Mechatronics xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Real time implementation of socially acceptable collision avoidance of a low speed autonomous shuttle using the elastic band method☆

Haoan Wang[a,c], Antonio Tota[d], Bilin Aksun-Guvenc[a,b,*], Levent Guvenc[a,b,c]

[a] Automated Driving Lab, Center for Automotive Research, Ohio State University, Columbus, OH 43212, USA
[b] Department of Mechanical and Aerospace Engineering, Ohio State University, Columbus, OH 43210, USA
[c] Department of Electrical and Computer Engineering, Ohio State University, Columbus, OH 43210, USA
[d] Department of Mechanical and Aerospace Engineering, Politecnico di Torino, 10129 Torino, Italy

ARTICLE INFO

Keywords:
Socially acceptable collision avoidance
Collision avoidance
Autonomous shuttle
Elastic band method
Hardware-in-the-loop simulation
Road testing

ABSTRACT

This paper presents the real time implementation of socially acceptable collision avoidance using the elastic band method for low speed autonomous shuttles operating in high pedestrian density environments. The modeling and validation of the research autonomous vehicle used in the experimental implementation is presented first, followed by the details of the Hardware-In-the-Loop connected and autonomous vehicle simulator used. The socially acceptable collision avoidance algorithm is formulated using the elastic band method as an online, local path modification algorithm. Parameter space based robust feedback plus feedforward steering controller design is used. Model-in-the-loop, Hardware-In-the-Loop and road testing in a proving ground are used to demonstrate the effectiveness of the real time implementation of the elastic band based socially acceptable collision avoidance method of this paper.

1. Introduction

Autonomous driving has been divided into six categories with Level 0 being a non-automated and Level 5 being a fully autonomous vehicle according to the Society of Automotive Engineers [1]. Currently available automated driving technology falls under Level 2 and Level 3 which are partial and conditional automation, respectively. Level 2 partial automation is available in series production vehicles with lane centering control for steering automation and adaptive cruise control and collision avoidance for automation in the longitudinal direction. Partial automation is characterized by all driving actuators being automated and the presence of a driver who can intervene when necessary. Recently introduced autopilot systems for cars are examples of conditional automation where the car takes care of driving in some driving modes (like highway driving) but the human operator is always in the driver seat to take over control if necessary. Level 3 autonomous highway driving systems in which almost all highway driving functions are carried out autonomously with the driver needing to take over only if something goes wrong are expected to reach series production by 2020. A Level 4 autonomous highway driving extension in which the driver is still in the driver seat while the vehicle can perform highway driving completely autonomously, without the need for driver interaction, is expected to enter the market around 2025. In future Level 5 autonomous driving, there is no need for a driver as the vehicle takes care of all driving tasks autonomously.

Autonomous shuttles in smart cities used for solving the first-mile and last-mile problem form another well-known, emerging application of autonomous road vehicles that are currently at Level 2 or Level 3. These shuttles operate at relatively lower speeds which definitely improves safety levels. These shuttles operate in significantly less structured environments with unpredictable interaction with vulnerable road users like pedestrians and bicyclists. The roads they follow involve pedestrian crosswalks, intersections with or without traffic lights, roundabouts and sharper turns as lower speed of operation is possible. Successful Level 4 like autonomous driving of these low speed shuttles is possible in fixed routes within blocked traffic environments as all the uncertainties that the vehicle can face are taken out of the picture by using a lane dedicated only to these shuttles (no other traffic) and by using a fixed route. However, a true Level 4 autonomous driving capability of these autonomous shuttles requires autonomous decision making. The most basic and critical decision making is autonomous collision free path planning and collision avoidance maneuvering of these shuttles in a smart city setting where the autonomous shuttles also have to work in areas that are highly populated by groups of pedestrians. A university campus, an outdoor shopping area, downtown areas closed to mainstream traffic are typical examples where low speed

☆ This paper was recommended for publication by Associate Editor K Yi.

* Corresponding author at: Automated Driving Lab, Center for Automotive Research, Ohio State University, Columbus, OH 43212, USA.
E-mail address: aksunguvenc.1@osu.edu (B. Aksun-Guvenc).

https://doi.org/10.1016/j.mechatronics.2017.11.009
Received 2 January 2017; Received in revised form 6 September 2017; Accepted 14 November 2017
0957-4158/

autonomous shuttles have to interact with groups of pedestrians and autonomously plan their collision free paths and avoid collisions with them. This is the main focus of this paper.

Collision free path planning and collision avoidance require situational awareness using the autonomous vehicle perception sensors as was done in the work of Aufrere et al. [2] where a probabilistic collision prediction and warning system was also presented. As compared to reference [2], we concentrate on the collision free path planning and collision avoidance maneuvering rather than perception and situational awareness in the current paper. The collision prediction and warning system in [2] is based on checking all trajectories out of a set of possible ones for collisions. As compared to this brute force approach of reference [2], we use the fact that the road to be followed defines the initial trajectory which should be modified around the obstacle in a natural and simple manner. The elastic band method of collision avoidance used in this paper is not based on checking all possible trajectories and, thus, naturally works faster in real time. Ferrara and Vecchio [3] have formulated collision cones in their work on collision avoidance of vehicle platoons. They have also considered platoon and pedestrian collision risk and have used sliding mode control as their collision avoidance control method. As compared to the simulation only approach of reference [3], this paper concentrates on real experiments in a proving ground and also in a Hardware-In-the-Loop simulator where real time implementation issues are also considered. The sliding mode control of [3] and the parameter space based robust collision free steering of this paper are both robust controllers in the presence of model uncertainty and disturbances. The parameter space based controller of this paper is much easier to implement in real time and results in a characterization of all controller gain combinations with a graphical display of the results in comparison to obtaining only one controller with possible chatter problems in the sliding mode control method of [3]. A collision free path planning and following framework is presented by Khajepour et al. [4] for the collision avoidance of autonomous vehicles. The desired tracking path was generated by a three dimensional virtual potential field based on road and obstacle information in [4]. The elastic band method used in this paper is similar to that in [4] but does not suffer from the singularities of the virtual potential field approach. As the road to be followed results in the trajectory to be followed and forms the original elastic band before deformation about pedestrian(s), the computation is much simpler than trying to find the collision free path within an artificial potential field as in ref. [4].

For the path tracking steering controller design, a Multi-constrained Model Predictive Control (MMPC) optimal problem was formulated and used to prevent collisions with both static and dynamic obstacles [4]. The parameter space based robust steering controller is much easier to design and implement in real time as compared to the MMPC approach of [4]. Fu et al. [5] presented a novel obstacle avoidance algorithm called the navigation circle which is a method for real-time path planning. A collision-free path generated by the navigation circle was optimized through the kinematic model of the autonomous vehicle to obtain a kinematically feasible trajectory in [5]. A real-time path-planning algorithm was proposed by Chu et al. [6] for off-road autonomous driving in the presence of static obstacles. A set of predefined waypoints was used to generate path candidates and each candidate was evaluated using obstacle data. Safety, smoothness and consistency costs were considered during the selection of an optimal path to evaluate the effects of environment uncertainty and vehicle dynamics. The elastic band method of this paper is a much more efficient method computationally and results in a smooth trajectory without having to search over a set of possible trajectories as in refs. [5,6]. The method presented here also uses a social distance for collision free path planning and collision avoidance maneuvering about pedestrian(s). It is also possible to use a conservative pedestrian safety zone in the computations to treat moving pedestrian(s).

Based on the comparisons above, this paper uses the elastic band method for collision avoidance as it is both a relatively easy and natural way of implementing collision free path planning for vehicles following a road and as it can also be operated in real time. In addition, the method also works well if the vehicle is following a path that is not constrained by a road and also the concept of socially acceptable collision avoidance can easily be incorporated into the elastic band method. The elastic band method was first proposed by Quinlan and Khatib [7] for collision free path planning and collision avoidance for mobile robots. The elastic band method was applied to road vehicle collision avoidance by Ararat and Aksun-Guvenc [8]. They presented realistic simulation results with several road vehicles for higher speed highway driving [8]. Driving in city roads involves a mixed traffic environment where there are also pedestrians, i.e. vulnerable road users. In contrast to reference [8], this paper concentrates on low speed autonomous shuttles that operate in large walkways shared with pedestrians. This is a very common situation in university campuses, outdoor shopping areas and downtown areas closed to mainstream traffic. As the autonomous shuttles and pedestrians share the same walkway or road in those cases, a collision avoidance method that also respects the socially acceptable distance around groups of pedestrians is needed. A modified elastic band based collision avoidance method was, therefore, applied in Emirler et al. [9] to avoid collision risk with stationary pedestrian groups while keeping a socially acceptable distance.

This paper is an extension of the earlier work of some of the authors in [8] and [9] and concentrates on real time implementation of the method using an actual vehicle and also considers the case of moving pedestrians. As compared to reference [8], the socially acceptable collision avoidance region was added to the calculations here, similar to the more recent reference [9]. In comparison to reference [9], the method and algorithm had to be modified to be able to work directly with a trajectory of GPS waypoints that were broken down into segments that were fit by cubics. Both of these previous papers [8] and [9] were based on simulation studies. The current paper concentrates on real time implementation of the method. Even though the same elastic band method was used, the algorithm had to be changed for real time implementability. The changes were re-coding of the algorithm to calculate the deformed path only locally around the pedestrian(s) in real time after detection, using analytical expressions for derivatives as compared to numerical differentiation, smoothing the shape of the deformed trajectory to have a more feasible path and equating second derivatives of cubic polynomial fits also (as opposed to polynomial continuity and first derivative) at the intersection of the segments for a smoother transition. In comparison to reference [9], the possibility of moving pedestrian(s) was also considered in a conservative manner by adjusting the corresponding distance $d_{pedestrian}$ to accommodate for this. In this paper, a feedforward plus feedback architecture is used as the steering controller as opposed to use of feedback control alone in [9]. The feedforward controller acts like a human driver and the feedback controller is designed using parameter space robust control methods [10–12].

The concept of *social acceptance* has been widely studied in the robotics area. Chan et al. [13] have defined socially acceptable robotics for object handovers, where a framework was proposed to enable robots to learn proper grasp configurations for handovers through observations. Socially acceptable robotic navigation was introduced and used by Shiomi et al. [14] and Vasconcelos et al. [15]. In crowded areas like shopping malls or other high pedestrian density places, the social distance between pedestrians and robots provide people with comfort and safety. In this paper, the same idea of social acceptance is applied to a low speed autonomous shuttle operating in a smart city for automated collision avoidance in a crowded urban area. Such low speed autonomous shuttles are also used to solve the first mile (access to transportation choice) and last mile (from transportation station to final destination) problems and to help the elderly and people with mobility impairment. As compared to references [13–15], the social distance is incorporated directly into the algorithm which runs in real time and