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Intelligent Rain Sensing and Fuzzy Wiper Control Algorithm for Vision-based Smart Windshield Wiper System

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Windshield wipers play a key role in assuring the driver's safety during precipitation. The traditional wiper systems, however, requires driver's constant attention in adjusting the wiper speed and the intermittent wiper interval because the amount of precipitation on the windshield constantly varies according to time and vehicle's speed. Because the manual adjustment of the wiper distracts driver's attention, which may be a direct cause of traffic accidents, many companies have developed automatic wiper systems using some optical sensors with various levels of success. This paper presents the development of vision-based smart windshield wiper system that can automatically adjust its speed and intermittent interval according to the amount of water drops on the windshield. The system employs various image processing algorithms to detect water drops and fuzzy logic to determine the speed and the interval of the wiper.

Key Words : Smart Wiper System, Intelligent Vehicle, Rain Sensing, Wiper Control, Vision Sensor, Fuzzy Control

1. Introduction

Intelligent vehicles offer the potential to enhance safety and convenience significantly for both drivers and passengers. As a component of the intelligent transportation system (ITS), the intelligent vehicle uses various intelligent sensing and control algorithms to assess the vehicle's environment and assist the driver with safe driving. These algorithms include the driver assistance system that partially controls the vehicle for the driver's convenience, and the collision warning system that provides emergency information to allow the driver to avoid a collision. Because of their ability to enhance the safety and convenience, intelligent vehicles become a crucial research area for the intelligent transportation system (Broggi, 2000; Figueiredo et al., 2001).

Among the vehicle parts that influence the driver's safety and convenience, a windshield wiper is an important part that allows a driver to collect visual information during precipitation. The traditional wiper systems, however, requires driver's constant attention in adjusting the wiper speed and the intermittent wiper interval because the amount of precipitation on the windshield constantly varies according to time and vehicle's speed. Because the manual adjustment of the wiper distracts driver's attention, which may be a direct

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cause of traffic accidents, many companies have developed automatic wiper systems using some optical sensors with various levels of success.

Many smart wiper systems try to regulate the wiper's speed and intermittent interval automatically according to the amount of rain or snow (Cheok et al., 1996 ; Kato et al., 1990). The key element of these systems is the sensor to measure the amount of water on the windshield. In most systems, an optical sensor is used for this purpose (Cheok et al., 1996). This type of sensors uses the fact that the refraction angle and the amount of reflection of the light are different when the windshield is wet. Many sensors use several LEDs to emit the light into the windshield at a small incident angle. The light travels through the glass with several reflections at the glass-air border. Opposite to the LEDs, there are several photo sensors to detect the arriving light after the reflections. When the windshield has water on its surface, the refraction angle and the amount of reflected light are changed, resulting in the different photo sensor output. This difference is used to determine the amount of water on the windshield.

The optical rain sensors have some disadvantages even though they are widely used. One of disadvantages is the sensitivity to external light. That is why many systems have a dark filter on the windshield surface where the sensor is attached in order to block the external light. However, many systems still activate the wiper when the car comes out of tunnels or underground parking lot. Another shortfall, maybe a major one is that the sensing area is a relatively small portion of windshield. This makes the wiper system operate only with limited information. The wiper system may fail to activate when there are some raindrops on the driver's line of sight, but not on the sensing area.

For solving these problems, this paper presents a vision-based smart wiper system that can measure a relatively wider windshield area than the conventional system. Especially, the vision sensor has advantage that can measure not only the amount of rain but also the distribution of raindrops. This information can allow the system more intelligently without disturbing drivers.

In this paper, we present the concept and key algorithms for a vision-based smart wiper system. More specifically, this paper shows an effective rain sensing algorithm that can characterize the rainfall during the day and night. In addition, this paper introduces an intelligent wiper control algorithm based on fuzzy logic that can regulate the wiper speed and interval. Finally, experital results under the laboratory settings are presented to evaluate the efficacy of the proposed system.

This paper consists of six sections including this introduction. Section 2 introduces the basic structure of a vision-based smart wiper system, and Section 3 presents the rain sensing algorithm. The intelligent wiper control system using fuzzy logic is described in Section 4, and the experimental results are given in Section 5. Finally, the conclusions are presented in Section 6.

2. Structure of Vision-Based Smart Wiper System

In many cases, the sensing area of an optical smart wiper system is very small ; the area is at most 10 mm wide and 30 mm long. This makes the whole system operate on very limited information. When it starts to rain, the wiper begins to move only after some raindrops fall on to the sensing area. Moreover, the wiper may not start at all when water is splashed by other cars on to the area other than the sensing area.

In order to avoid these problems, we developed a smart wiper system using a vision sensor as shown in Fig. 1. The smart wiper system consists

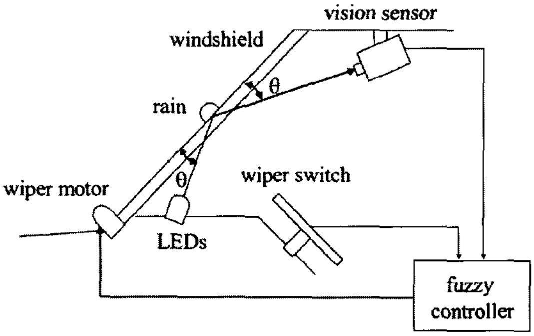


Fig. 1 Schematic diagram of vision-based smart wiper system

of a wiper motor, a wiper switch, a fuzzy controller, a vision sensor, and light emitting diodes (LEDs). Here, the wiper switch is used for activating the smart wiper system. The fuzzy controller performs two functions : the rain sensing algorithm that calculates the rain intensity and rain distribution from the image captured by the vision sensor, and the fuzzy wiper control algorithm that computes the wiper speed and wiper interval based on rain intensity and distribution. Finally, the vision sensor is installed on the ceiling of the vehicle to capture the windshield image, and the LEDs are installed in order to provide some lighting during the nighttime.

To guarantee the performance of the vision-based smart wiper system, the external background outside of the vehicle must be ignored, and only the raindrops on the windshield can be extracted from the image captured by the vision sensor. For this purpose, we have focused the vision sensor on the windshield with low depth of field by opening the aperture to the maximum. The captured images as shown in Fig. 2 show that the external background outside of the windshield is blurred while the raindrops on the windshield are distinct.

Finally, the vision sensor can be affected by an external light source such as sunlight in the daytime, street lamps, tail lamps, and headlamps in the nighttime. Part of disturbances such as sunlight and street lamps can be avoided by installing the vision sensor tilted downward as shown in Fig. 1. However, other disturbances such as tail lamps and headlamps cannot be eliminated. Therefore, an appropriate image processing algorithm is necessary to eliminate the effect of these external light sources. For this purpose, we have an additional image processing step for the nighttime.

3. Rain Sensing Algorithm of Smart Wiper System

Figure 3 shows the rain sensing algorithm for the vision-based smart wiper system. The algorithm takes a captured image as its input and produces the state of precipitation described by two variables, i.e., rain intensity and rain distribution as its outputs. In order to obtain the outputs, the algorithm employs a series of image processing techniques. In the figure, after the wiper switch is set to "auto" mode, the vision sensor acquires an image of the windshield. Then, depending on whether the headlamps are on or off, the algorithm decides whether the additional nighttime processing is required. After appropriate image processing techniques are applied, the algorithm computes rain intensity and distribution that are used to

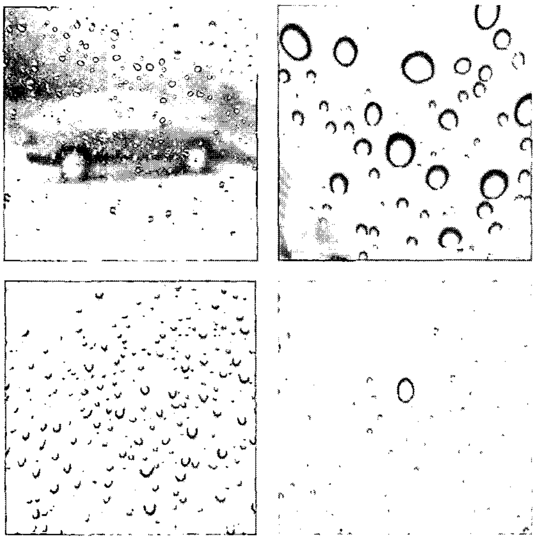


Fig. 2 Raindrop image wity low deqth of field

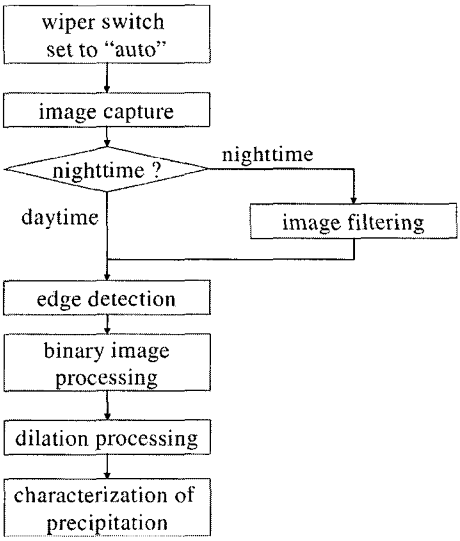


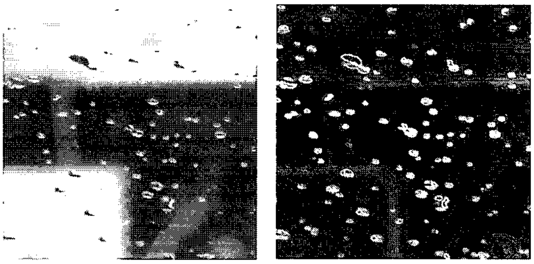
Fig. 3 Flowchart of rain sensing algorithm

determine the wiper speed and interval. The rain intensity represents the amount of rain on the windshield while the rain distribution indicates how widely the raindrops are distributed on the windshield.

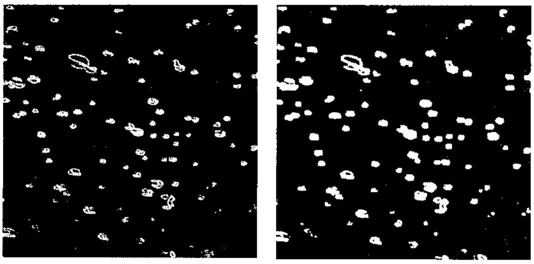
3.1 Daytime image processing algorithm

In order to detect raindrops on the windshield, the algorithm finds the boundaries of raindrops by using an edge detection technique. Among many techniques such as Sobel, Prewitt, Roberts, Laplacian, and Laplacian of Gaussian (Gonzalez et al., 1992), the Sobel mask is selected because its edge detection capability is neither too bad to detect raindrops nor too good so that the edge of background is detected. Fig. 4(a) shows an original image of raindrops while Fig. 4(b) shows the image after the Sobel mask is applied. In the figure, we can see that the boundaries of raindrops are clear without any noticeable edges from the background.

The image in Fig. 4(b) still has the boundaries of the background, though not very visible, that are represented gray pixels. This is because the background image is blurred due to the low depth of field. In order to remove these background boundaries and shorten the processing time, a single threshold T is applied as shown in Eq. (1) where and are the old and new values for the pixel, respectively (Crane, 1997). In this equation, the value for T is selected as 125 after some trials and errors.



(a) Original image (b) Image after Sobel mask



(c) Image after threshold (d) Image after dilation

Fig. 4 Result of image processing for the daytime

$$F(x,y)=\begin{cases} high\ (255) & if\ f(x,y)\geq T \\ low\ (0) & otherwise \end{cases} \tag{1}$$

Figure 4(c) shows the image after thresholding where we can see that the gray background boundaries are completely gone.

The next step is to whiten the pixels inside the boundary. For this purpose, we use the dilation operation (Gonzalez et al., 1992) as an approximation. In general, the dilation makes an object enlarged because the operation extends the outermost pixels of the boundary. Therefore, the raindrops will be slightly larger and some of raindrops still may have black pixels inside the boundary. In this work, a 3□3 dilation mask, whose pixel values are all zeros, is used for faster computational speed (Jang, 1999). Fig. 4(d) shows the final image after the dilation operation. Comparing Fig. 4(c) with Fig. 4(d), we can verify that most raindrop boundaries are filled with white pixels.

3.2 Nighttime image processing algorithm

As mentioned earlier, the nighttime images tend to contain more disturbances such as street lamps, tail lamps, and headlamps. When the daytime processing algorithm is applied to the nighttime image, the effect of disturbances is still remaining in the final image. This indicates that the nighttime processing algorithm should be different from the daytime algorithm.

For this purpose, we focus on the fact that sharp features, in general, have relatively high frequency elements, while blurred features have relatively low frequency element's. That is, the raindrops under the internal LED light are distinct and have high frequency elements whereas the external light sources are blurred by the low depth of field and have low frequency elements. Therefore, disturbances by the external light source can be removed by eliminating low frequency elements from the image.

For removing low frequency elements, we choose the Butterworth high pass filter that can be expressed as follows:

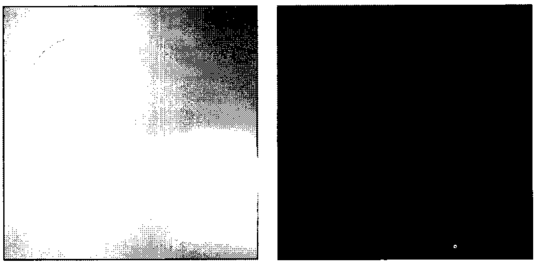
$$H(u,v)=\frac{1}{1+[D_0/D(u,v)]^{2n}} \tag{2}$$

where $D(u,v)$ is the distance from the origin to (u,v) on the frequency plane. In this work, the cutoff frequency is selected to be 32, and n is selected to be 16 via some trials and errors. Fig. 5(a) shows a nighttime image containing a tail lamp. Fig. 5(b) shows the image where the tail lamp is effectively removed after the high pass filter is applied to the original image.

3.3 Characterization of prediction

The wiper operation algorithm requires some input values derived from the processed image. Therefore, we need a step, i.e., characterization of precipitation, to represent the processed image by some values. In order to derive these values we rely on the notion that the factors that hinder the driver's view are the amount of water and the number of raindrops on the windshield. First, when the windshield is covered by the significant amount of water, the driver will have difficulty in finding lanes and obstacles. However, the amount of water is not the only factor because the driver's view is considerably blocked when numerous but very small raindrops are covering the windshield.

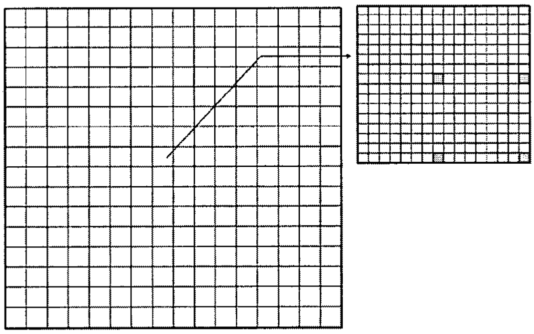
Therefore, we define two variables: rain intensity and rain distribution. The rain intensity is defined as the number of pixels representing raindrops (its value is high) in the processed image (256×256 pixel). The rain distribution is computed as follows: 1) divide the overall area of 256×256 pixel image into 16×16 pixel unit areas, 2) if there is at least one pixel representing a raindrop in the 16×16 pixel unit area, assign high value to all pixels of the 16×16 unit area, 3) the rain distribution is defined as the ratio of the number of pixels with high value to the number of overall pixels (65, 536).



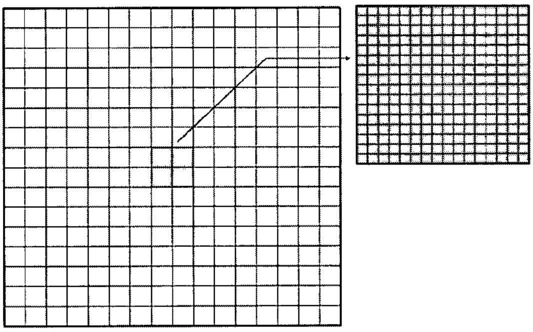
(a) Original image (b) Image after high pass filtering

Fig. 5 Result of high pass filtering for the nighttime image

Figure 6 shows an example how the rain intensity and rain distribution are calculated. The large square represents the 256×256 captured image while the small square represents the enlarged 16×16 unit area. Fig. 6(a) represents the case for drizzle or mist. Suppose that raindrops are of the size of one pixel and they are evenly distributed so that each 16×16 unit area contains four raindrops as shown in the small square in Fig. 6(a). Then, the rain intensity is the number of raindrop pixels which equals 1024 (4 in each unit area 16×16 unit areas in the processed image). The rain distribution is 100% because all pixels of a unit



(a) Mist



(b) A single large raindrop

Fig. 6 Example of rainfall condition by wetness and distribution area should have high value due to four pixels in the unit area, and all unit areas have high value due to the even distribution. In contrast, Fig. 6(b) represents the case of a single big raindrop at the center of the image. In this case, the raindrop is as large as four unit areas that contain 1024 pixels. Therefore, the rain intensity is 1024. The rain distribution is 1.56% because only four unit areas have high value out of 256 unit areas (4/256× 100).

4. Fuzzy Wiper Control Algorithm

In this paper, a fuzzy control algorithm is used to regulate the wiper speed and wiper interval using the calculated rain intensity and distribution after the image processing. The major rationale to use fuzzy logic is that the fuzzy logic allows mimicking the human drivers' decision making with relative ease and that the outcomes of the logic can be tuned or customized for individual drivers by adjusting membership functions (Lee et al., 2003 ; Foo, 2000).

Figure 7 shows the structure of the fuzzy wiper control algorithm of the smart wiper system. In the figure, the fuzzy controller consists of three parts : fuzzifier, inference engine, and defuzzifier. The fuzzifier converts the rain intensity and distribution into linguistic values. The inference engine creates the fuzzy outputs using fuzzy control rules generated from expert experiences. Finally, the defuzzifier calculates the wiper speed and wiper interval from the inferred results.

To acquire the fuzzy control rules, we summarize the wiper control rules based on the general behavior of human drivers as shown in Table 1 (Cheok et al., 1996). That is, if it is a light drizzle or several raindrops are on the windshield, the wiper should be set to low speed with a long interval. However, if it is raining heavily or raindrops are all over the windshield, the wiper should be set to high speed with zero interval. The rules in Table 1 are converted into more structured rules considering the input variables of rain intensity and distribution as shown in Table 2.

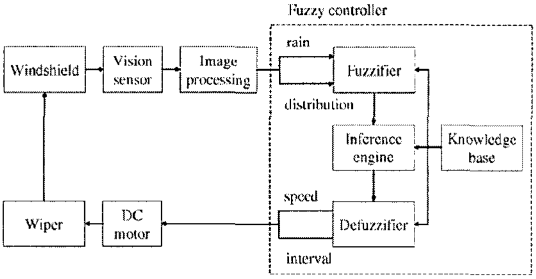


Fig. 7 Schematic diagram of fuzzy controller

Table 1 General linguistic rule for wiper control

Antecedent	Consequence
IF it is not raining or drizzling	THEN the wiper should be set to "Off"
IF it is drizzling lightly	THEN use a long delay interval setting on the wiper
IF it is drizzling heavily	THEN use a short delay interval setting on the wiper
IF it is raining lightly	THEN use the continuous low speed setting on the wiper
IF it is raining heavily	THEN use the continuous high speed setting on the wiper

Table 2 Fuzzy control rules for wiper control

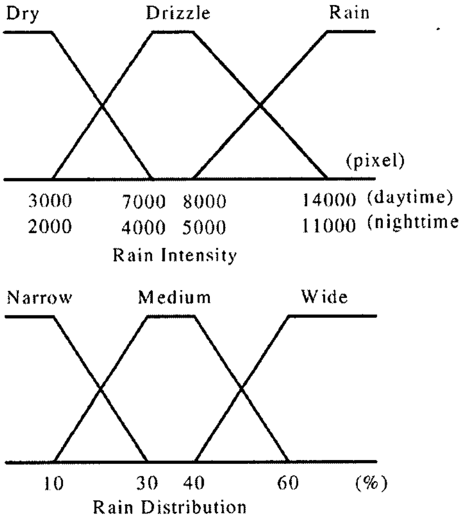
(a) Speed

Rain Intensity / Distribution	Dry	Drizzle	Rain
Narrow	Zero	Low	Low
Medium	Low	Low	Low
Wide	Low	Low	High

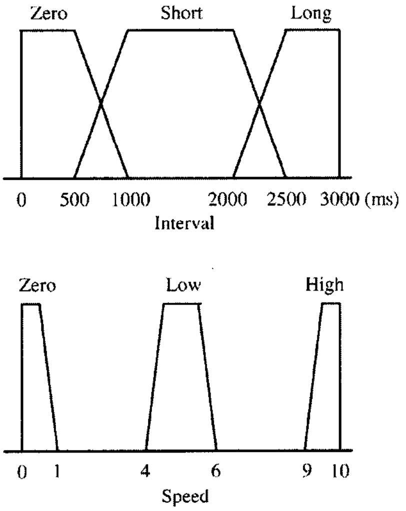
(b) Interval

Rain Intensity / Distribution	Dry	Drizzle	Rain
Narrow	Long	Long	Short
Medium	Long	Short	Zero
Wide	Short	Zero	Zero

Figure 8 shows the membership functions of the fuzzy input and output linguistic variables. The linguistic variables for the rain intensity are defined as Dry, Drizzle, and Rain while those for the rain distribution are defined as Narrow, Medium, and Wide as shown in Fig. 8(a). In the figure, the membership functions of rain intensity are different depending on whether it is daytime or nighttime. This is to compensate the boundary detection capability in the nighttime because almost all the boundaries of raindrops are detected in the daytime while the algorithm tends to miss some raindrops in the nighttime. The linguistic variables for the wiper interval are defined as Zero, Short, and Long as shown in Fig. 8(b). Here, we define that the wiper interval varies from zero to 3,000 msec. The linguistic variables for the wiper speed are defined as Zero, Low, and High as shown in Fig. 8(b).



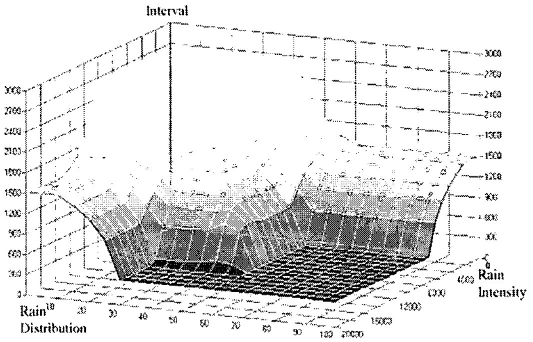
(a) Membership functions of fuzzy inputs



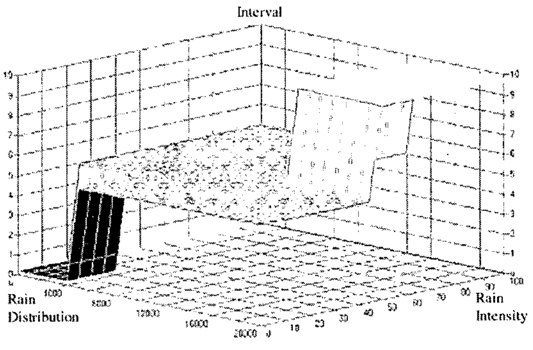
(b) Membership functions of fuzzy outputs

Fig. 8 Membership functions of fuzzy input and output variable

For faster execution of the fuzzy logic controller, the Mamdani's min-max inference method is used. For defuzzification, the MoM (Mean-of-Maximum) method is used for the wiper speed, and the CoA (Center-of-Area) method is used for the wiper interval (Lee, 1990a; Lee, 1990b). The reason for using the MoM method is to obtain the output that changes discretely instead of varying continuously. This is because the wiper motors operate at two different speeds, i.e., high and low instead of continuously varying speed. In this paper, we have the wiper stop if the output value is smaller than one, run at high speed if the output value is larger than 9, and run at low speed



(a) Wiper interval



(b) Wiper speed

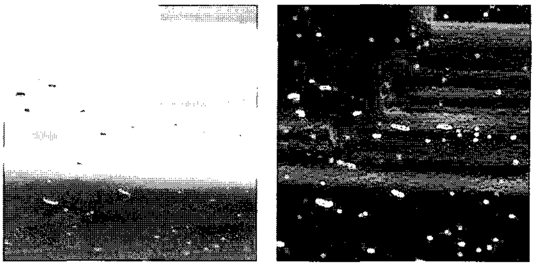
Fig. 9 Output maps for wiper interval and speed otherwise. The output maps for speed and interval are shown in Fig. 9.

5. Performance Evaluation of Vision-Based Smart Wiper System

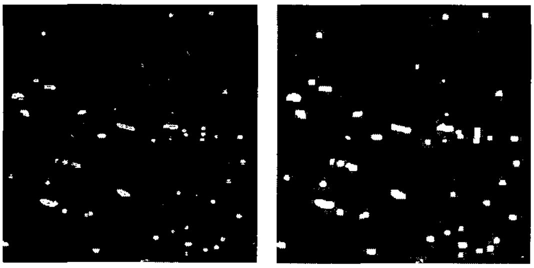
In order to evaluate the efficacy of the vision-based smart wiper, we have set up an experimental test bed in a laboratory environment. The test bed has a windshield and a wiper removed from a car. The image processing and fuzzy logic algorithms are implemented on a PC with a frame grabber (Euresys' Picolo board) and a CCD camera (Pulnix's TM-200). The PC is also connected to an interface circuit that can drive the wiper motor. The camera's aperture is adjusted to open as wide as possible (f=1.4).

5.1 Experimental results for daytime operation

In order to emulate the drizzle in the daytime, water is sprayed on to the windshield with the laboratory lights turned on. Fig. 10 shows the images throughout the processing, i.e., Sobel mask, thresholding, and dilation as explained earlier. The final image contains 2,183 white pixels (rain intensity of 2, 183) and has 30.5% of 16□16 unit areas with at least one raindrops (rain distribution of 30.5%). Using these two values, we can calculate that the wiper interval is 2,450 msec, and that the wiper speed is low from the fuzzy wiper control algorithm. Fig. 11(a) shows the captured image of the windshield when a large amount of water is dropped to emulate the rain in the daytime. From the final image, the rain intensity is 15,831 pixels, and the rain distribution is 83.2%. This gives us 350 msec for wiper interval and high for wiper speed. Comparing these results, we can see that the fuzzy logic behaves as intended although the maximum wiper interval of three seconds may be too small for real applications.

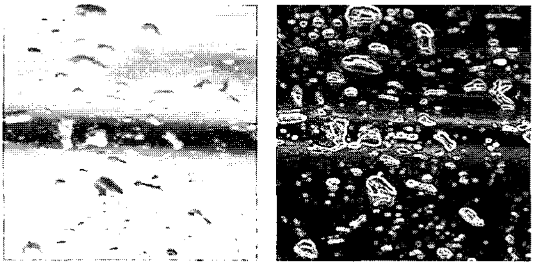


(a) Original image (b) Image after Sobel mask

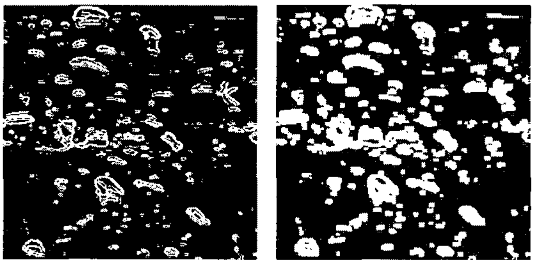


(c) Image after threshold (d) Image after dilation

Fig. 10 Result of image processing for drizzle in the daytime



(a) Original image (b) Image after Sobel mask

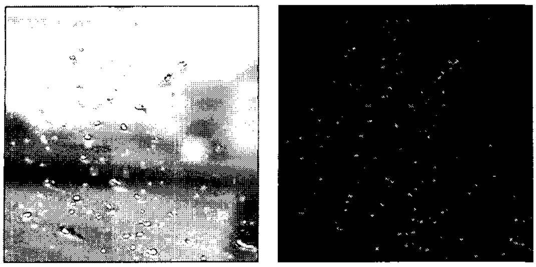


(c) Image after threshold (d) Image after dilation

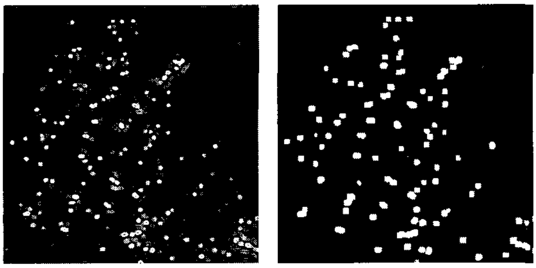
Fig. 11 Result of image processing for rain in the daytime

5.2 Experimental result for nighttime operation

The nighttime environment is emulated in the laboratory by conducting the experiment after nightfall with the lights turned off. Fig. 12 shows the images obtained during an experiment mimicking a drizzle in the nighttime. The capture image shown in Fig. 12(a) shows some background objects due to other external light. After applying the Butterworth high pass filter to the original

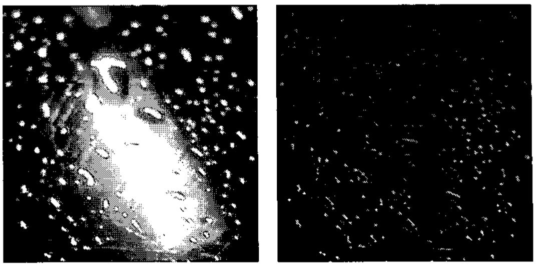


(a) Original image (b) Image after high pass filter

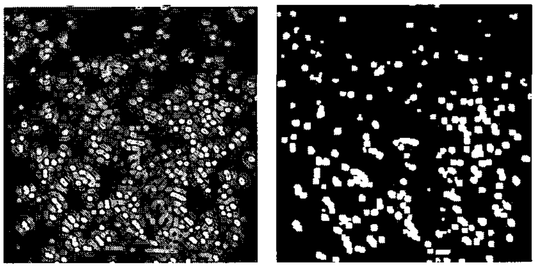


(c) Image after Sobel mask (d) Image after Threshold dilation

Fig. 12 Result of image processing for drizzle in the nighttime



(a) Original image (b) Image after high pass filter



(c) Image after Sobel mask (d) Image after Threshold dilation

Fig. 13 Result of image processing for rain in the nighttime

image, we obtain an image as shown in Fig. 12(b) where raindrops are too dark to see. After edge detection, thresholding, and dilation, however, we can obtain the final image shown in Fig. 12(d) where raindrops are represented by white pixels. From the final image, we can calculate that the rain intensity is 3,352 pixels, and that the rain distribution is 44.5%. These input values result in the wiper interval of 1,840 msec and the low wiper speed.

Figure 13 shows the results of an experiment for nighttime rain with an external light disturbance. In the experiment, several LEDs are used as the external light source as shown in Fig. 13(a). After performing image processing procedures for nighttime images, most of disturbance is removed as shown in Fig. 13(d). In this case, the rain intensity is 8,449 pixels and the rain distribution is 73.0%. These results in the wiper interval of 350 msec and high wiper speed. In real application, if the wiper interval is too short, e.g., 500 msec or less, the wiper should operate continuously.

The experimental evaluation shows that the proposed vision-baser smart wiper system can be used instead of existing optics-based systems. The proposed system may allow the developers to avoid existing patents and make the system more intelligent not to irritate the drivers due to improper operations. For practical automotive application, the algorithms should be implemented on some type of embedded system such as an electronic control unit (ECU) that has some moderate computation speed because the algorithms need to be run from time to time, say once in a few seconds. In addition, the wiper system may share camera and image capture board in the future with other vision-based smart systems such as lane tracking system or collision warning system.

6. Summary and Conclusion

In this paper, we proposed a vision-based smart wiper system to improve the safety and convenience of drivers. The system employs a series of image processing steps to remove background objects and identify raindrops on the windshield. From the processed image, rain intensity and distribution are calculated as two inputs to the fuzzy logic algorithm selecting wiper speed and interval. In order to demonstrate the efficacy of the proposed system, the system was evaluated through a series of experiments under laboratory settings. The conclusions derived from the research are as follows.

It is demonstrated that the vision-based wiper system is technically viable by combining appropriate image processing steps. This vision-based approach provides far more information that the existing optics-based systems. The optical sensor's sensing area may be too small to detect the sparsely distributed raindrops and the sensor cannot detect the raindrops directly on the line of sight of driver. In contrast, the vision sensor can cover an area large enough to detect sparsely distributed raindrops and raindrops on the driver's line of sight.

Rain intensity and distribution may be suitable variables to characterize a rainfall. The amount of water used to be the only variable to characterize a rainfall in existing systems. However, we have added another variable, rain distribution to represent how raindrops are distributed on the windshield. By using these to variables and a set of simple fuzzy rules, we were able to determine the wiper speed and intermittent interval.

In spite of the above conclusions, the vision-based wiper system is not still economically viable due to the extra cost for camera, frame capture circuitry, and controller. We hope that the advantages of vision-based wiper system will outweigh the extra cost and complexity in the near future when intelligent vehicles begin to appear. When the proposed system begins to make sense economically, the proposed algorithms should be tested in the field and the logics should be fine-tuned by observing drivers' behavior.

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