Research on Generalized Error Control Mechanism of Monocular Vision Ranging Method

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Abstract. Distance perception is the basis and necessary prerequisite of environment perception, attitude perception and obstacle avoidance of intelligent vehicle and unmanned vehicle. Monocular vision ranging method is one of the mainstream distance sensing methods at present. In order to improve the accuracy of monocular vision ranging, a monocular vision ranging method based on machine learning is proposed. The monocular vision ranging method studied in this paper has the advantages of high accuracy, simple training data, simple ranging formula and can be explained, but the uncontrollable generalization error is one of the disadvantages of this method. Therefore, in order to explore the relationship between generalization error and training error, according to the monocular vision ranging method based on the pinhole imaging principle and a large number of measured data, this paper uses the polynomial method in the curve fitting toolbox of MATLAB to fit the functional relationship between coordinates and image distance, so as to obtain the model parameters. Finally, the threshold value of the optimal model is 0.5%, 49 training data and 21 test data. The extreme value of the ratio of the generalization error to the threshold value of the training error is 1.68, which can be used to control the generalization error of the monocular vision ranging method.

1. Introduction

1.1. Background and Current Situation
Distance perception, environment perception and self attitude perception are the key technologies to realize driverless and intelligent driving, and distance perception is the basis of environment perception and self attitude perception. Traditional distance sensing adopts multi-sensor fusion sensor system, which has complex operation, high cost and large data processing requirements. So people put forward a vision based ranging method. Visual ranging is divided into monocular vision ranging and binocular vision ranging. Pasquale Ferrara compares the advantages and disadvantages of the two methods, and obtains the advantages of the accuracy of binocular vision ranging. However, binocular vision needs accurate registration, which requires time cost and poor real-time performance; In addition, binocular measurement has high requirements for camera resolution, imaging quality, optical axis distance between left and right cameras, camera focal length and other special constraints, and strict requirements for camera quality, installation and measurement platform standards [1]. Therefore, monocular vision ranging has become the main research direction of vision ranging. At present, there are four kinds of monocular vision ranging methods. Based on geometric relations, based on imaging model, based on machine learning, and based on unsupervised deep learning.
Boban P et al. Proposed a monocular ranging method based on area ratio, and calculated the target distance by calculating the pixel area change of the target. The advantages of this method are simple model and strong interpretability; The disadvantage is that the measurement accuracy is poor, the static average error is 2.38%, the maximum error is 8%, the dynamic average error is 12.41%, the maximum error is 30%, and there is no compensation and control method for the error [2]. Dongsheng Bao et al. Put forward a vehicle monocular ranging method based on the change of target width. The distance is measured by using the relationship between the change of vehicle width and the distance. The accuracy of the front ranging is 97%. The model is simpler than using area to measure distance, with fewer parameters. However, due to different vehicle widths, the average width is used to replace the width of all vehicles, and the maximum error of the final distance measurement is 3%. The author thinks that the error of the model meets the actual demand, so the error causes are not analyzed, and the corresponding error control mechanism is not proposed [3].

Wei Lu proposed a monocular ranging method based on the imaging model, which uses the world coordinate, camera coordinate, pixel coordinate transformation relationship and camera parameter matrix to ranging. After analyzing the causes of the errors, the inaccuracy of the camera pitch angle will greatly affect the accuracy, so the pitch angle correction scheme is proposed, and the average ranging accuracy is 95.43% verified by experiments. Although the error correction scheme is proposed, 4.57% is the average absolute error, not the maximum error, so the accuracy is not clear and the error is large [4]. Based on the imaging model, Sun young Hwang uses information to estimate the size and position of the vehicle in the virtual horizon image and calculates the distance through the target detection algorithm. There is no analysis and error compensation mechanism for the error formation of the model, and the accuracy of the model fluctuates greatly when the vehicle speed is different [5].

Ayoub khammari proposed a detection method combining machine learning and prior knowledge for forward vehicles. In addition, on the basis of vehicle detection, the shadow location method at the bottom of the vehicle is improved to obtain the accurate position of the vehicle, and the position information imaging model method is used to measure the distance of the vehicle, which can detect the vehicle position better. However, the model does not specifically analyze the deviation of the detected vehicle position, and the model is wrong due to the poor interpretability of the parameters of machine learning. The difference is uncontrollable and it is difficult to propose the error compensation mechanism [6]. Shen Zhixi proposed a distance measurement method based on regression model. Using different reference distances and their positions in the image to calculate the regression model to measure the distance, the maximum error is 9.78%. The model needs to detect the position of obstacles in the image first, so it needs to consume a certain amount of time, and it will produce errors and is difficult to control, so it is difficult to realize the further reduction of the algorithm [7].

Reza mahajourian uses unsupervised CNN depth learning to build point distance estimation model and camera attitude estimation model. The lowest accuracy of the model is 93.7%. Because the camera attitude is estimated, it is unnecessary to set the camera attitude as a fixed value, which enlarges the feasibility of the ranging method. However, unsupervised learning needs a lot of learning data, and the learning time is long, and the test accuracy is related to the training data. The final model parameters are difficult to explain, so the control of generalization error cannot be effectively realized [8]. Tinghui Zhou uses CNN to generate left and right binocular images from monocular images, and then estimates the depth or distance of the target through the parallax of binocular vision. The time to produce binocular view is 35ms, the lowest accuracy is 86.2%, the average accuracy is 96%, and the general error can be controlled within 3%. He advantage of this model solves the problem that traditional binocular vision is difficult to achieve synchronization. Binocular vision has a wider field of vision, but the disadvantage is that the production of binocular image by monocular image will produce time cost, the model based on deep learning is difficult to explain, and it is difficult to further
improve the accuracy, and the difference between the minimum accuracy and the average accuracy of the model is large, that is, the error fluctuation of the model is large and difficult to control [9].

To sum up, the error control of monocular vision ranging method is difficult to achieve, and there is an upper limit of generalization error. Therefore, in order to find out the cause of error and realize the control of generalization error, this paper first studies the relationship between generalization error and threshold, the size of training set, and obtains the minimum value of the ratio between generalization error and threshold. According to the minimum value, generalization error in ranging can be controlled.

1.2. Paper Outline
The specific chapters are as follows:
- Chapter one: introduction. This paper introduces the background and development of monocular vision ranging.
- Chapter two: using the model. This paper introduces the principle of the distance measurement method, and lists the calculation formula and model operation steps.
- Chapter three: the relationship between generalization error and training error threshold. Gradually carry out the operation of the experiment, and display the data in the middle of the experiment.
- Chapter four: analysis and discussion. The experimental data were analyzed and discussed.
- Chapter five: conclusion. Summarize the research results of this paper.

2. Materials and Methods

2.1. Ranging Model
In this paper, the ranging model based on pinhole imaging proposed by Zhao Haiping and others is used. In this model, the ranging formula is shown in Formula 1. Where \( H \) is the camera height, \( y \) is the pixel ordinate of the measured point, \( X \) is the pixel abscissa of the measured point, and \( V \) is the distance from the image plane to the optical center (i.e. image distance). The inverse formula of image distance \( V_0 \) is shown in formula 2, where \( D \) is the real distance. It is mentioned in the model that the image distance \( V \) will change with the position of the measured point, that is, there is a functional relationship between the image distance and the coordinates of the measured point, which can be expressed by formula 3. By using the fitting tool in MATLAB to fit the pixel coordinates and image distance, the formula of fitting image distance \( V \) is shown in formula 4, where \( p \) is the parameter matrix after fitting image distance \( V_0 \) and pixel coordinates \( x, y \). By adjusting the ordinate to compensate for the error caused by the up and down tilt angle of the camera [10].

\[
d = \sqrt{X^2 + Y^2} = H \sqrt{\frac{y^2}{y^2} + \frac{x^2}{v^2}} \tag{1}
\]

\[
v_0 = \frac{\frac{p^2y^2}{H^2} + \frac{p^4y^4}{H^4} - 4x^2y^2}{2} \tag{2}
\]

\[
v = v(x, y) \tag{3}
\]

\[
v_0 = p(x, y) \tag{4}
\]

2.2. Model Ranging Steps
1. Take out the pixel coordinates \( (x_0, y_0) \) of the measured ground point in the picture.
2. The image distance \( V_0 \) is calculated by the actual distance and pixel coordinates.
3. Fit the image distance \( V_0 \) in the training set with the pixel coordinates \( (x_0, y_0) \), and get the parameter matrix \( P \) in formula (4).
4. Using the parameter matrix \( P \) to calculate the fitting image distance \( V \) of the training set.
5. Using pixel coordinates \((x_0, y_0)\) and fitting image distance \(V\) to calculate the distance \(D\) of the training set and the calculation error with the real distance \(D\).

6. Adjust the training set's ordinate to reduce the error, fit the adjusted ordinate \(y\) with the original ordinate \(y_0\), and get the expression of \(y = a \cdot y_0 + b\).

7. Using fitting image distance \(V\), fitting ordinate \(y\) to calculate the distance of the test set, and calculate the generalization error.

3. The Relationship between Generalization Error and Training Error Threshold

3.1. Threshold Selection

In the research of ranging model, the smaller the generalization error is, the better the ranging model is, that is, the stronger the generalization ability of the model is, and the wider the application range is. However, in the current ranging model, the generalization error is more than or equal to 3%, so this paper hopes to reduce the generalization error of the ranging model to less than 3%, and because the generalization error is generally larger than the training error, the training error threshold in this paper is at least less than 3%. Because the distance measurement model used in this paper has good fitting effect when the training set is set reasonably, and the training error almost does not exist more than 2% data, so the initial training error threshold is set to 1% in this paper, and the generalization error is calculated preliminarily. Table 1 shows the maximum generalization error and the ratio of the maximum generalization error to the training error threshold when the threshold value is 1%. The total number of data refers to the total amount of data used for training and testing. The maximum generalization error is the maximum test error when the data amount is determined, and the ratio is the ratio between the maximum generalization error and the threshold value. Table 1 shows that with the increase of the total number of model data, the ratio of the maximum generalization error to the training threshold will show an extreme point \((70,0.86)\). If this extremum exists in every model, then finding this extremum can control the generalization error.

| Threshold value | total data number | maximum generalization error (%) | ratio |
|-----------------|-------------------|----------------------------------|-------|
| 1.00%           | 10                | 4.36                             | 4.36  |
|                 | 20                | 2.86                             | 2.86  |
|                 | 30                | 3.41                             | 3.41  |
|                 | 40                | 1.96                             | 1.96  |
|                 | 50                | 1.24                             | 1.24  |
|                 | 60                | 0.88                             | 0.88  |
|                 | 70                | 0.86                             | 0.86  |
|                 | 80                | 0.89                             | 0.89  |
|                 | 90                | 0.91                             | 0.91  |
|                 | 100               | 0.92                             | 0.92  |

Therefore, this paper puts forward a hypothesis: there are extreme points in the generalization error and training error thresholds of the models under different thresholds. In order to test this hypothesis, the thresholds are set to 1%, 0.5%, 0.25%, 0.1% respectively. The ratio of model generalization error to threshold under different thresholds is calculated, and the extremum is verified.

3.2. Experiment

3.2.1. Software and hardware configuration.
- Hardware equipment: a camera, a laptop, a handheld laser rangefinder.
- Software equipment: MATLAB 2016a
- Experimental site: outdoor road
- Camera height: 0.864m
- Image format: 1920 * 1080
3.2.2. Distribution and grouping. In this experiment, a section of road 2-8m away from the camera was evenly divided into 20 parts, each area was randomly distributed with 5 points, a total of 100 points. In this paper, we choose 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 data models to compare the results. The ratio of training set to test set of each model is always 7:3. And the training set is obtained by the method of average extraction from each region, while the test set is randomly extracted from the overall sample. In this way, it can not only ensure that the training set can cover the whole experimental area, but also ensure that the test set will not deviate from the training area, so as to improve the generalization ability of the training model. Fig. 1 shows the experimental site and some points of this experiment.

![Image of experimental scene](image1.png)

**Figure 1.** Experimental scene

- Data processing: since the origin of the picture coordinate system in MATLAB is the top left corner of the picture, it is necessary to convert the coordinate system to the origin of the picture center, and calculate the image distance according to formula (2).

- Grouping: take the model of 10 pieces of data as an example, the training set is 7 pieces of data. In order to ensure the generalization ability of the model, the training data should theoretically cover the whole sample area. In this experiment, the road was divided into 20 areas, as shown in Fig. 2 and Fig. 3. One piece of data is randomly selected from the area numbered 1-4 in Figure 2. Similarly, one piece of data (5 pieces in total) is randomly selected from the areas numbered 5-8, 9-12, 3-16 and 17-20 respectively, and one piece of data (2 pieces in total) is randomly selected from the areas numbered 1-10 and 11-20 in Figure 3 respectively, thus forming the training set of the model. Three pieces of data in the test set are randomly selected from all areas except the training set. The first group of grouped data is shown in Table 2. Using the same method, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 pieces of model initial data are selected.

![Table 2. Grouped data](image2.png)

**Figure 2.** Horizontal point drawing

![Table 3. Vertical point drawing](image3.png)

**Figure 3.** Vertical point drawing
Table 2. Group 1 data

| x0  | y0  | Actual distance D(m) | x    | y    | v0  |
|-----|-----|-----------------------|------|------|-----|
| train | 1141 | 796 | 2.947 | 17.3704 | 24.0376 | 80.1280 |
|    | 808  | 765 | 3.211 | -14.5873 | 21.1268 | 77.1493 |
|    | 651  | 667 | 4.629 | -29.6545 | 8.1690 | 54.1775 |
|    | 866  | 627 | 5.809 | -9.0211 | 7.6056 | 53.9991 |
|    | 1036 | 621 | 6.19  | 7.2937  | 18.9671 | 75.4469 |
|    | 1175 | 742 | 3.563 | 20.6334 | 11.5493 | 62.9170 |
|    | 840  | 663 | 4.785 | -11.5163 | 11.5493 | 62.9170 |
| test | 267  | 819 | 2.718 | -66.5067 | 26.1972 | 48.6682 |
|    | 728  | 658 | 4.885 | -22.2649 | 11.0798 | 58.5544 |
|    | 691  | 604 | 6.553 | -25.8157 | 6.0094 | 37.5622 |

3.2.3. Fitting image distance and initial error. The x, y, v0 vectors of each training set are fitted in MATLAB, and the calculation formula of fitting image distance V is obtained. Taking the model of 10 groups of data as an example, the fitting results are shown in Figure 4.

\[
f(x, y) = p_0 + p_1(x+y) + p_2(x^2+y^2) + p_3x^2y + p_4x^2 + p_5y^2 + p_6x^2y^2
\]

- \( p_0 = 20.24 \) (15.73, 24.74)
- \( p_1 = 0.1666 \) (-0.02979, 0.363)
- \( p_2 = 5.732 \) (4.827, 6.637)
- \( p_3 = -0.01595 \) (-0.02264, -0.000256)
- \( p_4 = 0.02655 \) (-0.04856, -0.004543)
- \( p_5 = -0.1904 \) (-0.2378, 0.143)
- \( p_6 = 9.76e-05 \) (2.16e-05, 0.0001741)
- \( p_7 = 0.0006915 \) (0.0001357, 0.001247)
- \( p_8 = 0.001055 \) (0.00016, 0.00195)
- \( p_9 = 0.002408 \) (0.00108, 0.003135)

Figure 4. Image distance fitting results

Use the above fitting results to calculate the fitting image distance V of the training set, and use the distance formula 1 to calculate the distance D and the relative error E (d) as shown in Table 3.

Table 3. Training error after image distance fitting

| x0  | y0  | Actual distance D(m) | v    | d    | E(d)(%) |
|-----|-----|-----------------------|------|------|---------|
| 733 | 896 | 2.176                 | 81.449 | 2.179 | 0.148   |
| 757 | 826 | 2.648                 | 79.588 | 2.636 | 0.445   |
| 923 | 759 | 3.282                 | 78.273 | 3.292 | 0.309   |
| 686 | 733 | 3.590                 | 70.934 | 3.607 | 0.468   |
| 1068| 671 | 4.675                 | 65.726 | 4.6737 | -0.028  |
| 786 | 654 | 5.047                 | 59.840 | 5.015 | -0.643  |
| 778 | 626 | 5.794                 | 51.328 | 5.801 | 0.123   |

3.2.4. Training error control. The Algorithm steps of training error control are as follows:

- After the first fitting between the actual distance and the pixel coordinate to get the image distance formula, adjust the pixel ordinate y0 for the data items whose error is greater than the threshold value. Generally, when the camera tilt up and down is not big, the pixel ordinate y0 can be adjusted in unit pixel each time.
- After all the errors are adjusted below the threshold value, the adjusted ordinate Y1 is used to fit the original coordinate linearly again, and the adjusted pixel ordinate and the formula about the coordinate are obtained, such as \( y = a \ast y0 + B \);
Calculate the ordinates of all points in the training set again with the formula of quadratic fitting, and get the new pixel coordinates Y1, so as to get the new fitting image distance, distance and distance error.

If all the distance errors in the training set are less than the threshold value, the process of reducing the difference is over. If there is still a data item with an error greater than the threshold value, go back to the first step and repeat the above operations until the distance error obtained after the coordinate change is less than the threshold value.

Table 4 shows the fitting results of the ordinate parameters of some models when the threshold value is 1%.

| Threshold value | Number of training data | a       | b       |
|-----------------|-------------------------|---------|---------|
| 0.10%           | 7                       | 1.0013  | -1.0150 |
|                 | 14                      | 0.9989  | 0.3137  |
|                 | 21                      | 1.0000  | 0.0000  |
|                 | 28                      | 1.0000  | -0.0178 |
|                 | 35                      | 1.0001  | -0.0402 |
|                 | 42                      | 1.0000  | 0.0000  |

3.3. Ratio of Generalization Error to Threshold under Different Thresholds

The generalization error of the model and the ratio of the maximum generalization error to the threshold value when the threshold value is 0.5% are shown in Table 5.

Table 5. Generalization ability when threshold is 0.5%

| Threshold value | total data number | maximum generalization error (%) | ratio |
|-----------------|-------------------|----------------------------------|-------|
| 0.50%           | 10                | 4.36                             | 8.72  |
|                 | 20                | 2.21                             | 4.42  |
|                 | 30                | 3.41                             | 6.82  |
|                 | 40                | 1.96                             | 3.92  |
|                 | 50                | 1.25                             | 2.5   |
|                 | 60                | 0.88                             | 1.76  |
|                 | 70                | 0.84                             | 1.68  |
|                 | 80                | 0.86                             | 5.42  |
|                 | 90                | 0.91                             | 2.46  |
|                 | 100               | 0.92                             | 1.84  |

The generalization error of the model and the ratio of the maximum generalization error to the threshold value when the threshold value is 0.25% are shown in Table 6.

Table 6. Generalization ability when threshold is 0.25%

| Threshold value | total data number | maximum generalization error (%) | ratio |
|-----------------|-------------------|----------------------------------|-------|
| 0.25%           | 10                | 4.62                             | 18.48 |
|                 | 20                | 2.77                             | 11.08 |
|                 | 30                | 3.41                             | 13.64 |
|                 | 40                | 1.81                             | 7.24  |
|                 | 50                | 1.24                             | 4.96  |
|                 | 60                | 1.13                             | 4.52  |
|                 | 70                | 0.95                             | 3.80  |
|                 | 80                | 1.15                             | 4.6   |
|                 | 90                | 1.23                             | 4.92  |
|                 | 100               | 1.40                             | 5.6   |

The generalization error of the model and the ratio of the maximum generalization error to the threshold value when the threshold value is 0.1% are shown in Table 7.
Table 7. Generalization ability when threshold is 0.1%

| Threshold value | total data number | maximum generalization error (%) | ratio |
|-----------------|-------------------|-----------------------------------|-------|
| 0.10% 10        |                   | 4.59                              | 45.9  |
| 0.20% 20        |                   | 2.52                              | 25.2  |
| 0.30% 30        |                   | 3.41                              | 34.1  |
| 0.40% 40        |                   | 2.01                              | 20.1  |
| 0.50% 50        |                   | 1.39                              | 13.9  |
| 0.60% 60        |                   | 1.27                              | 12.7  |
| 0.70% 70        |                   | 1.35                              | 13.5  |
| 0.80% 80        |                   | 1.29                              | 12.9  |
| 0.90% 90        |                   | 1.43                              | 14.3  |
| 1.00% 100       |                   | 1.61                              | 16.1  |

4. Results
The data drawing curve in Tables 1, 5, 6 and 7 is shown in Figure 5.
In Figure 5, when the threshold value is 1%, and the data amount is equal to 70 pieces, the maximum generalization error of the trained model reaches the minimum, and the maximum generalization error is 0.86%, which is 0.86 times of the threshold value, with an accuracy of 99.14%; When the threshold value is 0.5%, the maximum generalization error of the trained model reaches the minimum, and the maximum generalization error is 0.84%, which is 1.68 times of the threshold value, with an accuracy of 99.16%. When the threshold value is 0.25%, the maximum generalization error of the trained model reaches the minimum, and the maximum generalization error is 0.95%, which is 3.8 times of the threshold value, with an accuracy of 0.84% When the threshold value is 0.1%, the maximum generalization error of the trained model reaches the minimum, and the maximum generalization error is 1.27%, which is 12.7 times of the threshold value, and the accuracy is 98.73%.

Figure 5. Curve of the ratio of maximum generalization error to threshold value

5. Discussion
Based on the above data, the following conclusions can be drawn:
When the amount of data is less than or equal to 30, the ratio between the maximum generalization error of the model and its threshold value fluctuates. The reason may be that the amount of data is too small to guarantee the stability of the generalization ability of the model. However, when the amount of data is more than 30, the ratio between the maximum generalization error of the model and its threshold value shows a decreasing trend, and both reach the minimum value when the amount of data is a certain value, and then increase again. The reason may be that as the amount of data increases, the generalization ability of the model will decrease, but when the amount of data reaches the limit value, the training points in the model are too dense, and there will be overfitting phenomenon. Although the training error will decrease, the generalization error will increase instead. Therefore, the larger the number of training data, the stronger the generalization ability of the model is incorrect.

When the threshold value is 0.5%, the model generalization ability is the strongest, and the highest accuracy is 99.16%. Therefore, 0.5% is selected as the most suitable training error threshold of the generalized error control model.

When the threshold value is 0.5%, the ranging method in this paper can guarantee 95% accuracy through the model trained by 7 points. When the training data is 49 and the test set is 21, the highest accuracy is 99.16%.

As the amount of training data increases, the training error of the model decreases, but when the amount of data is more than 70, that is, the training set data is 49, the generalization error of the model is the smallest. After that, the amount of data is increased, the error is no longer reduced, and there is fluctuation.

6. Conclusions
In this paper, the ratio of the maximum generalization error to the threshold value of the model under different training error thresholds is calculated from the measured data of monocular vision ranging, and it is verified that there is an extreme value in the ratio of generalization error to training error. It is found that the training error of the ranging model selected in this paper can be controlled below 0.1% in static state, and if the training data is less than 21, the generalization ability of the model fluctuates. When the training set continues to increase, the generalization error gradually decreases until the extreme point is encountered, and then the generalization error increases. At the same time, the generalization error can be effectively controlled by carefully selecting training threshold and training set size. The experimental data shows that the model is optimal when the threshold is 0.5%, the training set is 49 data, and the test set is 21 data. At this time, the accuracy reaches 99.16%, that is, the maximum generalization error is 1.68 times of the threshold. By using the threshold and ratio, the generalization error of the model can be controlled within 0.84%, which is more accurate than other ranging methods, and makes up for the disadvantage that the generalization error of other ranging methods is not controllable, and realizes the generalization error controllable of monocular vision ranging method.

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