From Software-Defined Vehicles to Self-Driving Vehicles: A Report on CPSS-Based Parallel Driving

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Abstract—On June 11th, 2017, the 28th IEEE Intelligent Vehicles Symposium (IV'2017) was held in Redondo Beach, California, USA. As one of the 8 workshops at IV'2017, the cyber-physical-social systems (CPSS)-based parallel driving (WS'08), organized by the State Key Laboratory for Management and Control of Complex Systems (SKL-MCCS), Institute of Automation, Chinese Academy of Sciences, China, Xi'an Jiaotong University, China, Tsinghua University, China, Indiana University-Purdue University Indianapolis, USA, and Cranfield University, U.K, has attracted both researchers and practitioners in intelligent vehicles. About 60-70 participants from various countries had extensive and deep discussions on definition, challenges and alternative solutions for CPSS-based parallel driving, and widely agreed that it is a novel paradigm of cloud-based automated driving technologies. Six speakers shared their ideas, studies, field applications, and vision for future along these emerging directions from software-defined vehicles to self-driving vehicles.

I. Introduction

Self-driving vehicles have been one of the significant applications within the field of intelligent transportation systems (ITS). A variety of research projects have advanced the enabling technologies in environmental perception and vehicle control and have produced experimental implementations to show how automation technologies could be applied to self-driving vehicles. These have led to major demonstrations all over the world, which have attracted intermittent attention. There has been ongoing academic research as well, largely out of sight of the general public. Currently, the integration of more and more sensors, such as camera, radar, GPS, and communication network technologies, opens up a whole new design space for self-driving vehicles. The concept of future self-driving vehicles does not represent only a vision, but a viable reality due to a new class of emerging wireless ad hoc networks for vehicular environment.

Great efforts have been made to improve driving safety by applying advanced and complicated technologies and high-precision equipments, which result in the increasing cost of self-driving vehicles. However, if simple technologies and conventional equipments are used, driving safety would be cut down for cost reduction. Hence, vehicles are no longer isolated mechanical machines used solely for transportation. They are connected through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, i.e., connected vehicles. Connected vehicles mean applications, services and technologies that connect a vehicle to other vehicles and its surroundings. Currently, wireless communication technologies including WAVE, UMTS, WiMAX, and LTE-V, are subsequently offering a foundation for the development of the next generation of telematics technology. Conventional Vehicular Ad Hoc Networks (VANETs) [1], [2] are evolving into the Internet of Vehicles (IoV) [3], [4]. The former focuses on information transmission among vehicles; while the latter integrates humans and vehicles, that is, IoV interconnects vehicles and humans within and around vehicles. By using intelligent systems on vehicles and different cyber-physical systems, IoV combines sensors, vehicles and mobile devices to create a global network system. The main target of IoV is to combine multiple users, vehicles, things and networks to consistently provide the high-quality, controllable, manageable, operational and credible connection.

However, due to the inseparable relationship between self-driving vehicles and pedestrian/passengers, social-based relationships and mobility aspects of vehicles and pedestrian have been attracted great attention [5]–[9]. It can be well foreseen that in the coming two to four decades (e.g. up to 2050), the road transportation system would be consisting of a mix of connected vehicles with different levels of automation, which necessitates a unified approach for future smart and safe driving. This considerably motivates the development of cyber-physical-social systems [10], [11] (CPSS)-based parallel driving. It would be the best approach to achieve the optimal balance between safety and cost.

As known, the management and control of self-driving systems are commonly static and offline based on mathematical modeling, computation and simulations. However, it is not easy to derive accurate models for complex self-driving systems to test, evaluate and predict the short-term and long-term actions. The artificial societies, computational experiments and parallel execution (ACP) approach was originally proposed for the purpose of modeling, analysis, management and control of complex systems [12]. Along with ACP-based parallel management and control and its wide real-world applications in the past decade [13]–[19], CPSS-based parallel driving has been steadily developed [20], [21]. This is also greatly correlated with the emerging development in connected and automated vehicles. This workshop aims to compile the latest research and development advances in CPSS-based parallel driving, and to present and highlight the emerging new technologies in connected and automated vehicles in China [22]–[27].

II. CPSS-Based Parallel Driving

A. The Workshop

The participants of the workshop agreed that CPSS-based parallel driving, as a new paradigm in intelligent vehicles (IV), will emerge as a new and great direction for IV. The study of parallel driving will provide us with more reliable, safe and low-cost vehicles, and comfortable scenarios if we can use the related strategies and techniques effectively and efficiently.

Six lecturers shared their research and studies from various perspectives in this new area (Fig. 1). The first talk is "Parallel Vehicles Based on the ACP Theory: Safe Trips via Self-Driving" as shown in Fig. 2(a) [22]. 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

FIG 1 Organizers and lecturers of the workshop.

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 equipment on the actual self-driving vehicles via remote processing and intelligent road(side) infrastructure, and also achieve significantly improved safety and reliability via remote control, guidance and planning.

The second talk, from University of Michigan, USA, is titled by "How safe is safe enough?—Evaluation and testing of intelligent vehicles" as shown in Fig. 2(b) [23]. It is necessary to thoroughly evaluate the safety of Automated Vehicles (AVs) before their release and deployment. Current evaluation approach mainly relies on i) testing AVs on public roads or ii) track testing with scenarios defined in a

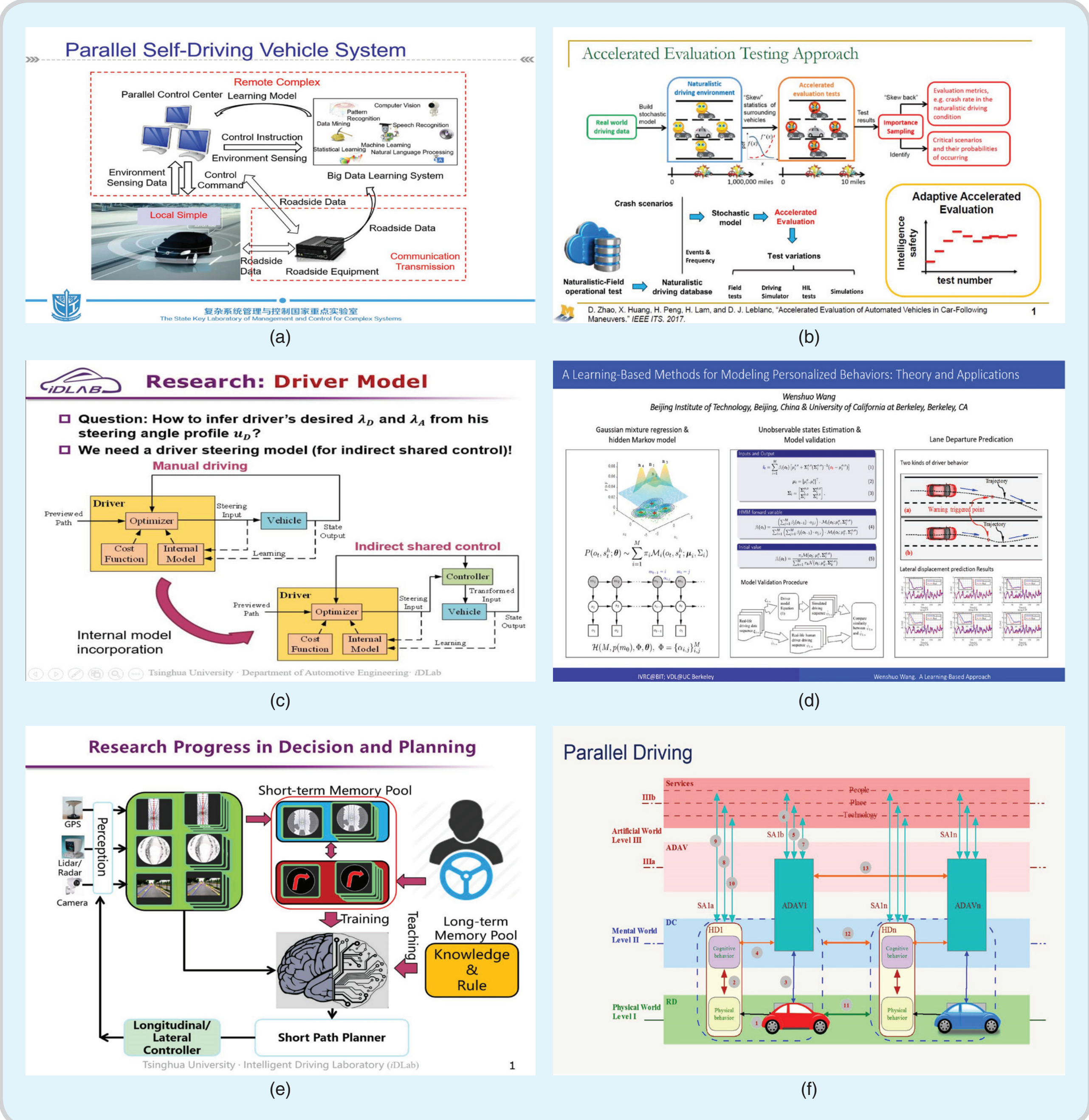

FIG 2 The main idea of the six talks during the workshop.

test matrix. These two methods have completely opposite drawbacks: the former takes too much time to execute but is realistic; and the latter can be finished in a short time but has no clear correlation to the safety benefits in the real world.

To avoid the aforementioned problems, they propose the Accelerated Evaluation approach focusing on the lane change and car-following scenarios. The stochastic human-controlled vehicle (HV) motions were modeled based on 1.3 million miles of naturalistic driving data collected by the University of Michigan Safety Pilot Model Deployment Program. The statistics of the HV behaviors were modified to generate more intense interactions between HVs and AVs to accelerate the evaluation procedure. The Importance Sampling theory was used to ensure that the safety benefits of AVs is accurately assessed under accelerated tests. Crash, injury and conflict rates for a simulated AV are simulated to demonstrate the proposed approach. Results show that the test duration is reduced by a factor of 300 to 100,000 compared with the non-accelerated (naturalistic) evaluation. In other words, the proposed techniques have great potential to accelerate the AV evaluation process. Hardware-based validation progress at UofM will also be introduced in the presentation.

The third talk, from Tsinghua University, is titled by “Driver-Automation Indirect Shared Control of Highly Automated Vehicles with Intention-Aware Authority Transition” as shown in Fig. 2(c) [24]. Shared control is an important approach to avoid the driver-out-of-the-loop problems brought by imperfect autonomous driving. Steer-by-wire technology allows the mechanical decoupling between the steering wheel and the road wheels. On steer-by-wire vehicles, the automation can join the control loop by correcting the driver steering input, which forms a new paradigm of shared control. The new framework, under which the driver indirectly controls the vehicle through the automation’s input transformation, is called indirect shared control. This paper presents an indirect shared control system, which realizes the dynamic control authority allocation with respect to the driver’s authority intention. The simu-

FIG 3 Map of Intelligent Vehicle Proving Center (iVPC).

lation results demonstrate the effectiveness and benefits of the proposed control authority adaptation method.

The fourth talk, from University of California, Berkeley, USA, presented about "A learning-based method for modeling personalized driver behaviors: theory and application" as shown in Fig. 2(d) [25]. Modeling and understanding driver behaviors bring great challenges for developing ADASs and interactions between human-driven vehicles and autonomous vehicles. In this talk, a learning-based method is shown, where the model structure is established by combing Gaussian mixture model and hidden Markov model. Two case studies in terms of modeling and predicting lateral and longitudinal driver behaviors (i.e., lane departure behavior) are respectively given to show the benefits of our proposed methods.

The fifth talk discussed the recent technical progress in Tsinghua University on transforming driver assistance systems to autonomous vehicles as shown in Fig. 2(e) [26]. The design of autonomous vehicles is to replace the drivers perception, decision, and manipulation with sensors, controllers and actuators. Any design becomes more challenging when coming to China, especially considering the complexity of mixed traffic, irregularity of road environments, and randomness of driver behaviors. This presentation will talk about new arising challenges and opportunities in autonomous vehicles, especially when facing the complex road environments, driver behaviors, and traffic flow in China. It also talks about main technical progress in Tsinghua University in terms of environmental perception, decision making and dynamical control for autonomous vehicles.

The last talk, from Indiana University-Purdue University Indianapolis, USA, Qingdao Academy of Intelligent Industries, China, and University of Chinese Academy of Sciences, China, presented "Parallel Driving: A Novel Paradigm of Cloud-based Unmanned Driving Technologies" as

FIG 4 Parallel testing system.

shown in Fig. 2(f) [27]. Unmanned vehicles and internet of vehicles are two main topics of the current R&D of intelligent vehicles. How to integrate the technical aspects of these two areas puts forward a big challenge. ACP theory-based parallel driving framework provides a novel solution to enable cloud-based unmanned driving technologies. This talk introduces the latest research progress, technology development, and application examples of parallel driving systems and their subsystems.

B. The Applications

In 2013 and 2014, two consecutive "intelligent vehicles future challenges (IVFC)" were successfully held by the Changshu Municipal People's Government, Xi'an Jiaotong University, Institute of Automation, Chinese Academy of Sciences, Changan University, and Qingdao Intelligent Industry Technology Research Institute, in High-tech Industrial Development Zone, Changshu City, Jiangsu Province. They then jointly set up Intelligent Vehicle Proving Center (iVPC). The iVPC is positioned as the platform of science and technology innovation platform, public technical service platform and technology trading platform of China Intelligent Automobile Industry. iVPC has owned CNY 150M investment in 3 years, 20000 m^2 static testing area, 350000 m^2 proving ground and 2M m^2 expanded testing area (Fig. 3).

After the establishment of iVPC, the seventh and the eighth IVFC were successfully held in 2015 and 2016, respectively. CPSS-based parallel driving testing and evaluation methods (Fig. 4) have been exploited during the eighth IVFC in 2016.

C. The Perspectives

Currently, significant R&D work on CPSS-based parallel driving system has been finished. Now, it is focusing on the R&D of control&prediction algorithms, intelligent road(side) system and vehicle/road sensors. Based on the parallel approach and the ACP theory, CPSS-based parallel driving system consists of front-end intelligent vehicles&infrastructures and background service platform, which are software-defined self-driving vehicle system and remote control system, respectively. The former mainly focus on environment sensing and intelligent vehicle control, etc. The latter is for artificial intelligence, machine learning, and deep learning, etc. By the theoretical foundation and technical support, CPSS-based parallel driving system would be manufactured for different functional modules, such as parallel self-driving logistics vehicles, parallel self-driving bus, parallel self-driving taxi, parallel self-driving subway and so on.

The 2018 IEEE Intelligent Vehicles Symposium (IV'18) will be held in Changshu, Suzhou, China, on June 26-July 1, 2018. Together with IV'18, the Chinese Tenth Intelligent Vehicles Future Challenge (IVFC 2018, June 30-July 1, 2018) will be held at Intelligent Vehicle Proving Center, Changshu, Suzhou, China. Demonstration and Exhibition related the intelligent vehicles are also welcome.

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