



Visibility Detection of Unmanned Vehicle in Fog Based on Fast-Guided-Filtering

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Abstract: Unmanned vehicles detect the traffic environment through on-board sensors, automatically identify road safety information without human control, and automatically plan parameters such as driving speed and route. However, foggy weather will reduce the detection accuracy of visibility by unmanned vehicles and affect the driving safety of unmanned vehicles. In order to reduce the probability of dangerous accidents of unmanned vehicles caused by fog and improve the unmanned vehicle driving capability in foggy environments, a fast-guided-filtering fog road visibility detection algorithm is proposed. Firstly, the original image is processed by dark channel prior, and the values of atmospheric light intensity and transmittance are calculated respectively. Secondly, the fast-guided-filtering is applied to the dark channel image to enhance the edge details of the image. The atmospheric scattering coefficient is estimated by selecting double reference points. Finally, combined with the definition of visibility, its value detection based on video image sequence is realized. The experimental results confirm that the accuracy of this method for detecting visibility on foggy roads can reach 92.3%. It can provide reliable detection data support for the subsequent driving decision of unmanned vehicles such that vehicles can reasonably plan driving speed and route and ensure driving safety with certain practicability and feasibility.

Keywords: Unmanned Vehicle, Visibility Detection, Foggy Road, Dark Channel Prior, Fast-Guided-Filtering

1. Introduction

With the rise of unmanned vehicle technology, autopilot is gradually applied to all walks of life, such as the military field for environment reconnaissance and material delivery, and also the civil field where autopilot can serve as auxiliary driving, optimize the travel route, etc. [1]. Due to weak visibility on the foggy road, unmanned vehicle driving cannot timely identify traffic information and surrounding obstacles, there is a certain security risk. As one of the important indicators of meteorological warning, highway and environmental quality detection etc., visibility refers to the maximum distance that separates the target from the background within the normal visual range. In terms of transportation, visibility is susceptible to fog, haze and rain, which greatly increases the occurrence of traffic accidents.

For example in 2016, heavy fog caused several vehicle rear-end accidents on Shanghai Pudong Expressway, resulting in 9 deaths and many injuries [2]. In 2018, two traffic accidents involving 21 vehicles on Qingyin Expressway results in many injuries. In December 2022, more than 200 vehicles collided in both directions on the Xinzheng Yellow River Bridge. It was later determined that the visibility of roads was seriously reduced due to sudden fog and road icing. Therefore, the detection of road visibility during foggy days is of great significance for the risk prevention of unmanned vehicle driving and transportation management.

The traditional fog visibility measurement methods are mainly divided into two categories: manual observation and instrumental detection [3]. The artificial method is mainly based on the distance observed by the human eye to roughly

judge the value of visibility, which is easily affected by the clarity of the target and subject to the observer with large errors and lack of stability. Laser visibility meter detection is a common way to obtain traffic condition, but due to the high price, high maintenance cost and complicated layout, it is difficult to realize the large-scale application and easily affected by water vapor particles. As a result, the visibility detection accuracy in fog and haze environments is low, accompanied by certain safety hazards. In recent years, with the development of smart recognition methods and technologies, intelligent visibility detection based on video image sequences has become one of the main research trends. To a certain extent, it overcomes the shortcomings of complex layouts, poor applicability, and high maintenance cost in instrument detection. Compared with manual and instrument detection methods, this method has the advantages of low cost, convenient data acquisition, and stable and reliable effect.

Some research has been carried out to obtain the atmospheric visibility value based on image processing technology. For example, Baumer *et al.* [4] used the panoramic camera to detect the target and calculate the visibility, but this method is costly and susceptible to camera imaging noise. Liu *et al.* [5] presented a simple convolutional neural network modeling, the original image is divided into blocks to obtain information and extract the visibility value. Chen *et al.* [6] obtained visibility by extracting the region of interest of the image and combining the basic parameters of camera calibration. Venkata R *et al.* [7] proposed a BPNN model to predict the problem of low visibility on foggy days, which has certain predictability, but the prediction accuracy is low and does not meet the visibility error index. Cai *et al.* [8] used the dark channel prior theory to enhance the contrast between the target and the background of the video image, and then obtained the corresponding atmospheric visibility. Xu [9] detected the visibility of a single image based on SSR and analyzed the relationship between the transmittance and the brightness in the image to obtain the visibility estimation of the foggy image. There are still problems such as low detection accuracy and low adaptability.

Aiming at the problem of visibility detection of unmanned ground vehicles this paper proposes a fog visibility detection algorithm for unmanned vehicles based on video image sequence. The algorithm combines the foggy imaging model and the dark channel prior principle to obtain the atmospheric light intensity A and the atmospheric transmittance $t(x)$. Aiming at the problem of dark channel image blurring, histogram equalization is used to enhance global contrast, and fast-guided-filtering is introduced to retain more image edge information. Combined with down-sampling operation, the computational complexity is greatly reduced. The double reference points in the figure are selected to estimate the depth of the scene, and then the value of visibility is detected. The experimental results show that this method has certain feasibility and effectiveness.

Specifically, the main research work of this paper is

divided into four sections: In section 2, the dark channel prior is used to process the original image, and the fast-guided-filtering and histogram equalization are used to optimize the obtained dark channel image to enhance the global contrast and retain more edge information, then the visibility value is calculated. In section 3, the visibility level of the experimental results is evaluated, and the method in this paper is compared with the guided filtering. Section 4 summarizes the research work of this paper.

2. Visibility Detection Algorithm

2.1. Visibility Calculation Overall Flow Chart

In this paper, the input original image is processed by dark channel prior theory, and the obtained dark channel image is optimized by fast guided filtering to retain more edge information. Histogram equalization is used to enhance the global contrast, which is convenient for subsequent feature extraction of the image. Due to the uncertainty of the actual distance from the camera to the observation point, this paper selects the double reference points in the figure to calculate the scene depth. Combined with the atmospheric light intensity and atmospheric transmittance calculated by the dark channel prior theory, the visibility value is finally obtained by using the formula. The overall process of the algorithm in this paper is shown in Figure 1.

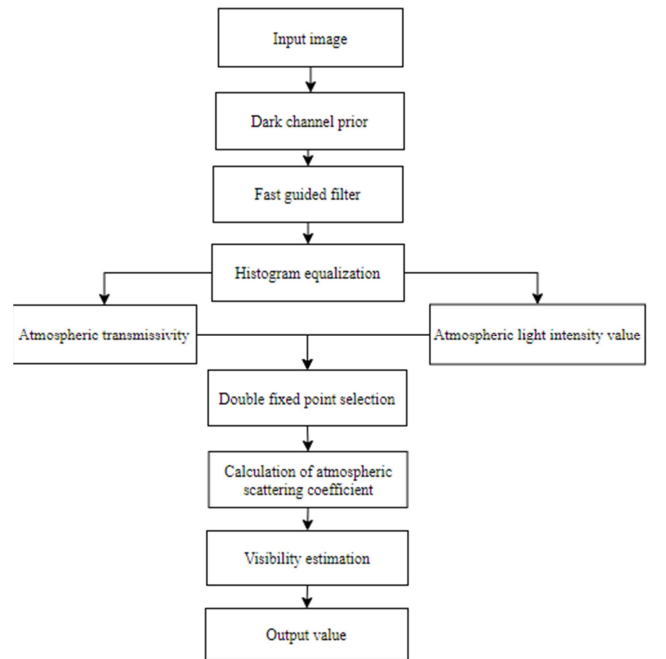


Figure 1. Visibility estimation flow chart.

2.2. Dark Channel Prior Theory

The dark channel prior theory is a breakthrough dehazing algorithm proposed by Kaiming He in 2009. It obtains the energy progress information in the image is obtained by estimating the atmospheric transmittance of the target point. In the non-sky local area map, at least one of the three color

channels of some pixels and the surrounding area has a very low gray value, which approaches 0. The schematic diagram of the dark channel principle is shown in Figure 2 [10].

Reference [11] shown that the commonly used fog imaging model can be expressed as Equation (1) [11].

$$I(x) = J(x)t(x) + A(1-t(x)) \quad (1)$$

In the formula, x is the position of any pixel in the image; $I(x)$, $J(x)$ is expressed as the observed foggy image and the fog-free image that needs to be restored, A is the atmospheric light value, and $t(x)$ is the atmospheric transmittance.

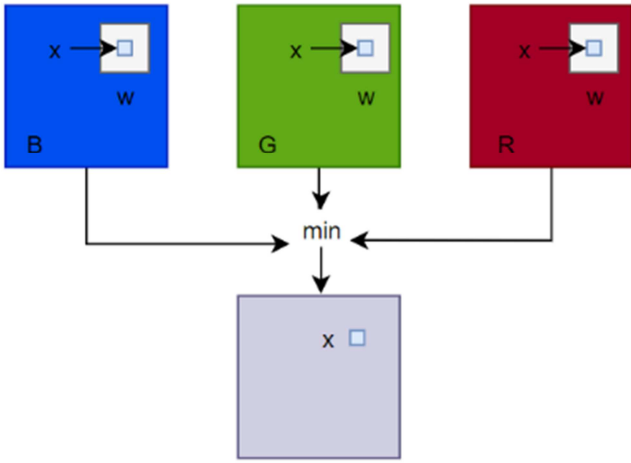


Figure 2. Dark channel schematic diagram.

For a haze-free image, its dark channel can be expressed as Equation (2).

$$J^{dark}(x) = \min_{c \in (r, g, b)} \left(\min_{y \in \omega(x)} J^c(y) \right) \approx 0 \quad (2)$$

In the formula, $J^c(y)$ represents any color channel of the haze-free image J , $\omega(x)$ is a local area centered on x , and the size of the local window is 9×9 .

According to the above analysis, for the fog-free image J , the value is about zero, and the calculation process of A can be obtained as follows (3).

$$I(k) \approx A(k)(1-t(k)) = A(k) = A \quad (3)$$

By extracting the minimum pixel value in each channel domain of the original image, the result of simplifying Equation (1) is shown in Equation (4).

$$\min_{y \in \Omega(x)} \left(\frac{I^c(y)}{A^c} \right) = t(x) \min_{y \in \Omega(x)} \left(\frac{J^c(y)}{A^c} \right) + (1-t(x)) \quad (4)$$

In the formula, $I^c(y)$ represents any color channel obtained by the foggy image I , and A^c represents the atmospheric light value in any channel.

Due to the presence of more or less suspended particles in the atmosphere, in order to restore the initial image as much

as possible, a weight factor ω is introduced when estimating the transmittance of each pixel, and the value is 0.95. According to the dark channel prior, the fog-free image channel approaches zero, and the calculation process of the atmospheric transmittance can be obtained as shown in Equation (5).

$$t(x) = 1 - \omega \min_{c \in (r, g, b)} \left(\min_{y \in \Omega(x)} \left(\frac{I^c(y)}{A^c} \right) \right) \quad (5)$$

2.3. Image Enhancement

In the actual road monitoring, there are often a variety of external interference factors that affect the captured video images. In order to enhance the contrast of the image and facilitate the subsequent extraction of more effective feature information, the invention uses the histogram equalization method to enhance the global contrast of the image. The essence is to widen the number of pixels in the image and reduce the number of pixels to achieve the purpose of clear image [12].

In general, the probability distribution of pixel values can be assumed to obey a uniform distribution [13], that is, the expression of the gray level 1 of each pixel after equalization is as follows (6).

$$S_k = \sum_{i=0}^k \frac{n_i}{N} \times (L - 1) \quad (6)$$

In the formula: N is the total number of pixels in the figure; $i = 1, 2, \dots, L-1$, where L is the number of total gray levels; n_i is the number of the i th gray level pixels in the original image.

2.4. Fast-Guided Filter

The image obtained by the dark channel prior theory is blurred, which is easy to cause the loss of edge information, resulting in a large error in the numerical measurement of visibility. In order to obtain more accurate numerical information, this paper uses fast guided filtering to optimize the dark channel image.

For guided filtering [14], under local window w_j , the linear relationship between the guided image I and the output image q can be expressed as (7).

$$q_i = a_j I_i + b_j, \quad \forall i \in w_j \quad (7)$$

In the formula, the coefficient a_j, b_j is the corresponding constant in the range of window w_j where w_j is represented as a local window with a size of 9×9 .

In order to preserve more edge details of the original image, the regularization parameter ε is introduced, and the loss function E is expressed as Equation (8).

$$E(a_j, b_j) = \sum_{i \in w_j} ((a_j I_i + b_j - p_i)^2 + \varepsilon a_j^2) \quad (8)$$

In the formula, ε is the regularization parameter that adjusts the accuracy of image edge detection, and the value is 0.01.

The expression of a_j, b_j can be obtained by minimizing the loss function, as shown in Eq. (9) and Eq. (10).

$$a_j = \frac{\sum_{i \in w_j} I_i p_i - b_j \sum_{i \in w_j} I_i}{\sum_{i \in w_j} (I_i^2 + \varepsilon)} = \frac{\frac{1}{|w|} \sum_{i \in w_j} I_i p_i - \lambda_j \bar{p}_j}{\sigma_j^2 + \varepsilon} \quad (9)$$

$$b_j = \frac{\sum_{i \in w_j} p_i - a_j \sum_{i \in w_j} I_i}{|w|} = \bar{p}_j - a_j \lambda_j \quad (10)$$

In Equations (9) and (10), λ_j and σ_j^2 are the mean and variance of the original image I in the range of local window w_j , $|w|$ represents the total number of pixels in the window, and \bar{p}_j represents the mean of the input image p in the range of window w_j .

Because the difference of local window size will lead to the difference of output image q_i , the mean value of pixel i in window w_j is calculated, and then the output result of guided filtering is obtained as shown in formula (11).

$$q_i = \frac{1}{|w|} \sum_{i \in w_j} (a_j I_i + b_j) = \bar{a}_i I_i + \bar{b}_i \quad (11)$$

In the formula, \bar{a}_i, \bar{b}_i is the mean value of window w_j on all pixels i .

Fast guided filtering is further optimized on the basis of guided filtering. The main idea is to reduce the pixels by down-sampling the input image, and restore the size of the original image after up-sampling after calculating \bar{a}_i and \bar{b}_i [15].

2.5. Atmospheric Visibility Detection Principle

Due to the uncertainty of the actual distance from the camera to the observed target position, this paper adopts an estimation method based on atmospheric scattering coefficient. It is known that the distance between adjacent vehicle auxiliary lines in the road is 9m. Two reference points are selected from the figure, and the distance difference between the two reference points is used to replace the distance between the camera and the target point to obtain the atmospheric scattering coefficient value. The distance difference between the selected reference points is assumed to be 9m, as shown in Figure 3.

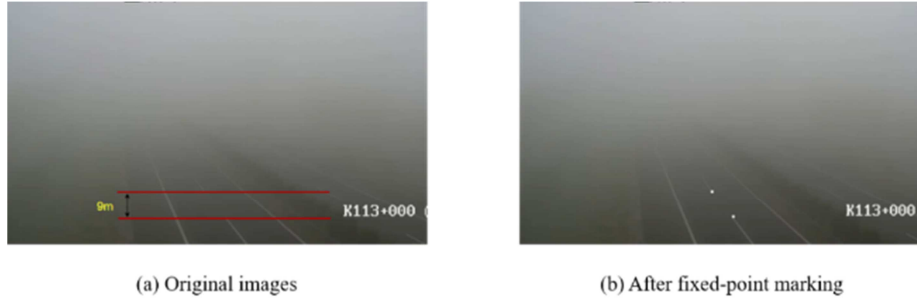


Figure 3. Selection of double reference points.

The value of atmospheric transmittance $t(x)$ can be obtained from formula (5). According to the definition formula of atmospheric transmittance, the formula of atmospheric scattering coefficient can be derived as shown in formula (12).

$$t(x) = e^{-\beta d(x)} \quad (12)$$

In the formula, β is the atmospheric scattering coefficient, and d is the actual distance from the observation point to the observation target position.

The expression of the atmospheric scattering coefficient obtained by the transformation of formula (12) is as shown in formula (13).

$$\beta = -\frac{\sum_{i \in R_2(x)} \ln t(i)}{|p_R| (D_2 - D_1)} + \frac{\sum_{i \in R_1(x)} \ln t(i)}{|p_R| (D_2 - D_1)} \quad (13)$$

In the formula, $R(x)$ is the selected pixel area with a size of

7×7 ; p_R is the number of pixels in the selected area; $D_2 - D_1$ is the distance difference between the selected two reference points.

It is assumed that the atmospheric extinction coefficient is composed of scattering coefficient and absorption coefficient within the distance between the camera and the highway. When the target position is close to the observer, the absorption effect of the atmosphere can be ignored, so the atmospheric scattering coefficient β can be used instead of the atmospheric extinction coefficient σ . Bring the value of the atmospheric scattering coefficient β into the visibility formula to obtain the visibility results, as shown in Formula (14) [16].

$$V = \frac{\ln(\varepsilon)}{-\sigma} = \frac{\ln(\varepsilon)}{-\beta} \quad (14)$$

In the formula, ε is expressed as the contrast visual threshold, and the value is 0.05.

Therefore, according to the above method, the atmospheric transmittance and atmospheric light intensity A obtained by the dark channel prior and the atmospheric scattering coefficient β obtained by the double reference point are brought into the formulas (13) and (14), and the fog visibility V can be obtained.

3. Results and Analysis

3.1. Analysis of Image Processing Results

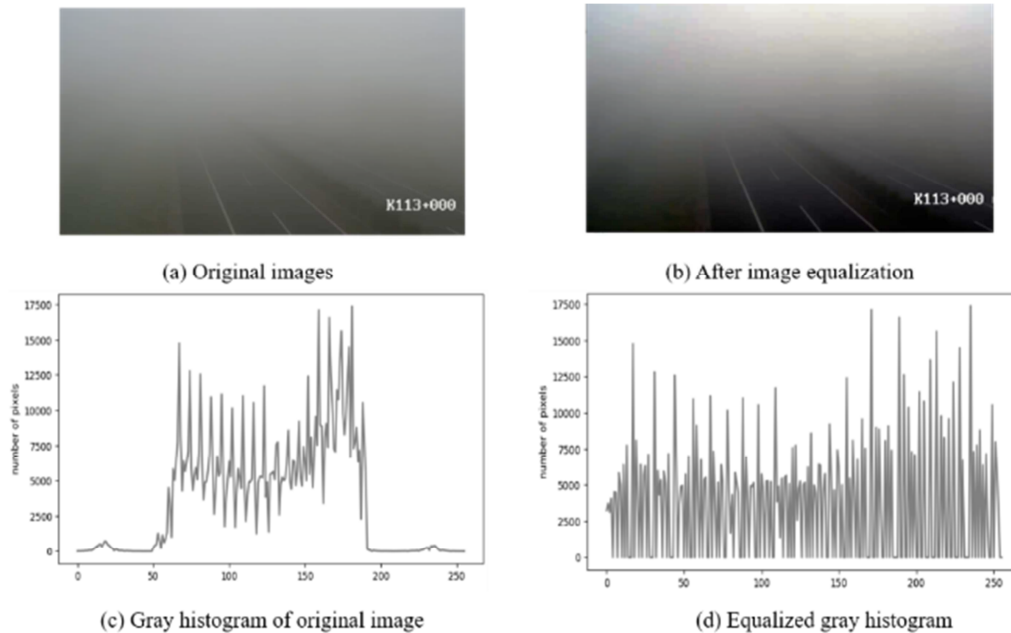


Figure 4. Contrast image before and after image enhancement.

In order to further obtain more accurate information, fast-guided-filtering is used to optimize the dark channel image. Figure 5 is the comparison diagram before and after the fast-guided-filtering processing. Compared with the original algorithm, the filtering preserves the edge information and image details better, which is conducive to

accurately capturing the position information. Because the fast-guided filter performs down-sampling on the input image, the resolution of the image is reduced, so the computational complexity of the filter can be effectively lowered with fast running speed.

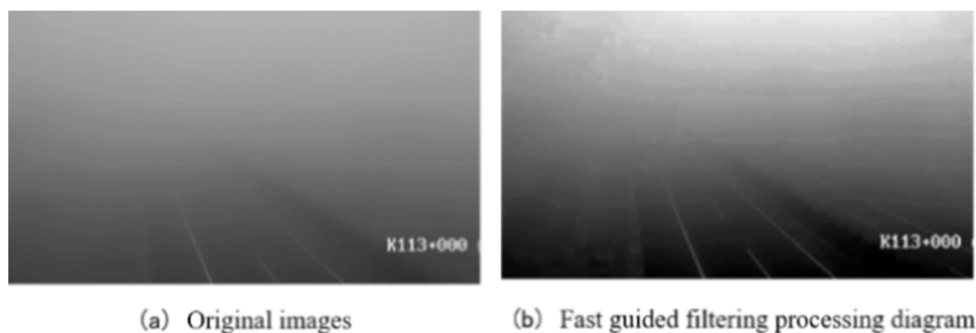


Figure 5. Comparison diagram before and after fast guided filtering processing.

3.2. Analysis of Visibility Results

The experiment in this paper is only for the visibility measurement of highways in foggy days. In the traffic

management, in order to ensure the safe and efficient operation of the expressway, and according to the Standard on Meteorological Industry (People's Republic of China), the visibility range of the expressway is set according to different fog concentrations, and divided into four levels as shown in

Table 1 [17]. When the visibility is less than 50 meters, the visibility level is 0, and the relevant department issues a red alert and implements a full-line or partially closed road; when the visibility is between 50 and 500 meters, the visibility level is 1 and 2, and the relevant department will

issue orange and yellow alert to carry out traffic control to ensure driving safety. When the horizontal visibility is greater than 500 meters, the visibility level is 3 or higher and no alert will be issued, so people can drive normally.

Table 1. The visibility energy level division standard of fog.

Visibility Grade	Horizontal Visibility W (m)	Fog Grade	Alert
0	$W \leq 50$	Dense fog	Red alert
1	$50 < W \leq 200$	Thick fog	Orange alert
2	$200 < W \leq 500$	Fog	Yellow alert
3	$500 < W$	Moerate fog	

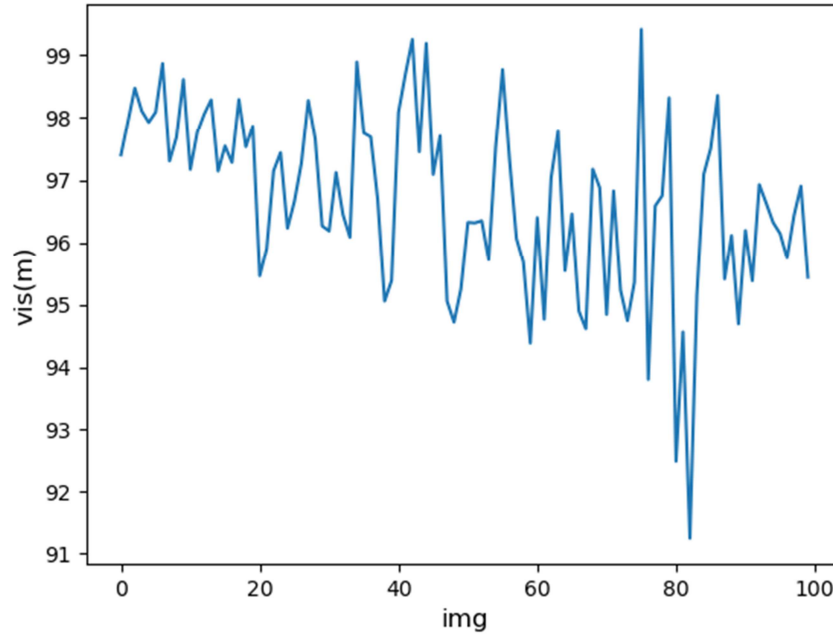


Figure 6. Visibility change curve diagram.

After processing 100 road images, the visibility change curve is shown in Figure 6. It can be seen from the diagram that the visibility range calculated by the algorithm in this paper is among 92 and 101 meters. In the actual road shooting, due to the vibration of the camera caused by wind or other interference, the detected visibility will have a small change, which is analogous to actual situation. According to the matching to visibility grade divided by meteorological traffic, it can be concluded that the horizontal visibility of the road is greater than 50 meters and less than 200 meters, which belongs to grade 1 dense fog. The traffic management department will issue orange alert and implement monitoring and control.

In order to further verify the effect of the visibility detection algorithm in this paper, the visibility detection of the known meteorological measuring instrument is about 105

meters, and the visibility value detected in this paper is compared with the meteorological measuring instrument. It can be seen from Table 2 that the average accuracy of the visibility detected by the algorithm in this paper is about 92.3%. The error may be caused by two aspects: (1) the quality of the image captured by the monitoring may cause the visibility estimation error of the model; (2) The deviation between the indirectly obtained lane line distance and the actual one will lead to the systematic error of visibility estimation. It meets the visibility monitoring technical indicators of Highway Visibility Detection and Early Warning and Forecast of Thick Fog. When the visibility is less than 2000 meters, the allowable error is $\pm 10\%$. It shows that the algorithm can detect the visibility of the road, and the estimation of the results is in line with the actual situation, which has certain feasibility and effectiveness.

Table 2. Visibility data recording.

	Figure 20	Figure 40	Figure 60	Figure 80	Figure 100
Meteorological monitor/m	105.0	105.0	105.0	105.0	105.0
ours/m	99.2	95.8	94.4	99.6	95.8
Guided filter/m	97.8	95.3	94.3	98.3	95.4
Our accuracy /%	94.5	91.2	89.9	94.8	91.2

4. Conclusions

This paper focuses on the visibility detection based on unmanned vehicles on foggy roads. The algorithm uses the dark channel prior theory to optimize the input image to obtain the atmospheric transmittance. The fast-guided-filtering and histogram equalization are used to accelerate the running speed and enhance the global contrast. The double fixed points are selected as the scene depth, so as to realize the detection of atmospheric visibility. The experimental results show that the average accuracy of the visibility detected by the algorithm is about 92.3%. Compared with the traditional visibility measuring instrument, the algorithm has the advantages of fast operation speed, low maintenance cost and strong applicability. Due to the limited road monitoring data obtained in this paper and the limited road lighting at night, the algorithm is not suitable for night visibility detection, so it is used as the next research work.

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