Analysis and Review of State-of-the-Art Automatic Parking Assist System

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***Abstract*—The emerging advanced technology, automatic parking assist, makes it possible to free drivers' hands from bored parking maneuvers and offers the possibility of reducing driver stress. Toyota Prius hybrid vehicle unveiled in 2003 is the first automobile equipped with automatic parking assist system(APAS), the research and development in APAS has become a growing trend spread from automobile enterprises to vehicle research centers of institutions and universities over ten years. APAS consists of four parts----environment recognition module, path planning generation module, path tracking controller subsystem and improved actuators like active steering/breaking subsystem. This paper mainly dealt with the new progress of APAS, on the basis of brief introduction of system with nonholonomic constraints. Firstly, the basic structures and operating principles of APAS were elaborated, and meanwhile, two methodologies applied for analyzing APAS from the vehicle engineers and robot scientists were taken into consideration respectively. Then, the products and hot topics of APAS were categorized and demonstrated, in terms of environment recognition (including vehicular position perception and obstacles detection using ultrasonic radars and vision-based sensors), path planning generation algorithms involved with continuous-curvature path using clothoid curves, different trajectory tracing control strategies based on fuzzy logic controller and fractional order controller, so as to present a detailed state-of-the-art research situation. Last but not the least, based on the current research situation, some urgent problems and development trends were discussed.**

Keywords—automatic parking assist system; path planning; enviroment recognition; path tracking conroller

I. Introduction

Automatic parking assist system (APAS) is a well-designed apparatus for enhancing drivers' comfort and safety during parking maneuvers. For most drivers, APAS not only could offer the convenience automatically park the vehicles in constrained environments where much attention and experience is required, but also should result in reduced stress levels [1]. As a significant part of Advanced Driving Assistance Systems (ADAS), APAS has aroused a growing interest for engineers and scientists in research and development departments from car manufacturers to automotive research institutes.

According to the extent of the drivers' involvement during parking process, one can distinguish semi-APAS [2-5] from fully-APAS [6-8]. The semi-APAS leaves the brake pedal and accelerator to the drivers to control, which means the longitudinal motion control is by human beings. When taking legal policy and costs into consideration, there are more advantages in developing semi-APAS. In most countries, it is required by insurance regulations that a driver should stay in full control of the vehicle's velocity control at all time. And as a parking assistant is not a security-related feature, a low-price production could take up the market rapidly. So a detailed elaboration for semi-APAS was given in this paper with a brief introduction about research situation of fully-APAS.

Currently, there existed a large number of literatures demonstrating APA technology. A series of pioneering work had put forward the researches of APAS, which had achieved a far-reaching consequence. On the basis of past work, a state-of-the-art APAS technology review was proposed in this paper. Firstly, the working principle of APAS was illustrated in the Overview of System with detailed analyses for four-wheel vehicle's kinematic model, following by two approaches from the perspectives of vehicle engineers and robot scientists. Moreover, the research situation and hot topics were investigated, and the APAS products were categorized. Lastly, based on the research situation, problems to be solved and development trends were discussed.

II. Overview of System

In order to ensure automatic behavior, several tasks should be deal with as follows: target position designation and vehicular status estimation should be fulfilled via ultrasonic radars, laser sensors or cameras and global positioning system (GPS) in environment recognition module; then with its position and orientation acquired as aforementioned, a reference motion path calculated in path planning generation module should be able to guide the cars into parking lot correctly; meanwhile this reference path should be tracked as accurately as possible based on path tracking controller; and finally, when improved actuator received control signal, active steering or braking subsystem should execute instructions effectively and efficiently. These tasks are finished by separate interconnected subsystems which are presented in Figure 1.

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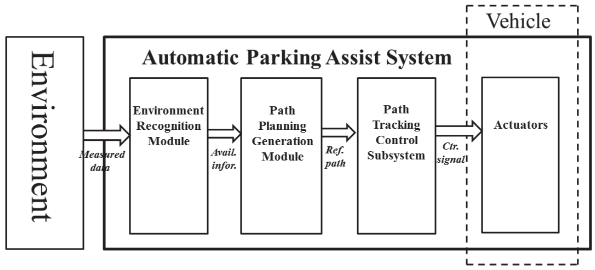

Fig. 1. Structures of the Automatic Parking Assist System

A mathematical model of kinematic vehicles is usually adopted to investigate the motion relationship during parking maneuvers [9-11]. If the mathematical model of the vehicle is known, based on the motion equations, then the path planning algorithm and trajectory tracing controller can be well-designed with respect to the well-estimated vehicle states.

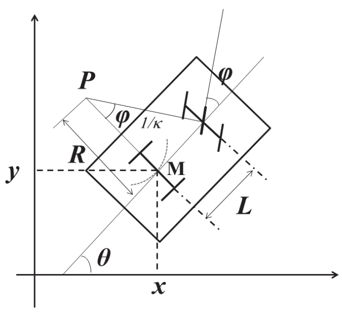

Fig. 2. Kinematic model of the vehicle in the x-y plane

Consider the kinematic car depicted in Figure 2. The Ackermann steering geometry is supposed to be respected, hence all wheels turn around the same point, denoted by P, which is on the line collinear with the rear axle of the vehicle. The configuration of the vehicle ($\dot{q}$) is described by four state variables: position of the reference point M(x, y), the orientation of the car denoted by θ, and the curvature κ, which is the inverse of the turning radius. The motion relationship can be fully described by (1):

$$\dot{q} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \\ \dot{\kappa} \end{bmatrix} = \begin{bmatrix} \cos\theta \\ \sin\theta \\ \kappa \\ 0 \end{bmatrix} v + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \sigma \qquad (1)$$

The longitudinal velocity of the car is given by v and the velocity of the change in curvature is denoted by σ. And φ denotes the angle of the front wheel with respect to its longitudinal axis, and L is the distance between the front and the rear axles. The following relationship is easily obtained:

$$\kappa = \frac{1}{R} = \frac{\tan\varphi}{L} \qquad (2)$$

$$\sigma = \dot{\kappa} = \frac{\dot{\varphi}}{L\cos^2\varphi} \qquad (3)$$

Both the curvature and curvature derivative are with their limitations:

$$|\kappa| \le \kappa_{max} \;, |\sigma| \le \sigma_{max} \qquad (4)$$

A. Vehicle engineers' views

From the perspective of vehicle engineers, to design the tracking controller for semi-APAS, which means the longitudinal velocity of the vehicle is generated by driver, a simplified version of (1) without the curvature can be expressed as:

$$\dot{q} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta \\ \sin\theta \\ \frac{\tan\varphi}{L} \end{bmatrix} v_d \qquad (5)$$

Where the driver velocity is denoted by v_d. And v_d here can be controlled by driver. According to data measured by sensors, real-time system state variables (x, y, θ) can be solved by (5). As long as reference path is well-designed and tracking controller is well-performed, the destination parking lot (x_d, y_d, θ_d) can be achieved.

B. Robot scientists' standpoints

Robot scientists regarded automated vehicle as a car-like mobile robot (CLMR)[12-18]. They argued that parking problem was mainly a "motion planning" instead of "path planning" problem in their terms. It was noted that "motion planning" problem is to find a collision-free path between initial and final configuration, while meeting the nonholonomic constraints:

$$\dot{y}\cos\theta - \dot{x}\sin\theta = 0 \qquad (6)$$

That specifies the tangent direction along any feasible path for the robot and a bound on the curvature of the path, and decreases a control dimension from three to two. System with nonholonomic constraints refers to the degrees of position or shape freedoms are more than independent control inputs. In their views, accurate mathematical model is not necessary to generate reference path, a complete and efficient motion planner for a car-like robot is rather important [12]. Most well-known motion planning algorithms from robotics theory such as rapidly-exploring random tree (RRT) [13-14], artificial potential fields (APF) [15-18] could solve the collision avoidance problem and generate feasible trajectories. However, the cost is considerable expense on computational power [5] and the thoughts are lack of sufficient considerations on motion limitations of four-wheel vehicles.

III. Research Situation and Hot Topics

A. Environment Recognition

Environment recognition module maps the environment of the vehicle and the existence of accessible parking place where the vehicle can park into. In fact, environment recognition module comprises target position designation and vehicular position with its posture perception.

On the one hand, vehicle status should be well-estimated by vehicular sensors like antilock braking system (ABS) and GPS. ABS utilizes angular encoders measuring the speed of the four wheels. The real-time-kinematic global positioning system (RTK-GPS) can estimate the vehicle position and orientation accurately, but it is too expensive for practical application. In paper [19], the authors proposed several ways to estimate the vehicle state from signals available in production passenger cars.

On the other hand, target positon designation should fulfill the requirements that mark proper parking lot and detect outside obstacles via various sensors. According to paper [20], it could be roughly divided into three categories, including active ultrasonic or laser-sensor-based, vision-based and infrastructure-based methods.

The ultrasonic radars are the most common method, and it is mutual enough to become commercialized. For the sake of avoiding obstacles, authors of literature [21] installed twelve ultrasonic sensors for vehicles to complete perpendicular parking maneuvers, which had two more additional sensors on the side of the rear bumper than in parallel parking assist system, as shown in Figure 3. However, the approach usually failed when there existed no parked car or obstacles in nearby parking lot.

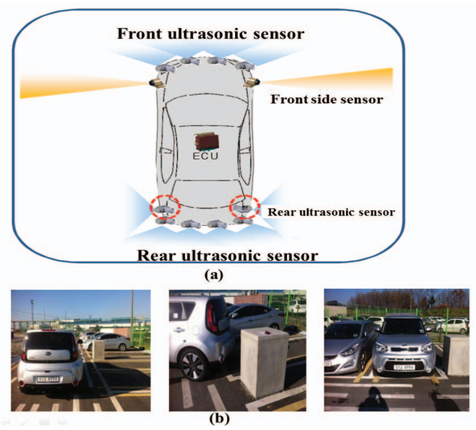

Fig. 3. (a)Additional rear ultrasonic sensors, (b)Vehicle test of perpendicular parking assist system[21]

A number of papers focused on the vision-based technology relying on image processing. In papers [22-23], the conventional 3D vision technology was used to recognize adjacent vehicles as the boundary of the available parking lot, whereas paper [24] proposed a monocular vision system, which contributed in marking line-segment recognition using peak pair detection in Hough space and structural pattern recognition of parking slot markings. To deal with a poorly lit environment, which was common for indoor and underground car parking lots, literature [25] proposed a light-stripe-projection-based target position designation method that could solve the parking problem in various illumination situations. And recently, journal [20] implemented a robust ridge detector to extract slot markings, and detailed the image processing using a sequential random sample consensus (RANSAC) line fitting algorithm to remove the noises (as shown in Figure 4), which contributed greatly in target parking lots designation.

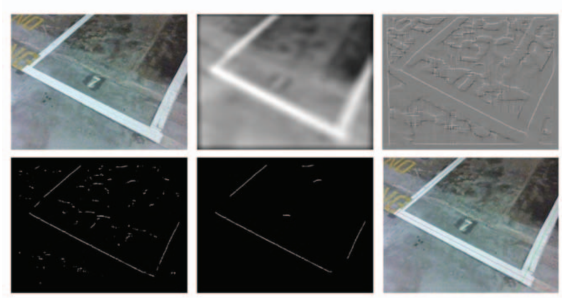

Fig. 4. RANSAC----image processing from journal [20] to remove noises (rowwise: original, smoothed, ridgeness, threshold, filtering, and line assignment).

The infrastructure-based method needs additional hardware installation on vehicles or parking lots. Paper [26] proposed a smart parking system consisting of wireless transceivers, parking belts, and vehicular receivers. In literature [27], a local GPS, a car park digital map, and communication with the intelligent parking administration systems were required. Nissan had combined advanced parking system with wireless EV charging technology [28], which is deemed to be the most promising way to advocate the infrastructure-based method.

B. Path Planning Generation Algorithm

Path planning generation algorithm determines a suitable collision-free path from a given start to a required goal position within the parking space, which is the core issue of APAS. Path planning can be classified into different types based on various criteria. From the shapes of parking lots, there are parallel parking lots, perpendicular parking lots and echelon parking lots. Based on the complexity of parking maneuvers, there exist one trial parking and back-and-forth several trials parking maneuvers. According to the velocity of vehicle, there are variable speed and constant speed parking.

The very first path planning problem was tackled for the Dubins's car [9], as well as for Reeds and Shepp's car [10] in the domain of robotics. Since then, a series of researches were developed in motion planning, such as methods in papers [29-32] based on fuzzy logic or neural networking algorithm to learn a human technique to generate the parking path, the so-called navigation functions proposed in book [33] could solve very general obstacle-avoidance and navigation problems, and other intelligent path generation algorithm like artificial potential algorithm [34], genetic algorithm [35] and so on. However, these mentioned approaches were not possible to apply to the real-world parking problem due to the limitation to human experts' knowledge (for the learning step) and present expensive computational power.

To overcome this difficulty, paper [36] adopted the concept of way-points, proposed the double circular trajectory in which the first arc followed the minimum turning arc and the second arc depended on the available space. The drawback here was the vehicle need to stop at the curvature discontinuities, which also means steering at the stop causing damage to the steering column and inducing faster wearing of the tires. Thus, ever since pioneering works pointed out in paper [10] by Reeds and Shepp that the shortest paths for a car to move from one pose to another consisted of arcs of circles and straight line segments, more and more empirical methods are applied for continuous-curvature path generators based on geometrical information [37-39]. Based on journal [40], Figure 5 has shown the discrepancy in continuous-curvature path and Reeds and Shepp's path.

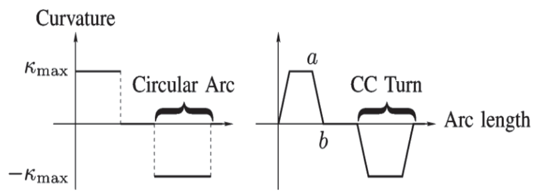

Fig. 5.. Discontinuous curvature profile of a Reeds and Shepp path (left) versus piecewise-continuous curvature path (right). The part from a to b is a clothoid arc [40].

Based on paper [8], continuous-curvature paths are created from smooth curves and can be roughly divided into two categories: curves with coordinates that can be expressed in a closed-form such as B-splines, polar splines or quantic polynomials and parametric curves for which curvature is a function of their arc length such as clothoids, cubic spirals or intrinsic splines. As depicted in Figure 6, it was noted in journal [7] that clothoids trajectories can complete the task that parking the cars in one or several maneuvers for any initial position and orientation of the vehicle at the lowest cost of computational power.

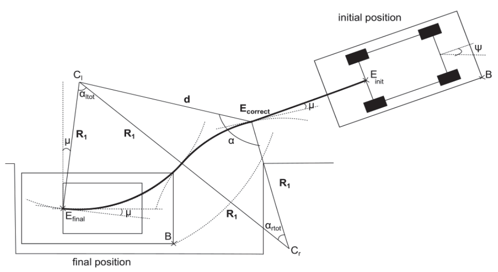

Fig. 6. Clothoids-arc trajectories to park in one maneuver [7].

C. Path Tracking Controller

Path planning is merely an open-loop method---- it should cooperate with tracking controller to make actual APAS work out so that forming a state feedback closed-loop control. One typical control strategy was fuzzy logic controller, paper [29] and handbook [41] pointed fuzzy strategy was an effective solution to deal with uncertainties and inaccuracies in environment mapping, and fuzzy logic controller was not sensitive to system parameters, which means a strong adaptability in all kinds of vehicle models. However, it was demanding to park the car into regular size parking lot-----fuzzy logic controller need relatively long parking space to park the car.

In paper [6], the authors proposed the classical PID controller to track the collision-free path that guided the car into confined parking places. As shown in Figure 7 , a steering PID controller and a novel longitudinal motion controller which adopted a dual-closed-loop PID controller contributed greatly to track the path in a fully-APAS. The advantage was the parking lot is only 0.9 meters longer than the length of vehicle. However, error accumulation was the tough task for PID controller. Paper [2] introduced fractional order $PI^{\lambda}D^{\mu}$ controller for APAS, which eliminated the following error, and address the parameters tuning problem via improved genetic algorithm. Simulation results and experiments had shown that the fractional order $PI^{\lambda}D^{\mu}$ controller was reliable and stable in solving the high-precision tracking problem.

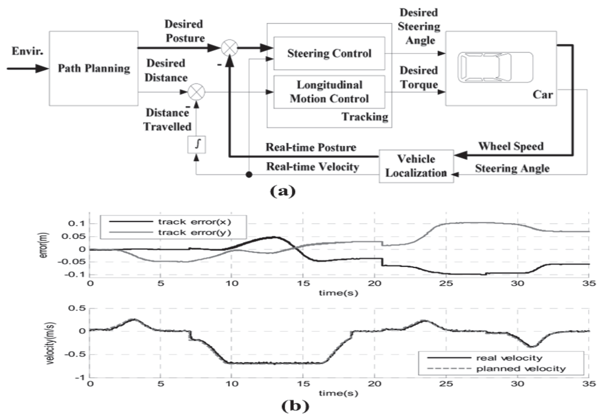

Fig. 7. Structure of controller proposed in paper [6] and its performance. (a)Structure of tracking controller (b) Performance of tracking controller

Recently, it was noted in paper [42] that model free adaptive control (MFAC) scheme was well-performed in APAS. MFAC scheme only depended on the input and output data without any model information, made it possible in realizing parametric adaptive and structure adaptive control of the unknown controlled system. As depicted in Figure 8, the simulation results had shown that the MFAC scheme performed more accurate than the PID scheme in terms of tracking the orientation angle and position of cars. Sliding mode control (SMC) is another path following controller design advantaged in quick response, good transient tracking and robustness with respect to system uncertainties and disturbances. Based on SMC, journal [20] proposed an improved SMC scheme to suppress unexpected spikes arise which would induce strong vibrations to the vehicle. The revised SMC was simpler than fuzzy logic controller, and was able to generate a smooth control output with very small position and orientation errors, as shown in Figure 9.

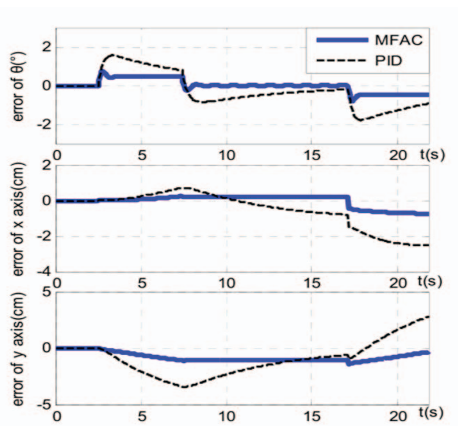

Fig. 8. Parking error comparisons between MFAC and PID [42].

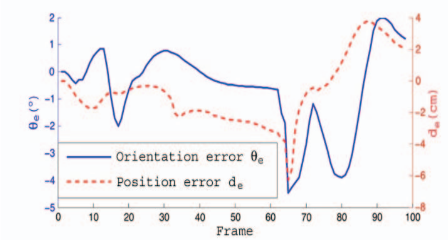

Fig. 9. Position and orientation error using SMC during one trial [20].

D. Application/Products

Researches have been developed extensively and intensively on APAS. And there are a large scale of applications and products fitted on premium vehicles. In 2003, the Aisin Seiki Group collaborated with Toyota had offered the first commercial Intelligent Parking Assist apparatus as an option for Prius hybrid vehicles, which were semi-APAS with the parallel parking capability [43]. The Evolve project which consisted of a group of Linkoping university students worked with Volvo developed a fully-APAS in 2004, by refitting Volvo S60, the Evolve car could automatically perform a cis-row parking maneuver [44]. In 2005, Bosch cooperated with Citroen had unveiled City Park---a semi-APAS on Citroen C3, which supported automatic parallel parking, and recently Bosch updated the remote versions that could complete the fully automatic parking[45]. In 2006, Lexus had added semi-APAS to the redesigned LS460, namely advanced parking guidance system (APGS), which parallel parked as well as angle parked. The same year, Ford had released semi-APAS on Lincoln models called "active park assist (APA)", which only supported automatic parallel parking. In 2007, Valeo group had developed semi-APAS called PARK 4U for Volkswagen, and fitted on the Touran Cross and Tiguan. Moreover, the remote version was released in 2011 as a fully-APAS, which allowed the driver to leave the vehicle before the parking maneuver, while retaining control via smartphone [46].

Due to the cost and regulation, there is few commercialized fully-APAS. The current road safety law regulated the drivers' attention and judgment shall not be replaced by parktronics. And in practical environment, there existed blind spots where the sensors cannot be reached. Up to now, APAS were being developed by several automobile manufactures and component factories, a series of products were listed in Table I.

TABLE I. AUTOMATIC PARKING SYSTEM ASSEMBLY CASE OF CAR MANUFACTURERS [47]

	Volkswagen	Mercedes	Toyota	BMW	Ford	Citroen
Parallel parking	√	√	√	√	√	√
Perpendicular parking	√	√	√	√	×	×
Types of sensors	Ultrasonic sensors	Ultrasonic sensors	Millimeter-wave radars and CCD image sensors	Ultrasonic sensors	Ultrasonic sensors	Ultrasonic sensors
Velocity requirements	≤30km/h	≤36km/h	unknown	≤35km/h	unknown	≤25km/h
Length of parking lots	≤Vehicle length +1.1m	≤vehicle length +1.2m~1.3m	≤vehicle length+1m	≤vehicle length +1.2m	unknown	unknown
Price	700 euros	867 euros	1000 dollars	550 euros	535~599 euros	850 euros
Cooperative enterprise	Valeo	Bosch	Aisin seiki	Valeo	Valeo	Bosch
Vehicle models	Turan,Tiguan, Passat,Magoton, Audi A3	B-class B200, AMG-class,CLS350CGI, A-class:A180	Prius hybrid, Lexus, Crown	BMW-5 series:535Li, BMW-7 series.	Lincoln-MKS, Lincoln-MKT	C3,C4

IV. PROBLEMS TO BE SOLVED AND DEVELOPMENT TRENDS

Although the researches on APAS had made considerable progress, there still existed some issues to be solved due to the insufficient theoretical investigation and practical engineering experience, which mainly manifested in following aspects:

Theoretically, environmental information measured by sensors should be further processed, especially by adopting proper signal processing algorithm; general adaptive algorithms should be explored for path planning generation; a robust tracking controller should be well-designed with respect to artificial intelligent algorithms like machine learning.

Practically, for the sake of applying real-time operation in APAS, vehicular CPU with affordable computational power should be developed; considering the inaccurate conversion from the steering motor turning angle to the vehicle turning radius, advanced steering angle sensors with good performance were needed; high-precision and reliable actuators should take into consideration in case of unexpected error between wheels and driving motors; human machine interface (HMI) played an important role in the mutual commercial APAS products via fusing with information communication technology and so on.

Similar to autonomous driving technologies, the serious problem faced by APAS are the regulations and policies. Authorities should adapt existing rules and create new ones in order to ensure the compatibility of APAS with the public's expectations regarding safety, legal responsibility and privacy. With growing markets in vehicle electrification and smart transportation, further researches and developments on APAS are warranted in the near future.

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