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A Historical Review on Lateral and Longitudinal Control of Autonomous Vehicle Motions

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***Abstract*— In this research, brief survey of literature on current developments in the field of lateral and longitudinal control of autonomous vehicle motions. The paper categorizes the motions of vehicle to: car following, lane keeping, lane changing, subsequently, longitudinal control (brake and throttle), lateral control (steering) and integration of these controls for autonomous vehicles was investigated. Also different equipment and approaches to control of motions in each field was proposed.**

Keywords-car following, lane keeping, lane changing, lateral control, longitudinal control, autonomous vehicle

I. INTRODUCTION

In recent years, a number of studies have been done on intelligent vehicle highway systems (IVHS) and automated highway system (AHS). There are two basic tasks for vehicle control within an IVHS and AHS. Longitudinal control mainly refers to vehicle speed regulation to maintain adequate spacing between vehicles. On the other hand, lateral control includes automatic vehicle steering to follow a track reference, while maintaining good ride comfort. Longitudinal control involves the vehicle's throttle and brake.

The basic functions of automated longitudinal vehicle control are keeping the vehicle a safe distance behind another vehicle, maintaining a relatively constant speed with the least brake use and applying the brake as fast as possible in emergency situations. Many incidents occur when vehicles rear-end another one because there was not have an enough time for the driver to apply the brakes.

Lateral vehicle control involves the steering of the vehicle. There are two ways to design steering controllers: imitating human drivers and using dynamic models of car and control methods based on linear control theory. The first approach does not need detailed knowledge of car dynamics, much in the way the driver of a car does not. The control-system approach requires detailed knowledge of the dynamics of the car and has to use different algorithms to perform the different maneuvers.

Lateral control keeps the vehicle in the center of the lane (lane-keeping maneuver) and steers the vehicle into an adjacent lane (lane-change maneuver), while maintaining good passenger comfort. Lateral control concerned with lane keeping, turning, lane changing and avoiding objects that might appear in front of the vehicle. About a third of all U.S. highway fatalities are from single vehicles leaving the road. Automated steering could greatly reduce highway deaths by preventing lane departure and steering overcorrection due to a blown or separated tire.

This paper reviews some of the developments in the main areas of autonomous vehicle control over the recent years. It is organized as follows: section 2 covers car following; section 3, lane keeping and finally last section was dealt with lane changing.

II. CAR FOLLOWING

Car-following, which describe the processes by which drivers follow each other in the traffic stream and try to have safety distance and avoid collisions. In recent years, many car following models and controllers were developed [1]. Car following is related to longitudinal control. The control of the vehicle's speed and its adaptation to road features, using the throttle [2] and the brake pedal as needed [3], [4]. The challenges handled in the design of the longitudinal control system include nonlinear vehicle dynamics, string-stable operation with very small inter-vehicle spacing, operation at all speeds from a

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complete stop to high-speed cruising, and the execution of longitudinal split and join maneuvers in the presence of communication constraints [5]. The autonomous vehicle control option on vehicles only controls the throttle and allows vehicle without driver maintain a relatively constant velocity. The brakes need to be used by controllers that were fed with different system such as Vision [6], [7]; GPS [8], [9], Lidar [10] and etc, to maintain a constant velocity when the vehicle travels down a steep incline. Intelligent autonomous controllers with the use of sensing, devices such as radar could be able to determine and maintain safe headway among vehicles at given velocities and vehicle conditions (brake, throttle, vehicle wind drag, tire traction, weight, weight distribution) while maximizing road capacity. These controllers need to determine when to choose the throttle [11], [12] or brake [13], [14] and minimize the switching between the two for a smooth and fuel efficient ride.

A platoon is a group of two or more closely spaced vehicles traveling with the same velocity in the same lane. A platoon consists of N vehicles following a lead vehicle. One of the main approaches in this field to forming platoons: Autonomous intelligent control (AIC) does not communicate with exterior sources, the driver needs to set the desired speed and headway. (See [15], [16], [17] for example). Lijuan Wu and his colleagues present a platoon control algorithm based on fuzzy logic [18]. [19] Considers the problem of longitudinal control of a platoon of automotive vehicles on a straight lane of a highway and proposes control laws in the event of loss of communication between the lead vehicle and the other vehicles in the platoon.

In [20], [21] by use of fuzzy logic, acted to control of vehicle in car following. [22] Described a car following controller based on fuzzy inference. [23] Surveys a longitudinal controller based on neural network. A. Ghaffari and his colleagues by use of Emotional Learning Fuzzy Inference System (ELFIS) approach, design a longitudinal controller for car following [24]. In [25], a combined brake/throttle fuzzy controller that uses a neural system to learn the fuzzy rules is designed to control the velocity and the distance between cars in single-lane platoons. [26] Presents a neuro-fuzzy controller for intelligent cruise control of semiautonomous vehicles. This paper addresses the problem of longitudinal control that aims at regulating the speed of the controlled vehicle in order to maintain constant time headway with respect to the vehicle in front. In [27] was described a control law for Longitudinal and lateral motions for automatic vehicle following. [28] was concerned with robust longitudinal control of vehicles in intelligent vehicle highway systems by adaptive vehicle traction force control. Ya-Fu Peng *et.al* proposes a robust intelligent backstepping control (RIBC) scheme for the car-following control of a platoon of automated vehicles using a recurrent cerebellar model articulation controller (RCMAC) via the H_∞ control technique [29]. [30], [31] *et al.* Proposed longitudinal controllers that rely on the generation of "second order" sliding regimes. [32] was concerned with robust longitudinal control of vehicles in intelligent vehicle highway systems by adaptive vehicle traction force control. [33] Considers the theoretical part for longitudinal control of merging maneuver for Automated Highway System. By using backstepping control method, in [34] controlled vehicle for both longitudinal and lateral. [35] Considered the longitudinal and lateral fuzzy control vehicle systems separately due to the decoupling under the assumption of small varying velocity and steering angle. A neural network (NN) adaptive model-based combined lateral and longitudinal vehicle control algorithm for highway applications is presented in [36]. [37] Designed a feedforwd controller for longitudinal control of autonomous ground vehicle based on the analysis the force of the vehicle in Off-road Environment. [38] was concerned with robust longitudinal velocity tracking of vehicles using traction control and brake control.

Fault Tolerant in longitudinal control wasn't dealt a lot. In [39] an observer-based fault tolerant control (FTC) approach is proposed for hybrid systems with uncontrollable state dependent switching, parametric uncertainties and without full continuous state measurements.

Longitudinal controller has the main roll to avoid collision when vehicles which are following each other. This controller must maintain the safety distance between vehicles [40], [41], [42]. Jeich Mar *et.al* presents a controller based on an adaptive network fuzzy inference system (ANFIS) for the car-following collision prevention system to nonlinearly control the speed of the vehicle [43] and also [44] used this approach. This paper presents an adaptive recurrent cerebellar-model-articulation-controller (RCMAC) for the car following collision prevention system [45]. According to implementation longitudinal controller, various different approaches are found such as collision warning systems [46]–[48], collision warning and avoidance systems [49], [50], autonomous intelligent cruise control systems [51], expert knowledge-based systems [52], and artificial-intelligence based systems [53]. Chun-Fei Hsu *et al.* proposed an intelligent wavelet neural network (IWNN) control system for the car-following collision prevention system based on the wavelet neural network (WAW) approach [54].

There are also a few reported studies [55], [56] on rear-end collision avoidance, with both control objectives being: 1) minimization of the safety distance error and 2) tracking of the velocity of the heading vehicle.

III. Lane Keeping

The main objective of lane keeping is to perform automatic steering of the vehicle in order to keep it in the middle of the road in spite of changes in road conditions and other disturbances. The control system for lane keeping is usually designed to detect any difference between host vehicle and the reference line on the road with on-board sensors [57]. Lane keeping is combined of longitudinal and lateral control [58]. In lane keeping, lane detection [59] is the most important part of this motion. Lane detection is a well-researched area of computer vision with applications in autonomous vehicles and driver support systems. A lane detection system must be able to pick out all manner of markings from cluttered roadways and filter them to produce a reliable estimate of the vehicle position and trajectory relative to the lane as well as the parameters of the lane itself such as its curvature and width [60]. The generic obstacle and lane detection system developed by the University of Parma in Italy is a stereo vision based one in their experimental vehicle named ARGO [61-64].

Many lane keeping was done with vision technology [65-69]. In [70] was dealt with the vehicle lateral control problem. In practice, this measure can be obtained by a vision system. The solution is robust with respect to road curvature and lateral wind. In this paper, a vision-based lane-keeping automated steering system is proposed and is successfully verified in our vehicle platform, TAIWAN IIS-I [71]. Jin Wang *et al.* described the technology fields that will have a significant impact on the deployment of a centimeter-level vehicle-positioning system will be discussed. Vision based lane-recognition (VBLR) systems are relatively mature and have already been introduced to the market for lane departure warning, etc [72]. R. Risack and his colleagues propose a lane keeping assistance system which warns the driver on unintended lane departures. Based on an existing robust video-based lane detection algorithm we compare different methods to detect lane departure [73]. [74] Proposed a nested PID steering control for lane keeping in vision based autonomous vehicles is designed to perform path following in the case of roads with an uncertain curvature. The control input is the steering wheel angle: it is designed on the basis of the yaw rate, measured by a gyroscope, and the lateral offset, measured by the vision system as the distance between the road centerline and a virtual point at a fixed distance from the vehicle.

Designing a fault-tolerant lane-keeping controller for automated vehicles has been considered in recent researches [75], [76]. The static feedback control strategy is adequate to achieve the requirement of lane-keeping task by combining the longitudinal and lateral control [77].

Lane keeping assistance systems are designed mainly to compensate minor disturbances, for instance road curvature, road bank angle or wind gusts, in order to decrease driver's workload [78], [79] but these modern systems couldn't be placed in this paper, because of their different issues from the subject of this research.

IV. Lane Changing

Vehicles change lane in order to continue the journey. Then lane changing provides a maneuver for a fast vehicle to pass a slow vehicle, which can be observed everywhere on the highway [80]. Lane changing decisions in urban driving situations including the influence of traffic signals, obstructions and different vehicle types such as heavy vehicles [83] and dissatisfaction of driving conditions.

Vehicle lateral control [81], [82] is a challenging problem in areas of Intelligent Transportation Systems (ITS) and automatic control for autonomous vehicles. Major substantial issues of lane change maneuvers include (1) tracking control under the ride comfort constraint, (2) position estimation using sensors mounted on the vehicle (on-board sensors), and (3) transition between lane change maneuver and lane following maneuver. In this paper, the sliding mode controller using filtered error has been proposed as a tracking control algorithm and the reduced order Kalman filter is designed as a state estimator [83].

Researchers during last years proposed many control approaches to overcome the problem of this phenomenon. [84] Describes an efficient lane-change maneuver control system for platoons of vehicles. [85] Considers the problem of combined longitudinal and lateral control of a platoon of non-identical vehicles on a curved lane of a highway. This paper presents the design and experimental implementation of an integrated longitudinal and lateral control system for the operation of automated vehicles in platoons. Also [86-88] used this combination. Hatipoglu *et al.* [89] reported the design of an automated lane-change controller. [90] Addresses the modeling and control of the lateral motion of a highway vehicle. In particular, a steering controller is designed that tracks the center of the present lane on both curved and straight highway sections without knowledge of the radius of curvature of the road.

There are other techniques for controlling steering, such as H∞, Adaptive, and PID, as described by Chaib *et al.* [91]. In [92] a feed forward term from road curvature and a PID on a weighted sum of the heading error and the lateral offset are used as steering controller. [93] Provides an analytic approach for the systematic development of controllers that will cause an autonomous vehicle to accomplish a smooth lane change suitable for use in an Automated Highway System. Jie Ji *et al.* describe the lateral control of vehicles in Automated Highway Systems with the main emphasis on the lane change maneuvers. The desired trajectory for the lane change maneuvers, called the Virtual Desired Trajectory (VDT), is designed considering passenger's comfort and required transition time for the maneuver [94]. In this paper, a development of steering control for automated cars based on fuzzy logic and its related field tests are presented. Artificial intelligence techniques are used for controlling a broad range of systems, trying to emulate the human behavior when classical control models are too much complex and require a lot of design time [95]. [96] Explained a lane changing for overtaking maneuver based on fuzzy logic controller. D. Pomerleau *et al.* Proposed the steering was controlled by the neural-network-based Rapidly Adapting Lateral Position Handler (RALPH) [97]. [98], [99] Describe some of PATH researches were done on lateral control.

Lane change models do not consider the uncertainties and perceptions in human behavior that are involved in modeling lane changing and it cause the notable fault in the results of lateral controller. In the present study, fuzzy reasoning in lane changing model is introduced to reflect these uncertainties and perceptions to represent lane changing behavior more realistically [100]. In [101], was proposed an expert fuzzy controller, which is based on a 2 Degree of Freedom (2DOF) vehicle lateral dynamic model, to solve the problem both in simple driving task and big curvature crossing turning action. [102], [103] Describe an adaptive fuzzy controller for lateral control in intelligent highway system. One of critical importance for the lateral controller to be robust with respect to model uncertainties and various road conditions under the constraints of limited actuator power, [104] proposed a controller design method which consists of two steps: (i) designing a state-feedback controller of an "augmented plant" by assuming all state variables are available and (ii) converting it to an output-feedback controller. [105] Explained Genetic algorithm (GA) based fuzzy logic controller (FLC) design methods are presented for the step lane-change maneuver of an autonomous ground vehicle.

Collision avoidance is one of most important issue in lane changing and lateral control. Lane changing/merging collisions are responsible for one-tenth of all crash-caused traffic delays often resulting in congestion. In [106], Hossein Jula and his colleagues analyze the kinematics of the vehicles involved in a lane changing/merging maneuver, and study the conditions under which lane changing/merging crashes can be avoided. [107] Presents an Adaptive Cruise Control (ACC) and Collision Avoidance (CA) system for vehicle autonomous driving. The control scheme is designed to improve drivers' comfort during multi-vehicle driving situations and to completely avoid rear-end collision using severe braking and lane change maneuver.

There are two main approaches for automated steering and lateral control: look-down and look-ahead reference systems. But a few works deals with the combination of two system, [108] presents a vehicle lateral control approach which combines the advantages of both look-down (using magnetic markers without any encoding of road geometry) and look-ahead reference systems (using GPS). Also [109], [110], [111], [112] used this combination. In the next part, we explain about two reference system. A new design for the collision prevention system based on cascaded fuzzy inference system (CFIS) for lane-changing maneuver and car-following is proposed. The lane-changing is combined with car-following to save the processing time of the lane-changing maneuver [113].

A. Look-Down Reference

Look-down systems follow wires or magnets [114] embedded in the middle of the lane (magnetic marker) [115] or in [116] the infrastructure-guided lane-change scenario, additional magnetic markers are installed between lanes to provide a reference path for automated guided-vehicles at certain locations on highways. This scheme alleviates the control and estimation problems by limiting lane-change maneuvers to specific locations; however, it also reduces the automated vehicles' flexibility on smart highways. [117] Reviews the development of the University of California's magnet-following steering control system in a eight vehicle platoon tested on 1-15 in San Diego, CA. Also [118] describe one of PATH researches in the field of look down reference. The particular problem of lateral control with respect to a marked lane is considered in [119], [120].

Look-down reference systems calculate the lateral displacement from a point very close to the vehicle. These systems have the advantage of being reliable, yielding accuracy and good performance under any weather or light conditions. Another advantage when using this technique is that other vehicles will not occlude the lateral displacement sensing signal [121]. In this paper two methods were discussed that were successfully employed in the platoon scenario of the 1997 National Automated Highway Systems Consortium Feasibility Demonstration in San Diego, USA: infrastructure-guided lane changes using an additional cross-over marker reference, and free lane changes using a yaw rate sensor for dead reckoning [122]. A fuzzy logic controller (FLC) is designed and implemented in real time on a Toyota Celica test vehicle to achieve control of the lateral motion of the vehicle. These fuzzy logic control strategies are implemented on the test vehicle, automatically following a multiple-curved track using discrete magnetic markers on the roadway and magnetometers on the vehicle as a lateral error reference/sensing system [123]. This paper deals with lateral dynamic control of electric vehicles in an urban environment, where the lateral displacement is obtained from a on board sensor, interacting with a road infrastructure [124]. In this paper side acceleration of vehicles is measured which provides necessary measurement data from sensors for sliding estimation [125]. [126] Used from look-down reference system, too. [127] Describes a robust control design for automatic steering of passenger cars with look-down reference systems which use only one sensor at the front bumper to measure the lateral displacement of the vehicle from the lane reference. An additional lateral displacement sensor is added here at the tail bumper to solve the automatic steering control problem.

B. Look –ahead Reference

Look-ahead reference systems resemble human driving by measuring the lateral displacement from the lane reference ahead of the vehicle (e.g., radar and machine vision)Many look-ahead systems use cameras for lane following, radar for following the preceding vehicle and lasers or cameras for lane switching. Look-ahead systems [128], [129] replicate human driving behavior by measuring the lateral displacement ahead of the vehicle like machine vision [130], radar reflective strips. [131] presents a simulation of vehicle driving control system in terms of lateral and longitudinal control using image processing. [132] is conducted for the development of overtaking analysis system to gain higher efficiency with machine vision [133], also [134], [135], [136] have similar subjects. In [137] used this technique to lane changing and overtaking. In [138], a set of sensors including far radar, stereo vision system and side radar are set up for monitoring the left side of the vehicle.[139] Describe the vehicle detection with distance estimation algorithm is proposed by using two CCD cameras mounted on the both side mirrors of our experimental car, TAIWAN *i*TS-1. Radar is also used in this field [140], [141], [142].

GPS [143] is one of most important sensor in look-ahead system. [144] uses combination of GPS and artificial-intelligence-based techniques behaves outstandingly. [145] Describes the development and implementation of a high integrity navigation system, based on the combined use of the Global Positioning System (GPS) and an inertial measurement unit (IMU), for autonomous land vehicle applications. Prof. Tsugawa and his group keep researching on autonomous vehicles, having developed controllers for lateral and longitudinal control, which are mainly based on classical geometric control global positioning system (GPS) and inter vehicle communications [146].

V. CONCLUSION

This paper highlights some of the recent work was done involving lateral and longitudina1and combined of them vehicle controls in IVHS and AHS. In this paper was tried to cover researches from 1990 to 2010. NOUVELIERE

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