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THICKNESS MEASUREMENT OF IMMERSION METAL CARBON SLIDE BASED ON IMAGE SEGMENTATION

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The thickness of a metal-immersed carbon slide mounted on a train's flow shoe was measured by using machine vision and deep learning. A method for measuring the thickness of carbon slide plate based on improved U^2-Net is proposed. Aiming at the problem that the edge feature extraction is not obvious, a new feature extraction module is designed. Efficient Channel Attention (ECA) mechanism and pool residual structure are used to make the network more suitable for metal-immersed carbon slide image segmentation. The experimental results show that the improved U^2-Net network accuracy reaches 99,4 %, and the average absolute error is only 0,4 %. The thickness measurement accuracy of metallized carbon slide using improved U^2-Net network reaches 0,5 mm.

Keywords: rail, immersion metal carbon slide, image segmentation, U^2-Net

INTRODUCTION

The metal-impregnated carbon slide on the flow shoe is used to obtain electricity from the rigid power supply rail to meet the power demand of the urban rail train. In long-term operation, it is susceptible to high temperature and vibration, and when the carbon skateboard is worn to a certain limit, it will greatly affect the normal operation of the train, and even cause major traffic accidents, resulting in casualties and property losses.[1] Therefore, detecting the thickness of the carbon slide of the flow shoe in order to replace it in time can reduce the probability of the failure of the flow sensor, which has important significance in ensuring the stable operation of the train and the safety of life and property.

Metal impregnated carbon slide wear test bench

The wear test bench of metal-dipped carbon slide is shown in Figure 1, including the control cabinet of the test bench, the flow shoe, the simulated contact rail (turntable), the turntable speed controller, etc. The test bench uses the turntable to rotate to simulate the sliding of the contact rail relative to the metal-dipped carbon slide during the actual operation of the train. Metal-impregnated carbon skateboards have better material properties than skateboards made of other materials, as shown in Table 1.

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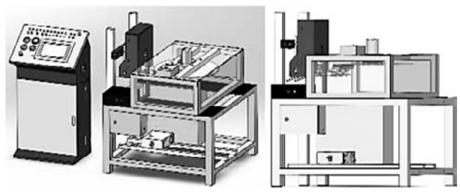

Figure 1 Carbon slide wear testing platform

Table 1 **Comparison of mechanical properties of skateboard materials**

Materials	Metallized carbon	Nodular cast iron	Stainless steel
Brinell hardness	733 HB	180-230 HB	150-187 HB
Shore hardness	90 HS	26~34 HS	23~29 HS
Tensile strength/(Mpa)	≥ 460	≥ 500	≥ 515
Yield strength/(Mpa)	≥ 350	≥ 320	≥ 310

Improved U^2-Net network

The U^2-Net network uses a two-level nested U-shaped network structure, mainly composed of Residual U-blocks (RSU) and the outer U-shaped structure connected to the RSU, which is used to extract multi-scale features.[2] Unlike traditional methods, the network design does not need to rely on the backbone network of image classification, and can be trained completely from scratch with excellent results. At the same time, the U^2-Net network structure is deeper to obtain high-resolution feature maps without increasing the computational cost. Therefore, the excellent performance of U^2-Net has also been applied in other fields in recent years.

In order to solve the problem that U^2-Net network has weak edge feature extraction effect on metal-impregnated carbon slide, the original U^2-Net network structure is optimized as follows. A new codec feature extraction module, RSU-S, is established. Deep separable convolution is introduced into the RSU-S module to reduce the number of network parameters, and ECA attention module is used to increase the global awareness of the network during the codec feature fusion stage.[3] In the coding stage of RSU-S module, multi-scale information is fused by pooling residual operation, which can improve the extraction of semantic features of carbon skate edge and reduce the overfitting of network model. The external structure of U^2-Net network is pruned, which can accelerate the inference time and reduce the computation and memory usage.

When U^2-Net network uses RSU module to extract image feature information, the parameters are too redundant, and the final segmentation accuracy is not greatly improved when the model size of the network is increased. To solve this problem, RSU-S module is designed. In order to reduce the parameter and calculation amount of RSU module in feature extraction, deep separable convolution is adopted in RSU-S module.[4] Depth-separable convolution consists of a channel-to-channel convolution and a point-to-point convolution, as shown in Figure 2. Where n is the length and width of the feature graph.

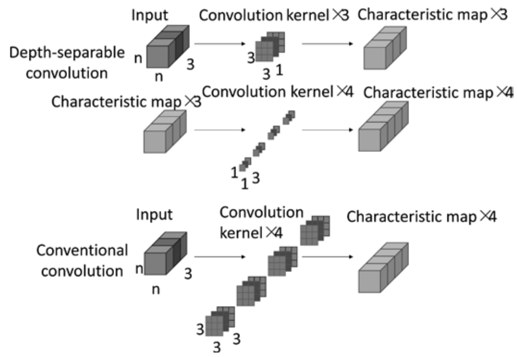

Figure 2 Depth-separable convolution and conventional convolution

In order to enhance the ability of the model to pay attention to different channel information, ECA attention mechanism is introduced into the residual connection of RSU-S module to improve the attention of the network to edge semantic information. By using the ECA attention mechanism, the model can adaptively adjust the weight of each channel to better capture task-relevant features. This attention mechanism can improve the expressiveness and generalization ability of the model, and also has advantages in terms of computational efficiency, because it only involves operations on the channel dimension, and does not need to compute operations on the spatial dimension. In order to solve the problem that the gradient in deep network is easy to disappear, pooled residuals and bilinear interpolation residuals are added to the coding stage and decoding stage of RSU-S module respectively. The problem of gradient disappearance in network training can be alleviated by adding the maximum pooling operation on the short-cut branch line. The bilinear interpolation residual operation can make the input feature map of the previous step directly skip the current layer to add to the output feature map, and only learn the residual part. This makes the network more focused on learning the edge information in the image, thus improving the training effect of the network. Compared with the original RSU module, RSU-S module has the advantages of small parameter number, preventing overfitting, and focusing more on edge features.

Compared with other networks, U^2-Net can deal with complex image semantic information better, but the structure of the network is too complex, and it needs a lot of computing resources and time to complete the training. To solve this problem, the network framework of U^2-Net was redesigned, structural pruning was carried out for the four deep codec stages, and ECA attention mechanism was introduced in the final feature fusion stage to compress the network model size and reduce the network training time without loss of accuracy, as shown in Figure 3.

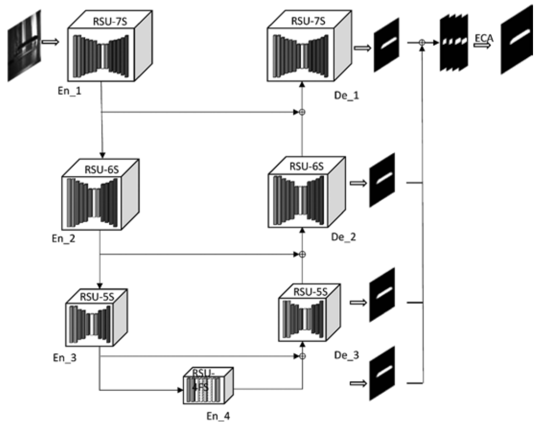

Figure 3 Improved U^2-Net network structure diagram

In order to solve the problem of gradient disappearance in deep network training and improve the convergence speed of convolutional neural networks, this algorithm adopts deep supervision method. This method monitors the backbone network by adding auxiliary classifiers to the hidden layer of the network. Therefore, for the image segmentation network, the calculation formula of the loss function is:

$$L = \sum_{m=1}^{M} W_{side}^{m} l_{side}^{m} + W_{fuse} l_{fuse}$$

Where: m is the m side branch in the network; l_{side}^{m} is the loss between the feature map output on the side of the network and the real label of the input image; l_{fuse} is the loss between the final prediction probability graph of the network and the real label of the input image; w_{side}^{m} and w_{fuse} represent the weight of each loss. Since significance target detection belongs to binary classification task, binary cross entropy is used to calculate the loss value for each item l in the formula.

Improved network validity verification

In order to more accurately evaluate the improved performance of U²-Net network, three kinds of networks were used to detect the collected images of metal-dipped carbon skateboards. The comparison results of various algorithms were shown in Table 2 under $MAF_β$, Accuracy, MAE and model size indexes.

Table 2 **Algorithm index comparison**

Model	$MAF_β$/%	MAE/%	Accuracy/%	Model size/MB
U-Net	96,6	0,9	97,2	51,1
U²-Net	98,4	0,6	98,8	167,83
Improve U²-Net	98,5	0,5	99,4	24,52

According to the data in Table 2, it can be observed that the model size of the improved U²-Net network on the metal-immersed carbon slide data set is reduced by 85,4 % compared to the original U²-Net network, thanks to pruning operations on the four deep codec modules in the network. When the model size is reduced, the improved U²-Net network can still maintain a higher $MAF_β$, and the Accuracy index is increased by 0,5 % and 2,27 % compared with U²-Net network and U-Net network, respectively. This shows that the improved network can effectively extract the semantic features of images by using RSU-S module with residual connection and attention mechanism in the codec stage. The results show that the improved idea of RSU-S module + ECA attention + structure pruning is correct in the task of metal-immersed carbon slide segmentation.

Immersion metal carbon slide thickness measurement experiment

According to the relevant data query, when the deviation of the thickness measurement of the metal-dipped carbon slide is within the range of 0.5 mm, it can fully meet the daily detection needs of the flow shoe. In this experiment, a vernier caliper was used to measure the same carbon slide for several times. The average value of the measured data was calculated, and the average value of the manual measurement was compared with the measured value based on image segmentation, thus verifying the accuracy of the thickness measurement method of metal-dipped carbon slide based on image segmentation, as shown in Table 3

In this paper, the manual measurement results are used as reference values, and several groups of manual measurement data are compared with the measured values obtained by the algorithm. By analyzing the numerical difference between the two measurement methods, the accuracy of the system error value of the algorithm is determined. According to the data in Table 3, it can be seen that in the given measured data, the maximum error between the value measured based on the improved U²-Net method and the average value measured manually is 0,46 mm, which meets the daily detection requirements of the receiving shoe.

Table 3 **Measurement data based on image segmentation**

Slide number	Manual measurement	Measurement of image segmentation	Error value
1	31,08	31,45	0,37
2	30,12	30,54	0,42
3	30,51	30,05	-0,46
4	28,03	27,65	-0,38
5	29,57	29,93	0,36
6	28,06	27,81	-0,25

CONCLUSION

In order to realize the non-contact measurement of the thickness of the carbon slide of the receiving shoe and solve the shortcomings of the traditional manual measurement method, an improved U²-Net network is designed to measure the thickness of the carbon slide of the receiving shoe. In the improved network, a feature extraction module integrating deep separable convolution, ECA attention module and pooled residual was established, which effectively improved the network's ability to extract the feature information of the carbon slide, and the structure pruning of the improved network was carried out to reduce the number of network parameters and facilitate the network deployment to the mobile end. The method of camera calibration, distortion correction and scale calibration in machine vision is used to provide data support for thickness measurement, and the actual thickness of carbon slide is calculated by correlation function in Opencv.

The experimental results show that: The $MAXF_β$, Accuracy and MAE of the improved U²-Net network reach 98,5 %, 99,4 % and 0,5 % respectively, and the detection accuracy of the machine vision carbon slide based on the improved U²-Net network reaches 0,5 mm, meeting the thickness measurement standard of the carbon slide of the train receiving shoe. It provides an effective non-contact measurement method for measuring the thickness of carbon slide of the receiving shoe.

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Note: The responsible translator for English language is J.H. Li - NCST.