THMR-V: An Effective and Robust High-Speed System in Structured Road *

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Abstract - *Many systems have been developed which can drive autonomously in structured road, but little works have been reported that describe the specific system solution in a high-speed (more than 120km/h) situation. This paper presents THMR-V (Tsinghua Mobile Robot V), a system that performs well with a speed up to 150km/h. Multi-region and bi-threshold edge extraction is used for image processing, and an ATN-based approach is used for lane line location.*

Keywords: Lane Detection, ATN, Lane Model, System Model.

1 Introduction

Many systems have been developed which can drive autonomously in structured road, but little works have been reported that describe the specific system solution in a high-speed (more than 120km/h) situation. This paper presents THMR-V (Tsinghua Mobile Robot V), a system that performs well with a speed up to 150km/h.

THMR-V is developed by National Key Lab of Intelligent Technology and System in Tsinghua University. The laboratory has done a lot of research work on mobile robot since 1990. The system is hierarchical hybrid architecture, involving three levels which are intelligent level, coordinate level, executive level.

Just like most of the other autonomous systems, THMR-V consists of the vision process module and the control module. What is different from others is that special designs are implemented to satisfy the critical require of the high-speed vehicle. When the speed reaches 150km/h, the vehicle run more than 40m in one second. Apparently, there are two key issues in such a system: one is the efficiency of the vision process, which might makes the system cost as low as possible; the other is the robustness of the control algorithm, which should hold vehicle at the center of the lane.

There are two steps in the vision module. The first is lane line detection. The multi-region bi-threshold approach is used to process the origin image, and then a binary image is made.. In the second step, ATN-based approach is achieved to recognize the lane line.

A two-segment road model is used to analyze and control the vehicle. It involves the advantage of the linear model and the curvilinear model. Three parameters are designed to describe the orientation and position of the vehicle and the lane.

The control system has three subsystems. Fuzzy logic control and PID control are utilized in the system, and they perform well even at a speed of more than 120km/h.

Figure 1. THMR-V in the campus of Tsinghua University

2 Lane Line Recognition

2.1 Multi-region Bi-threshold Edge Extraction

The lane is perceived by CCD camera on top of THMR-V, the image sequences are grabbed into the computer through Matrox Meteor-PPB card and saved in memory for edge extraction.

Edge extraction is a very basic subject of image procession research and there have been many operators raised to achieve it, such as Roberts operator, Prewitt operator, Sobel operator, Isotropic Sobel operator, Canny operator, etc. Considered the quality and the efficiency of the operator, we choose Sobel operator to complete this task.

Then all the pixels in the gray-scale image will be classified into two groups: the lane pixel and the non-lane pixel. It makes the lane line pixels left for processing in following steps and reduces the disturbance of non-relative points.

An appropriate threshold is the key to the binary image. If the threshold is too high, few pixels will be left, and many useful pixels might be omitted from the first group list; if the threshold is too low, much noise might be classified into the lane pixel group, which makes the final result less precise. In the conventional approaches, a fixed threshold or some kind of single variable is used for classification. However when the surface of the road is dirtied by shadow or puddle, it is really difficult to get the correct boundary of the lane by using one threshold.

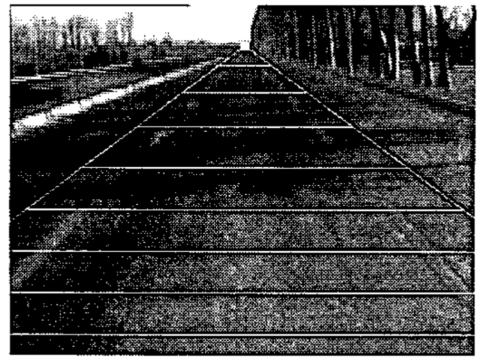
To deal with these problems, we use a bi-threshold approach for the line location. It is obviously that the lane line is white, yellow, or some other bright colors. Meanwhile the boundary caused by shadow or puddle is much darker in most of time. So it is possible to use the following criteria:

$$color_{origin} > threshold_{origin} \;\&\; color_{edge} > threshold_{edge} \quad (1)$$

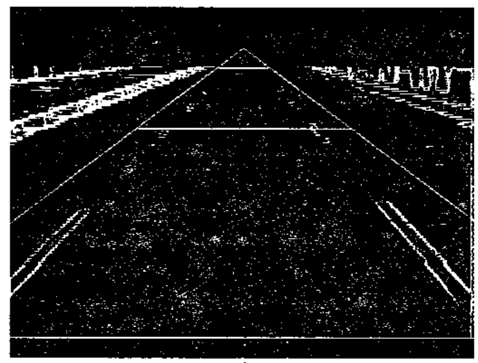
where $color_{origin}$ and $color_{edge}$ are the gray value of the current processing pixel in the origin image and processed image. The system samples the origin image to determine $threshold_{origin}$. $threshold_{edge}$ is a constant of the processed image.

In the experiment we find that bi-threshold approach still has difficulty in handling some special scenes. For example, when the road is interfered by strong sun shine, it is hardly to get a fixed value that is fit for the entire image. So we extend bi-threshold approach to multi-region bi-threshold approach, which does not rely on a fixed threshold, but several thresholds sampled simultaneously.

The full image is divided into several regions in the vertical direction, as can be seen from Figure 2. (a). The system samples a specific region to calculate the threshold in that region, which reflects the lane status of a specific distance from the vehicle. It performs well when parts of road is extraordinarily lightened or darkened by the environment. Most of the noise is cleaned and the result is shown in Figure 2. (b).



(a)



(b)

Figure 2. Multi-region bi-threshold edge extraction (a) the origin image from CCD. (b) the processed image

2.2 ATN-Based Image Comprehension

ATN(Augmented Transition Networks) is firstly raised by W.Woods in 1970. It is brought in from the field of natural language understanding. In THMR-V, we use ATN in the vision-based navigation for the mobile robot and use language theory and techniques to detect and perceive the lane environment. The perception is actually a procedure that the environment sends the information to the mobile robot, and the useful information is collected and analyzed by the intelligent system.

The whole procedure for lane recognition may include following steps:

1) Find the environment characteristic interested by the system, and define the environment language on the basis of the environment characteristic.

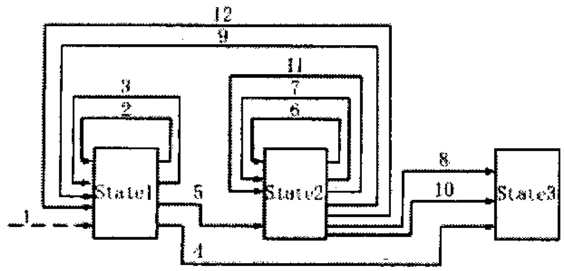


Figure 3. The semantic network FLL built to detect left lane line

2) Define the elements of the environment language on the basis of the environment characteristic.

3) Define the sentences on the basis of permutation and combination of the position and gesture in feature space.

4) Define the sentence grammar on the basis of permutation and combination of the position and gesture in feature space.

5) Determine the ATN structure of the sentence to be analyzed.

6) Figure out all the possible states when a specific sentence is analyzed.

7) Determine the condition when a state transfer is required.

8) Determine the testing and debugging when a state transfer is required.

9) Determine the state action and the transfer action for every state.

10) Optimize the structure of ATN.

In THMR-V system, points whose gray value is 255 is defined as the elements of environment language, lane line is defined as the sentences of environment language, and the information of lane lines is defined as the semantic in the sentences of environment language.

The ATN network FLL shown in Figure 3 is built to detect LLN (Left Lane Mark). It consists of 3 states, 12 arcs, and 5 registers. State 1 is the original state of the FLL. FLL will remain in this state until it find the first qualified pixel in LL and transfer to State 2 through a specific arc. The role of State 2 is to find out all the others pixels which belong to LLN. It will come to State 3 when the work is completed.

After the first recognition is achieved, the system estimates the lane position and gesture on the basis of the previous frame, and searches the targets around the estimated position when the next frame comes, which greatly shrink the range to search. The whole procedure of the lane detection for one frame is less than 30ms in a 256MB, PIII-500 PC.

3 Vehicle Control

3.1 System Model and Control Parameter

The structured road has two lanes or more. Each lane is separated by two parallel lines. The lane line in the grabbed images is approximately straight when the distance is less than 70m. So the model for structured road we use consists of two segments, as shown in Figure 4. The lower segment is linear lane model (Figure 4. (3a)), described by two straight lines; the upper segment is curvilinear lane model (Figure 4. (3b)), described by curves.

The model does not need complex computation. It

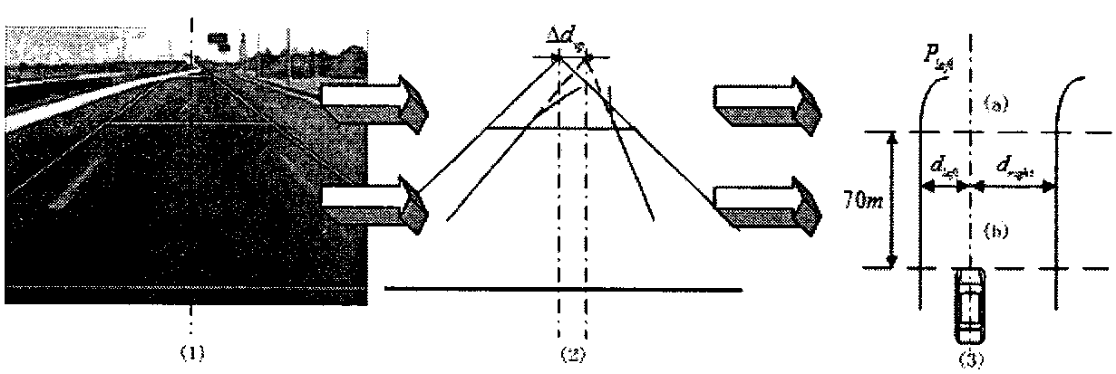


Figure 4. Road model for THMR-V (1).the origin image, (2).the lane lines and vanish point, (3).the projected image

mainly has three parameters. The first parameter can be determined from the two located lane lines. It equals to the horizontal distance from the vanish point of the lines to the center of image, which is depicted in the left part of Figure 4. (2). Method of least squares is used to determine the straight line equation:

$$k=\frac{n\sum_{i=1}^{n}x_iy_i-\sum_{i=1}^{n}x_i\sum_{i=1}^{n}y_i}{n\sum_{i=1}^{n}x_i^2-\left(\sum_{i=1}^{n}x_i\right)^2},b=\frac{n\sum_{i=1}^{n}x_i^2\sum_{i=1}^{n}y_i-\sum_{i=1}^{n}x_i\sum_{i=1}^{n}x_iy_i}{n\sum_{i=1}^{n}x_i^2-\left(\sum_{i=1}^{n}x_i\right)^2} \quad (2)$$

where n is the count of points in a specific line; x_i, y_i is the abscissa and ordinate of the point in the line. Having had k and b of the two lane lines, we can get the point of intersection, which is also called vanish point.

The vanish point is right on the horizontal center of the image when the direction of the vehicle is parallel to the lane lines. It deviates the center when the direction changes. The more is the turn, the more is the deviation. So this parameter is sensitive to the direction change and utilized by the algorithm mentioned later.

Before working on the second parameter, a projection from the image plane to the ground plane is needed. We use a simple algorithm to achieve it, which is extending every horizontal line to a constant length. After the projection, we may get two peak value points, which indicates the two lane lines position. The second parameter γ equals to the ratio of the left free space width d_{left} to the right free space width d_{right}:

$$\gamma=\frac{d_{left}}{d_{right}} \quad (3)$$

This parameter reflects the vehicle position in the current lane, so it is used to recenter the vehicle when the vehicle has obviously started to slide right or left.

The third parameter P_{left} is designed to reflect whether there is a sharp turn far away. It equals to the percent of the points on the left of the corresponding peak point. When P_{left} is near 1 or 0, it means that a sharp turn exists, and the system should make necessary steering.

This model prevents the complexity caused by normal curve models, for it does not need any curve fitting computation, which is very costly.

3.2 Control Algorithm

The control system has three subsystems: a "spinner" that maintains the vehicle at the center of the lane, a roadway departure prevention system and a specific steering system that handles the sharp turn, as shown in Figure 5.

Firstly P_{left} is used to check the existence of a sharp turn:

If $P_{left} > 0.8$, then a left turn exists.

If $P_{left} < 0.2$, then a right turn exists.

If $0.2 \le P_{left} \le 0.8$, then no sharp turn exists.

The system will make a turn, if P_{left} satisfies the first or second condition. The strength of the steering action is determined by the value of P_{left}.

If the lane is approximately straight, the flow will continue to evaluate the vehicle position to see whether it stays relatively in a safe place. If it does so, the spinner corrects the posture of THMR-V on the basis of Δd_{vp},

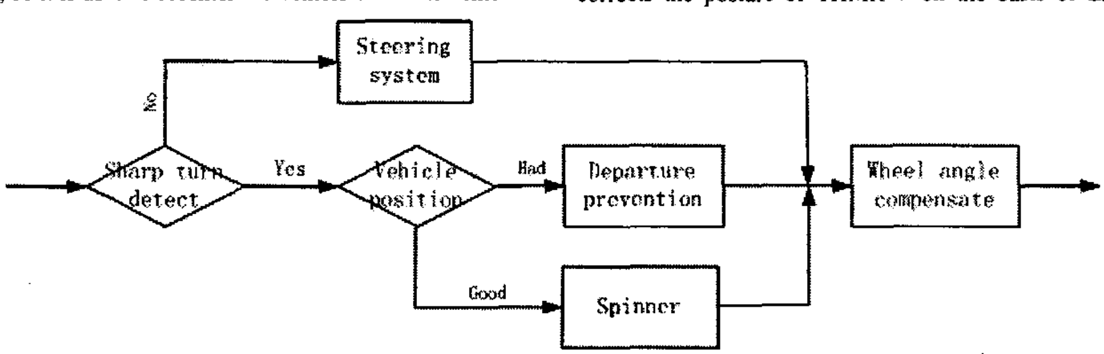


Figure 5. The contrl strategy of THMR-V, consisted of three subsystems.

which is the deviation of the current vanish point from the origin position. In the experiment, the vehicle is under the control of the spinner more than 80% of the total time.

The departure prevention system will be on when the vehicle position is not so good. Method of fuzzy logic control and PID control is introduced in. According to the different value of the orientation Δd_{vp} and the position P_{left}, the corresponding controlling quantity for the vehicle is defined.

At last the compensation to the wheel angle should be considered, especially when a large angle steering is executed. The strength and continuance of the compensation is judged by several factors, such as orientation deviation, the different effect of the recenter action in slant condition, etc.

4 Conclusions

In the last six month we have had more than 70 experiments in several common roads in Beijing, include BeiQing Road and JingChang Highway. All the experiments last more than 200 hours totally. In these experiments, the average speed is above 100km/h and the process speed is 30ms/frame.

The system we developed can adapt different width of the lanes, even when the width changes often. It also works well in most of the situations we have encountered, even when one of the two road strips is dirtied with oil or under partial occlusion. CCTV(the national TV network of China) has recently made a program of our autonomous system – THMR-V.

5 Acknowledgment

The authors express their gratitude to Zhang Pengfei and Li Bing for their outstanding suggestions, to Wang Yunchuan, Jin Hui, Liu Huaping and all other members involved in this project for their enthusiastic development.

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