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Review

Autonomous vehicle perception: The technology of today and tomorrow

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ABSTRACT

Perception system design is a vital step in the development of an autonomous vehicle (AV). With the vast selection of available off-the-shelf schemes and seemingly endless options of sensor systems implemented in research and commercial vehicles, it can be difficult to identify the optimal system for one's AV application. This article presents a comprehensive review of the state-of-the-art AV perception technology available today. It provides up-to-date information about the advantages, disadvantages, limits, and ideal applications of specific AV sensors; the most prevalent sensors in current research and commercial AVs; autonomous features currently on the market; and localization and mapping methods currently implemented in AV research. This information is useful for newcomers to the AV field to gain a greater understanding of the current AV solution landscape and to guide experienced researchers towards research areas requiring further development. Furthermore, this paper highlights future research areas and draws conclusions about the most effective methods for AV perception and its effect on localization and mapping. Topics discussed in the Perception and Automotive Sensors section focus on the sensors themselves, whereas topics discussed in the Localization and Mapping section focus on how the vehicle perceives where it is on the road, providing context for the use of the automotive sensors. By improving on current state-of-the-art perception systems, AVs will become more robust, reliable, safe, and accessible, ultimately providing greater efficiency, mobility, and safety benefits to the public.

1. Introduction

Autonomous vehicle (AV) technology is making a prominent appearance in our society in the form of advanced driver assistance systems (ADAS) in both research and commercial vehicles. These technologies aim to reduce the amount and severity of accidents, increase mobility for people with disabilities and the elderly, reduce emissions, and use infrastructure more efficiently (Fagnant and Kockelman, 2015). One of the major motivations accelerating the advancement of AV technologies is their insusceptibility to human-related errors, such as distraction, fatigue, and emotional driving, which currently cause approximately 94% of accidents according to a statistical survey completed by the National Highway Traffic Safety Administration (NHTSA) (Singh, 2015).

As research, testing, and deployment of vehicles with AV technology is escalating around the world, the development of standardized guidelines and regulations has become a major focus to ensure safe integration into society. The U.S. Department of

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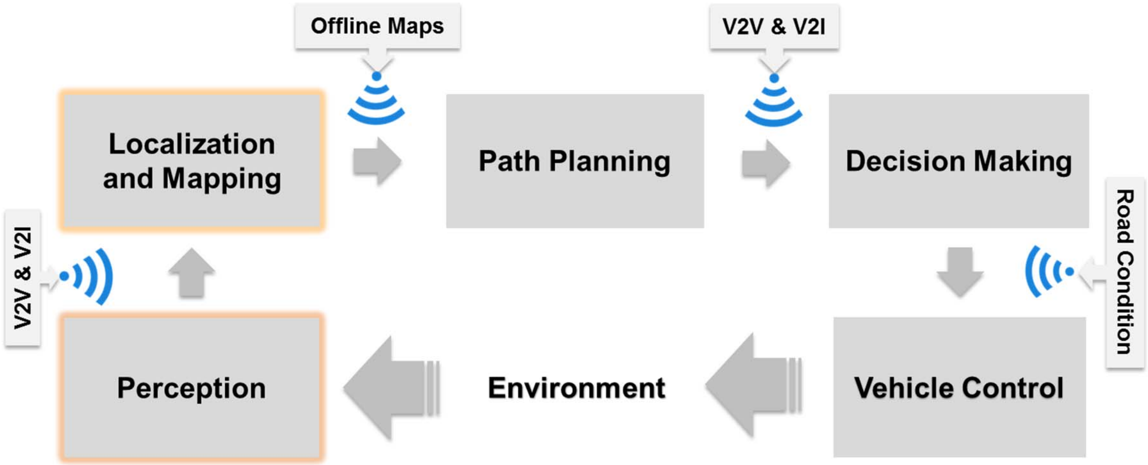

Fig. 1. Overview of the autonomous navigation process.

Transportation and the NHTSA have recently adopted the Society of Automotive Engineers international standard for automation levels which define autonomous vehicles from Level 0 (the human driver has full control) to Level 5 (the vehicle completely drives itself) (Transportation, 2016). Currently, due to limitations and high costs of available sensors, most commercial vehicles only include Level 1 to Level 2 autonomy, which require constant driver attention and control. The autonomous features in these vehicles generally consist of emergency braking, blind spot detection, and/or lane keeping. Nonetheless, Level 3 autonomous features are available in the Tesla Model S and Model X. However, recent accidents have initiated concerns regarding the drivers' understanding and capability of using the technology safely (Krisher and Durbin, 2016).

Presently, a major concern is the occurrence of new, unsafe driving practices as a result of drivers who do not understand or are not aware of how the AV technologies work (Kyriakidis et al., 2017; Lu et al., 2016). Furthermore, in order for autonomous features and vehicles to have significant, far-reaching effects in improving safety, mobility and efficiency, the public must understand the capabilities of the technology (Kyriakidis et al., 2015, 2017; Lu et al., 2016). This includes important factors such as the limitations of the technology, the application for the technology, and the appropriate scenarios to use and/or rely on the technology.

As a brief overview, autonomous vehicle navigation can be visualized as five main components (Fig. 1): Perception, Localization and Mapping, Path Planning, Decision Making, and Vehicle Control (Cheng, 2011). Perception uses sensors to continuously scan and monitor the environment, similar to human vision and other senses (Maurer et al., 2016). Localization and mapping algorithms calculate the global and local location of the ego-vehicle and map the environment from sensor data and other perception outputs (Maurer et al., 2016). Path planning determines possible safe routes for the ego-vehicle based on perception, and localization and mapping information (Katrakazas et al., 2015). The decision-making component is responsible for calculating the optimal route based on the possible paths, the current vehicle state, and the environment information (e.g., road attributes, weather conditions, road signs, etc.) (Maurer et al., 2016). The vehicle control module will then calculate the appropriate vehicle command (torque, acceleration, steering wheel angle, etc.) in order to follow the optimal route decision, such as a lane change, a right turn, or another maneuver (Gruyer et al., 2016b). It is important to note that the autonomous navigation process is a high frequency recursive process. This allows AVs to effectively handle high-speed motion and dynamic objects, such as pedestrians, motorcycles, and cars (Julier and Durrant-Whyte, 2003). An overview of the autonomous navigation process is shown in Fig. 1. This paper will focus on the "Perception" and "Localization and Mapping" stages.

This paper aims to provide a comprehensive review of the state-of-the-art AV perception technology to address a lack of synthesized information about sensor, hardware, and algorithm requirements for effective AV perception. In general, robust and reliable perception, and localization and mapping are required in order to make accurate and reliable decisions for vehicle control. This paper provides a review of the current sensor technology used for perception, as well as an overview of the methods used for localization and mapping.

In essence, this paper aims to answer the following questions:

- Which sensors are currently used in prominent research and commercial vehicles?
- What are the current advantages and shortcomings of the sensors?
- Which localization and mapping techniques are being used in research and commercial vehicles with respect to sensing the ego-vehicle's environment?
- What are the shortcomings of these localization and mapping methods and how can they be improved?
- What are the current areas of research that need to be addressed?
- How will this technology evolve in the future?

The paper is organized as follows. Section 2 introduces the background of AV research. Section 3 discusses the capabilities and