an example, it consumes 320 INT8 TOPS of AI computing power with a budget of 500 watts. Moreover, if a replicated system is installed to ensure the reliability of autonomous driving, the total power consumption may be as high as nearly 2000 W.

Besides, take the electric vehicle (EV) as an example, suppose that in the United States, the total mileage of each EV is composed of 55% of city mileage and 45% of highway mileage, and each EV travels on cities and highways at a speed of 31 mph and 56 mph, respectively. In this case, the annual energy consumption of EVs nationwide for computation is around 180 terawatt-hours.[6] It is reported that Google data centers now use around 12 terawatt-hours of electricity per year,[7] so we infer that the national energy consumption of EVs is approximately equal to the total energy consumption of 15 representative technology companies' data centers each year.

Therefore, how to deal with a large amount of energy consumption is an important issue. Moreover, since most of the energy is consumed by the electric motor of the vehicle, it is necessary to jointly design the battery, energy management system, and computing system to realize energy-efficient autonomous driving.

Computation Offloading

Although future CAVs will be endowed with server-level computing power to process sensing data, it becomes evident that safe and reliable autonomous driving requires effective V2X computations to transmit critical information. Accordingly, vehicles and connected devices/things usually work together to process the sensing data, extend their sensing capabilities, and coordinate their decisions.

Nonetheless, collaborative computing between CAVs and connected devices/things is not always feasible due to the latency and reliability constraints. Considering the heterogeneity of the computing capabilities and the interdependency of computing tasks, researchers have formulated optimization problems for task scheduling. Lots of works has focused on task offloading algorithms to optimize the computation offloading. For example, a resource allocation method is proposed to optimize the performance of task offloading when the computation requirement is unknown.[8] Similarly, Tran *et al.*[9] propose a task offloading model to optimize the cost of the computation. However, all the work is based on simulations, and the evaluation in the real-world application scenarios is still missing.

Security and Privacy

The security of CAVs has evolved from the hardware damage of conventional vehicles to comprehensive security with multidomain knowledge.[10] Here, we introduce several security problems strongly related to CAVs including the mainstream attacking methods.

Sensing Security

The security of sensors is of paramount importance. Generally, jamming attacks and spoofing attacks are two main attacks for various sensors. For instance, a spoofing attack generates interference signals, which can cause the vehicle to capture fake obstacles. Hence, effective protection mechanisms for sensing security are desired.

Data Security

Data security denotes preventing data leakage from the perspectives of transmission and storage. How to protect real-time and historical data is waiting for more advanced solutions.

Communication Security

Communication security includes the security of internal communication (such as CAN, LIN, and FlexRay) and external communication that has been studied in VANETs with V2X communications. Although cryptography is a frequently used solution, the usage of cryptography is limited due to the high computational cost.

Control Security

With vehicles' electronification, drivers could control their vehicles (e.g., open the door) through apps or voice. However, this also leads to new attack surfaces with various attack methods, including jamming attacks, replay attacks, etc.

Privacy

CAVs rely heavily on data from the surrounding environment and generate personalized driving data, which usually contains private information. For example, an attacker can obtain the location information directly from the captured GPS data. Therefore, more data desensitization methods are needed to protect the privacy of drivers and passengers.

CONCLUSION

In this article, we first present the vision for vehicle computing in the connected and autonomous driving era. Then, we depict several reasons why vehicle computing is important and emerging, followed by several case studies to further illustrate our vision. Finally, we conclude the article by listing several technical challenges.

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