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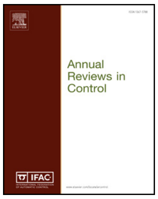

Control of connected and automated vehicles: State of the art and future challenges

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ABSTRACT

Autonomous driving technology pledges safety, convenience, and energy efficiency. Its challenges include the unknown intentions of other road users: communication between vehicles and with the road infrastructure is a possible approach to enhance awareness and enable cooperation. Connected and automated vehicles (CAVs) have the potential to disrupt mobility, extending what is possible with driving automation and connectivity alone. Applications include real-time control and planning with increased awareness, routing with micro-scale traffic information, coordinated platooning using traffic signals information, and eco-mobility on demand with guaranteed parking. This paper introduces a control and planning architecture for CAVs, and surveys the state of the art on each functional block therein; the main focus is on techniques to improve energy efficiency. We provide an overview of existing algorithms and their mutual interactions, we present promising optimization-based approaches to CAVs control and identify future challenges.

1. Introduction

Autonomous driving has been the object of great research efforts in the last decades. Human errors are a prominent cause of road accidents and fatalities. Road congestion causes inefficiency in daily commutes and other aspects of road transportation. A transportation system that is less reliant on human drivers allows all the passengers to better use their traveling time and is associated with fewer road accidents.

While the idea has been around for almost a century, it was in the 1980s that the technological advances in sensing and computing made it realistic. Much of the early research on automated driving was in the field of automated highway systems. The California PATH program, started in 1986, demonstrated automated driving on four vehicles on the I-15 in San Diego in 1994 (Shladover, 2007; Shladover et al., 1991). Other early successes were the PROMETHEUS project (Dickmanns, 1997; Dickmanns & Graefe, 1988) and the CMU NAVLAB (2018), that demonstrated the capability of driving for hundreds of miles with minimal human intervention. More recently, various research groups have committed to demonstrations of autonomous driving in a variety of scenarios, including the DARPA Grand Challenge in 2004 (Buehler, Iagnemma, & Singh, 2007), the DARPA Urban Challenge in 2007 (Buehler, Iagnemma, & Singh, 2009), the Intelligent Vehicle Future Challenge (Xin, Wang, Zhang, & Zheng, 2014), the Hyundai Autonomous Challenge in 2010 (Cerri et al., 2011), the VisLab Intercontinental Autonomous Challenge in 2010 (Broggi et al., 2012), the Public Road Urban Driverless Car Test in 2013 (Broggi et al., 2015), and the autonomous drive on the Bertha Benz historic route (Ziegler et al., 2014).

With a substantial body of knowledge and continuous improvements in perception technologies and computational power, autonomous driving features are being slowly introduced in everyday life. While all major brands have introduced advanced driving assistance systems, such as adaptive cruise control and automatic emergency braking, massive research efforts are being put into self-driving cars. The list of players includes manufacturers such as Tesla (Autopilot Tesla, 2018), Ford (Ford Autonomous 2021, 2018), and GM (Cruise Automation, 2018), suppliers such as Bosch (Self-driving car technology Bosch Global, 2018) and Delphi (nuTonomy-Home, 2018), and tech corporations such as Google (Waymo, 2018) and Uber (Self-Driving Cars Uber, 2018). The SAE standard J3016 (Taxonomy & Definitions, 2014) has classified six levels of driving automation, from level 0 (a human-driven vehicle) to level 5 (full autonomy in any driving scenario).

Vehicle connectivity has also been maturing in the past decades. Connectivity enables many convenience features and services, including emergency calls, toll payment, and infotainment. Connectivity has also emerged as a technology to improve safety, performance, and enable vehicle cooperation: in the aforementioned California PATH program (Shladover, 2007; Shladover et al., 1991), the concept of *platoon* (a group of vehicles traveling at small spacing) was

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demonstrated as a way to increase the throughput of automated highways. Vehicle-to-Vehicle (V2V) communication was used to coordinate multi-vehicle maneuvers, and - once a formation was established - to exchange vehicle states, enabling short headway time between vehicles. Other demonstrations of cooperative driving took place in the Demo 2000 program in Japan in 2000 (Kato, Tsugawa, Tokuda, Matsui, & Fujii, 2002), the Grand Cooperative Driving Challenge in 2011 and 2016 in the Netherlands (Englund et al., 2016; van Nunen, Kwakkernaat, Ploeg, & Netten, 2012), the SARTRE program (Robinson, Chan, & Coelingh, 2010), and the Energy-ITS program started in 2008 in Japan (Tsugawa, Kato, & Aoki, 2011).

Internet connectivity is now present in several vehicles, and the Dedicated Short Range Communication (DSRC) technology has been adopted for V2V and Vehicle-to-Infrastructure (V2I) applications by manufacturers such as Cadillac (V2V Safety Technology Now Standard on Cadillac CTS Sedans, 2017) and Audi (Audi, 2018), and transposed by the SAE in the J2735 standard (Message Set Dictionary(2016), DSRC). Developments in 5G technologies might also support V2I and even V2V communication in the future.

Connected and Automated Vehicles (CAVs) have the potential to extend what is possible with driving automation and vehicle connectivity alone. Connectivity has the potential to dramatically improve environment awareness, and thus safety, of autonomous vehicles, in spite of the limitations of perception systems. Autonomous vehicles can make full use of connectivity, especially fast V2V communication (10Hz or more) and V2I forecasts. CAVs enable a variety of applications in intelligent transportation systems, including traffic control, cooperative driving, improved safety, and energy efficient driving (Knight, 2015), although the power consumption of the sensing, computing and communication equipment of CAVs needs to be taken into account (Gawron, Keoleian, De Kleine, Wallington, & Kim, 2018).

This survey is focused on a control and planning architecture for CAVs, and particularly on approaches for the improvement of energy efficiency. We review the state of the art for the most relevant functional blocks of this architecture, including real-time controls, real-time motion planning, eco-driving, multi-vehicle coordination, and routing. To limit the scope of this survey, we focus on vehicle controls rather than traffic control, although, in some multi-vehicle applications, the difference is blurred. For the same reason, we dismiss the aspects of perception and environment prediction, both crucial parts of any autonomous driving control architecture.

The remainder of this paper is structured as follows. In Section 2 we describe the main components of a typical CAV system. In Section 3 we describe the control and planning architecture that is the scope of the paper. In Section 4 we survey the state of the art for real-time control and planning algorithms, that are generally implemented on-board. In Section 5 we survey the literature on longer-term planning and routing algorithms, that are generally implemented remotely. Some concluding remarks end the paper.

2. System components

As shown in Fig. 1, the successful deployment of CAVs in an intelligent transportation system depends both on the on-board instrumentation and on the surrounding environment, i.e. the road infrastructure (including signalized intersections, ramp meters, road signs) and the other road users (including other CAVs, non-cooperative vehicles, cyclists, and pedestrians). In this section, we give a brief overview of CAVs and the agents they interact with. While not strictly focused on algorithmic aspects, this short digression helps to evaluate the significance and technical soundness of the algorithms discussed later.

2.1. Connected and automated vehicle

We define as Connected and Automated Vehicle (CAV) a vehicle

Fig. 1. Cartoon depicting a variety of intelligent transportation systems on highway, arterial and urban roads enabled by connected and automated vehicles (CAVs). Each number refers to a CAV application discussed next. Communication with other vehicles enables (1) augmented awareness, (2) platooning, and (3) cooperative maneuvers. Communication with the infrastructure enables (4) enhanced approach and departure to signalized intersections. Cloud connectivity enables access to databases, forecasts, and remote computations. On-board perception, localization and maps are fundamental to navigate in known and unknown environments, that can include non-connected vehicles, cyclists, pedestrians. Traffic light controllers and in-roadway sensors (5) generate signal phase and timing (SPaT) and vehicle occupancy and speed (VOS) data, that can be stored in the cloud. Other applications include coordination of grid charging, parking, road works (6). (Created on https://icograms.com).