Autonomous Land Vehicle Guidance on Sharp-Curved Roads in Outdoor Environments[@]

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Abstract

A new approach to autonomous land vehicle (ALV) guidance on sharp-curved roads in outdoor environments is proposed. The dotted central path line, which is seldom affected by noise or occlusion on roads, is selected as the visual feature in this study. We check three continuous tangent lines, which are extracted from the visual feature in a sequence of images by the Hough transform, to judge whether an ALV is leaving a straight road and entering a curved road in a navigation session. When the ALV enters a curved road, the three tangent lines are used again to derive the navigation path in the current navigation cycle on the curved road. A smooth trajectory is then planned to guide the ALV to follow the derived navigation path. The navigation path is assumed to be a circle with respect to the current ALV location and is rederived cycle by cycle for safe navigation. Moreover, the three tangent lines can also be used to judge whether the ALV is leaving a curved road and entering a straight road. Successful navigation tests show that the proposed approach is effective for ALV guidance on sharp-curved roads.

I. Introduction

Several related works have been reported for vision-based ALV guidance on curved roads in outdoor environments [1-11]. Waxman et al. [1] used a sequence of image processing steps to extract dominant linear features from road boundaries, markings, and shoulders in road images. The steps include smoothing, gradient computation, extraction of dominant directions, and the Hough transform. Morgan et al. [2] and Campbell et al. [7] both employed edge-finder operators to extract edge points along road boundaries. Then the least square method was used to fit a curve from the edge points. Manigel and Leonhard [3], Dickmanns et al. [4], and Behringer [11] used the Kalman filter to estimate the curvature of the road ahead. Dickmanns and Mysliwetz [5] considered both the horizontal and the vertical road curvature dynamics. They used a 3-D dynamic road model and proposed a 4-D approach to real-time vision to recognize both horizontally and vertically curved roads. The AHVS system [6] uses an edge extraction algorithm to detect lane markings. It can drive at 50 km/h along a lane with a large curvature.

The ARCADE system [8] uses robust estimation to extract road curvatures and orientations from image edge points. RALPH [9] utilizes an "hypothesize and test" strategy to determine the road curvature ahead. The system hypothesizes several possible curvatures for the road ahead, and tests them to see how well they are. Kluge and Lakshmanan [10] proposed a deformable-template approach to lane detection. Their LOIS lane detection system includes three main components: (1) a model of lane shape which defines a set of parameters; (2) a likelihood function which provides a measure of how well a set of parameters match the given data in an input road image; and (3) an optimization algorithm (the Metropolis algorithm) used to find the best set of shape parameters by maximizing the likelihood function.

All of the above research works, which use path lines on the road or road edges to estimate the curvature of the road ahead, are based on the assumption that the detected lines on the curved road are curves. Hence the curvature can be estimated directly from the detected curves. Sometimes the detected features might not be curves because the curves to be detected are occluded or missing. Then we cannot estimate the curvature immediately from the detected lines and a new solution is required.

An example is shown in Fig. 1, where the right roadside disappears from the camera view because the road is sharp-curved, one car is driving along the left lane which causes the guidance features on the left roadside invisible, and only the dotted central path line is reliable, which is so used as the visual feature in this study for steady navigation. In the figure, only one line segment is extracted from the dotted central path line. Because the line segment is nearly straight, we cannot use it to estimate the curvature of the road directly. Nevertheless, it is reasonable to consider the line segment as a tangent line of the navigation path represented by the dotted central path line on the curved road. This observation gives us the motivation of extracting three tangent lines from a sequence of images as visual features for ALV guidance. In the proposed approach, the tangent lines are extracted by the Hough transform, and then are used to detect the curvature change of the road ahead and derive the desired path on the curved road during navigation. The navigation path is assumed to be a circle with respect to the current ALV location and is rederived cyclically for safe navigation. Furthermore, the tangent lines are also utilized for checking whether a curved road section is being entered or left. The proposed approach

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is proved effective after many practical navigation tests.

A new prototype ALV with smart, compact, ridable characteristics, as shown in Fig. 2, is constructed as a testbed for this study, whose dimension is 118.5 cm by 58.5 cm. It has four wheels in which the front two are the turning wheels and the rear two the driving wheels. Above the front wheels is a cross-shaped rack on which some CCD cameras are mounted, and above the rack is a platform on which two monitors, one being a computer monitor and the other an image display, are placed. Above the plateform is a vertical bar on which another camera used in this study is mounted. The central processor is an IBM PC/AT compatible personal computer (PC486) equipped with a color image frame grabber which takes 512 × 486 RGB images with eight bits for the intensity value of each image pixel.

The remainder of this paper is organized as follows. In Section II, the details of the proposed ALV navigation method is described. In Section III, the details of the proposed ALV location method is introduced. The descriptions of the used image processing techniques and some experiments are included in Section IV. Finally, some conclusions are stated in Section V.

II. Proposed ALV Navigation Method

Typically, there are two kinds of roads, namely, the *straight turning road* and the *curved turning road*, which cause the ALV to turn. Some examples are shown in Fig. 3. A state-transition diagram expressing the navigation process in this study is shown in Fig. 4. Initially, the ALV navigates on a straight road and the system is in state S0. When an unrecognized road is found (C0=2), the system enters the error state. If a turning road is detected (C0=1) in state S0, the system enters state S1. Then the system checks in the next cycle whether the turning road is straight or curved. If the turning road is straight (C1=0), the system goes back to state S0 immediately. Otherwise (C1=1), the turning road is curved and the system enters state S2. At this moment, the system derives a navigation path (a circle equation) in each navigation cycle from input images on the curved turning road, and plans a smooth route from the current position of the ALV to the derived navigation path. Finally, if an unrecognized road is detected (C2=2) in state S2, the system enters an error state. And if a straight road is detected (C2=1), the system returns to state S0 and the navigation on the curved road is finished.

To accomplish successful navigation on a sharp-curved road, we must choose proper and stable visual features on the road. From the previous observation of Fig. 1, we know that the dotted central path line is seldom affected by noise or occlusion and is always within the camera view even when the ALV navigates on sharp-curved roads. Hence we select the dotted central path line as the visual feature in this study for stable navigation. To construct the circle which represents the navigation path on the curved road, we extract three tangent lines. But because only two tangent lines at most can be extracted from the current image of a normal curved road, the additional third tangent line is chosen to be one of the two extracted lines from the previous images. The three extracted tangent lines are used for the following purposes in this study:

(1) judging whether the ALV exits a straight road and enters a turning road;

(2) judging whether the detected turning road is straight or curved;

(3) deriving a navigation path (a circle equation) in each cycle on the curved road; and

(4) judging whether the ALV exits a curved turning road and enters a straight road.

In the following, we first state the navigation process from a straight road into a turning road. Then the navigation process on a curved road is described, followed by the navigation process from a curved road to a straight one.

A. Navigation Process from Straight Road into Turning Road

When the ALV keeps driving on a straight road, we use the approach proposed in [15] to guide the ALV to follow the straight road. In the mean time, we use the condition variable C0 to judge whether the ALV meets a turning road or an unrecognized road, and the condition variable C1 to judge what kind turning road the current road is. If the ALV meets a straight turning road (C0=1 and C1=0), then we use the approach of [15] again to guide the ALV to follow the newly detected straight road. If the ALV meets a curved turning road (C0=1 and C1=1), then we derive a navigation path on the curved road and guide the ALV to follow it.

Before the condition variables C0, C1, and C2 are computed, we describe how to find the equations of the three tangent lines, denoted as L_1, L_2, and L_3, with respect to the current ALV position P_i. If two tangent lines are extracted from the current image I_i on the curved road, we extract the third tangent line from the previous image I_{i-1}, as shown in Fig. 5(a). In the figure, the line equations of the two extracted tangent lines L_2 and L_3 in I_i with respect to P_i, and the line equation of the third extracted tangent line L_1 in I_{i-1} with respect to P_{i-1} can be derived by using coordinate transformation techniques described in [12-13]. The relative location of P_{i-1} with respect to P_i can be estimated through the ALV control information by using a method proposed in [14]. Hence, the line equations of L_1, L_2, and L_3 with respect to the current ALV position P_i can be found.

If only one tangent line is extracted from I_i, the other two tangent lines either are both extracted from image I_{i-1} as shown in Fig. 5(b), or are extracted from image I_{i-1} and image I_{i-2} as shown in Fig. 5(c). For these cases, the line equations of the three tangent lines with respect to the current ALV position can also be found by using the same methods described above.

Let the three line equations with respect to the current ALV position with the system in state Si be L_1: $y = a_1^{(i)}x + b_1^{(i)}$, L_2: $y = a_2^{(i)}x + b_2^{(i)}$, and L_3: $y = a_3^{(i)}x + b_3^{(i)}$. We say that line ℓ_1: $y = a_1 x + b_1$ is *colinear* with line ℓ_2: $y = a_2 x + b_2$ (denoted by $\ell_1 \equiv \ell_2$) if and only if

$$|a_1 - a_2| \le TH-1 \text{ and } |b_1 - b_2| \le TH-2, \qquad (1)$$

where TH-1 and TH-2 are two preselected threshold values. And we say that ℓ_1 is not colinear with ℓ_2 (denoted by $\ell_1 <> \ell_2$) if and only if the above expression is not satisfied. Then the variable C0 used to determine whether the ALV meets a turning road is set as

$$C0 = \begin{cases} 0 \text{ (non-turning)} & \text{if } L_1^{(0)} \equiv L_2^{(0)} \equiv L_3^{(0)}, \\ 1 \text{ (turning)} & \text{if } L_1^{(0)} \equiv L_2^{(0)} \text{ and } L_2^{(0)} <> L_3^{(0)} \\ 2 \text{ (erroneous)} & \text{otherwise,} \end{cases} \qquad (2)$$

the condition variable C1 used to judge whether the detected turning road is straight or not is set to be

$$C1 = \begin{cases} 0 \text{ (straight)} & \text{if } L_2^{(1)} \equiv L_3^{(1)}, \\ 1 \text{ (non-straight)} & \text{otherwise,} \end{cases} \qquad (3)$$

and the condition variable C2 used to determine whether the ALV exits a curved turning road and enters a straight road is set as

$$C2 = \begin{cases} 0 \text{ (non-existing)} & \text{if } L_2^{(2)} <> L_3^{(2)} \text{ and } |a_1^{(2)}| \ge |a_2^{(2)}| \ge |a_3^{(2)}|, \\ 1 \text{ (existing)} & \text{if } L_2^{(2)} \equiv L_3^{(2)}, \\ 2 \text{ (erroneous)} & \text{otherwise.} \end{cases} \qquad (4)$$

Fig. 6 shows all meaningful combinations of the three extracted tangent lines and the corresponding condition variable value in each combination when the ALV turns to the right. Note that if C0=2 or C2=2, it is decided that an illegal combination of the three tangent lines is detected, which is mainly caused by erroneous extracted central path lines. Then the system enters the error state and the ALV is stopped.

B. Navigation Process on Curved Road

If C0=1 and C1=1, it is decided that the ALV meets a curved road. We then use the three extracted tangent lines to derive the navigation path on the curved road for the current cycle. Let L_1: $y = a_1 x + b_1$, L_2: $y = a_2 x + b_2$, and L_3: $y = a_3 x + b_3$ be the three extracted tangent lines with respect to the vehicle coordinate system (VCS). The VCS, denoted as x-y-z, is attached to the middle point of the line segment which connects the two contact points of the two front wheels of the ALV 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. As shown in Fig. 7, we can use L_1, L_2, and L_3 to construct the navigation path represented by the circle C'. In the figure, the three points A, B, and C of intersections of L_1, L_2, and L_3 can be solved to be

$$A: (x_1, y_1) = \left(\frac{b_1 - b_2}{a_2 - a_1}, \frac{a_2 b_1 - a_1 b_2}{a_2 - a_1}\right),$$
$$B: (x_2, y_2) = \left(\frac{b_1 - b_3}{a_3 - a_1}, \frac{a_3 b_1 - a_1 b_3}{a_3 - a_1}\right), \qquad (5)$$
$$C: (x_3, y_3) = \left(\frac{b_2 - b_3}{a_3 - a_2}, \frac{a_3 b_2 - a_2 b_3}{a_3 - a_2}\right).$$

Since $BD = BF$, $AD = AE$, and $CE = CF$, AD and CF can be expressed as

$$AD = \frac{1}{2}\left(\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} + \sqrt{(x_1 - x_3)^2 + (y_1 - y_3)^2} - \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2}\right),$$
$$CF = \frac{1}{2}\left(\sqrt{(x_1 - x_3)^2 + (y_1 - y_3)^2} + \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2} - \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}\right). \qquad (6)$$

Then the x, y coordinates of the three tangent points D, E, and F can be solved to be

$$D: (x_4, y_4) = \left(\frac{-N_1 - \sqrt{N_1^2 - 4M_1Q_1}}{2M_1}, a_1 x_4 + b_1\right),$$
$$E: (x_5, y_5) = \left(\frac{-N_2 - \sqrt{N_2^2 - 4M_2Q_2}}{2M_2}, a_2 x_5 + b_2\right), \qquad (7)$$
$$F: (x_6, y_6) = \left(\frac{-N_3 + \sqrt{N_3^2 - 4M_3Q_3}}{2M_3}, a_3 x_6 + b_3\right),$$

where

$$M_1 = 1 + a_1^2, \quad M_2 = 1 + a_2^2, \quad M_3 = 1 + a_3^2,$$
$$N_1 = 2a_1b_1 - 2x_1 - 2a_1y_1, \; N_2 = 2a_2b_2 - 2x_3 - 2a_2y_3,$$
$$N_3 = 2a_3b_3 - 2x_3 - 2a_3y_3, \; Q_1 = x_1^2 + y_1^2 + b_1^2 - 2b_1y_1 - \overline{AD}^2,$$
$$Q_2 = x_3^2 + y_3^2 + b_2^2 - 2b_2y_3 - \overline{CF}^2, Q_3 = x_3^2 + y_3^2 + b_3^2 - 2b_3y_3 - \overline{CF}^2 \qquad (8)$$

Based on D, E, and F, the equation of the circle C' with respect to the VCS can be derived to be

$$x^2 + y^2 + Ux + Vy + W = 0, \qquad (9)$$

where

$$V = (d_3d_5 - d_1d_7 + d_3d_6 - d_2d_7)/(d_4d_7 - d_3d_8),$$
$$U = -(d_4V + d_1 + d_2)/d_3, \qquad (10)$$
$$W = -(x_4^2 + y_4^2 + Ux_4 + Vy_4),$$

and

$$d_1 = x_5^2 - x_4^2, \; d_2 = y_5^2 - y_4^2, \; d_3 = x_5 - x_4, \; d_4 = y_5 - y_4,$$
$$d_5 = x_6^2 - x_4^2, \; d_6 = y_6^2 - y_4^2, \; d_7 = x_6 - x_4, \; d_8 = y_6 - y_4. \qquad (11)$$

After the navigation path on the curved road in the current cycle is found, we then plan a smooth trajectory for the ALV from the current ALV location to the derived path by using a closeness distance measure which will be described later. Besides, the navigation path is recalculated cycle by cycle for safe and smooth navigation.

C. Navigation Process from Curved Road into Straight Road

When the ALV navigates on a curved road, the system is in state S2. We then use the condition variable C2 to judge whether the ALV meets a straight road. If C2=0, the ALV keeps driving on the curved road and the system stays in state S2. If C2=1, a straight road is detected and the system returns to state S0. At this moment, the navigation-on-straight-road approach [15] stated previously is used again to guide the ALV to follow the detected straight road and the navigation process on a curved road is finished.

III. Proposed ALV Location Method

A. Estimation of Reference Navigation Path

The ALV keeps moving forward after an image is taken at the beginning of each navigation cycle on the curved road. When the image has been processed and the navigation path on the curved road has been derived, a certain amount of time has been used and the ALV has already traveled a certain distance S. Hence, the navigation path just derived has been changed because the VCS has been moved. To estimate the navigation path with respect to the new ALV location, we use the following information according to a method proposed by [14]:

(1) the obtained navigation path $C^{'}$: $x^2 + y^2 + ax + by + c = 0$ at the time instant of image taking;
(2) the traveled distance S;
(3) the pan angle δ of the front wheels relative to the y-axis of the VCS; and
(4) the distance d between the front wheels and the rear wheels.

Fig. 8(a) illustrates the navigation process, where B_i and E_i ($= B_{i+1}$) are the beginning and the ending time instants of cycle i, respectively. At time B_i, an image is taken and the current ALV location is assumed to be P_i. And at time E_i, the ALV location is assumed to be P_{i+1}. Let VCS_i, denoted as x-y, represent the vehicle coordinate system at P_i. And let VCS_{i+1}, denoted as $x^{'}$-$y^{'}$, represent the vehicle coordinate system at P_{i+1}. At time E_i, the navigation path $C_i^{'}$ with respect to the VCS_i has already been found, but the navigation path $C_{i+1}^{'}$ with respect to the VCS_{i+1} is unknown. At this moment, we use the control information given above to estimate the navigation path $C_{i+1}^{'}$ with respect to the VCS_{i+1}. What we desire to find first is the relative location of P_{i+1} with respect to P_i, denoted by a vector T. As shown in Fig. 8(b), by the basic kinematics of the ALV, the rotation radius R can be found to be

$$R = d / \sin\delta. \quad (12)$$

And angle γ can determined by

$$\gamma = S / R, \quad (13)$$

where S can be obtained from the counter of the system odometer. So, the length of vector T can be solved to be

$$\ell_T = R\sqrt{2(1-\cos\gamma)}, \quad (14)$$

and the direction of T is determined by the angle

$$\mu_T = \frac{\pi}{2} - \delta - \frac{\gamma}{2}. \quad (15)$$

By using the vector T, the VCS coordinates of location P_{i+1} with respect to P_i can thus be computed by

$$x_T = \ell_T \cos\mu_T, \quad y_T = \ell_T \sin\mu_T. \quad (16)$$

Then the coordinate transformation between the VCS_i and the VCS_{i+1} can be written as

$$(x, y, 1) = (x^{'}, y^{'}, 1)\begin{bmatrix} \cos(\mu_T - \frac{\pi}{2}) & \sin(\mu_T - \frac{\pi}{2}) & 0 \\ -\sin(\mu_T - \frac{\pi}{2}) & \cos(\mu_T - \frac{\pi}{2}) & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ x_T & y_T & 1 \end{bmatrix} \quad (17)$$

or

$$x = x^{'}\cos\theta - y^{'}\sin\theta + x_T, \quad y = x^{'}\sin\theta + y^{'}\cos\theta + y_T, \quad (18)$$

where $\theta = \mu_T - (\pi/2)$. Replacing x by $x^{'}\cos\theta - y^{'}\sin\theta + x_T$ and y by $x^{'}\sin\theta + y^{'}\cos\theta + y_T$ in the given navigation path $C^{'}$: $x^2 + y^2 + ax + by + c = 0$, we obtain the following estimated navigation path $C_{i+1}^{'}$ with respect to the VCS_{i+1}

$$C_{i+1}^{'}: \; x^{'2} + y^{'2} + (2x_T\cos\theta + 2y_T\sin\theta + a\cos\theta + b\sin\theta)\,x^{'} - (2x_T\sin\theta - 2y_T\cos\theta + a\sin\theta - b\cos\theta)\,y^{'} + x_T^2 + y_T^2 + ax_T + by_T = 0. \quad (19)$$

We then define

Reference navigation path of cycle i+1 = the estimated navigation path at time $E_i = B_{i+1}$. (20)

That is, $C_{i+1}^{'}$ is used as the reference navigation path of cycle i+1. The reference navigation path can be used for the following purposes:

(1) to speed up the line extraction process;
(2) to be followed by the ALV for more accurate and safe navigation.

B. Path Planning

To guide the ALV to follow the reference navigation path accurately, we have to plan a smooth trajectory for the ALV from the current ALV location to the derived reference navigation path in each navigation cycle. For this, a closeness distance measure from the ALV to a given path proposed by Cheng and Tsai [14] is employed, which is defined as

$$L(\delta) = \frac{1}{1+[D_F(\delta)]^2+[D_R(\delta)]^2} \quad (21)$$

where D_F and D_R are the distances from the front and the rear wheels of the ALV to the given path, respectively, after the ALV traverses a distance with the turn angle δ. A larger value of L means that the ALV is closer to the path. It is easy to verify that $0 < L \leq 1$, and that $L = 1$ if and only if both of the front wheels and the rear wheels of the ALV are located just right on the path.

To find the turn angle of the front wheel to drive the ALV as close to the path as possible, a range of possible turn angles are searched. An angle is hypothesized each time, and the value of L is calculated accordingly. The angle that produces the maximal value of L is then used as the turn angle to guide the ALV for safe navigation.

C. ALV Control Issues

There is always unavoidable mechanical inaccuracy within the ALV control system. If we use only the control information to drive the ALV, the ALV may be far away from the goal due to accumulated inaccuracy error when the navigation ends. Hence, we employ computer vision techniques to extract stable visual features, which are tangent lines in this study, as auxiliary tools in each navigation cycle to avoid gradual accumulation of control error. Of course, control error still exists in each navigation cycle.

Besides, it should be mentioned that allowing the ALV a larger angle to turn in a session of turn drive does not mean that better navigation can be achieved. It may cause serious twist. On the other hand, a smaller range of turn angles may cause only a slight closeness to the estimated navigation path, and the ALV cannot pass sharp-curved roads. Hence, the largest angle allowing the ALV to turn is a tradeoff between smoothness of navigation and closeness to the given path. In our experiment, we found through many iterative navigations that a turn from -10 degrees to +10 degrees is a good compromise.

IV. Image Processing Techniques and Experimental Results

A. Color Information Clustering

We use a color information clustering algorithm and an initial-center-choosing (ICC) technique proposed in [15] to divide a road into three clusters: (1) cluster-0: dark area, like shadows and trees; (2) cluster-1: gray area, coming from the main body of road; (3) cluster-2: bright area, like the sky and the white or yellow lines on the road. The ICC technique can solve the problem caused by great changes of intensity in navigation by choosing suitable initial cluster centers for the clustering algorithm in each navigation cycle. A clustering result is shown in Fig. 9, where Fig. 9(a) shows the input road image and Fig. 9(b) shows the three obtained clusters. We then extract tangent lines from the binary image representing cluster-2 pixels using the Hough transform. The extraction process is described in the following.

B. Tangent Line Extraction Using Hough Transform

Generally, two effective methods can be used for line extraction. One is the Least-Square (LS) line approximation [16, 17] and the other is the Hough transform [18]. The Hough transform can extract lines in any direction automatically even though they are dotted, whereas the LS line approximation has to select proper pixels before approximating lines and hence complicates coding and debugging. But if many candidate pixels in the XY plane are sent to the Hough counting space, it will take too much computing time. Hence, time is the vulnerability of the Hough transform. But because we check only the surrounding area of the reference navigation path and because the cluster-2 pixels in the surrounding area are few, the Hough transform does not take too much computing time and is used in this study. The surrounding area of the reference navigation path $(x-a)^2+(y-b)^2=r^2$ is defined as the area bounded by two circles C_1 and C_2 expressed in the following:

$$C_1:\ (x-a)^2+(y-b)^2=r_1^2,$$
$$C_2:\ (x-a)^2+(y-b)^2=r_2^2, \quad (22)$$

where $r_1 < r < r_2$, and r_1 and r_2 are two preselected threshold values.

C. Experimental Results

The prototype ALV constructed in this study was used for testing the proposed approach, and could navigate smoothly along part of the around-campus road in National Chiao Tung University for about 200m. The average cycle time is about 2.1 sec, and the average speed is 90 cm/sec or 3.3 km/hr on straight roads and 50 cm/sec or 1.8 km/hr on sharp-curved roads which are reasonable for the small-scaled and PC-based ALV. The ALV can navigate steadily on both straight and curved roads in spite of the fact that there were shades, vehicles, people, or degraded regions on the roadsides. Fig. 10 shows a sequence of images taken along a sharp-curved road and the clustering results, where the black lines denote the tangent lines extracted from the input images.

V. Conclusions

A new approach to vision-based ALV guidance on sharp-curved roads in outdoor environments using the dotted central path line information in a image sequence has been proposed. When tangent lines extracted from the dotted central path line in a single image are insufficient for deriving a navigation path on a sharp-curved road, additional tangent lines from the images of the previous navigation cycles are collected. Furthermore, the tangent lines can also be used to judge whether the ALV keeps driving on a straight road, is leaving a straight road and entering a curved road, keeps driving on a curved road, or is leaving a curved road and entering a straight road in a navigation session. Several techniques have been integrated in this study to provide an effective scheme for ALV navigation both on straight and on curved roads. A process of the reference navigation path estimation by basic vehicle kinematics and coordinate transformations has been implemented. The reference path not only can be used to save computing time in the tangent line extraction process, but also can be followed by the ALV for more accurate navigation. Smooth and safe navigations have been achieved by the use of a reasonable path planning method and some realistic vehicle control schemes. Successful navigation tests in general roads confirm the effectiveness of the proposed approach.

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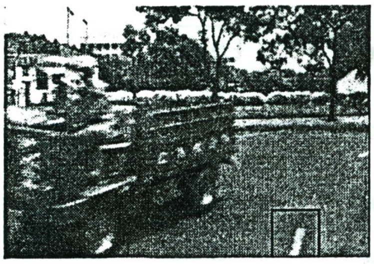

Fig. 1 A sharp-curved road image, where the right roadside disappears because the road is sharp-curved, the guidance features on the left roadside are invisible because one car is driving along the left lane, and only the dotted central path line is the reliable visual feature.

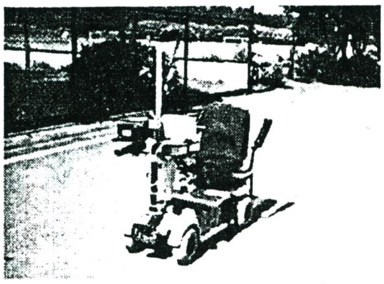

Fig. 2 A prototype ALV used in this study.

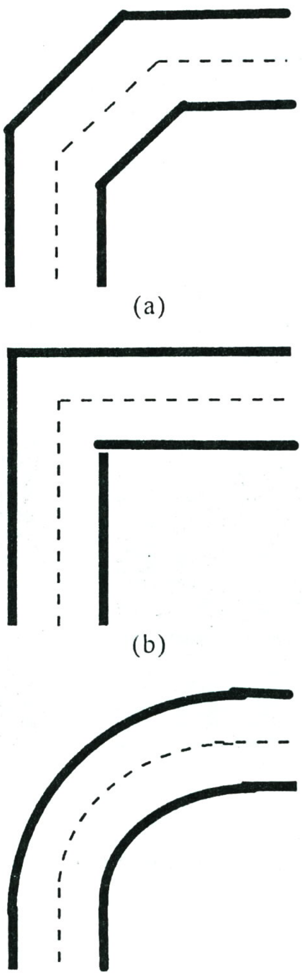

Fig. 3 Examples of turning roads. (a) A straight turning road. (b) Another straight turning road. (c) A curved turning road.

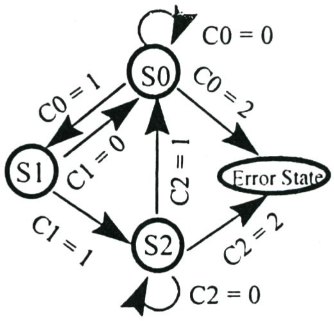

Fig. 4 A state-transition diagram expressing the navigation process proposed in this study.

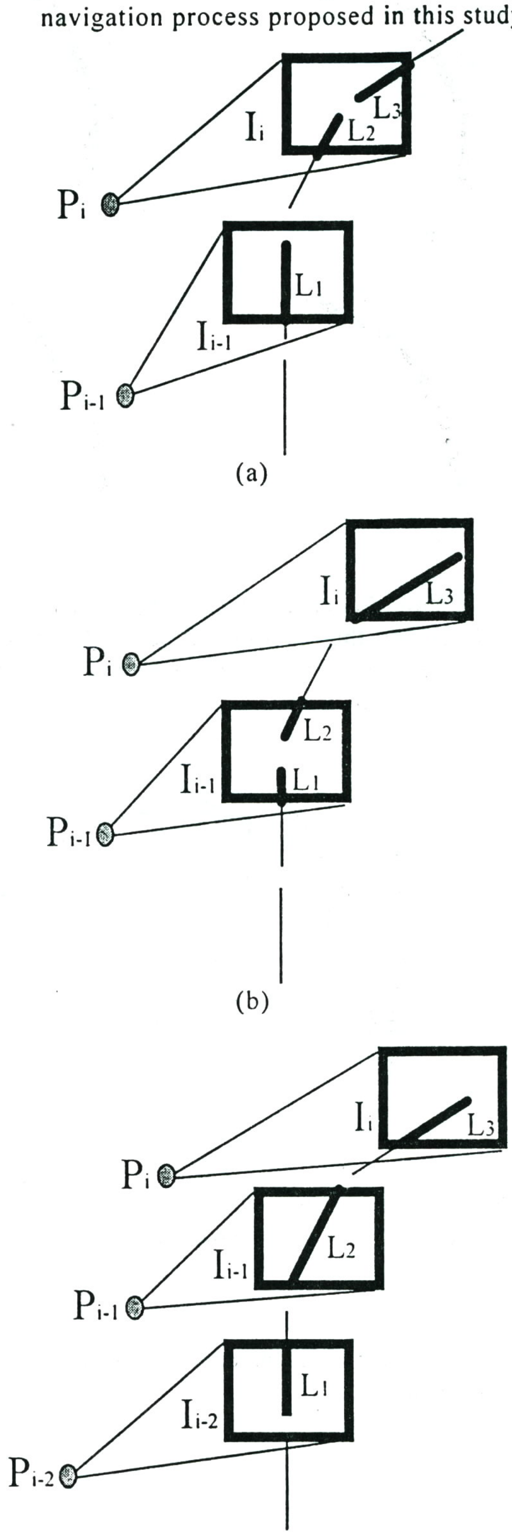

Fig. 5 Possible image sequences from which three continuous tangent lines are extracted.

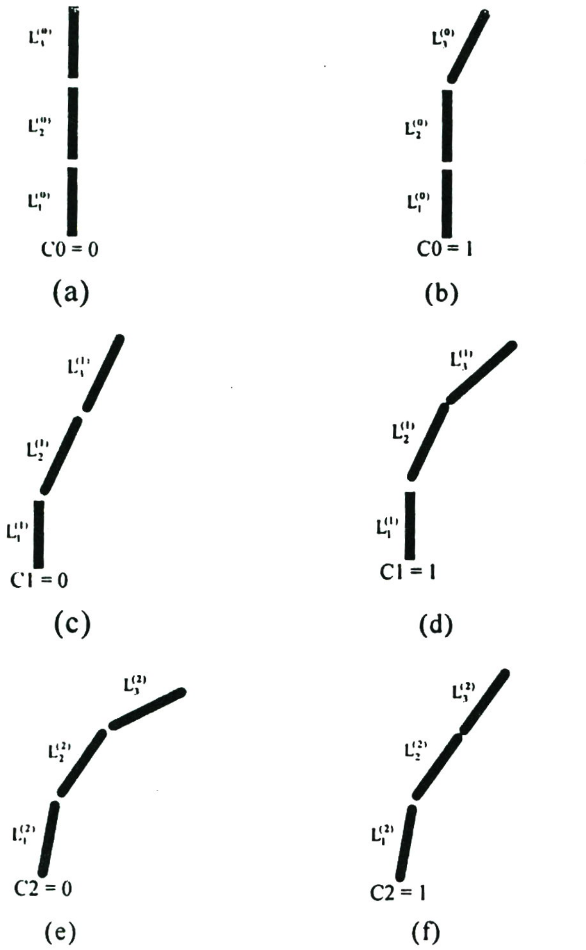

Fig. 6 Meaningful combinations of the three tangent lines and the corresponding condition variable value in each combination when the ALV turns to the right.

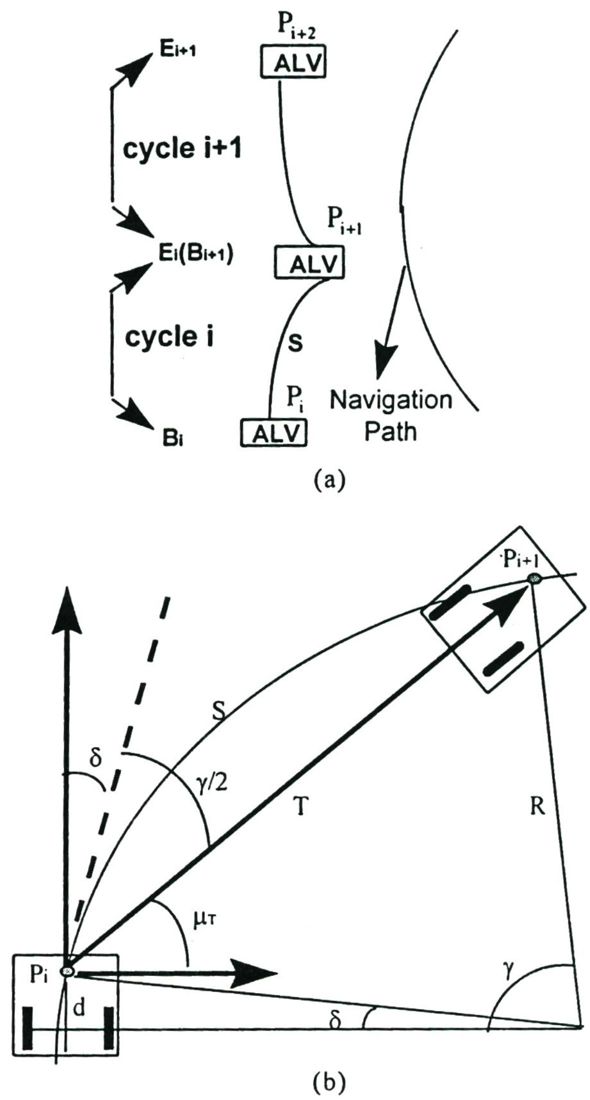

Fig. 8 Illustration of reference navigation path estimation. (a) The navigation process in a cycle by cycle manner. (b) The vehicle location before and after the ALV moves a distance S forward.

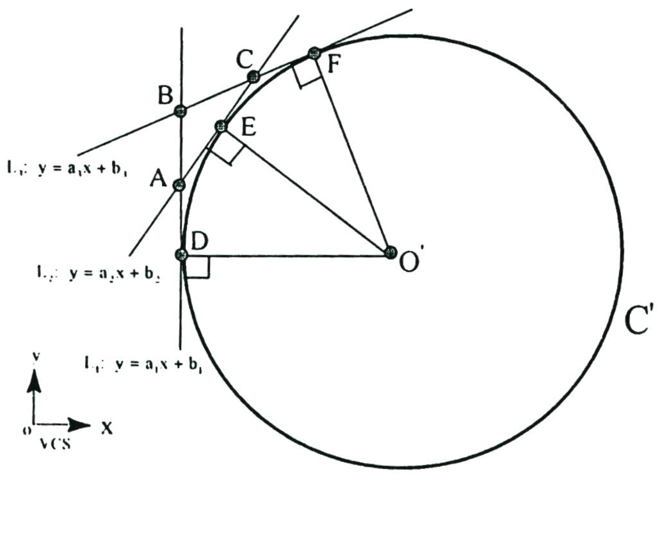

Fig. 7 The navigation path represented by a circle on a curved road.

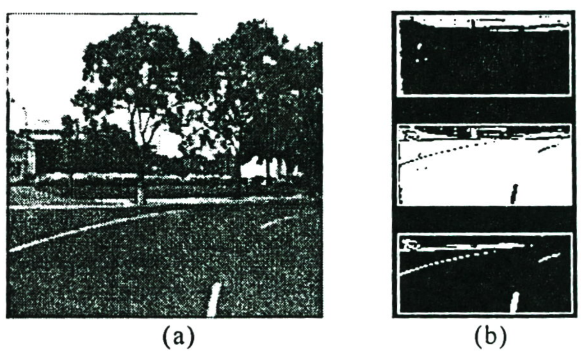

Fig. 9 A clustering result. (a) The input road image. (b) The three obtained clusters.

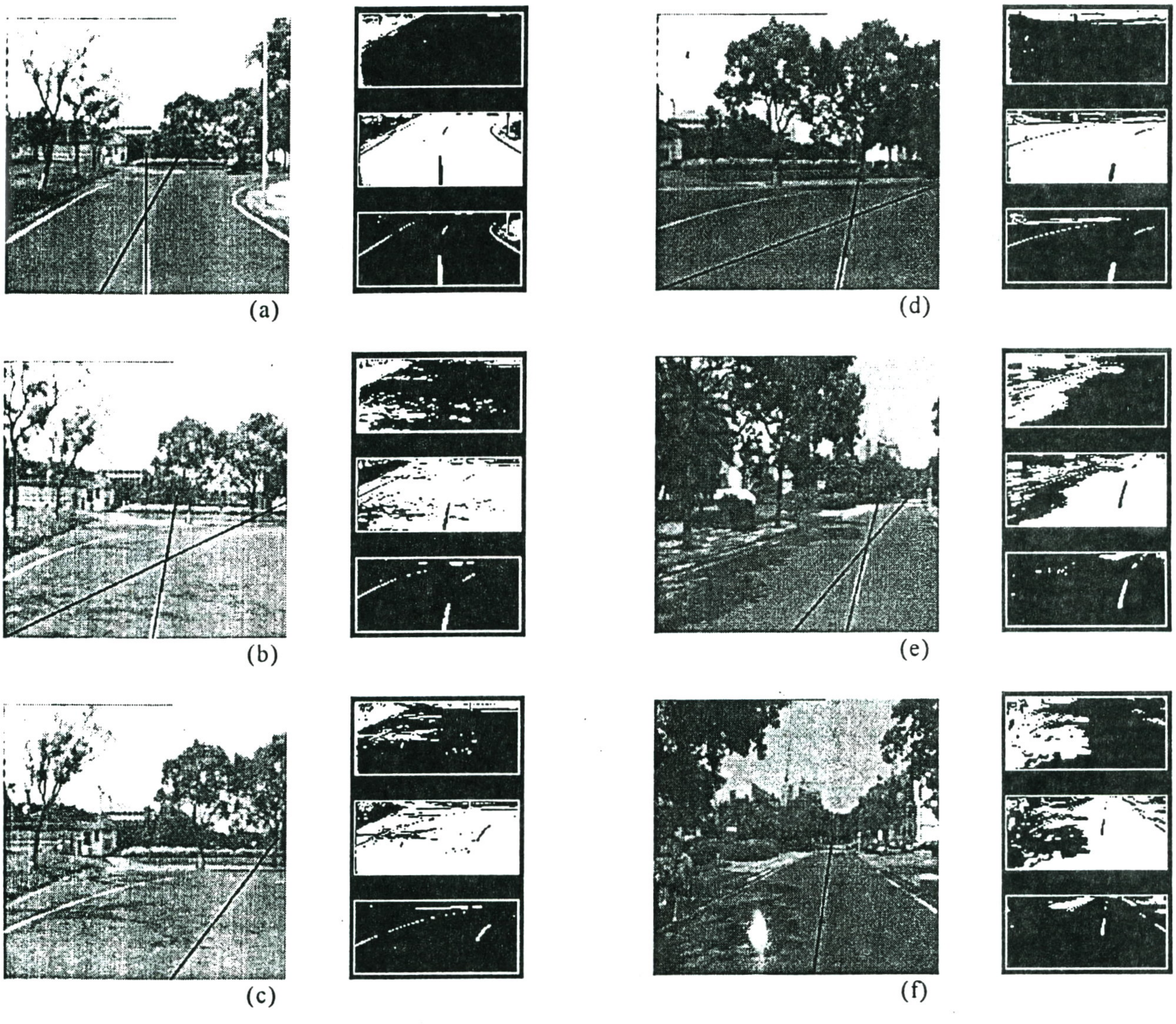

Fig. 10 An image sequence, where the black lines denote the tangent lines extracted from the images in the sequence.