Outdoor Autonomous Land Vehicle Guidance by Road Information Using Computer Vision and Fuzzy Wheel Adjustment Techniques[*]

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摘要

本論文提出一套用於戶外自動車導航的技術。我們選擇道路上的明顯路標（例如各種路線和燈柱邊緣）作爲導航的特徵，同時將燈柱位置和路況以人工測量的方式建立成簡單的模式資訊，用來作爲自動車定位的依據以輔助導航。本研究利用一個控制自動車沿線導航的方法，可以控制自動車在任何畫有路線的道路上行駛，並且藉著模式資訊來預測燈柱出現在影像中的時機，快速地抓出燈柱邊緣而正確地作自動車定位。在影像處理方面，我們以即時分析所攝得影像亮度的方法，來克服戶外光線變化的影響；同時我們使用一個改進過的最小平方誤差法來求得較爲精確的路線方程式。此外，我們還提出一個以車子偏離路線的距離和車子偏斜角度爲參數、利用模糊集合理論解決自動車輪向控制的方法。另外，因爲室外環境的高低起伏而使得車子不易定速航行，本文提出一個穩定車速的方法來達到平穩航行的效果。最後實際應用本論文所提的方法在一輛自動車的導引上，多次的實驗證實本系統可行。

關鍵字：自動車導航，沿線導航，模糊輪向調整。

Abstract

An approach to autonomous land vehicle (ALV) guidance for outdoor navigation by road information using computer vision and fuzzy wheel adjustment techniques is proposed. Several types of landmarks or features on roads, such as different kinds of path lines and lampposts, are utilized for vision-based navigation. Lamppost positions and road conditions are extracted as the model information for navigation guidance. Using a line following method, the ALV can be guided on roads with path lines on them. By model information, the time that lampposts appear in the image can be predicted. The edges of lampposts are extracted to locate the ALV correctly and quickly. A dynamic image thresholding method is used in real time to solve the problem caused by the sunlight change. A modified least-square-error line approximation method is employed to extract path lines. Fuzzy set theory is applied to determine the turn angle for wheel adjustment. In addition, a speed adjustment approach is used to keep the ALV at stable speeds on fluctuating roads. Lots of successful navigation experiments using a real ALV confirm the effectiveness of the proposed methods.

Key Words : ALV guidance, line following, fuzzy wheel adjustment.

1. Introduction

1.1 Motivation

With the availability of considerably cheap and fast computers and memory, mature techniques of CCD cameras, as well as quick image I/O and processing hardware, using computer vision techniques for the guidance of autonomous land vehicles (ALV's) has become feasible. A lot of related works have been conducted in recent years on account of its great application potential. Possible applications of the ALV include automatic freeway driving, guidance of the blind or disable, safety guarding, tourist guiding for sightseeing, unmanned transportation, coal mining, various military applications, etc. In the previous works, a lot of them are based on road following techniques; the global location of ALV is unknown in such approaches. Guidance using the model information of structured environments seems a more practicable strategy. The purpose of this study is to accomplish stable ALV navigation in outdoor environments using mixed methods of model matching and line following.

1.2 Survey of Related Studies

Several successful ALV systems have been established for various purposes. For outdoor environments, the CMU mobile robot system[1], Navlab, was equipped with multiple sensors, including color TV cameras, range sensors, odometers, etc., which are fused into the vehicle system. A road following approach was implemented in this system, where 3-D laser range data are used for obstacle detection and terrain analysis, and 2-D color image processing algorithms are used to do line tracking and region analysis. Using a Sun workstation, the Navlab was driven successfully in an outdoor environment at 10 cm/s. The Alvin [2] system is another successful outdoor ALV system develop by Turk et al. that also

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uses the road following approach. The image grabbed by a color video camera is first segmented into road and nonroad areas; then, the road edges are extracted by an edge-tacking process. After the fusion of video and range data, the abilities of obstacle detection and avoidance are achieved. By using a Vicom image processor and Intel multiprocessor system, the Alvin can be driven at speeds up to 10 km/hr and can be steered around obstacles. When on a straight and obstacle-free road, road following can be achieved at speeds up to 20 km/hr.

The goal of wheel adjustment is to drive the ALV as close to the desired path as possible. It is part of the pilot module of the whole ALV system. In Cheng and Tsai[6], a nonlinear function was proposed to evaluate the possibility of a turn angle according to the slant angle and deviation position of the vehicle. Because there is no formula solution for that function, an exhaustive search over the possible range of the turn angle was used to determine an optimum turn angle, based on the assumption that the moving distance of each cycle is constant and known. On the other hand, using fuzzy set theory by modeling the experienced operator's control action, two model cars [3,4] have been developed and designed to move through crank-shape corridors and to park itself to a garage, respectively.

To conduct ALV guidance research, three ALVs were developed by Tsai et al. [5-7]. In Ku and Tsai[5], a model-based navigation approach was proposed, and the corridor contour was used as the model. The input pattern extracted from the video camera image is matched with the model by an extended concept of generalized Hough transform. So, the global location of the ALV can be known. In Cheng and Tsai[6], a new guidance approach by model matching was proposed, where locations of vertical lines in indoor environments are used as the model. The vertical line position information is matched with the model and used to locate the ALV exactly. In Su and Tsai[7], an integrated approach to ALV guidance for automatic navigation and collision avoidance in building corridors and elevators was proposed. A model-base guidance using multiple corner points on walls is applied for automatic navigation and the reflex photoelectric sensors were used for obstacle avoidance. Furthermore, a radio equipment was employed to control the elevator operations of lifting up, lifting down, door closing, and door opening so that the ALV can accomplish elevator entering automatically.

1.3 Overview of Proposed Approach

Most of the ALV navigation approaches in outdoor environments are based on road following or line following techniques. A disadvantage of such approaches is that the ALV does not know its own global location. Using the model information of structured environments is a reasonable method to solve the problem. In this study , the positions of road lampposts in outdoor environments are used as the model of automatic ALV navigation, which are measured manually before navigation, and several types of path lines are used as the guiding lines for the line following method. The model consists a series of submodels that record the types of path lines to follow and the relative position of the next landmark for ALV location. Since fuzzy set theory shows a great success in the area of fuzzy logic control, a wheel adjustment method using fuzzy rules is employed in this study. In addition, the speed of the ALV varies with the fluctuation of the road and stable speed is usually not easy to maintain, so a stable speed adjustment approach is also applied. In summery, a ALV guidance approach combing line following, model matching, and fuzzy wheel adjustment and stable speed adjustment techniques are proposed.

As shown in Figure 1(a), we can see a yellow side path line and a lamppost clearly, so the ALV can determine the moving direction and locate itself by the positions of lampposts. Besides, three other kinds of path lines are used, too. They are central path lines, horizontal path lines, and two perpendicular path lines on the road intersection, which are shown in Figure 1(b), 1(c), and 1(d) respectively.

A navigation session proceeds in a cycle by cycle manner which can be divided into five stages. First, the ALV grabs an image and applies the relevant image processing techniques to extract road features according to the current submodel content. Second, the global location of the ALV is calculated if a lamppost is detected. Third, a line following method using fuzzy rules are applied, where the navigation path is selected in such a way the ALV moves parallelly to the path line. Fourth, because of the fluctuation of roads, we apply a speed adjustment method to keep the ALV in a stable speed. Finally, we test whether a new road feature appears and change the current submodel number to the next if the ALV reaches a new road feature. After these five stages are performed, the process goes to the first stage to repeat the cycle until the ALV arrives the destination.

1.4 System Description

A prototype ALV with smart, compact, ridable characteristics, as shown in Figure 2 is constructed as a testbed for this study. It is a commercial motor-driven vehicle modified by adding sensors, electronic control circuits, an on-board microcomputer, and several power conversion devices. It has four wheels in which the front tow can be controlled to turn leftward or rightward as desired by man or computer and the rear two can be controlled to go forward or backward. In the experiments of this study, we use two cameras as video sensors, which are mounted on the horizontal bar, one is on the right side and the other on the left side. The right camera is used to grab side path lines on the road, and the left camera to grab central path lines and the scene, during the right turning session.

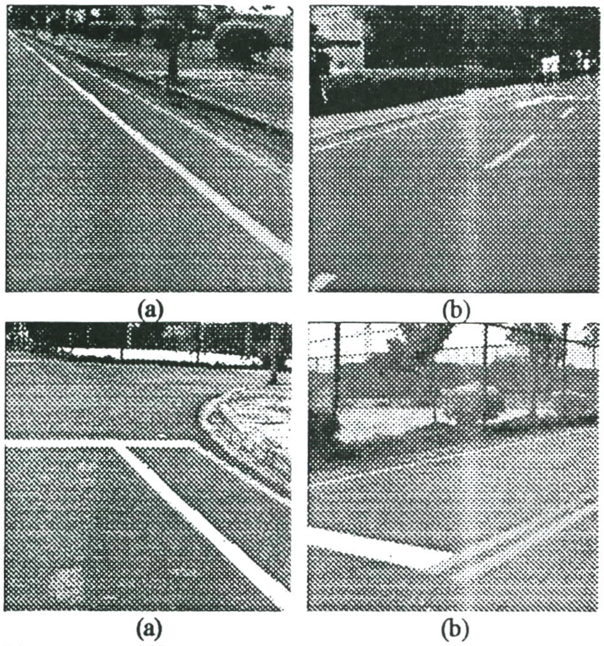


Figure 1 : Different types of landmarks in the outdoor environment. (a) A side path line and a lamppost. (b) A central path line. (c) A horizontal path line. (d) Two perpendicular path lines.

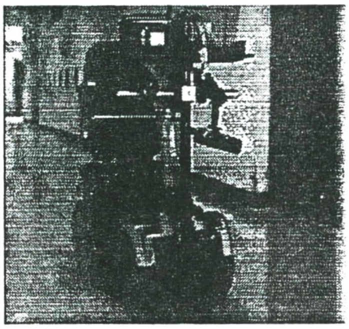


Figure 2 : The prototype ALV used in this study.

1.5 Paper Organization

In the remainder of this paper, we describe in Sec. 2 the necessary coordinate systems, transformations, and backprojection principle used for ALV location. The techniques for ALV navigation and location are described in Sec. 3. The proposed wheel and speed adjustment approaches are described in Sec. 4. Image processing techniques and experimental results are described in Sec. 5. Conclusions and suggestions for further study can be found in Sec. 6.

2. Coordinate Systems for Vehicle Guidance

2.1 Coordinate Systems and Transformations

In the ALV guidance process, the following four coordinate systems are needed to describe the vehicle location and the navigation environment. The corresponding transformations are also defined in this section for use in the following sections.

1. The vehicle coordinate system (VCS): denoted as x-y-z. The origin V is at the middle point of the line segment which connects the two contact points of the two front wheels with the ground. The x-axis and y-axis are on the ground and parallel to the short side and the long side of the vehicle body, respectively. The z-axis is vertical to the ground.
2. The camera coordinate system (CCS): denoted as u-v-w. The camera is associated with camera coordinate system and the origin C is attached to its lens center. The v-axis is along the optical axis and the u-w plane is parallel to the image plane.
3. The image coordinate system (ICS): denoted as u-w. The origin I is the image plane center and the image plane is coincident with the u-w plane of the CCS.
4. The global coordinate system (GCS): denoted as x'-y'-z'. The origin G is located at a certain fixed position on a certain landmark (the bottom of a road lamppost in our case). The x'-axis and y'-axis are defined to lie on the ground.

Figure 3 shows these coordinate systems. The ICS, CCS, and VCS are moving with the vehicle during navigation, while the GCS is located at the bottom of a lamppost and is relocated at the bottom of the next lamppost when the ALV sees the next lamppost. The transformation between the CCS and the VCS for a camera can be computed as the coordinates transformation formula developed by Ku and Tsai[5].

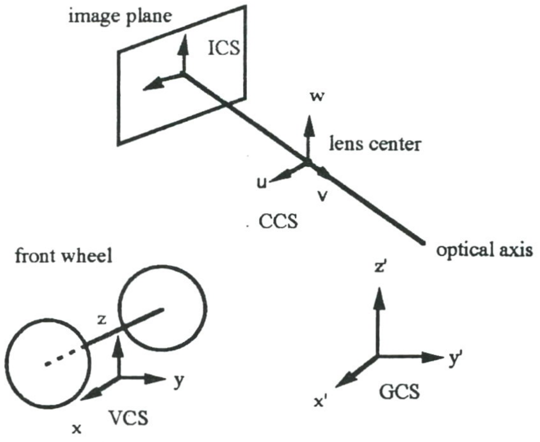


Figure 3 : The four coordinate systems ICS, CCS, VCS, and GCS.

As shown in Figure 4, since the x-y plane of the VCS and the x'-y' plane of the GCS are both defined on the ground, and since the vehicle is moving on the ground all the time, the relation between the 2-D coordinate systems x-y and x'-y' is sufficient to determine the position and orientation of the vehicle. The transformation between the GCS and the VCS can be written as

$$x' = x\cos\omega - y\sin\omega + x_p', \qquad y' = x\sin\omega + y\cos\omega + y_p'. \tag{1}$$

where (x_p', y_p') is the translation vector from the origin of x'-y' to the origin of x-y and ω is the relative rotation angle of x-y with respect to x'-y'. The vector (x_p', y_p') and the angle ω determine the position and the direction of the vehicle in the GCS, respectively. In the following sections, the combination of the vehicle position and direction is referred to as the vehicle location and is denoted by a triple (x_p', y_p', ω).

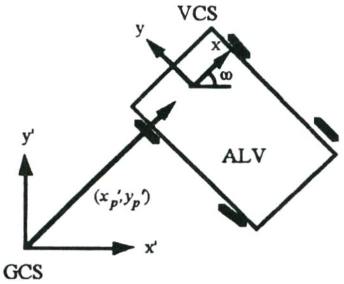


Figure 4: The relation between VCS and GCS.

2.2 Backprojection Principle

If the z coordinate (in VCS) of a point in the image plane is known, the x-y coordinate can be determined by the backprojection principle which is described below. As shown in Figure 5, after backprojecting the point P in the image into the VCS, we can get a line L which passes the lens center and P. The intersection point P' of this line L and the horizontal plane (denoted by $\prod$), whose z coordinate is known, is the corresponding space point of P which we want. Denote this point as P'.

The equation of the horizontal plane $\prod$ can be set as

$$z = h. \tag{2}$$

Assume that point P in the image plane has the CCS coordinate $(u_p, -f, w_p)$ where (u_p, w_p) is the position of P in the image and f is the focus length. By a coordinate transformation [5], the VCS coordinates (x_p, y_p, z_p) of point P in the image can be obtained. In addition, the equation of line L is

$$\frac{x - x_d}{x_p - x_d} = \frac{y - y_d}{y - y_d} = \frac{z - z_d}{z_p - z_d} = k. \tag{3}$$

Since point P' is the intersection point of the plane $\prod$ and line L, by substituting $z = h$ into Eq. 3, the desired VCS coordinate (x_p', y_p', z_p') can be solves to be:

$$\begin{aligned} x_p' &= x_d + \frac{h - z_d}{z_p - z_d}\left(x_p - x_d\right), \\ y_p' &= y_d + \frac{h - z_d}{z_p - z_d}\left(y_p - y_d\right), \\ z_p' &= h. \end{aligned} \tag{4}$$

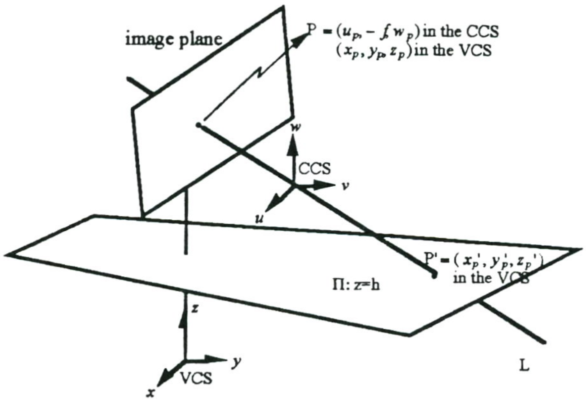


Figure 5 : Configuration of the system for finding the backprojection point for an image pixel.

3. Navigation and Location of ALV

3.1 Steps of a Navigation Process

The navigation of the vehicle proceeds in a cycle by cycle manner. The situation is shown in Figure 6. The bold box (VL_i) represents the actual ALV location and the plain box (VL_i') represents the estimated ALV location. In the beginning of cycle i, the ALV grabs an image and the ALV is located at VL_i at this time. The actual ALV position VL_i is unknown, but the estimated location VL_i' can be obtained from the control information and the previous cycle location VL_{i-1} computed by the image processing techniques. After adjusting the vehicle speed, checking whether the current submodel should be changed to the next one, applying corresponding image processing techniques to extract the path line, detecting a landmark, and computing the correct location VL_i, the ALV has moved from location VL_i to location VL_{i+1}; then, the wheel adjustment according to the estimated location VL_{i+1}' is applied to determine the wheel turn angle. Finally, the ALV will stop if the destination has been arrived; otherwise, the navigation cycle repeats again. The overall procedure is described in Algorithm 3.1.

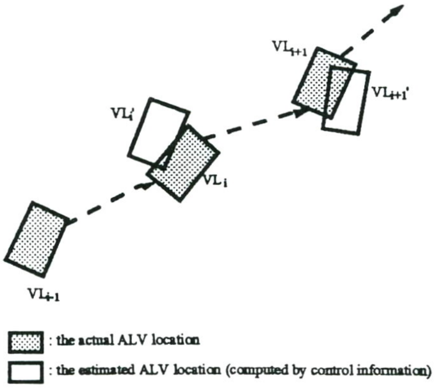


Figure 6 : The relationship between the actual ALV location and the estimated ALV location.

Algorithm 3.1. Navigation process

Method.

- **Step 1.** Perform necessary initialization tasks, including reading camera parameters, reading the data of the prebuilt model, setting up the navigation speed, etc.
- **Step 2.** Drive the ALV to see a lamppost and compute the starting position of the ALV in the GCS; then, start the ALV.
- **Step 3.** Take an image at the actual vehicle location VL_i(unknown yet).
- **Step 4.** Adjust the speed according to the feedback of the odometer.
- **Step 5.** According to the estimated vehicle location VL_i' to check if the current submodel should be changed to the next one.
- **Step 6.** Perform image processing and inverse perspective transformation to get the input pattern under the assumption that the current vehicle location is VL_i' and match the input pattern to the expected pattern (in the pre-built model).
- **Step 7.** Compute the vehicle location VL_i using the movement estimation based on [6]. During the computations of Step 3 through Step 7, the vehicle has moved from location VL_i to location VL_{i+1}.
- **step 8.** Compute the current the vehicle location VL_{i+1}' from the control information and the last location VL_i.
- **step 9.** Compute the deviation of the estimated vehicle location VL_{i+1}' from the desired path line; then, apply the wheel adjustment approach to determine Turn angle and drive the ALV to move close to the desired path.
- **step 10.** If the destination is arrived, stop the ALV; otherwise, go to Step 3.

3.2 Vehicle Location by Landmark Information

Using the road lamppost information stored in the model and image processing techniques, we can calculate the exact location of the ALV with respect to the GCS. First, the bottom of a lamppost can be detected by image processing techniques. Applying the backprojection principle described in Section 2.2, the VCS coordinates of the lamppost can be determined. By estimating the ALV location and substituting it into Eq. 1, we can get the GCS coordinates of the lamppost. Since, the estimated ALV location is not accurate due to the inaccuracies of the control actions, the GCS coordinates of the detected lamppost are not accurate either. We can choose the nearest lamppost from the model as the candidate to get the accurate GCS coordinates. The situation is shown in Figure 7(a). The dashed line L' and gray circle C are the estimated results, and the plain line L, black circle A, and black circle B are the path line and the nearest lampposts in the model, respectively. In this example, lamppost A is the matched model for lamppost C. After this matching process, the relation between the ALV and the environment becomes Figure 7(b). Then, the accurate GCS coordinates of the extracted lamppost C are obtained which are just the GCS coordinates of lamppost A stored in the model.

As mentioned in Section 2.1, the ALV location is described by the ALV slant angle ω and the ALV position (x_p', y_p'). After determining the accurate GCS coordinates of the extracted lamppost, we can derive the ALV location in the GCS by Eq 1. If the path line equation in the VCS is $ax + by = c$, the ALV slant angle ω can be computed according to the following equation:

$$\omega = \frac{\pi}{2} - \tan^{-1}\left(-\frac{a}{b}\right).$$

At last, substituting the GCS coordinates (x_p', y_p') of the matched lamppost A, the VCS coordinate (x, y) of the matched lamppost, and the ALV slant angle ω into Eq. 1, the position of the ALV in the GCS can be determined to be

$$x_p' = x' - x\cos\omega + y\sin\omega,$$
$$y_p' = y' - x\sin\omega - y\cos\omega.$$

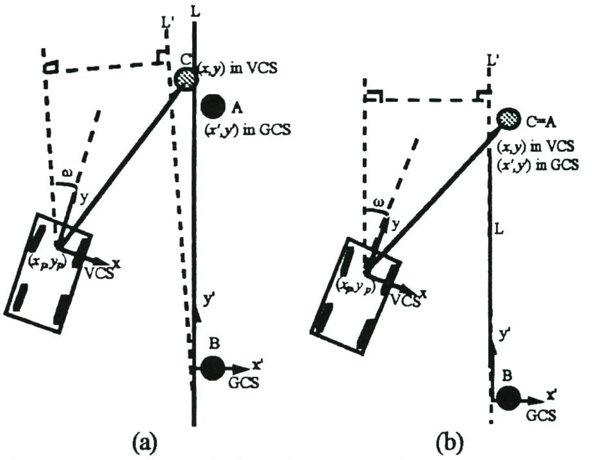


Figure 7 : The relation between the ALV and the environment model. (a) Before the model match process. (b) After the model match process.

4. Wheel and Speed Adjustment

4.1 Wheel Adjustment by Fuzzy Rules

The objective of ALV guidance is to drive the ALV as close to a give path as possible. Wheel adjustment is the subsequent procedure when the location of the ALV has been decided. Lots of related works have been studied in the past. Because fuzzy set theory can express effectively the heuristics and knowledge about how to make the decision of turning wheels, a wheel adjustment strategy using fuzzy control rules is proposed in this study. As shown in Figure 8, if the slant angle θ and the deviation distance d of the ALV from the desired path is known, a wheel adjustment controller is needed to derive the turn angle ϕ. Accordingly, an architecture of the wheel adjustment controller is proposed in Figure 9. The slant angle θ and the deviation d are the input values of the controller. The output of the controller is the wheel turn angle ϕ. The functions of the four modules in the architecture are described next.

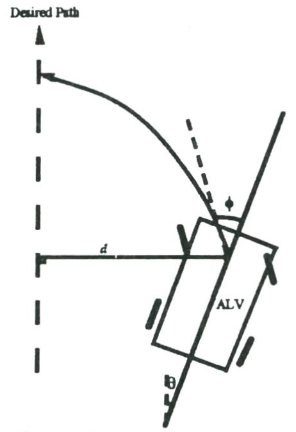


Figure 8 : The ALV moves along a desire path.

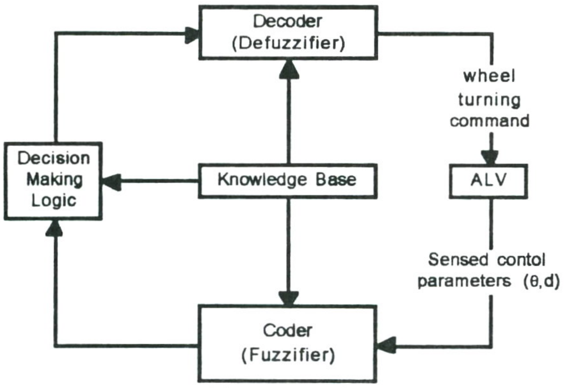


Figure 9 : The architecture of a wheel adjustment controller.

The main knowledge base is a rule base, including four rules using a set of linguistic variables that describe the values of control parameters θ and d. The four rules are described in the following:

Rule 1: if d is LEFT and θ is MIDDLE, then ϕ is RIGHT;
Rule 2: if d is RIGHT and θ is MIDDLE, then ϕ is LEFT;
Rule 3: if θ is LEFT, then ϕ is RIGHT;
Rule 4: if θ is RIGHT, then ϕ is LEFT;

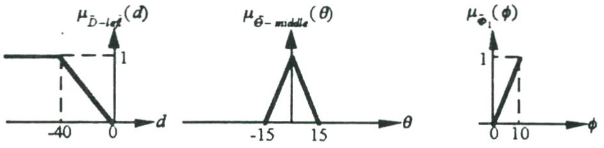
where LEFT, RIGHT, MIDDLE are linguistic variables whose meaning is represented by the corresponding membership functions, $\mu_{\tilde{\Theta}-right}(\theta)$, $\mu_{\tilde{\Theta}-left}(\theta)$, $\mu_{\tilde{\Theta}-middle}(\theta)$, $\mu_{\tilde{D}-right}(d)$, $\mu_{\tilde{D}-left}(d)$, $\mu_{\tilde{\Phi}_1}(\phi)$, $\mu_{\tilde{\Phi}_2}(\phi)$, $\mu_{\tilde{\Phi}_3}(\phi)$, and $\mu_{\tilde{\Phi}_4}(\phi)$. They are shown in Figure 10. Because the membership function of the conclusion of each rule is monotonic, Tsukamoto's defuzzification method[8] can be applied. The crisp control action is calculated by

$$\phi^* = \frac{\sum_{i=1}^{4} \omega_i \mu_{\tilde{\Phi}_i}^{-1}(\omega_i)}{\sum_{i=1}^{4} \omega_i}, \tag{5}$$

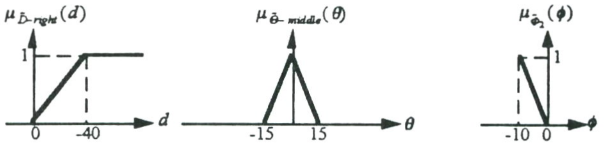
where ω_i is the firing strength of rule i, which are computed by

$$\begin{aligned}
\omega_1 &= \min\left\{\mu_{\tilde{D}-left}(d), \mu_{\tilde{\Theta}-middle}(\theta)\right\}, \\
\omega_2 &= \min\left\{\mu_{\tilde{D}-right}(d), \mu_{\tilde{\Theta}-middle}(\theta)\right\}, \\
\omega_3 &= \mu_{\tilde{\Theta}-left}(\theta), \\
\omega_4 &= \mu_{\tilde{\Theta}-right}(\theta);
\end{aligned}$$

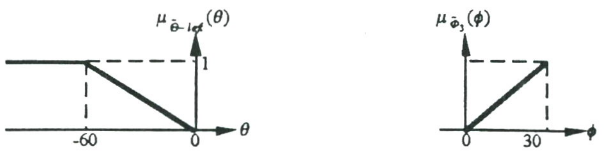
and $\mu_{\tilde{\Phi}_i}^{-1}(\omega_i)$, is the inverse function of $\mu_{\tilde{\Phi}_i}(\phi)$. We denote the result of Eq. 5, ϕ^*, as $\Phi(\theta, d)$ for use in the following sections.



(a) Rule 1



(b) Rule 2



(c) Rule 3

(d) Rule 4

Figure 10 : Membership functions used in this study.

4.2 Wheel Adjustment Strategy for Line Following

Path lines are good guidance marks for ALV guidance. In this study, the straight side path lines, central path lines, and curved side path lines are used for guidance. Once any kind of these path lines is found, the problem becomes how to apply the wheel adjustment function described in the previous section to the case. Because the environment model is prebuilt in the database, the desired path can be derived by the path line which is extracted by image processing.

Consider the case of straight side path lines. As the vehicle moves at the right side of a road, the side path line is located at the right side of the ALV. Like the example shown in Figure 11, we can set the desired path to be one with a distance D to the left edge of the side path line. Then the input value of the wheel adjustment function, θ and d, can be computed to be

θ = the angle formed by the y coordinate of the VCS and the side path line,
$d = vl\_dis - D.$

where the vl_dis is the distance form the origin of the VCS to the left edge of the side path line. Consequently, the wheel turn angle is $\Phi(\theta, d)$.

Analogously, a central path line is in the middle of a road and is located at the left side of the ALV. Hence, the desired path is to the right edge of the central path line with a distance D. The third case is moving along a curved side path line. Because the radius of the curve is very large, a segment of a curved path line near the ALV can be considered as a straight line and the wheel adjustment function for the straight path line can be used.

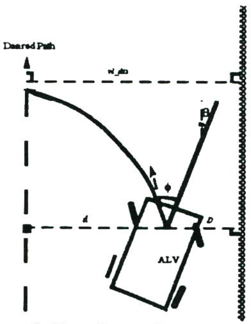


Figure 11 : Line following along a straight path line.

4.3 Wheel Adjustment during Turning Session on Road Intersection

During the turning session on a road intersection, the ALV cannot view the path line all the time and there is no guidance mark to follow. As the ALV knows the location of itself as described in Section 3.2, we can figure out a desired circular path in advance. Like the example shown in Figure 12, the circle center O (x_o, y_o) and the radius R is predefined and the ALV is at V (x', y') in the GCS. Then the deviation distance d is computed by $d = \sqrt{(x' - x_o)^2 + (y' - y_o)^2} - R$ and the slant angle θ is formed by the y coordinate of the VCS and the tangent line that passes the intersection of line $\overline{OV}$ and the circular path. As mentioned in Section 5.1, the wheel adjustment method assumes that the path is a straight line. And so a modification is required for navigation along a circular path. The turn angle ϕ is changed to be

$$\phi = \theta + \Phi(d, 0). \tag{6}$$

Eq 6 means that the ALV will turn the angle of θ to go along the circular path and the deviation distance d is considered in $\Phi(d, 0)$ too.

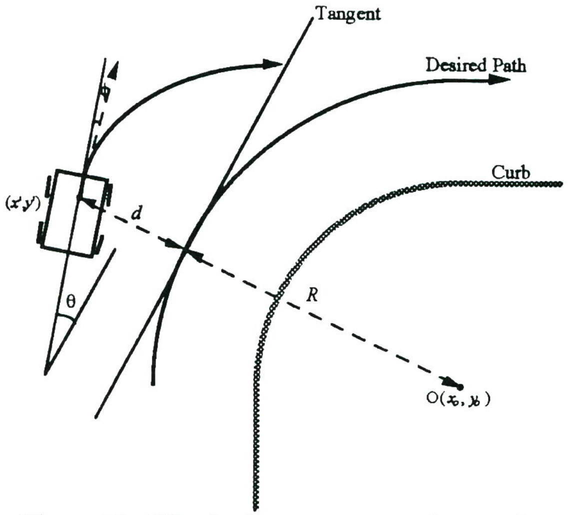


Figure 12 : Wheel adjustment on turning session.

4.4 Speed Adjustment Strategy

The outdoor road topography is more varying than the indoor one. There are up slopes, down slopes, speed bombs, and so on. Hence, the speed of the ALV usually varies with the fluctuation of roads. In this section, a speed adjustment is proposed to keep a stable ALV speed. Because the ALV is mounted with an odometer, we can compute the speed by dividing the counter value by the time spent in each cycle. If the speed increases when the ALV goes down a slope, the command of lower speed is sent to motor control system. On the contrary, the command of faster speed is sent when the ALV speed slows down.

5. Image Processing and Experimental Results

5.1 Results of Image Processing

Because the weather is probably cloudy or sunny, and the sunlight is changing all the time during navigation, a fixed threshold value is not feasible for the extraction of path lines. In this study, the threshold value is changed according to the intensity change of the image. That is, we choose a threshold value TH_0 for a standard image that was taken in a proper illumination condition and compute a middle mean gray value M_0. Then, the threshold value, TH, of an arbitrary image can be calculated to be $TH = TH_0 + (M - M_0)$.

Given a set of candidate pixels for one line, LSE line approximation is usually applied to estimate the line equation. However, it will get a considerably poor result when there are some noise pixels which are far away from the desired line. Therefore, a modified method is described to solve this problem. Because the error results from the involving of all pixels even though noises exists, we can compute several line equations by using only four consecutive pixels in the candidate list. In other words, one line is computed from the first pixel through the fourth pixel and another from the second pixel to the fifth pixel, and so on. For each line, we count the number of pixels whose distances to the line are smaller than a threshold value. The line with the maximum count is called the best fitting line. At last, the pixels that are close enough to the best fitting line are taken as input into the LSE line approximation process again to get the final result.

By using the dynamic thresholding approach described above and some appreciate edge operators, we can get a set of candidate pixels of an edge. By entering these pixels to the modified LSE line approximation, the equations of the edges of path lines or lampposts are obtained. As shown in Figure 13, Figure 13(a), 13(b) and 13(c) are the extraction examples of different types of path lines and Figure 13(d) shows an extraction result of a lamppost.

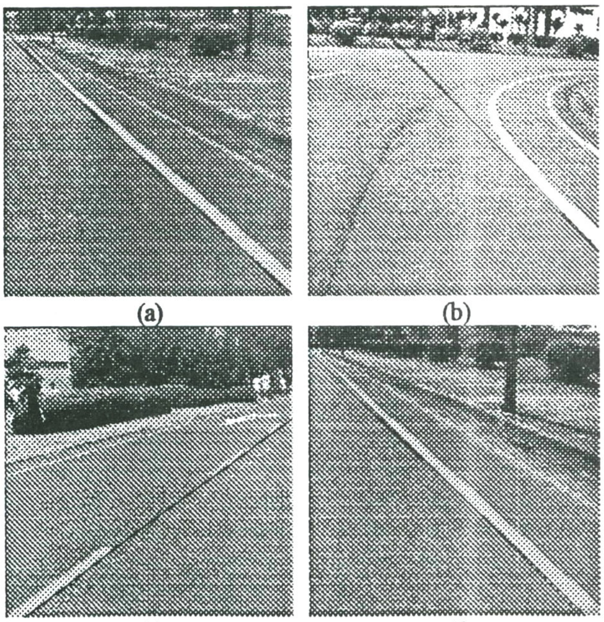

(a) (b) (c) (d)

Figure 13 : Example of extraction results. (a) A straight side path line. (b) A curved side path line. (c) A central path line. (d) A lamppost.

5.2 Results of ALV Navigation

A series of ALV navigation experiments have been performed to test the feasibility of the proposed approach. The navigation environment is a portion of the campus of National Chiao Tung University. There are totally 16 submodels in the experimental environment. Each model includes the type of the path line for the ALV to follow and the GCS coordinates of the next landmark, Several kinds of landmarks were used as the characteristics of the model. The lampposts are used as location marks and path lines are used as guidance marks. After the ALV is located by an arbitrary lamppost in the model, an experimental navigation session can start in front of the lamppost. Then, it drives along the predefined path. It stops when the last model is achieved. The navigation speed of the vehicle is up to about 30 cm/s along the side path line. Because the central path line is dashed, it slows down to 15 cm/s for the stable navigation along the central path line. The computation time of a navigation cycle ranges from 1 to 2 seconds for line following and ranges from 2 to 3 seconds when adding the process of locating the ALV by the lampposts.

5.3 Discussion

After observing a lot of navigation experiments, some discussions are included in this section.

First, many complete navigation sessions show the feasibility of road following by path lines. By using a line following method, the ALV can be guided on any road with path lines on it, such as the highway, city roads, and factory environments. Meanwhile, the environment models utilize the coordinates of lampposts and the types and locations of the lines as the model information. Only a few features need be stored, so only a little memory space is used and the extension of the model is easy.

Second, although the fuzzy wheel adjustment is proved practicable, the vehicle will oscillate along the desired path when it moves at a higher speed. The reason is that the speed of image processing cannot provide the sensing data, θ and d, described in Section 4.1, for the fuzzy wheel adjustment controller to fire the proper wheel adjustment action quickly enough. Since all the image processing works are implemented in software on a PC486 now, some special-purpose hardware should be considered in the future to improve the computation needs of image processing.

Last, the distance of the whole navigation path is considerably long, and it takes a long time to go through the path. If a dramatic sunlight happens during the navigation session such that the aperture level is not readjusted, the contrast of the grabbed image will be too low and the whole image is almost dark or bright. As a result, the image processing described previously will fail. For this situation, the use of an auto-iris lens is a possible solution. An auto-iris lens is one connected to a CCD camera which can adjust automatically the aperture to a preset level according to the brightness feedback to make the grabbed image at the same intensity level.

6 Conclusions and Suggestions for Future Works

An approach to outdoor ALV guidance by road information using computer vision techniques is proposed. The main idea of the proposed approach is to combine line following and model-base guidance. By following the path lines, the ALV can navigate smoothly on the roads. Furthermore, the positions of lampposts and several types of path lines were used for the location of ALV. To improve the extraction accuracy of path lines, a modified LSE line approximation method was applied. In addition, fuzzy set theory was utilized to adjust the wheel direction and a speed adjustment is used to keep the ALV in a stable speed. A lot of successful navigation sessions have shown the capability of the established ALV system.

Some works that should be considered in the future to promote the stability and performance of the ALV or to make the ALV more intelligent are described as follows.

(1) The ability of an ALV system should not be limited to going along the road. It should also include detecting and avoiding obstacles. To achieve the obstacle avoidance capability, a 3-D range sensor is an effective equipment to fulfill the purpose.

(2) Since there is no path line in some roads, road following by tracing the road boundary may be used in the future to get a robust road following system.

(3) The environment models are constructed by manual measurement in this study. How to automatically establish the environment model seems a necessary and interesting research direction.

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