Driving Environment Recognition System on Highway

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We at Fujitsu Ten have been studying image processing as the key technology of support systems for driving and automatic driving systems of the future. The image processing technology enables recognition of a driving lane (lane marks) and a preceding vehicle, and can achieve a high level of recognition when used in combination with a radar sensor.
In this report, we will describe the mechanism of a driving environment recognition system we have developed for use on highway and verify the results of testing this technology on an adaptive cruise control system.

1. Introduction

In recent years, various electronic technologies have been incorporated into automobiles while a lot of research has been conducted to improve the safety and ease of driving. Of such research, image processing has been attracting considerable attention with its ability to directly recognize visual information on which a driver depends almost entirely for driving.

After developing a car-mounted image processing unit as a support system for driving, we have researched an adaptive cruise control system. By combining the image processing technology with a radar system, this system enables a vehicle to automatically keep a safe distance from the preceding vehicle. The combined use of an infrared camera for capturing images with a millimeter-wave radar achieves highly reliable driving environment recognition,

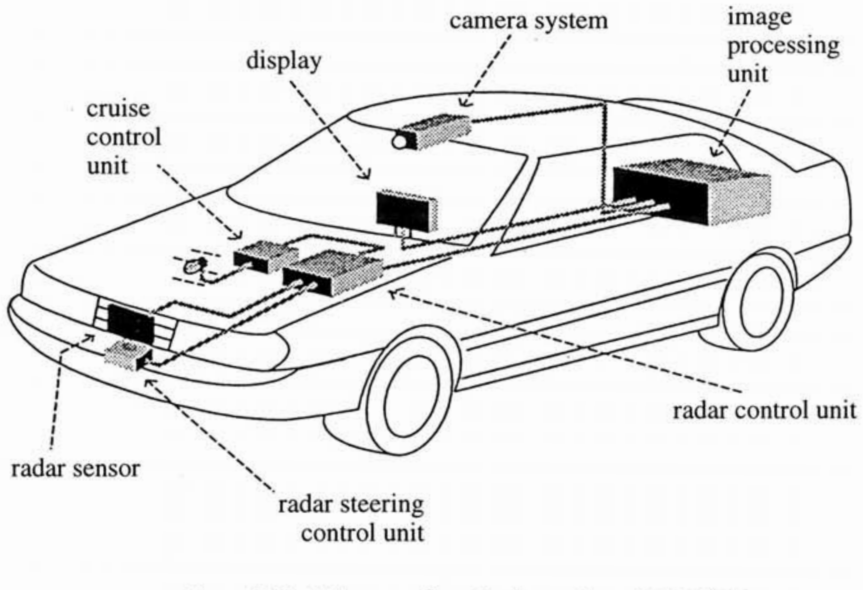


Figure 1 Block diagram of an adaptive cruise control system

allowing a vehicle to perform stable adaptive cruising without being affected by environmental conditions.

In this report, we will introduce to you the mechanism of an image processing unit and the system for recognizing driving environment such as lane marks and preceding vehicles as well as the way the system is actually applied to an adaptive cruise control.

2. System configuration

Figure 1 shows the configuration of our adaptive cruise system. When a vehicle moving at a speed set by the driver approaches a preceding vehicle, this system will be automatically activated to control the distance between the two vehicles. The information required for adaptive cruise will be supplied by the driving environment recognition unit.

Recognition of the driving environment is achieved based on the information provided by two sensor sources. One is a millimeter-wave radar which detects the distance from and approaching speed of a target vehicle. Although laser radars have been the mainstay of car-mounted radars and some of them were commercialized before the millimeter-wave type, laser radars have the problem of being easily dispersed or absorbed by rain and mist. Due to these characteristics, performance of laser radars is likely to be limited under poor visibility conditions where drivers need to depend most strongly on radars. On the other hand, millimeter-wave radars will not be affected by such weather conditions and thereby can ensure highly reliable sensing.

Another sensor source used in the system is a CCD camera which detects lane marks and preceding vehicles. The camera system is installed facing forward inside the car so that it can cover the visual range of a driver. To ensure a high recognition level under poor visibility conditions or at night, we have employed a high-performance CCD which can provide equal sensitivity both in the near infrared area and visible ray area.

The millimeter-wave radar is equipped with a device for controlling sensing direction. This allows the system to detect the precise location of a preceding vehicle moving in the same lane.

3. Recognition technology

3.1 Millimeter-wave radar

We have employed FM-CW type radar and applied FFT frequency analysis using DSP for signal processing. This has enabled the system to detect distance and speed with high precision and to distinguish each one of the plural target vehicles. Table 1 shows the system specifications[1].

Table 1. Specifications of millimeter-wave radar

Radar system	FM-CW
Sensor central frequency	60 GHz
Sensor frequency modulation width	75 MHz
A to D converter resolution	12 bits
Sampling frequency	200 kHz
FFT data count	128
FFT theoretical frequency resolution	1.5625 Hz
Detection distance	approx. 100 m

3.2 Image processing system

Figure 2 shows how the information is processed by an image recognition system. Basically, the process of recognizing lane marks and a preceding vehicle is conducted in parallel, except that the judgment on whether a preceding vehicle is in the same lane will be made only after the lane mark recognition is complete.

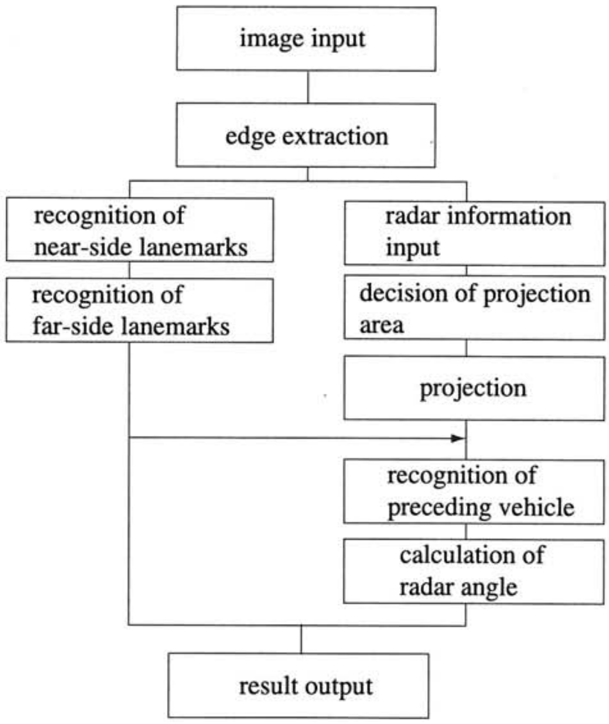


Figure 2. Driving environment recognition algorithm

3.3 Lane mark recognition

Defining the lane mark as a bright section inside the road area can be affected by shadows or dirt on lane marks, so we have adopted the method based on edge. Edge refers to a portion inside the image where a certain level of variation in density is observed. The advantage of using edge standard is that it is much less susceptible to changes in the absolute volume of density caused by shadows or dirt.

The Edge can be classified into "positive" and "negative" types depending on the inclination of density variation, and into "horizontal" and "vertical" types depending on the direction of density variation. With most of the conventional image recognition methods, the information consists of 2 values which simply indicate whether the edge exists or not. However, since this 2-value system cannot provide relative location of each edge, precision of the resulting recognition level has been limited. To solve this problem, we have classified the edge into 9 different values.

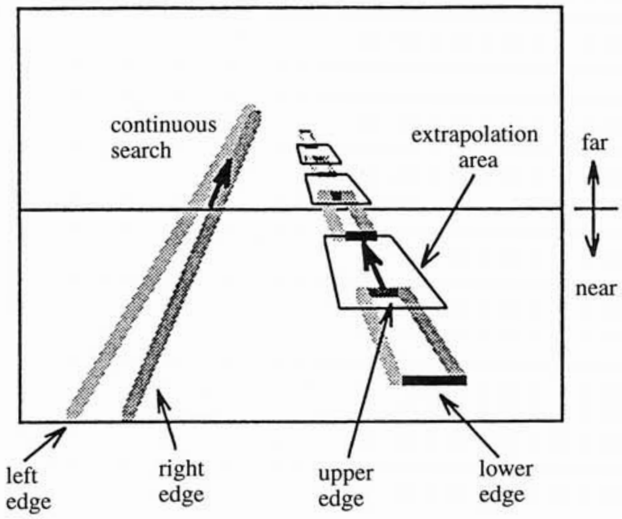


Figure 3. Image of lane mark recognition

In the recognition process, the image is divided into far side and near side to compensate the difference of resolution in each area. (See Figure 3)

1) Extracting the candidate point:
   Within the near side of the image area, the system extracts the candidate point which satisfies both the direction of the 2 edges and the width of the lane mark specified by the ordinance.
2) Confirming the lane mark location on the near side:
   Based on the drive lane width specified by the ordinance, the system weights the above candidate point. It then uses its linearity to connect each candidate point to confirm the lane mark position on the near side.
3) Tracking the lane mark onto the far side:
   By referring to the confirmed lane mark position on the near side, the system keeps tracking candidate points along the continuity line onto the far side. Where the continuity of lane marks is broken, the confirmation of candidate points is done by the extrapolation from the already confirmed lane marks.

3.4 Recognition of a preceding vehicle

There is a fixed relation between the distance/location to the preceding vehicle detected by the radar system and the location of the preceding vehicle captured by the camera system onto the image. We have used this relation to develop an algorithm which allows the radar system and the camera system to mutually compensate their weaknesses.

3.4.1 Principle

Figure 4 shows parameters of the camera system. X, Y and Z are road coordinates which respectively indicate horizontal, vertical and driving directions. H shows the

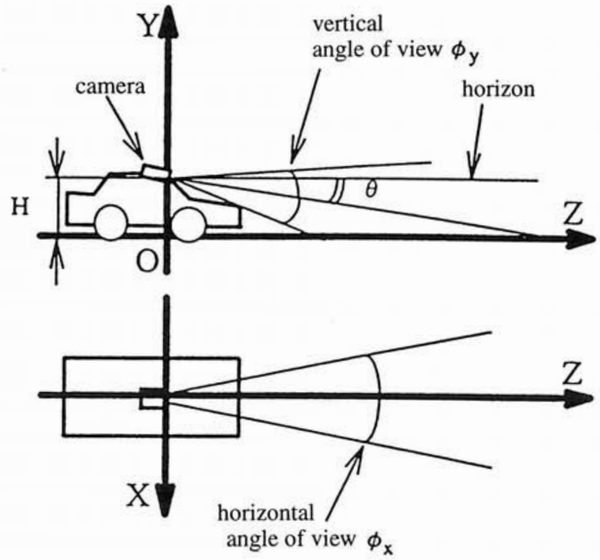


Figure 4. Camera parameter

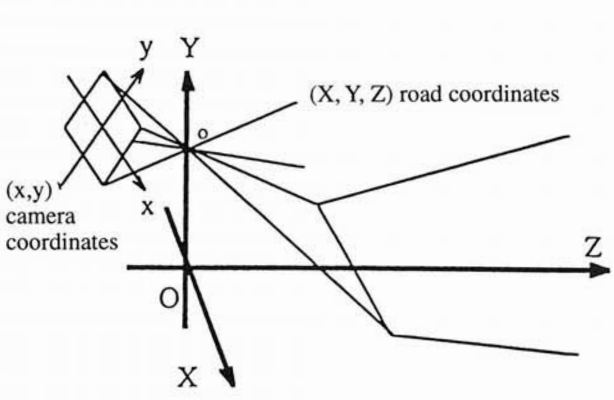


Figure 5. Definition of the coordinates

height of the installed camera while Θy and Θx respectively indicate vertical and horizontal field angles. Θ indicates a depression angle. The camera-road coordinates are shown in Figure 5. On the camera coordinates, x indicates a horizontal axis while y indicates a vertical axis. The focal point of the camera is allocated on Y-axis.

The relation between the camera coordinates (x,y) and the road coordinates (X,Y,Z) can be defined by the following formula:

$$x = \frac{X(\sin^2\Theta - \cos^2\Theta)}{J(H\sin\Theta + Z\cos\Theta)} \quad (1)$$

$$y = \frac{Z\sin\Theta - H\cos\Theta)}{K(H\sin\Theta + Z\cos\Theta)} \quad (2)$$

where

$$X = \frac{d\tan\delta}{\sqrt{1+\tan^2\delta}} \quad (3)$$

$$Z = \frac{d}{\sqrt{1+\tan^2\delta}} \quad (4)$$

$$K = \tan(\frac{\phi_y}{2}) \Big/ (\frac{R_y}{2}) \quad (5)$$

$$J = \tan(\frac{\phi_x}{2}) \Big/ (\frac{R_x}{2}) \quad (6)$$

d indicates the distance to a preceding vehicle detected by the radar while δ indicates an angle between the radar sensing direction and the Z-axis (radar angle). R_x and R_y respectively show the resolution level to x and y directions.

3.4.2 Coupling the image processing with the radar

Generally, it is not easy for a single camera to recognize 3-dimensional objects such as vehicles for which there is no explicit definition of features. With conventional methods, attempts have been made to enhance the recognition of preceding vehicles by confining the search area to the same driving lane or limiting the search objects to those moving at relatively close speeds. However, none of these methods have been able to provide sufficient results.

In the method we have developed, the results on the road coordinates detected by the radar are converted into the image coordinates using the above formulas, and recognition of vehicles is performed within the limited image area which corresponds to the distance and location detected by the radar. (See Figure 6) This method has significantly reduced the burden of image processing and enabled easy and highly reliable recognition of preceding vehicles. Features of this method can be summarized as follows:

1) Highly reliable recognition can be achieved by using radar information.
2) High-speed recognition is possible as a result of specifying the image processing area.
3) The recognition process can be simplified as the target vehicle can be easily detected by the radar. (1/10 compared with our previous methods.)

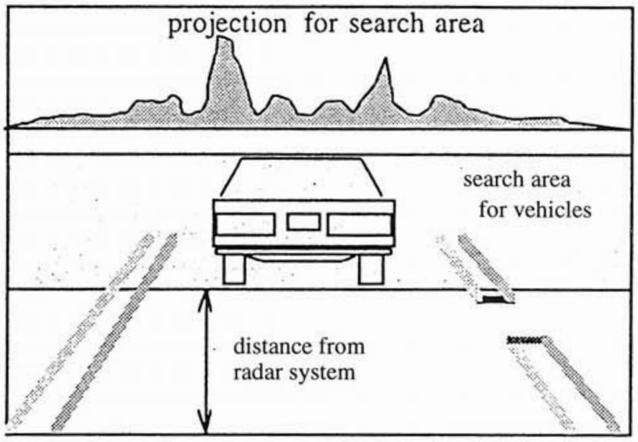


Figure 6. Image of recognizing a preceding vehicle

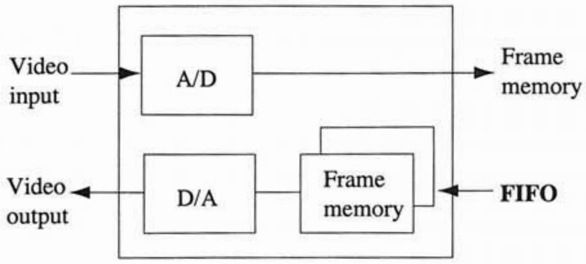
While a radar is highly effective in detecting the target and measuring the distance to it, the sensing area of a radar is relatively limited. In addition, a radar is not capable of locating the position of a detected object on the road. To solve this problem, we have provided a steering mechanism for the radar sensor which can control the radar angle based on the image processing result. The radar steering control unit ensures precise tracking of the target by adjusting radar sensing direction to the drive lane which has been recognized by the image processing.

Thus, by optimally combining the features of radar and image processing, we have been able to significantly enhance the reliability of the driving environment recognition system.

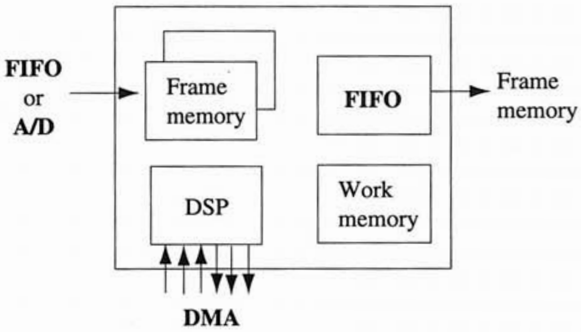
4. Image processing unit

Figure 7 shows the block diagram of our image processing unit. We have employed TI TMS320C40 (50MHz) for DSP.

This unit consists of 3 DSP boards, A/D and D/A board. One of the DSP boards is mounted with 2x512x512 word video memory, and each DSP is connected with FIFO line and DMA line to achieve efficient data transfer. The 1st DSP receives the input image from A/D and classifies edge information into 9 values. The 2nd DSP receives the edge information and recognizes the lane marks. In parallel with this process, the 3rd DSP receives the distance to the target from DMA line (connected with the radar) and recognizes the vehicle by combining this information with the drive lane data from DSP2. By so doing, the 3rd DSP determines



(a) A/D, D/A board



(b) DSP board

Figure 7. Image processing unit

whether a preceding vehicle exists in the same drive lane and calculates the radar angle. Then it outputs this data to each control ECU. The camera we have employed for the unit has practical sensitivity characteristics within the 350nm to 910nm range. We have also used visible ray and infrared ray cut-off filters as required to achieve the desired characteristics. The CCD output can be compensated by the auto-iris function to ensure the image quality.

5. Test

5.1 Driving environment recognition

Figure 8 shows the result of image recognition. The lane marks are indicated by thick white lines and the preceding vehicle in the same drive lane is indicated by the square. You can see that precise recognition has been achieved despite the existence of shadow projected from the road side or the vehicle in the next lane.

Figure 9 shows the result of a recognition test conducted at night. (a) and (b) respectively indicate the result with the visible ray and the infrared ray. The result shows that while the recognition of lane marks is almost impossible with the visible ray, the recognition level achieved by using infrared ray is high enough for controlling the radar angle.

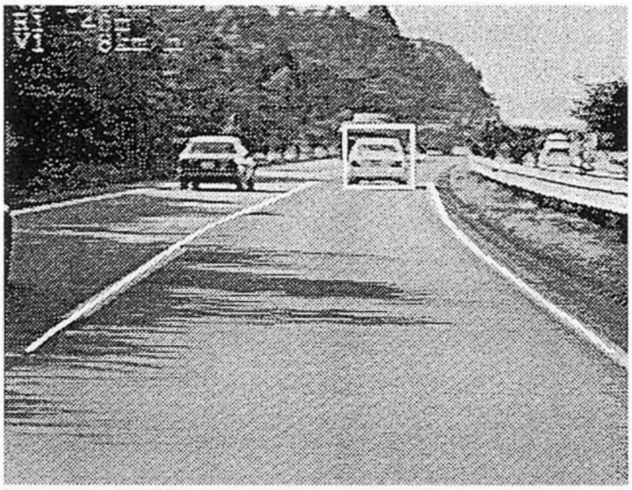
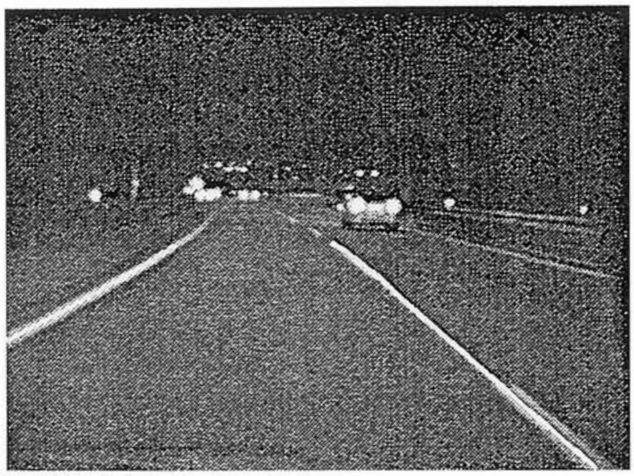


Figure 8. Result of image recognition

(a) Visible ray



(b) Infrared ray

Figure 9. Recognition result at night

5.2 Adaptive cruise control

We have tested the practicability of our driving environment recognition system by applying it to the adaptive cruise control system. We first made an experiment of adaptive cruise on a test course in order to investigate controllability effected by speed or accuracy of recognition. In result, the system could surely recognize a preceding vehicle and smoothly control speed of the car. The next was carried out on the highway in order to understand performance of system, except that only radar angle was controlled. The result of the driving test conducted on the highway is shown in Figure 10 and can be summarized as follows:

- It was rightly recognized the preceding vehicle on the same lane ahead of a curve, and also distinguished the vehicle on the next lane beyond a curve. (Figure 10-b, 10-c)
- The radar angle was adjusted smoothly to trace the road shape. (Figure 10-d)
- The control remained stable inside the tunnel.

Although the auto-iris function of the camera was temporarily disabled at the entrance and exit of the tunnel, the millimeter-wave radar remained unaffected and provided stable recognition. We believe from this result that the system allows a vehicle to perform stable adaptive cruising also on highway.

As deceleration had to be controlled by the engine brake and the release of overdrive, the adaptive cruise control system could achieve only a limited speed reduction. Therefore, the driver was required to operate the brake when the approaching speed of their vehicle to the preceding vehicle exceeded a certain level. As a next step, we will be working on the development of an automatic brake control system.

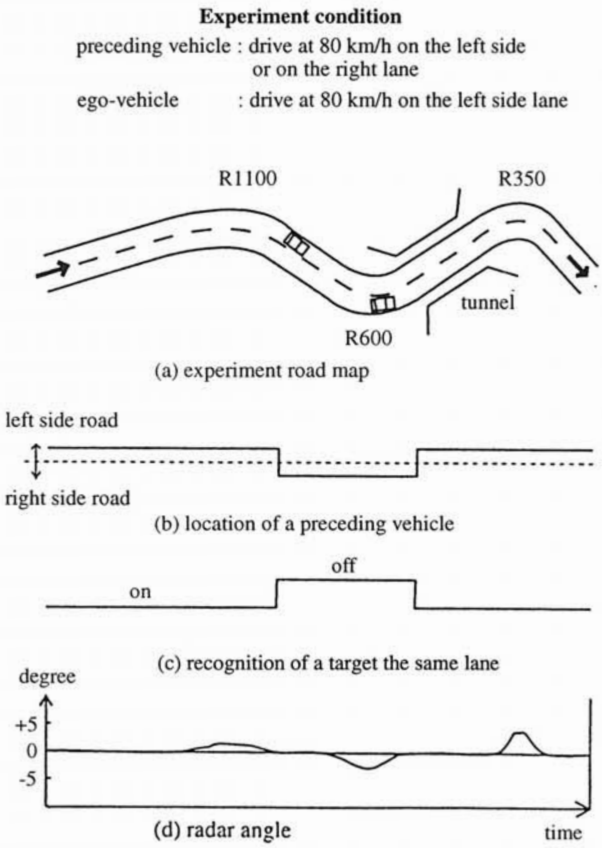


Figure 10. Result of the adaptive cruise control

6. Conclusion

The highway driving environment recognition system successfully combines the technology of image processing with that of radar. By employing CCD which can retain its sensitivity in the infrared area as an image processing sensor, the system provides stable performance at night or inside the tunnel. Furthermore, the millimeter-wave radar used in the system allows for recognition of plural targets even under hazardous weather conditions such as rain or snow, thus ensuring the high reliability of the system.

We have been able to verify the practicability of the driving environment recognition system by actually testing it on the adaptive cruise control system.

Our research efforts are currently directed toward providing a recognition system which can remain highly reliable under varying conditions as well as toward the development of an adaptive cruise control system that can support entire speed range from low-speed during traffic jams to cruising speed. We believe that these studies represent one significant step toward the development of automatic driving systems of the future.

References

[1] M. Kamimura and N. Shima, et. al., "Millimeter-Wave Automotive Radar Using Digital Signal Processing", SAE PAPER No. 930552, 1993.

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