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Design of Fuzzy Logic based Parking System for Autonomous Vehicle

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(Abstract)

This research deals with a fuzzy logic based parking system for an autonomous mobile car. An existing system using a conventional fuzzy logic method has some disadvantages, and it considers only rectangle parking spaces.

A simple-structured FLS(Fuzzy Logic System) is designed, which is applied to rectangular and slant parking spaces. The objective of this study is to improve the trajectory of different scale cars so that they can be parked well in the desired parking space. The implementation shows that the SFLC can be effectively used for this purpose.

Ⅰ. Introduction

1. Background

Fuzzy logic was first introduced by Lotfi A. Zadeh[1] in 1965 as a generalization of the classical binary logic. In his study he introduced the concept of "linguistic variables", which in this article equates to a variable defined as a fuzzy set. This was followed by the first industrial application (i.e. a cement kiln built in Denmark, came on line in 1975).

Fuzzy logic system has been proved to be effective ill-posed problems, linguistically controlled devices, complex systems without exact mathematical models, and etc. Nevertheless some demerits also accompany the FLS, in that; too many parameters are required for tuning. Furthermore, the FLSs have not been viewed as a rigorous science due to a lack of formal synthesis techniques, which guarantee the basic requirements of global stability and acceptable performance. Therefore, a new FLS called SFLS (Simple-structured FLS)[9] has been introduced.

Over the past decade, the field of automated intelligent vehicle system has been the focus of rigorous research. Man has long dreamed of designing machines that are capable of operating themselves. One of the basic milestones is to develop truly intelligent systems that can intuitively learn how to perform specific operations and execute them to perfection. One field in which several branch have been made to this end is that of automated parking systems.

In the autonomous vehicle area, autonomous parking problems have attracted a great deal of attention and more intelligent technologies are being applied to automobiles. An important part of them is the autonomous parking problem. The garage parking and parallel parking schemes have been proposed in many papers ([2]-[8]). The basic method is to design a control algorithm that makes an automobile follow a reference trajectory via a tracking method.

Sugeno and Murakami [2] proposed an experimental study on fuzzy logic system using model car, which is equipped with on-board microprocessor and two supersonic sensors for the measurements of the relative distance and direction. Sugeno et al. [3] adopted the hardware arrangement presented by L.A Zadeh [1], in order to execute the garage parking by employing fourteen fuzzy oral instructions. A study by A. Ohata et al. [4] was reported a control law for guiding a car from any position to an appointed parking position and it was studied through trajectory simulations. They showed that the car could be guided along the minimum path combined with changing a straight guideline. Yasunobu and Murai [5] studied the state evaluation fuzzy logic system and the predictive fuzzy logic system to achieve the drive knowledge. Some computer simulations showed the effectiveness of the proposed parking control system. Daxwanger et al. [6] presented a skill-based visual parking control using neural networks and fuzzy logic system. They used two control architectures, the direct neural control and the fuzzy hybrid control, to generate the automatic parking commands. Similarly, M.C. Leo et al. [7] developed a near-optimal fuzzy controller for maneuvering a car in a parking lot. Near-optimal car trajectories were here created from the cell mapping data, and trajectories with similar features were collected to form groups. Fuzzy control rules and membership functions were then expressed with respect to the trajectory groups instead of individual cells. An et al [8] developed an online path-planning algorithm that guided an autonomous mobile robot to avoid a obstacles in an unpredictable environment. The established autonomous mobile robot could not move omni-direction and run on two wheels equipped with a CCD camera. A study on autonomous fuzzy parking control of a model car was described in the reference [13], which was simulated by using real-time image processing. In [9], authors suggested a simple but powerful FLS design method using a sole fuzzy input variable instead of the error and the change-of-error to represent the contents of the rule antecedent.

In this dissertation, we designed a conventional FLS and SFLS (Simple structured Fuzzy Logic System) [9] for the backward and forward parking of an autonomous vehicle. A promising feature of our design is that a conventional FLS and SFLS for the forward parking of an autonomous vehicle in a slant garage parking space is designed. It was found that the parking system in a rectangular space is just a special case of the slant parking space. In addition SFLS uses only 7 rules compared to 49 of the conventional FLS. Furthermore, the effectiveness of SFLS is also confirmed by simulation results.

2. Scope of Research

The scope of our research is to design fuzzy logic based parking systems for an autonomous vehicle. We perform some simulations to show the effectiveness and feasibility of the proposed method. The results show that the good agreement with conventional FLS and SFLS methods. We also introduce a method based on image processing in real time, to recognize the parking line. The parking line recognition includes not only the rectangular space proposed earlier [10], but also development of the algorithm which works well in a different space including the slant parking space. In the parking algorithm part, we first discuss a trajectory in the parking space and simulate its efficiency. Additionally, different scale and different shape of parking space is also described. In this thesis, we deal with the analysis and design of the SFLS for the different parking algorithms and various parking spaces. The encouraging simulation results confirm the effectiveness of the algorithms designed by us.

3. Organization

This study focuses on the design of an autonomous vehicle. This thesis has been organized as follows: Section II deals with the derivation of modeling equation, parking line recognition and parking algorithms for rectangular and slant space for backward and forward parking. In Section III, fuzzy logic systems based on conventional FLS and SFLS parking algorithm are designed. The effectiveness of the proposed methods are given by simulations in Section IV. And Section V discusses the concluding remarks.

Ⅱ. System Description

1. Modeling of an Autonomous Car

The controlled process is the four-wheeled car shown in Fig. 1.

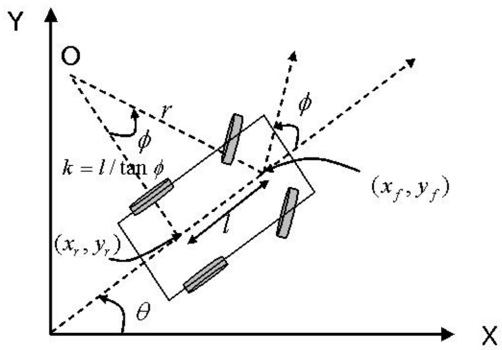


Fig. 2.1. Kinematic model of mobile-car.

We assume that the wheels are fixed parallel to car body and allowed to roll or spin but no side-slipping. The front wheels can turn to left or right, but the left and right front wheels must be parallel. All the corresponding parameters of the mobile car depicted in Fig. 2.1 are explained in Table 1.

The rear wheel is always tangent to the orientation of the vehicle. The no-slipping condition mentioned previously requires that the mobile car travels in the direction of its wheels. Thus, we have

$$\dot{y}_r cos\theta - \dot{x}_r sin\theta = 0. \tag{2.1}$$

This is the so-called nonholonomic constraint.

The front of the mobile car is fixed relative to the rear, thus the coordinate (x_r, y_r) is related to (x_f, y_f)

$$x_r = x_f - l\cos\theta \\ y_r = y_f - l\sin\theta. \qquad (2.2)$$

Differentiating both sides of (2.2), we have

$$\dot{x}_r = \dot{x}_f + \dot{\theta} l \sin\theta \\ \dot{y}_r = \dot{y}_f - \dot{\theta} l \cos\theta \qquad (2.3)$$

By substituting (2.3) to (2.1), we can get

$$\dot{x}_f sin\theta - \dot{y}_f cos\theta + \dot{\theta} l = 0. \qquad (2.4)$$

Table 1. The meaning of parameters for a mobile car

Parameter(s)	Meaning
(x_f, y_f)	position of the front wheel center
(x_r, y_r)	position of the rear wheel center
ϕ	orientation of the steering-wheels with respect to the frame of the mobile car
θ	angle between vehicle frame orientation and X-axis
l	wheel-base of the mobile car
O	center of curvature
r	distance from point O to point (x_f, y_f)
k	curvature of the fifth-order polynomial

From Fig. 1, we have

$$\dot{x}_f = v\cos(\theta + \phi)$$
$$\dot{y}_f = v\sin(\theta + \phi). \tag{2.5}$$

Substituting (2.5) to (2.4), we can derive

$$\dot{\theta} = v\frac{\sin\phi}{l}. \tag{2.6}$$

Equations (2.5) and (2.6) are the kinematic equations of mobile car with respect to the axle center of the front wheels.

These equations are used to generate the next backward state position of the vehicle when the present states and control inputs are given.

Similarly, we can get the kinematics of mobile car with respect to the axle center of the rear wheels:

$$\dot{x}_r = v.\cos\theta\cos\varnothing$$
$$\dot{y}_r = v.\sin\theta\cos\varnothing$$
$$\dot{\theta} = v.\frac{\sin\varnothing}{l}. \tag{2.7}$$

2. Recognition of Parking Line

(1) Introduction

M.M.Suruz [5] reported a method to recognize a parking line and parking slots for Automatic Parking Assist System [5], which consisted of six phases:

a. construction of the bird's eye view edge image of input image captured with wide-angle lens,

b. Hough transform of edge image, marking line recognition by peak pair detection,

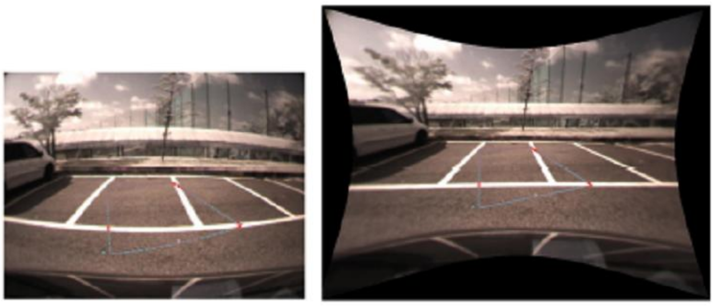
c. marking line-segment recognition,

d. guideline recognition using modified distance between a point and a line-segment,

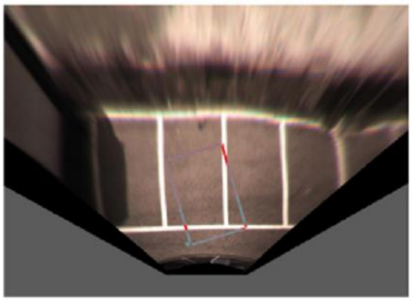
e. and dividing marking line-segment recognition.

(2) Parking-slot-markings recognition algorithm

The six phases of the proposed method will be discussed in the following section.



(a) Input image (b)Undistorted image



(c) bird's eye view image

Fig. 2.2. Construction of bird's eye view image

a. Bird's Eye View Edge Image

Rear-view image captured with wide-angle lens is transformed into bird's eye view image. First, input image is undistorted by radial lens distortion model [17]. Then, undistorted image is transformed into bird's eye view image with homography, which defines one-to-one relation between two coordinate systems [18]. Fig. 2.2 shows the bird's eye view image of input image.

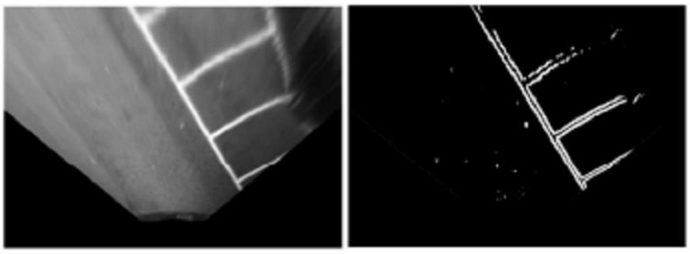


Fig. 2.3 Bird's eye view image and edge image

$$E(x,y)=\left|\sum_{i=-1}^{1}\sum_{j=-1}^{1}Sobel_{vertical}(i,j)\bullet B(x+i,y+j)\right| + \left|\sum_{i=-1}^{1}\sum_{j=-1}^{1}Sobel_{horizontal}(i,j)\bullet B(x+i,y+j)\right| \quad (2.8)$$

Edge image is generated from bird's eye view image(Fig. 2.3.) using Sobel edge detector. Each pixel of the edge image is the summation of Sobel horizontal mask application and Sobel vertical mask application like (2.8). Fig. 2.3. shows a bird's eye view image and resultant edge image.

b. Hough Transform of Edge Image

Hough Transform is one of the most popular methods for the detection of line in binary image.

In general, Hough transform uses normal vector direction ϕ and distance ρ as Hough space axes. In this research, for the sake of easier interface with another components of vision system, somewhat different axes are used: orientation angle θ instead of normal vector direction ϕ, signed distance d instead of positive distance ρ.

$$\begin{aligned} y &= a\cdot x + b = \tan\theta\cdot x + d \\ d &= b\cdot|\cos\theta| \end{aligned} \qquad (2.9)$$

Equation (2.9) shows the definition of θ and d.

c. Marking line-segment recognition

ID(one-dimensional) filtering and clustering in Hough space are developed to detect peak pairs, whose two peaks have the same θ value and fixed internal-distance W in d axis in Hough space.

Equation (2.10) and Fig. 2.4 shows the structure of designed 1D filter. $HS(\theta,d)$ is the value of a Hough space element at (θ,d). $HS(\theta,d-w/2)$ and $HS(\theta,d+w/2)$ are considered to be the peaks. P_A, P_B denotes respectively each value of two peakness-testing coordinates. $S(\theta,d)$ is the application result of the designed filter. Only when $S(\theta,d)$ is positive, $L(\theta,d)$ is defined as a likelihood ranging between 0-1. When the valley values are all zeros, $S(\theta,d)$ has its maximum value, P_A+P_B. If $L(\theta,d)$ is greater than the threshold $\theta_{dual\,peaks}$, the coordinates (θ,d) in

Hough space becomes a candidate of marking line-segment.

$$S(\theta,d) = -HS(\theta,d-W) + P_A - HS(\theta,d) + P_B - HS(\theta,d+W)$$

$$P_A = \max_{i=-1-1} HS(\theta, d - \frac{W}{2} - i)$$
$$P_B = \max_{i=-1-1} HS(\theta, d + \frac{W}{2} - i) \qquad (2.10)$$

$$L(\theta,d) = \begin{cases} \frac{\min(P_A, P_B)}{\max(P_A, P_B)} \cdot \frac{S(\theta,d)}{P_A + P_B}, & S(\theta,d) > 0 \\ 0, & S(\theta,d) < 0 \end{cases}$$

$$C(\theta,d) = \begin{cases} 1 & , L(\theta,d) > \theta_{dual\ peak} \\ 0 & , L(\theta,d) \le \theta_{dual\ peak} \end{cases}$$

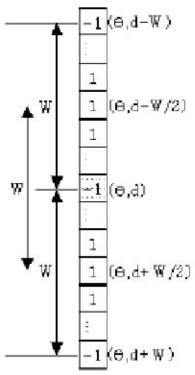
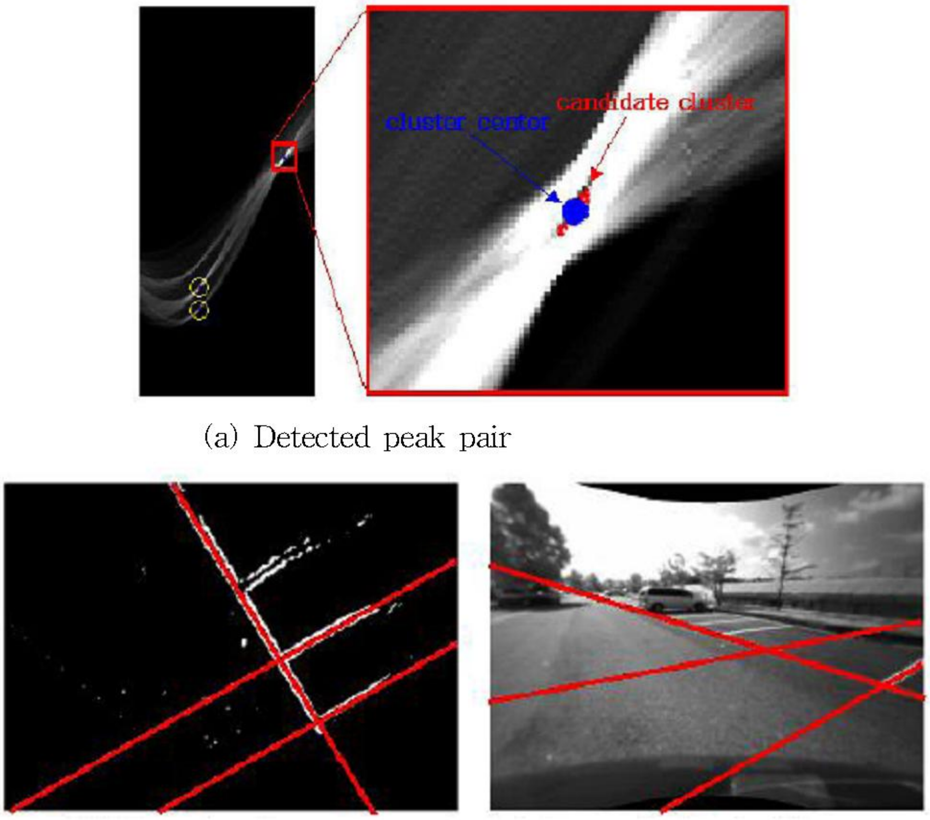


Fig. 2.4 Structure of 1D filter

Fig. 2.5(a). shows detected candidate clusters and their centroids. Fig. 2.5(b). and (c). show overlaid lines designated by detected centroids in edge image and undistorted image.



(a) Detected peak pair

(b) In edge image (c) In undistorted image

Fig. 2.5 Recognized marking lines

Marking line-segment is recognized as a section of detected marking line, which satisfies the condition of marking line-segment.

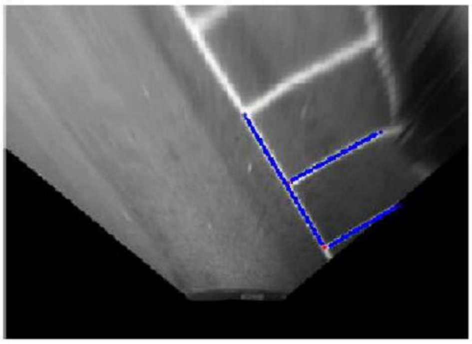
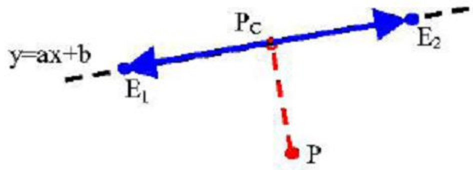
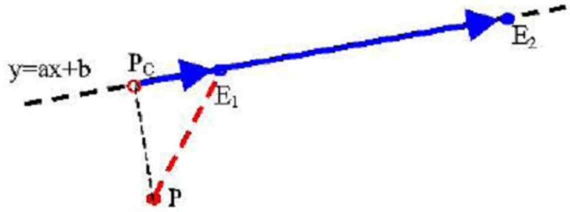


Fig. 2.6. Recognized marking line-segment

d. Guideline recognition



(a) When P_C is in the line-segment



(b) When P_C is out of the line-segment

Fig. 2.7 Distance between a point and a line-segment

Distance between a point and a line-segment is defined as one of two values: distance between the point and a line extending the line-segment, minimum of two distances between the point and the two endpoints of the line-segment. In other words, if the foot of a perpendicular is in the line-segment as shown in Fig. 2.7(a), distance between the point and the line-segment is defined as distance between the point and the foot of a perpendicular. In opposite case as shown in Fig. 2.7(b), minimum of two distances between the point and two endpoints of line-segment is selected. Equation (2.11) shows the equations of the extending line and normal line. Equation (2.12) shows the equation of cross point P_C as the solution of above two line equations. Equation (2.13) defines distance between a point P and a line-segment S. In this application, the given point P is always the camera position and two endpoints of the given line-segment S are previously defined P_{start} and P_{stop}. P_{start} is nearer to the camera. Modified distance from a point P to a line-segment S, $D(P,S)$, is defined like equation (2.14) and a line-segment with minimum modified distance is selected as a guideline. Fig. 2.8 shows the example. Although the start-point of line-segment S_2 is nearer than the start-point of guideline S_1, because the direction of line-segment S_2 is similar to the gaze direction, S_2 has greater modified distance than S_1. Fig. 2.9 shows the detected guideline.

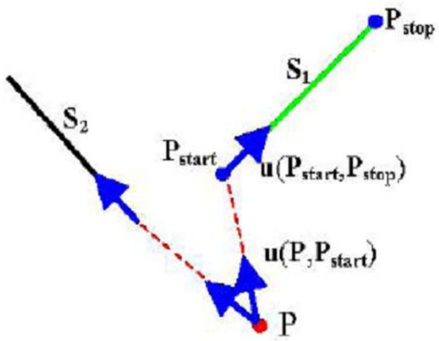


Fig. 2.8. Guideline is likely to be normal to the gaze

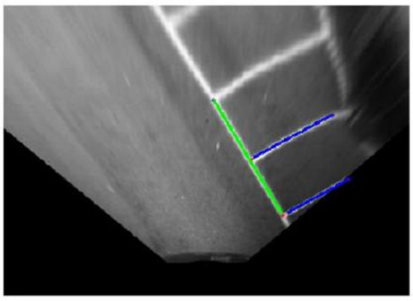


Fig. 2.9. Recognized guideline

e. Dividing marking line-segment

Using the difference between the intensity of pixel on marking and the intensity of pixel off marking along the guideline, marking line-segment dividing parking slots can be detected. By detecting a position where the intensity difference becomes small definitely, 'T'-shape junctions between the guideline and dividing marking line-segments can be recognized successfully. Furthermore, since 'T'-shape junction is found along a whole line extending the guideline, therefore additional dividing line-segments can be detected, which are not detected during peak pair detection because they are located far and blurred.

$$\begin{cases} y = a \cdot x + b \\ y = -\frac{1}{a} \cdot x + \frac{1}{a} \cdot x_p + y_p \end{cases} \tag{2.11}$$

$$P_C(x_C, y_C) = \left(\frac{a}{a^2+1}\left(\frac{1}{a}x_p + y_p \pm b\right), \frac{a}{a^2+1}\left(x_p + a \cdot y_p + \frac{b}{a}\right) \right) \tag{2.12}$$

$$distance(P,S) \begin{cases} distance(P, P_C) & P_C P_{\star t} \cdot P_C P_{stop} < 0 \\ distance(P, P_{\star t}) & P_C P_{\star t} \cdot P_C P_{stop} > 0 \end{cases} \tag{2.13}$$

$$D(P,S) = distance(P,S) \times (u(P, P_{\star t}) \cdot u(P_{\star t}, P_{stop})) \tag{2.14}$$

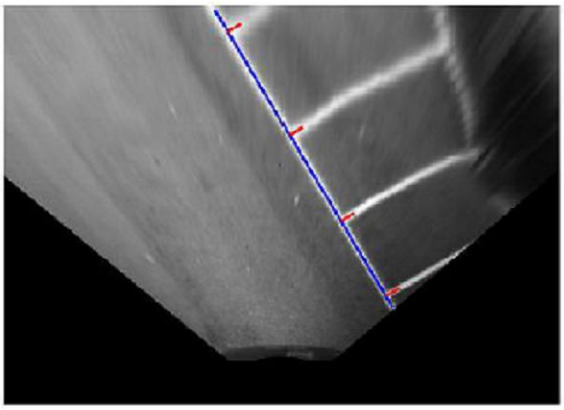


Fig. 2.10. Recognized dividing marking line-segment

(3) Computation of the slope of the parking line

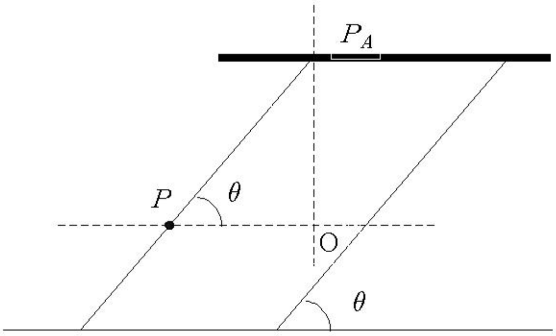


Fig. 2.11. Slant parking angle

Suppose P_A is one of the parking slots in the binary image. And there exist a lots of lines which are parallel of the guideline. Suppose which one of them looks like in the Fig. 2.11. and meet a crosspoint P. It is easy for us to count out the pixels between the point P_A to point O, and the pixels between the point P to the point O. So we can count out the angle θ in here.

(4) Regulation of the parking garage size

In reference[21], a law of the Ministry of Construction and Transportation No. 29 in 2006.05.30. To the 6th item first law rule. We can see the definition that for a number car the width must 2.3 meters upper, and length 5 meters more. (For minicompact car, the unit of parking space and length must be 2 meters and 3.5 meters higher, respectively). Similarly similar regulations about the disables and large size cars are also present, but in this study we considered the car of the large size and not the cars for special situations.

3. Parking Algorithm for a Rectangular Space

A reference trajectory is needed for a mobile car to be successfully parked in the garage. In this regard, If the reference trajectory has low feasibility, then the vehicle can not follow the trajectory accurately. Therefore, the reference trajectory must be set up to the track. The two cases of parking, i.e. backward parking and forward parking are presented as follows.

For backward garage parking the steering wheel is typically turned to the right and the care is moved back. Accordingly the care will result in an arc trajectory on entrance to the garage. Hence, a quarter circle is used to form this trajectory. The reference trajectory for backward garage parking includes a circular motion and a straight-line motion. Fig. 2.12. shows the proposed trajectory, where (x_e, y_0) is the virtual center of the circle, (x_g, y_o) is the connection point, (x_e, y_e) is the initial location of the reference trajectory, and (x_g, y_g) is the final location for (x_r, y_r).

The reference rear trajectory during backward garage parking is represented as a function $y_r = f(x_r)$. The general form for circular motion and line motion are as follows:

$$(x_r - x_e)^2 + (y_r - y_o)^2 = (x_e - x_g)^2$$

$$x_r = x_g \text{ and } y_g \le y_r \le y_o. \tag{2.15}$$

on successful accomplishment of the said trajectory the vehicle can be correctly parked in the garage.

As regards the forward garage parking, lets assume that the garage is wide enough to park the vehicle directly. The corresponding reference trajectory is shown in Fig. 2.13.

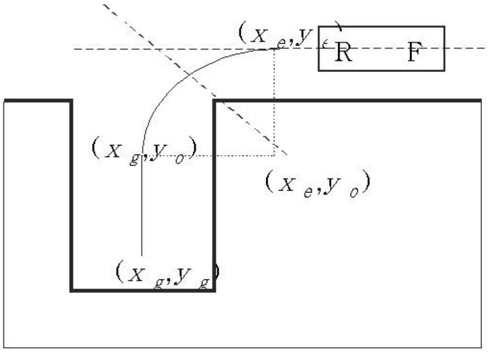


Fig. 2.12. Reference trajectory for backward garage parking.

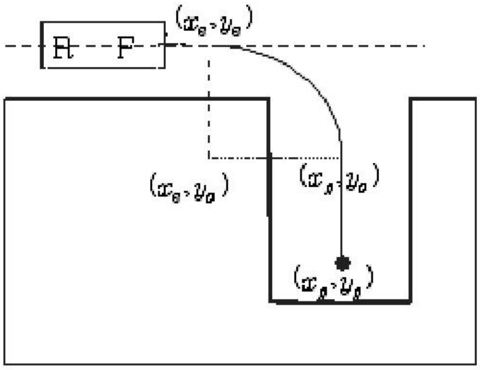


Fig. 2.13. Reference trajectory for forward garage parking

The reference trajectory during forward garage parking is represented as function $y_f = f(x_f)$. The general form for circular motion and line motion are as follows:

$$(x_f - x_e)^2 + (y_f - y_o)^2 = (x_g - x_e)^2$$

$$x_r = x_g \text{ and } y_g \leq y_r \leq y_o. \tag{2.16}$$

In the real world, there exists various types of vehicles which have different scales including length width and height. For research, we search for a great deal of data and divide them in classes. Research reports [19][20], mention that in the market is to see the different scales of the vehicles. The usual scales of vehicles refers to the European and Asian cars, Compared to some cars in Japan and America cars which in a bigger size. We just considered about the small and middle scale cars in the usual situation, where the length are between 3.6m to 4.9m, the width are in the range of 1.5m to 2m. Sure they also have different heights and other elements, but which we are not consider in this paper.
The range of scales about the car looks as follows:

Unit(Meter)	Length	Width	Height	Wheelbase	Model
EU, Asia Car:					
Minicompact car(2 room)	3.6-4	1.5-1.7	1.3-1.5	2.2-2.5	XIALI
minicompact car(3 room)	4.1-4.4	1.6-1.7	1.3-1.5	2.3-2.6	COROLLA
Midsize car	4.3-4.7	1.7-1.8	1.3-1.5	2.6-2.8	JETTA
Special Size:					
K-car	<3.7	<1.5	-	-	SUZUKI
Large station wagon	5.2-5.5	1.8-2.2	1.3-1.5	2.8-3.3	Lincoln Towncar
SUV	5-5.5	1.8-2.2	1.8-2.2	2.8-3.2	BUCK-GL8

4. Parking Algorithm for Slant Space

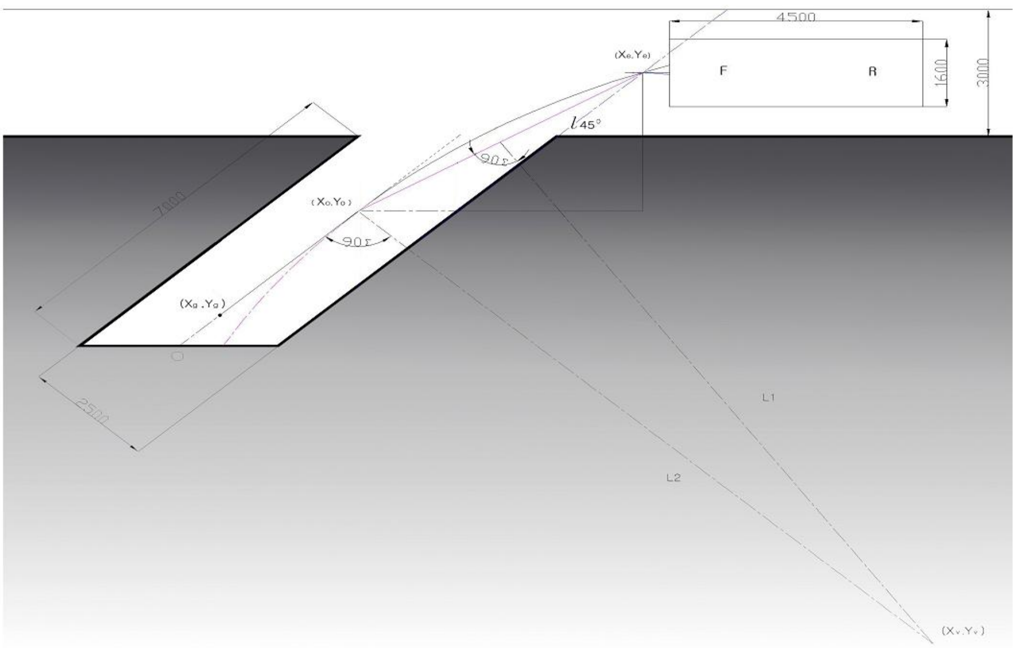


Fig. 2.14. Reference trajectories for forward garage parking in a slant parking space.

But we assume the parking of the autonomous mobile car in a new surrounding. i.e. a slant parking space shown in Fig. 2.14. shows the proposed trajectory, where (x_v, y_v) is the virtual center point of the circle, (x_o, y_o) is the connection point, (x_e, y_e) is the initial location of the reference trajectory, (x_g, y_g) is the final location for (x_f, y_f). θ is the slant angle of parking space. It is apparent that if the θ is 90^0 in here, then will be like the garage parking space like in Fig. 2.13.

In here, still there have a problem how to consider the initial location point (x_e, y_e), and how to find the connection point (x_o, y_o), and the virtual center point (x_v, y_v) of the circle.

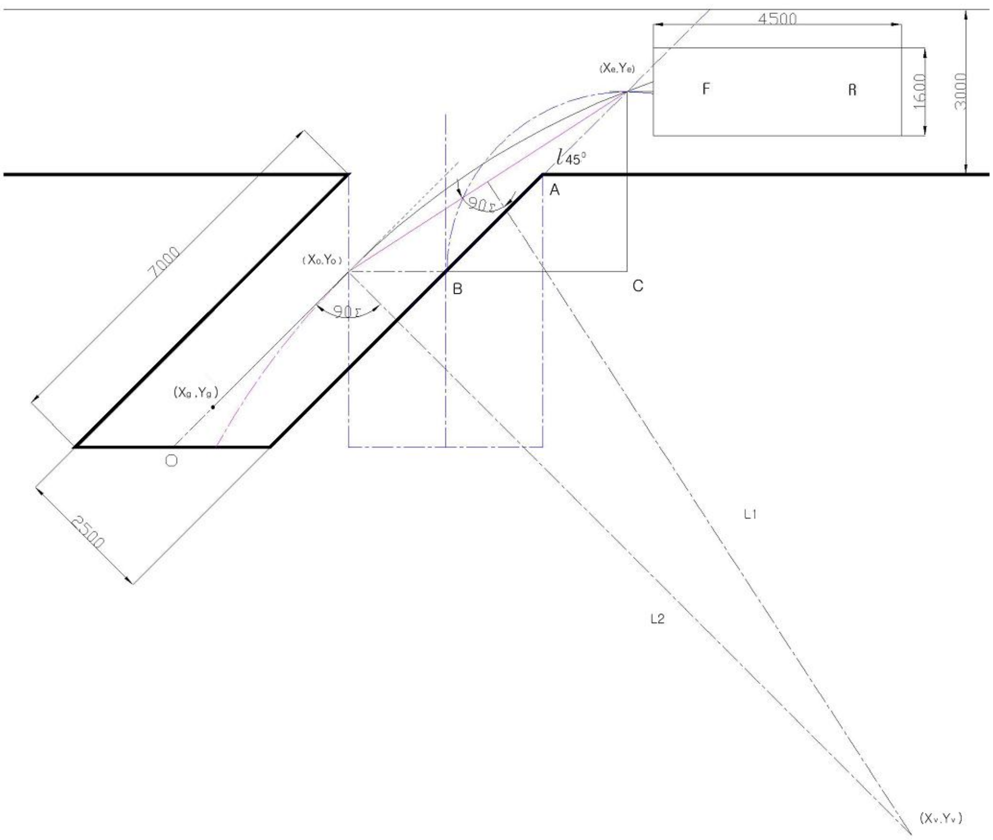


Fig. 2.15. For finding the reference trajectories for forward garage parking in a slant parking space.

In order to implement the slant parking, we adopt a circular arc and a tangent line of the circle though the connection point (x_o,y_o). In fact, several curves have been used to present the reference trajectory in the circular arc such as a circular arc through the initial location point (x_e,y_e),the connection point (x_o,y_o) and a point at the right corner of the bottom in the parking space, etc. However, at the straight-line motion where the straight-line should be the tangent to the circular arc then the trajectory will be the feasible and smooth.

First, at one side of the garage, we can find a line l_{45^0}, which is cross the point A and the slope which is 45^0. And a line which is cross the points of the front and rear wheels center of autonomous mobile car which are (x_f, y_f) and (x_r, y_r). Thus, the intersecting point of the two lines can be obtained.

Secondly, we have to find a connection point of the trajectory, for that lets assume a parking garage (Fig. 2.12) in a slant parking garage (drawn as dotted line in Fig. 2.15). As shown that the point A is no varied, therefore the line l_{45^0} is also unchanged. Thus, an intersecting point B of the lines which are the center line of the dotted line garage and the line l_{45^0}. Thus, there exist a circle which is cross the points (x_e, y_e) and the point B, and the center line of the dotted line garage is a tangent line of the circle. Here, we just consider the center point of the circle is C. Thus, we can get an intersecting point, the connection point (x_o, y_o) we considered, of the lines which is the line cross the points B, C, and the center line of the slant parking garage.

At last, the center point of the circular arc has to be determined. In Fig. 4.2. where we can get two straight line functions, one is though the points (x_o, y_o) and (x_g, y_g), and one is though the points (x_e, y_e) and (x_o, y_o). Which leads to two more lines L_1, L_2, where L_1 is the line which though the center point of the line function between (x_e, y_e) and (x_o, y_o) and vertical the line which is though the points (x_e, y_e) and (x_o, y_o), thus, we have the equation of l_1 as given as follows:

where

$$l_1:\ y_1 = -\frac{x_e - x_o}{y_e - y_o}\cdot\left(x_1 - \frac{x_o + x_e}{2}\right) + \frac{y_o + y_e}{2}, \qquad (2.17)$$

L_2 is the line function which though the point (x_o, y_o) and vertical the line which is though the points (x_o, y_o) and (x_g, y_g). Thus, the equation gives:

$$l_2:\ y_2 = -ctan\theta(x_2 - x_o) + y_o. \qquad (2.18)$$

Thus the crossing value of the lines l_1, l_2 can be obtained, which is the center point of the circular arc (x_v, y_v) we considered in here,
where the values of x_v, y_v as follows:

$$x_v = \frac{-(x_e^2 - x_o^2) - (x_e - x_o)^2 + 2x_o(x_e - y_o)ctan\theta}{2[(y_e - y_o).ctan\theta - (x_e - x_o)]} \quad (2.19)$$

$$y_v = -ctan\theta(x_v - x_o) + y_o. \quad (2.20)$$

Thus the reference the trajectory can be given as follows. Where the general form for circular motion is given by

$$(x_f - x_v)^2 + (y_f - y_v)^2 = (y_o - y_v)^2 + (x_o - x_v)^2, \quad (2.21)$$

where, the certain point of the circular arc is (x_v, y_v), the radius of the circular arc is the length of the point (x_v, y_v) to the point (x_o, y_o).
And the line motion gives

$$y_f = \tan\theta(x_f - x_o) + y_o \text{ and } y_g \le y_f \le y_o. \quad (2.22)$$

Which is a section of the center line of the slant parking garage, and it's tangent line of the circular arc.
Equations (2.21) and (2.22) are the reference front trajectory during front garage parking is represented as a function $y_f = f(x_f)$. We rewrite them in the following:
The circular motion is given by

$$(x_f - x_v)^2 + (y_f - y_v)^2 = (y_o - y_v)^2 + (x_o - x_v)^2. \quad (2.23)$$

And the line motion now is

$$y_f = \tan\theta(x_f - x_o) + y_o \text{ and } y_g \le y_f \le y_o. \qquad (2.24)$$

By large, on fulfillment of the reference trajectory effectively, the vehicle can be parked correctly in the garage.

Ⅲ Design of Fuzzy Logic based Parking System

In this section, we design two fuzzy logic systems for the garage parking of a mobile car, are designed.

A. Backward parking system via the conventional FLC

The main role of backward parking system is to make the mobile car follow the reference trajectory from the start position to the end position. The parameters used to construct the backward parking system is shown in Fig. 4, where (x_{r1}, y_{r1}) is the desired position of the reference trajectory at some sampling instants, θ_1 is its orientation angle corresponding to the X-axis, θ_2 is the orientation angle of the mobile car, and θ_3 denotes an orientation angle between the X direction and the line from (x_{r1}, y_{r1}) to (x_{r2}, y_{r2}).

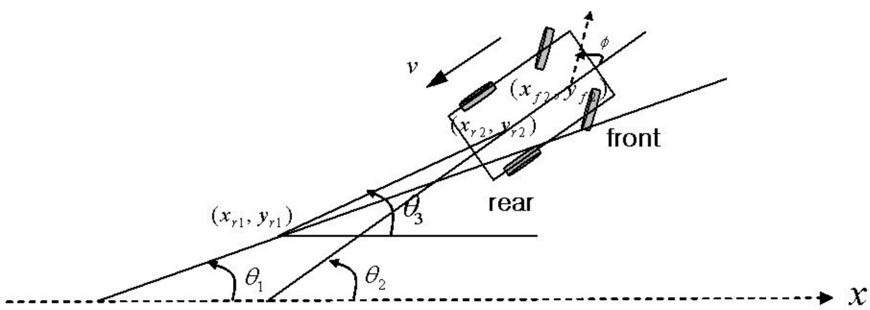


Fig. 3.1. Definition of parameters for backward parking system.

A FLC is an algorithm that can convert the linguistic control strategy based on the knowledge of expert or operator into an automatic control strategy. The rules of a FLC are usually determined by the human operator's behavior. The kernel of the FLC is a set of linguistic control rules. According to the parking skill in our daily life, fuzzy reasoning rules for the backward parking system can be expressed in linguistic form.

A two-input single-output FLC for the garage parking task, was designed. In this regard its input variables as follows:

$$\begin{aligned} u_1 &= \theta_3 - \theta_1 \\ u_2 &= \theta_2 - \theta_1 \end{aligned} \tag{3.1}$$

Then a sliding line is defined as follows:

$$\begin{aligned} s &= u_1 - u_2 \\ &= \theta_3 - \theta_2 \\ &= 0 \end{aligned} \tag{3.2}$$

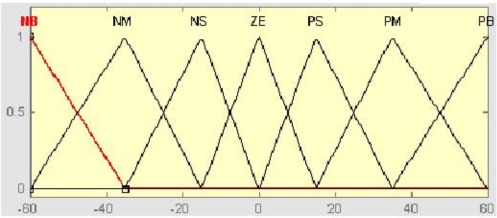
That is, $s=0$ or $\theta_3=\theta_2$ means that the mobile car follows the trajectory.

If the output linguistic variable as the steering angle $\varnothing$, the governing parameters for the conventional FLC can be set up, as given in Table 2.

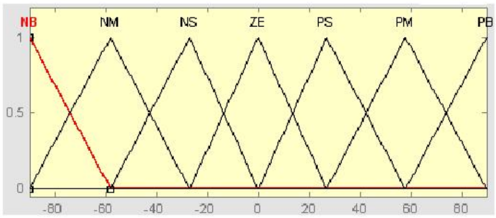
Table 2. Rule table for the conventional FLC (forward parking).

u_1 \ u_2	NB	NM	NS	ZE	PS	PM	PB
PB	NB	NB	NB	NB	NM	NS	ZE
PM	NB	NB	NB	NM	NS	ZE	PS
PS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
NS	NM	NS	ZE	PS	PM	PB	PB
NM	NS	ZE	PS	PM	PB	PB	PB
NB	ZE	PS	PM	PB	PB	PB	PB

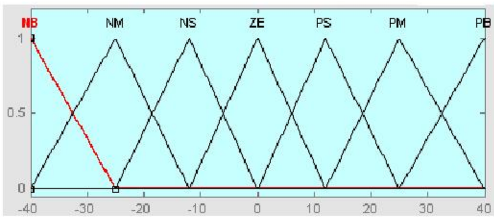
The membership functions of u_1, u_2 and $\varnothing$ are shown in Fig. 5, where they all are decomposed into seven fuzzy partitions, such as negative big(NB), negative medium(NM), negative small(NS), zero(ZE), positive small(PS), positive medium(PM), and positive big(PB).



(a) Membership function of u_1.



(b) Membership function of u_2.



(c) Membership function of Φ.

Fig. 3.2. Fuzzy membership functions for the input-output variables of the conventional FLC.

B. Backward parking system via the SFLC

The governing parameters can be changed and any similar type of table can be applied to Fig. 3.3.

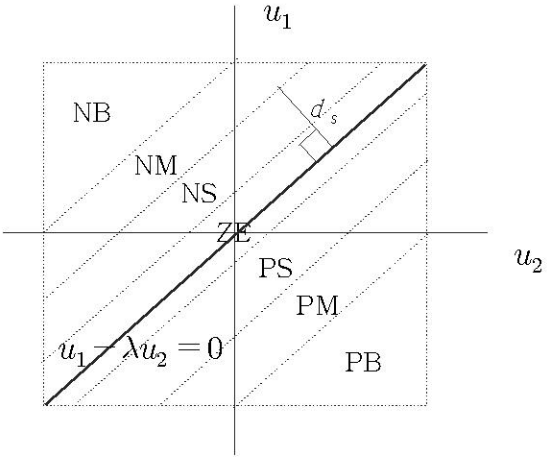


Fig. 3.3. Depiction of Table 2 with infinitesimal quantization levels.

Consider the line which passes the origin and is parallel to straight lines which are boundaries of control regions.

$$s_l : u_1 - \lambda u_2 = 0 \tag{3.3}$$

We call it the switching line.
We can now derive a single variable d_s from Fig. 3.3 [9]:

$$d_s = \frac{u_1 - \lambda u_2}{\sqrt{1+\lambda^2}} \tag{3.4}$$

It represents the distance with a sign from $s_l = 0$ to an operating point. Then the control rule table can be established by a single variable of d_s instead of two variables of u_1, u_2. We call it SFLC(Single-input Fuzzy

Logic System).
The output linguistic variable is still the steering angle $\varnothing$. Therefore the rule form for the SFLC is given as follows:

$$R_{SI}^{k}:\ IF\ d_s\ is\ LDL^{(k)}\ THEN\ u\ is L\varnothing^{(k)},$$

where $LDL^{(k)}$ is the linguistic value of d_s in the kth rule. $L\varnothing^{(k)}$ is the linguistic value taken by the process state variable. Then the rule table is established by Table 3.

Table 3. Rule table for the SFLC (backward parking).

d_s	NB	NM	NS	ZE	PS	PM	PB
$\varnothing$	NB	NM	NS	ZE	PS	PM	PB

The membership function of d_s for the SFLC is shown in Fig. 3.4.

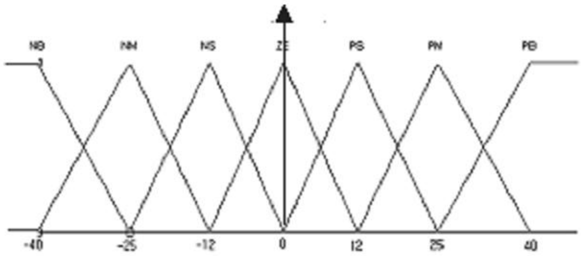


Fig. 3.4. Membership function of d_s.

From Table 3, we can see that the total number of rules is greatly decreased compared to the case of conventional FLC. So we can easily increase the number of rules for the purpose of a fine control.

C. Forward parking system via the conventional FLC

The reference trajectory for the forward garage parking was shown in Fig. 3.2 and equations (2.23) and (2.24).
In this case, if the mobile car is above the ideal trajectory, one should turn the steering angle to the right with a medium force to go along

the trajectory. So, we can derive the following rule: if u_1 is NS and u_2 is PS, then ϕ is PM. The control rules for the forward parking system are listed in Table 4, which is skew-symmetric to Table 2.
Except for the rule table, all the parameters and settings of the forward parking system are the same as those in the backward one.

D. Forward parking system via the SFLC

The corresponding reference trajectory and equations are the same as those described in Section C. In the forward parking system, the rule table for the SFLC is derived as Table 5 via the similar manipulations to Section B:

Table 4. Rule table for the FLC (forward parking).

u_1 \ u_2	NB	NM	NS	ZE	PS	PM	PB
NB	ZE	PS	PM	PB	PB	PB	PB
NM	NS	ZE	PS	PM	PB	PB	PB
NS	NM	NS	ZE	PS	PM	PB	PB
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NB	NB	NM	NS	ZE	PS	PM
PM	NB	NB	NB	NM	NS	ZE	PS
PB	NB	NB	NB	NB	NM	NS	ZE

Table 5. Rule table for the SFLC (forward parking).

d_s	NB	NM	NS	ZE	PS	PM	PB
∅	PB	PM	PS	ZE	NS	NM	NB

Ⅳ. Simulation and results

The computer simulation results of the autonomous mobile car are represented to demonstrate the effectiveness of the proposed control schemes. Taking into account real life, for forward parking, the length and width of the garage is about 1.5 times greater than the car size. The autonomous mobile car used in the simulation has the following dimensions: length m, width m, and wheel base m. We simulated some cases to demonstrate the effectiveness of the proposed scheme. Taking into account the real life, the length of the garage is about 2 times wider than that of a car for the garage parking.

A. Backward parking case

Suppose the initial postures of the mobile car is located at $(x_r, y_r, \theta_2) = (5, 6.5, 0^0)$.

First, we just simulate it with a line from the center position of the front wheels to the center position of the rear wheels. Simulation results are shown in Fig. 4.1 and Fig. 4.2. These are the cases of conventional FLC and SFLC, respectively. As we can see in figures, their results are almost the same.

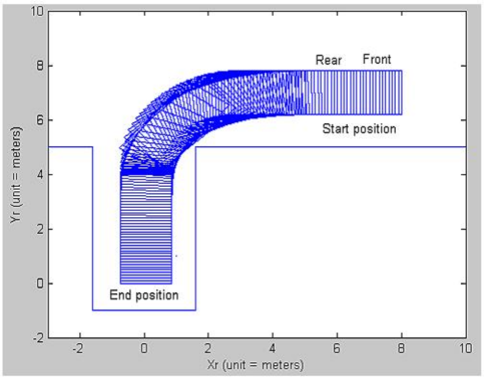


Fig. 4.1. Simulation result of the conventional FLC.

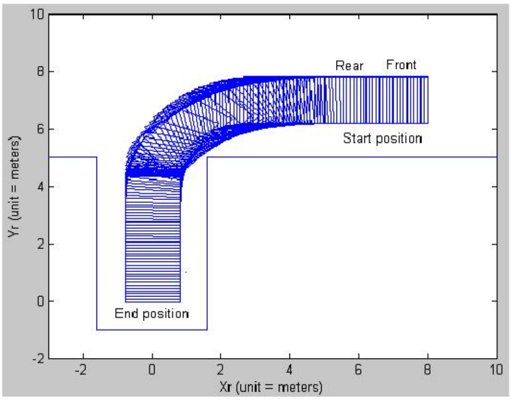


Fig. 4.2. Simulation result of the SFLC.

B. Forward parking case

We will now simulate the case of the forward parking system. We suppose the initial postures of the mobile car is located at $(x_f, y_f, \theta_2) = (-5, 6.5, 0^0)$. Simulation results are given in Fig. 10 and Fig. 11. These are the cases of conventional FLC and SFLC, respectively. Similar to the backward parking case, their results are almost the same.

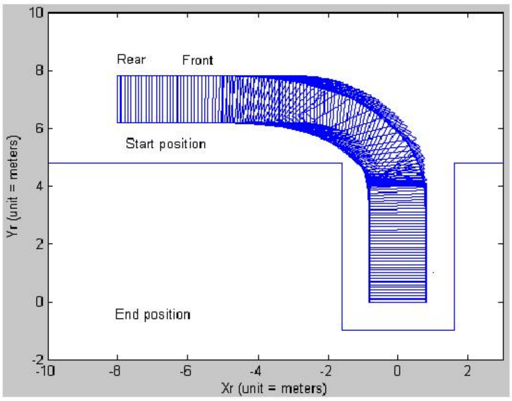


Fig. 4.3. Simulation result of the conventional FLC.

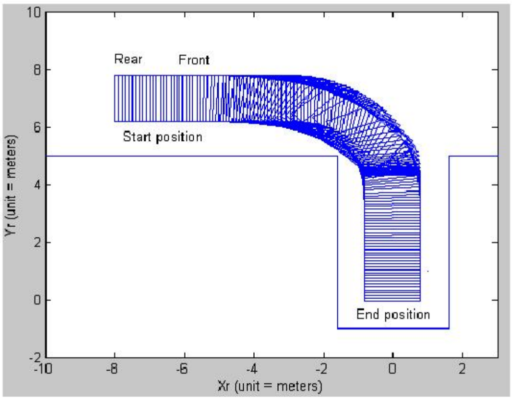


Fig. 4.4. Simulation result of the SFLC.

C. Slant parking case

Lets simulate the case of the forward parking system. We suppose the initial postures of the mobile car is located at $(x_r, y_r, \theta_2) = (5, 7, 0^0)$. The result given as follows, shows that the vehicle can follow this reference trajectory very efficiently.

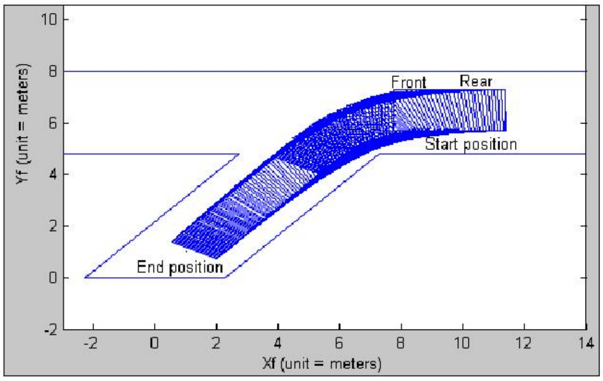


Fig. 4.5. Simulation result of the conventional FLS.

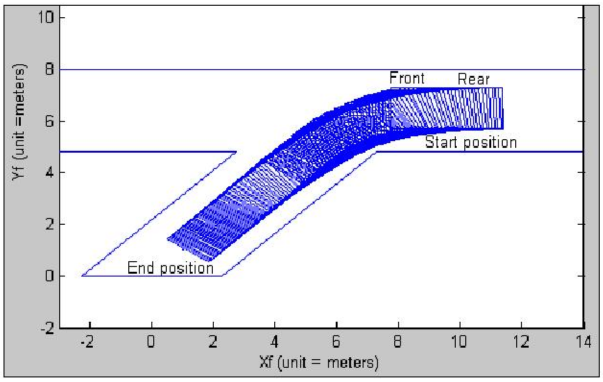


Fig. 4.6. Simulation result of the simple-structured FLS.

V. Concluding Remarks

In this paper, we introduced a method to recognize a parking line and recognize out the angle of the parking space. We just confirmed its performance available in theory, still its need to inspect in real-time testing. The remained problem is to recognize out the actual garage size in a real time image processing. We have also designed fuzzy logic based backward and forward parking system for an autonomous mobile car. We here introduced the reference trajectories for their garage parking. Additionally, we designed fuzzy logic based backward and forward parking system for autonomous mobile car, and designed the reference trajectories for their garage parking. We have also designed the SFLS for the backward and forward parking systems, respectively.

For improving the reliability of the simulation results. we analyzed for a great deal of data about the various types of vehicles and divided them into some classes. We made a simulation surrounding to the real world. What was interesting in the simulation was that if we change a angle of the slant garage parking space, the autonomous mobile car can still follow the trajectory well. It showed many other advantages. One of them was to reduce the number of the control rule greatly. Compared to the conventional fuzzy logic system design it could reduce the design time greatly and improved the processing speed. Also we confirmed the parking system not just in a rectangular spaces and also the slant parking spaces.

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무인 자율 주행 차량을 위한 퍼지논리기반의 주차 시스템 설계

학 양 화

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지도교수 최 병 재

(요약)

무인자동차에 관한 연구가 활성화되면서 무인 주차 또한 중요한 과제로 대두되고 있다. 본 논문에서는 무인 차량을 위한 주차 편의 시스템 설계를 위하여 퍼지논리시스템에 의한 주차 알고리즘을 설계하고자 한다. 기존의 논문들이 제시한 주차 알고리즘들을 분석하여 새로운 주차공간에 대한 주차 알고리즘을 설계, 구현하고, 시뮬레이션을 통하여 그 효용성을 확인하고자 한다.

감사의 글

이제 석사학위 논문의 끝을 감사의 글로 맺을까 합니다. 너무나도 멋진 사람들과 함께 할 수 있었던 시간들을 주신 최병재 지도교수님께 가장 먼저 감사드립니다.

부족한 학위논문이지만 시사해주신 류석환, 도용태 교수님께도 깊은 감사드립니다.

석사과정에서 어려울 때 격려해 주고 여러 가지 도움을 준 김종만, 김길수, 박수우 선배한테 감사드립니다. 항상 옆에 있어 주었던 태균과 동기인 윤수에게 감사의 말을 전합니다. ICONS에서 함께 했던 대현, 소진, 준영, 수정, 홍기, 진영, 기성, 철희, 유성, 재형 후배들에게 많은 도움을 주지 못하여 미안함이 남지만 함께 했던 시간 동안 편하고 즐거운 시간을 함께 보낸 것에 깊은 고마움을 느낍니다.

낯선 나라 한국에 혼자 떨어져 있다고 걱정해 주신 어머니와 저를 믿고 묵묵히 바라봐주신 아버지께 죄송하고 감사할 따름입니다. 앞으로 건강한 아들로써 더욱 열심히 한 모습을 보여드리도록 노력하겠습니다. 또한 지금까지 학교에서 학업에 전념하며 공부할 수 있도록 배려해 주신 노고에 깊이 감사드립니다.

나중에 직장 생활에서 어렵고 힘들더라도 학교에서 공부하며 익힌 끈기와 열정으로 열심히 하겠습니다. 이후에 회사 발전에 도움이 되고 더 나아가 중국과 한국의 발전에 큰 기여 하는 것이 저의 바램입니다.

또한 제가 한국에서 공부하고 생활하면서 많이 도와주신 김이현 형님께 감사드립니다.

마지막으로 저에게 사랑과 조언을 아끼지 않으며 언제나 저와 함께 해준 부인 왕리우와 여기에 나열하지 못한 고마운 분들께 미흡한 저의 논문을 바칩니다.