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Parallel Vehicles Based on the ACP Theory: Safe Trips via Self-Driving

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Abstract— **With the development of intelligent technologies, self-driving vehicles are considered as a promising solution against accident, traffic congestion and pollution problems. Intelligent vehicle techniques have been the research focus all over the world. However, full self-driving vehicles are still far away from its realization and extensive application due to safety requirements and cost considerations. As a novel breakthrough, PArallel VEhicles (PAVE) incorporate the ACP theory, which facilitates real-time interaction and optimization of the actual self-driving vehicles and the artificial ones. As a result, PAVE can maintain intelligent control of the actual self-driving vehicles and achieve the global optimization via software-defined self-driving vehicles, intelligent infrastructure construction, and parallel control center. Besides, PAVE can effectively reduce the cost of high-precision equipments on the actual self-driving vehicles via remote processing and intelligent road(side) infrastructure, and also achieve improved safety and reliability via remote control, guidance and planning.**

I. INTRODUCTION

Nowadays, with the development of technologies, vehicles are becoming smarter and smarter as manufacturers continually equip them with on-board computers, global positioning systems (GPSs), collision avoidance systems, dashboard cameras and so on [1]. Self-driving vehicles are capable to observe surrounding environment and control itself without human operations. To alleviate traffic congestion and improve traffic safety, many kinds of complex driving techniques are needed [2]–[4], for example, obstacles perception, vehicle localization, path planning and control etc. Further, many kinds of sensors, actuators, controller and computers are also required for improved safety and driving experience.

Worldwide vehicle corporations have paid significant attention to the research and development (R&D) and commercialization of self-driving vehicles [1], [5], [6]. For example, Google adopted laser ranging, lane keeping, stereo vision, GPS/inertial navigation system, etc. ULTra used rail transit method to develop self-driving vehicle without the aid of track. Baidu adopted speech recognition, image recognition and cloud deep learning technique, and has signed a strategic cooperation agreement with Chang'an Automobile. They are planning to realize commercialization and production within the next 3 and 5 years, respectively. Ibero adopted laser sensing technology to determine position, road conditions, etc., and is making relevant laws to regulate the management of self-driving vehicles in Germany. DeNA subsidiary Robot taxi company adopted autopilot system, and operated self-driving taxi experiments between neighbourhoods and supermarkets with a total distance of 2.4 km this year.

All the aforementioned companies have made efforts to guarantee driving safety by applying complicated technologies and high-precision equipments, which result in the increasing cost of self-driving vehicles. However, with simple technologies and conventional equipments, safety would be cut down for cost reduction. Therefore, in order to achieve the optimal trade-off between reliability and cost, the framework of PArallel VEhicles (PAVE)[1] is proposed in this paper, which is based on the ACP approach (i.e. artificial system, computational experiment and parallel execution) [9]. PAVE is consisted of actual self-driving vehicles and artificial ones, which comprehensively analyze Cyber-Social-Physical information. It involves artificial system modeling, computational experiments and analysis, and parallel execution [10], [11]. Due to the multi-field, interdiscipline, unpredictable and dynamic characteristics, self-driving vehicles can be considered as a typically complex system. Therefore, applying parallel system methods [12] in complex self-driving vehicles would significantly improve driving safety and reduce single vehicle's cost.

The proposed PAVE include actual software-defined vehicles, road(side) intelligent infrastructure, and artificial vehicles with parallel control center. Actual software-defined vehicles are able to use the collected traffic data from GPS-equipped devices to obtain traffic speed and know about traffic status, and to generate route guidance for travel planning with navigation systems. Road(side) intelligent infrastructures are equipped with traffic lights, cameras, communication devices, storage devices, simple processing units, etc. Artificial vehicles include big data processing, data mining, machine learning, etc., which could provide the global system route planning and design guidance by predicting traffic conditions. Meanwhile, for complicated traffic circumstances, the parallel control center would command self-driving vehicles for its safety on a real-time basis. By and large, through the seamless convergence among the resources from the Cloud, road(side) infrastructure and vehicles, PAVE

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[1]The main idea of PAVE was firstly proposed in [7], [8].

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would help to realize truly reliable, comfortable, fast and safe trips.

II. Parallel Management and Control System

The management and control of actual complex systems are commonly offline and static based on existing mathematical modeling, theoretical analysis and computational simulation results. However, for complex systems, it would be unfeasible to build accurate system models to evaluate and predict their short-term actions. Consequently, it is inevitable to make full use of the advantages of artificial systems from offline to online, from static to dynamic, and from passive to proactive. That is the main characteristics of the so-called parallel system [9].

A. Parallel System

The parallel system consists of actual system and artificial system. The interactions between the actual system and the artificial system help to complete the management and control of the actual complex system, experiment and evaluation of behaviors and decision, learning and training of operators and administrations. The purpose of this parallel system is to interact the actual system and its artificial systems for different purposes in some typical ways. By analyzing and comparing the actual system behaviors and artificial system behaviors, the management and control mechanisms could be mapped out and improved at a real-time basis, and the future actions could be predicted.

B. The ACP Approach

The ACP approach was firstly proposed for the purpose of modeling, analysis, management and control for complex systems. The ACP approach is the combination of artificial societies for modelling, computational experiments for analysis and parallel execution for management and control.

Artificial Societies: Currently, agent-based artificial systems might be the most promising methods for complex system modeling, especially those containing human and social behaviors. The modeling for artificial societies includes three main parts: agents, environments, and rules for interactions. In this modeling scheme, the artificial society modeled by artificial system is regarded as an alternative possible implementation of the target society.

Computational Experiments: The basic method of computational experiments is to generate artificial objects and to proactively create diverse behaviors of experimental systems in a bottom-up fashion through the interactions of artificial objects. With the artificial system, we can design and conduct controllable experiments, and evaluate and quantitatively analyze various factors. Meanwhile, the impact of various factors must be considered for analyzing system behavior. Besides, various methods and concepts of the experimental analysis can be directly applied to solve the corresponding problems for computational experiments.

Parallel Execution: Parallel execution provides a mechanism for the management and control of complex systems through evaluation and interaction with artificial systems. By parallel execution, the potential of artificial systems is explored from offline to online, from static to dynamic, and from passive to proactive, to make artificial systems play equivalent roles as actual systems. Generally, there are no optimal solution for complex systems. Therefore, parallel execution could provide an effective scheme to implement various methods, as well as evaluate and further enhance the performance for this complex system.

III. Parallel Vehicles

The concept and framework of PAVE are proposed and introduced in this section. Current self-driving transportation systems embody two characteristics considered in the ACP approach introduced in Section II (inseparability and unpredictability [9]). Furthermore, the main motivation of applying ACP approach in self-driving transportation systems is reliability requirements and cost considerations of self-driving vehicles.

A. Conventional Self-driving Vehicles

A self-driving vehicle is a vehicle with the ability to drive by itself without human intervention. A self-driving vehicle should be provided with basic functions: perception, localization, planning, control, and management system etc. Perception is a process that the self-driving vehicle senses the surrounding environment by the help of various types of sensors such as RADAR, LIDAR, and cameras etc. The localization is to provide the position of the self-driving vehicle with GPS, Inertial Measurement Unit (IMU) and roadway maps. The planning of a vehicle decides the motion and behavior of this self-driving vehicle based on the information coming from perception and localization function. The control is to implement the corresponding command received from the planning function, and thus to steer, accelerate, or brake the self-driving vehicle. Finally, the management system of this self-driving vehicle supervises the overall self-driving process.

In order to realize the functional components on a self-driving vehicle, there are generally two approaches: centralized self-driving system architecture and distributed self-driving system architecture.

Centralized Self-driving System Architecture: Most of the function modules are integrated into a single computing center for the centralized system architecture. All of the sensors and actuators are integrated and connected into one single centralized computing unit in the self-driving vehicle. The centralized self-driving system architecture could simplify system configuration because all of the devices are combined and connected to the so-called centralized computing unit. Therefore, it is feasible to share information without help of a determined transmission/communication network, thus minimum delay and information loss could be achieved. However, by the centralized system architecture,

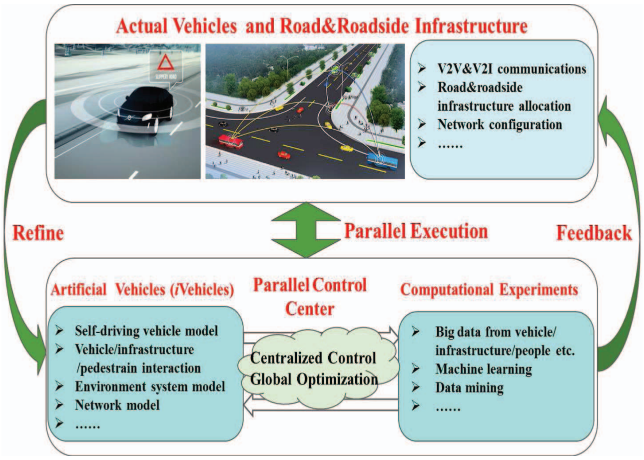

Fig. 1. The framework of parallel vehicles.

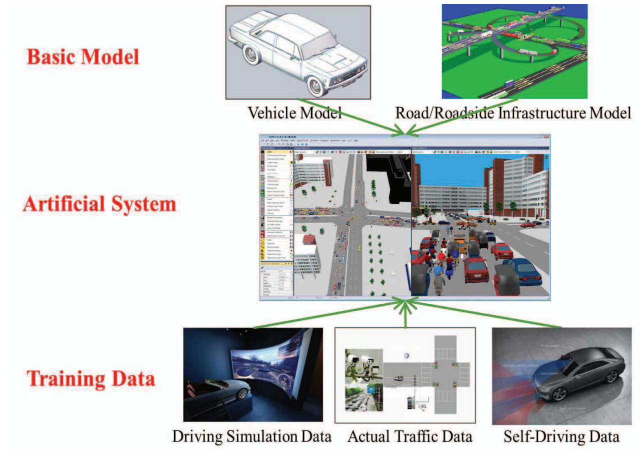

Fig. 2. The artificial self-driving vehicles.

high computational capability is required, and scalability and reliable fault tolerance ability is lacked.

Distributed Self-driving System Architecture: The distributed self-driving system architecture implements the function subcomponents into several local computing units. The common communication system is responsible for sharing the information from each computing unit. Consequently, the computational complexity can be reduced for the distributed system architecture, and fault management of the self-driving system can be much more easier compared to the centralized system architecture. Each module of the self-driving system can be independently developed, tested, and maintained.

Although the distributed system architecture owns the aforementioned advantages, all the processes are completed in a single self-driving vehicle. This causes a common disadvantage with the centralized system architecture, i.e., high cost for improved reliability and safety. It is difficult to strive the optimal trade-off between reliability and cost. That is the motivation of the proposed PAVE with the main idea of "Local Simple Remote Complex".

B. Parallel Vehicle Architecture

To achieve the optimal trade-off between the reliability and cost, PAVE are proposed in this section, which can significantly improve the reliability and reduce the cost of single self-driving vehicle. In addition, it could provide an significant scheme and an useful solution to jointly consider most of the concepts and methods in the fields of artificial intelligence and computational experiments, and thus bring real intelligence into self-driving area. Furthermore, PAVE synthetically integrate Cyber-Social-Physical systems, Big-Data computing, analysis optimization and prediction, and realize network connection between vehicles and vehicles, between vehicles and road(side) infrastructure, and between vehicles and pedestrians. Fig. 1 presents the framework of the proposed PAVE.

The key idea of PAVE is the coordination of the overall self-driving system via the interaction of actual and artificial self-driving vehicles, i.e.

$$\text{PArallel VEhicles} = \text{Actual Vehicles} + i\text{Vehicles},$$

where iVehicles are also called artificial vehicles, which are considered as the basic counterpart of computational experiments; meantime, the optimization of self-driving resources for an actual self-driving vehicle would be effectively combined with the dynamic status of traffic demands. As shown in Fig. 1, the parallel control center provides the centralized control and global optimization for vehicles modification, infrastructure configuration, network configuration and task allocation on vehicles, road(side) infrastructure, and control center.

1) Actual Self-driving Vehicles: The actual self-driving system consists of actual (i.e. physical) self-driving vehicles and intelligent road(side) infrastructure. One self-driving vehicle begins to move towards the next destination when requested by passengers or operators. In order to correctly react to traffic situations, cooperative perception is needed to merge local information with remote information from other vehicles, infrastructure and parallel control center. Based on the remote information from control center, the current vehicle could know the oncoming traffic status and situations ahead of it. Meanwhile, cooperative perception is able to provide both long-term and short-term perspective decisions at the same time. For example, for a long-term perspective, a near-future velocity benefit could be obtained after driving decision; while for a short-term perspective, hidden collision avoidance would improve the safety for self-driving cars.

The road(side) infrastructures are also intelligent. All the roads are equipped with underground sensors, video captures, digital speed limit sign, etc. Intersection lights and information signs thus are needed to become more intelligent and interact with vehicles to make traffic safer, greener and more efficient. The goal is to address the problems of driving safety and road capacity, by combining perception technologies and local databases with real-time network transmission technologies.

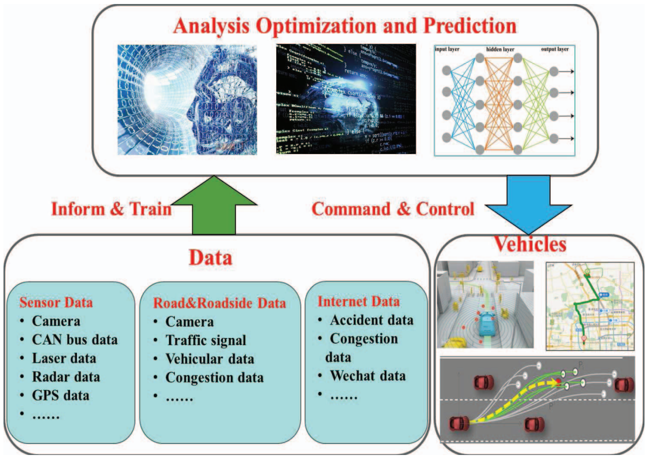

Fig. 3. The diagram of computational experiments.

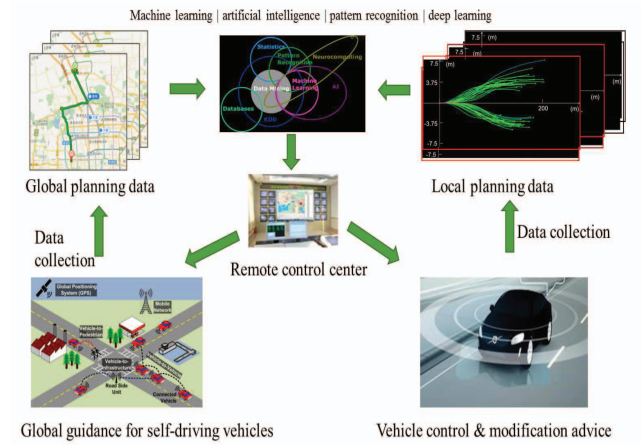

Fig. 4. The diagram of parallel execution.

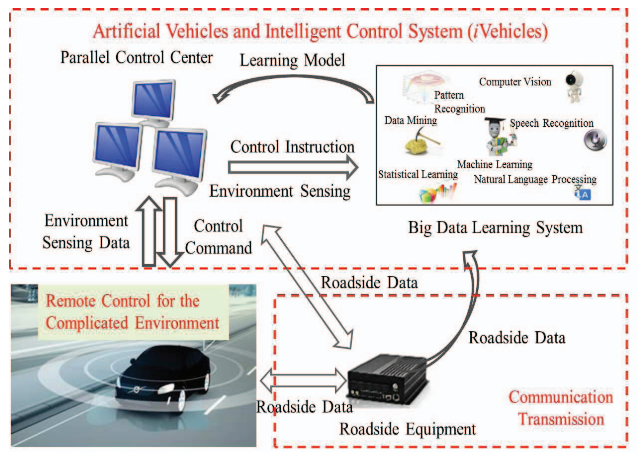

Fig. 5. The system diagram of PAVE.

2) Artificial Self-driving Vehicles: The two main foundations of PAVE are the modeling of the actual self-driving vehicles and the construction of its corresponding artificial self-driving system. As shown in Fig. 2, the artificial system includes artificial vehicles and road(side) infrastructure models, parallel process center, and training data collection. Consequently, unprecedented programmability, automation, and vehicle control are obtained, which thus enables to build highly scalable and flexible self-driving system to guarantee system reliability and cost reduction.

3) Computational Experiments: Based of the artificial self-driving system models, various features and behaviors of actual self-driving system can be analyzed and predicted by computational experiments. The artificial self-driving system can be considered as a controllable and repeatable system. Different experiments can be designed by introducing various uncertain factors, even those elements and events are difficult to be quantified by traditional ways. These computational experiments would be continuously repeated to collect and to analyze the statistical results via system simulation experiments and theoretically computational analysis of complex system.

As shown in Fig. 3, the processing center implements analysis optimization and prediction based on the data from sensors, road(side) infrastructures and communication network, including camera data, CAN-BUS data, laser data, radar data, GPS data, traffic signal, vehicular data, congestion/accident data, Wechat data, and so on. After various computational experiments, the control commands would be feed-back to the actual vehicles. For example, artificial vehicles could remind the status of actual vehicles' units, provide repair guidance, and also predict the upcoming possible traffic environments.

4) Parallel Execution: As given in Fig. 4, parallel execution between actual vehicles and artificial self-driving vehicles can be implemented by the help of the computational experiment results. On the one hand, various results deriving from computational experiments will help actual self-driving vehicles to obtain the global planning optimization, local planning guidance, traffic status prediction, vehicle status prediction and vehicle control&modification advice. On the other hand, to further improve or maintain the current operating status of PAVE, actual self-driving vehicles' data would also be fedback to the artificial self-driving vehicles for its modification and adjustment. Different methods of parallel execution can be designed for different purposes, such as training, management, control, optimization, evaluation, and so on.

IV. Key Technologies and Challenges

As shown in Fig. 5, parallel control center of the proposed PAVE is designed for environment sensing data collection and control command instruction. Meantime, all these data and command instruction are the training data for big data learning system to obtain the optimal guidance and decision by the help of learning algorithms, such as machine learning, statistical learning, data mining, pattern recognition, computer vision, speech recognition, natural language processing, and so on.

For the implementation and development of PAVE, there are several key technologies and challenges as follows.

A. Self-driving Vehicle Modification

The first technology is self-driving vehicle modification. The main advantage of the proposed PAVE is to achieve safety improvement and cost reduction. Remote control module is applied for reliability improvements by adding Wi-Fi, 4G/5G, V2X communications etc. The cost of single vehicle could be reduced by vehicle modifications, such as conventional GPS and multiple signal laser combination instead of differential GPS and multi-line laser, and so on.

The actual self-driving vehicles in PAVE mainly adopt moving and stationary object detection, lane and traffic signs detection, location, navigation, vehicle control and communication module. Here, data fusion between camera and LiDAR guarantees the accuracy and reliability of distance measurement, and still maintains the properties of images, such as color, texture, etc. These vehicles can detect lane and traffic signs with camera, create 3D map with labelled lane/traffic signs, locate vehicle with GPS, and match it to the map to detect and trace traffic signs or environment. Location is attained by GPS, BeiDou navigation satellite system (BDS) and CAN-BUS data. Navigation is acquired by high-precision map and positioning. Vehicle control includes steering control system, accelerator control system, and brake control system. It is worth to mention that all these data are transmitted by communication modules, which could transmit data from vehicles to road(side) infrastructure/control center, receive control commands, and implement V2X communications. Furthermore, all the functional modules in actual vehicles could be defined according to different traffic/user demands.

B. Intelligent Road(side) Infrastructure

The second main technology is intelligent road(side) infrastructure manufacture, which would be equipped with roadside cameras, 4G/WLAN, roadside processing unit, roadside communication devices, underground sensors, information release unit, etc. Roadside cameras are needed for red light violation detection, traffic flow detection, license plate automatic recognition, accident detection and recognition, etc. 4G/WLAN is exploited to transmit data of CAN-BUS and GPS to control center and transmit control commands to actual self-driving vehicles. The roadside processing unit is to store and process data from vehicular videos and roadside cameras, and then to transmit these data to control center through optical fiber. Communications between vehicles and road(side) infrastructure are implemented by road(side) communication devices. Traffic flow detection could be completed by underground sensors and cameras. Real-time information of accident and road maintenance is released to vehicles by information module.

C. Information Transmission

There are several unique characteristics in vehicular communications, such as short-time events, increases in traffic communications in congested areas, and data annotation, etc. Based on different scenarios, different communication techniques are needed. For the data transmission between road(side) infrastructure and parallel control center, optical fiber transmission would be the best choice for better reliability and higher transmission rate. Correspondingly, for V2V and V2I communications, wireless communication technologies are necessary. The development of wireless communications would be able to guarantee the vehicles to promptly obtain up-to-date traffic information and vehicle-shared information accurately, for example, massive MIMO, ultra-dense networking, all spectrum access, full duplex, device to device communications, and so on.

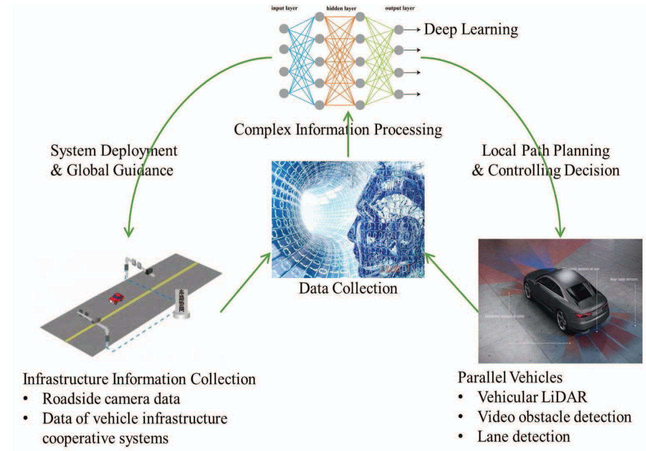

Fig. 6. The task allocation of PAVE system.

D. Task Allocation

The proposed PAVE aim at investigating the advantages of software-defined vehicles, road(side) infrastructure and parallel control center, as shown in Fig. 6. The goal is to realize "local simple" by "remote complex". Parallel control center is responsible for the global/local path planning, control system optimization, and status monitoring of self-driving vehicles; road(side) infrastructures collect the information of vehicle&infrastructure cooperative systems, transmit and process vehicular video data, and take charge of red light violation, traffic flow/accident detection, automatic vehicle license plate recognition, road condition monitoring, information dissemination, and so on. Actual software-defined self-driving vehicles support real-time and actionable analysis and processes, such as lane/traffic signs detection and recognition, moving and stationary object detection and recognition, real-time localization and navigation, real-time local path planning and vehicle control including steering control system, accelerator control system, brake control system.

By the interactions between the actual self-driving vehicles and artificial ones, the proposed PAVE in this paper could provide methods, theoretical models and specific algorithms to optimize the performance and to reduce the cost by balancing the workload among the aforementioned three main components. Meantime, the feedback information and data from the actual system would also help to modify and optimize the artificial self-driving vehicles for further approaching and effectively predicting the status and behaviors of actual self-driving vehicles.

V. CONCLUSIONS

This paper proposed the fundamental architecture of PAVE based on the ACP approach. PAVE would be a new generation of self-driving vehicles by the aid of artificial vehicles (iVehicles) based on big data of traffic and vehicles, computational experiments to predict the future status, and parallel execution to adjust/improve future PAVE system architecture. Unlike traditional self-driving vehicles, the proposed PAVE include low-cost software-defined self-driving vehicles, intelligent road(side) infrastructure, and remote parallel processing&control center supported by data mining and machine learning. It would not only significantly improve traffic safety and driving experience, but also could reduce the cost for self-driving vehicles. Finally, it would truly realize V2X interaction, multi-vehicle collaboration, parallel control, and safe trips.

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