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Real-time motion planning methods for autonomous on-road driving: State-of-the-art and future research directions

Christos Katrakazas [a], Mohammed Quddus [a,*], Wen-Hua Chen [b,1], Lipika Deka [a]

[a] School of Civil and Building Engineering, Loughborough University, Loughborough LE11 3TU, United Kingdom
[b] School of Aeronautical and Automotive Engineering, Loughborough University, Loughborough LE11 3TU, United Kingdom

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ABSTRACT

Currently autonomous or self-driving vehicles are at the heart of academia and industry research because of its multi-faceted advantages that includes improved safety, reduced congestion, lower emissions and greater mobility. Software is the key driving factor underpinning autonomy within which planning algorithms that are responsible for mission-critical decision making hold a significant position. While transporting passengers or goods from a given origin to a given destination, motion planning methods incorporate searching for a path to follow, avoiding obstacles and generating the best trajectory that ensures safety, comfort and efficiency. A range of different planning approaches have been proposed in the literature. The purpose of this paper is to review existing approaches and then compare and contrast different methods employed for the motion planning of autonomous on-road driving that consists of (1) finding a path, (2) searching for the safest manoeuvre and (3) determining the most feasible trajectory. Methods developed by researchers in each of these three levels exhibit varying levels of complexity and performance accuracy. This paper presents a critical evaluation of each of these methods, in terms of their advantages/disadvantages, inherent limitations, feasibility, optimality, handling of obstacles and testing operational environments.

Based on a critical review of existing methods, research challenges to address current limitations are identified and future research directions are suggested so as to enhance the performance of planning algorithms at all three levels. Some promising areas of future focus have been identified as the use of vehicular communications (V2V and V2I) and the incorporation of transport engineering aspects in order to improve the look-ahead horizon of current sensing technologies that are essential for planning with the aim of reducing the total cost of driverless vehicles. This critical review on planning techniques presented in this paper, along with the associated discussions on their constraints and limitations, seek to assist researchers in accelerating development in the emerging field of autonomous vehicle research.

1. Introduction

Autonomous vehicles are a promising evolution of current vehicle technology and advanced driver assistant systems, and are envisaged to be the sustainable future for enhanced road safety, efficient traffic flow and decreased fuel consumption, while improving mobility and hence general well-being (e.g. Thrun, 2010; Burns, 2013; Le Vine et al., 2015). Research on

* Corresponding author. Tel.: +44 (0) 1509228545.
E-mail addresses: c.katrakazas@lboro.ac.uk (C. Katrakazas), m.a.quddus@lboro.ac.uk (M. Quddus), w.chen@lboro.ac.uk (W.-H. Chen), l.deka@lboro.ac.uk (L. Deka).
[1] Tel.: +44 (0)1509 227 230.

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autonomous vehicles has been growing rapidly in recent years and encompasses different domains, including robotics, computer science, and engineering. Moreover, it should be noted that scientific advances have been made by car manufacturers who do not always publicly disclose the details on their approaches or algorithms, owing to commercial sensitivity.

Critical decision making is the key to autonomy and is realised through planning algorithms, incorporated within the middleware of an autonomous vehicle's navigation, situation understanding and decision making module. The main purpose of planning is to provide the vehicle with a safe and collision-free path towards its destination, while taking into account the vehicle dynamics, its manoeuvre capabilities in the presence of obstacles, along with traffic rules and road boundaries (Zhang et al., 2013). Planning is a memory consuming as well as a computationally intensive routine, which is run in parallel with other routine operations of the vehicle (e.g. obstacle tracking, data fusion and control modules). The inputs and outputs of a motion planning normally depend on these other modules. Reliable, robust and adaptable planning is essential, especially in an urban mixed traffic scenario. These algorithms receive inputs from the sensor framework and supplement these inputs with data from digital road maps in order to provide a full workspace in which the planning takes place.

Existing planning algorithms originate primarily from the field of mobile robotics, and have subsequently been applied to different on-road and off-road vehicles and operational environments (e.g. desert vehicles) (Thrun et al., 2006), planetary rovers (Pivtoraiko and Kelly, 2009) and buses (Fernandez et al., 2013). Furthermore, a large number of algorithms have been developed for non-holonomic and car-like robots planning in abstract, simulation-based environments (e.g. Scheuer and Fraichard, 1997). In the review presented in this paper, only approaches concerned with planning for on-road autonomous vehicles are analysed. In general, planning for autonomous or intelligent driving is divided into four hierarchical classes, as suggested by Varaiya (1993): (1) route planning, (2) path planning, (3) manoeuvre choice and (4) trajectory planning (termed as control planning in the work of Varaiya). Route planning is concerned with finding the best global route from a given origin to a destination, supplemented occasionally with real-time traffic information. Route planning is not within the scope of this paper and readers are referred to Thorpe and Durrant-Whyte (2009) for details on a route planner. Path, manoeuvre and trajectory planning components of autonomous on-road driving (often combined as one) take vehicular dynamics, obstacles, road geometry and traffic interactions into account, and are the main focus of this paper. It is important to emphasise that this paper presents a state-of-the-art review of motion planning techniques based on the works after the DARPA Urban Challenge (DUC) in 2007 (Thorpe and Durrant-Whyte, 2009) and is intended to serve as a key reference for researchers who are conducting research on the domain of autonomous vehicles. The focus on studies after the DUC is given because the challenge was a milestone in autonomous driving and resembles the state-of-the-art work until 2007, thus enabling research in autonomous driving to profoundly advance. The novelty of this work lies in the fact that, even though autonomous vehicles are at the core of technological research now-a-days and many attempts have focused on motion planning techniques for mobile robots, to our knowledge, no other work compares and contrasts the approaches concerning planning in all three levels (i.e. path, manoeuvre, trajectory) simultaneously for autonomous on-road driving.

The remainder of the paper is structured as follows: foundational definitions form the body of Section 2; while Section 3 presents an extensive literature review of motion planning approaches applied to autonomous vehicles, followed by their specific characteristics. Key limitations of the approaches are then described in Section 4. Finally, in Section 5 the paper discusses future research directions in order to overcome identified challenges.

2. Definitions

2.1. Definition of planning in the context of autonomous driving

This section describes the key conceptual terms commonly used in the literature within the field of planning for robots and, hence, autonomous vehicles. As mentioned previously, this paper focuses on planning at a local on-road level and not globally (e.g. routeing).

The set of independent attributes which uniquely define the position and orientation of the vehicle according to a fixed coordinate system is termed the *configuration* vector (Eskandarian, 2012). Consequently, the set of all the configurations of the vehicle constitute the *configuration space*.

The set of attribute values describing the condition of an autonomous vehicle at an instance in time and at a particular place during its motion is termed the '*state*' of the vehicle at that moment (Eskandarian, 2012). The most common set of attributes, defined as a vector, which are used to express the state of a vehicle are the position (x, y, z), the orientation $(\theta_x, \theta_y, \theta_z)$, linear velocities (v_x, v_y, v_z) and angular velocities $(\omega_x, \omega_y, \omega_z)$. Subsequently, *state space* represents the set of all possible states that a vehicle can be in. As will be seen in the next sections, the mathematical representation of a *state space* differs from the approach taken by vehicle planning. A trade-off between explicit representation and efficiency of the algorithms should be considered for every planning problem. Representations that can be used for constructing a configuration or a state space will be discussed in Section 2.2.

The *bicycle model* is a dynamic/kinematic model of vehicles, in which the two front and rear wheels are replaced by one front and one rear wheel respectively. The vehicle moves on the plane and its coordinates are described by the vector (x, y, θ) where x, y is the position of the centre of gravity and θ is the orientation of the vehicle. Steering angle of the front wheels is denoted by ϕ. A basic assumption of the bicycle model is that the inner slip, outer slip and steer angles are equal.

A robot is *holonomic* if the controllable degrees of freedom are equal to the total degrees of freedom. Cars or car-like robots are thus *non-holonomic* because they are described by 4 degrees of freedom (2 Cartesian coordinates, orientation