Solar Cells Various Appearance Defects Automatic Simultaneous Detection System of the Greenhouses

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Abstract
Solar cells were used in greenhouses to generate enough heat to keep vegetables warm in the cold. This paper takes the solar cells various appearance defects simultaneous detection system as the research plant. The appearance defects can be divided into four categories: grid defects, front defects, back defects and grid defects, which will seriously affect the quality of solar cells. In order to detect all appearance defects at the same time, a detection system based on machine vision was designed in this paper. A prototype has been developed and 10,000 pieces of 156×156 cells have been tested. The test results show that the false alarm rate of defects is 3.68%, the detection missing rate is 0.12%, and the single cell detection time is 1.35S. The system can detect many kinds of defects of cells at the same time and it is accurate, effective, efficient and reliable.

Key Words: Greenhouses ;Solar cells; Appearance defects; Local entropy image processing; MLP classifier; Morphological open-close operation; Local adaptive threshold segmentation method

1. Introduction
With the increasingly serious problems of environmental pollution and resource scarcity, renewable new energy has become the main direction of development. New energy mainly refers to solar energy, wind energy, tidal energy, geothermal energy, hydrogen energy and other energy sources. Among them, solar energy has become the most ideal renewable energy because of its abundant resources, wide distribution and convenient access [1]. Solar cell is the main way of utilizing solar energy. It uses photovoltaic effect of PN junction to convert solar energy into electric energy and store it. It is the most convenient and effective way to use solar radiation energy [2].

Solar cell is the core component of solar battery. Its quality will directly determine the performance of solar battery. Because some defects inevitably occur in the production process of solar cells, such as notches, short corners, edge breaks, grid breaks, scratches, electrode defects, surface contamination, etc., which will affect the quality of solar cells. Therefore, how to use effective detection methods to identify and detect the appearance defects of solar cells, so as to ensure the product quality and improve production efficiency is extremely important [3,4]. Traditional manual inspection relies on quality inspectors to inspect the quality of cells piece by piece in strong light environment. This method is characterized by labor intensity, high cost, low efficiency, and it is easy to be affected by subjective factors of quality inspectors and will be difficult to adapt to the current industrial production rhythm. In recent years, the detection technology based on machine vision has developed rapidly. With the advantages of high efficiency, high intelligence and low cost, various kinds of automatic vision detection systems have become the mainstream of quality detection in industrial production [5]. This method can effectively avoid the influence of subjective factors of quality inspectors on product quality evaluation in traditional manual testing, provide objective quality inspection results for the production of solar cells, and feedback test data to production managers in real time, which provide a strong basis for improving the production process of solar cells and promote the development of photovoltaic industry.

Many experts and scholars at home and abroad have carried out relevant research on defect detection of solar cells in the production process.

VINSPEC solar series automatic optical detection system introduced by German VITRONIC Company combines the printing quality of front and back sides of solar cells with the function of color sorting to realize the appearance detection of solar cells. It consists of a 64-megapixel color linear array industrial camera, LED lighting source, backlight source and a computer system. Combined with the software system independently developed by VITRONIC, it can realize the detection of appearance defects such as cracks, corner breaks, grid breaks, slurry contamination and color deviation, and make statistical analysis of the quality characteristics of cells, with the detection speed of 2400 pieces per hour [6].

FRV-3600 series solar cell exterior extension introduced by Malaysia TTVISION Company uses 16 million pixels linear array color camera to take images and high-energy white LED linear light source to illuminate. It can detect surface defects of cells such as surface scratches, holes, dirt, edge defects, and can also sort the color appearance of solar cells.

Although the solar cell detection system developed abroad has excellent performance, it is difficult to introduce such products due to technical barriers and high cost.
In China, many scholars have carried out relevant research in recent years, and put forward many methods and algorithms for the appearance detection of solar cells based on machine vision. Among them, Feng Bo et al. of Jilin University have studied a method based on penetration algorithm and tensor voting algorithm to detect surface cracks of solar cells. This method first detects crack pixels according to penetration model, and then senses crack pixel information in reconstructed image by tensor voting algorithm. However, this method has a low efficiency and cannot detect the too short cracks. Li Bin et al. of Hefei University of Technology have studied a defect detection method for solar cells based on bio-vision model. This method uses bio-vision model to extract the surface crack features of photoluminescence images of solar cells, and uses support vector machine to classify and recognize the extracted features. However, the main disadvantage of this method is that its efficiency is not high and it is difficult to adapt to industrial production speed.

Therefore, the purpose of this project is to design an automatic detection system to recognize and detect the appearance defects of single crystal silicon solar cells efficiently, accurately and automatically.

2. Overall Scheme Design for Defect Detection of Solar Cells

2.1 Working Principle based on Machine Vision System

![Schematic Diagram for the Structure of Machine Vision Detection System](image)

The structure sketch of the appearance defect detection system based on machine vision is shown in Fig. 1. The object to be measured is placed in the field of view of the industrial camera, and the object surface image captured by the industrial camera is input to the computer for processing. Through a certain software algorithm, the three-dimensional shape of the object to be measured can be restored or the required measured data can be calculated, and the final result can be displayed on the computer display screen. In particular, if the natural illumination conditions around the detection system are not good, the light source can be laid near the measured object to improve the imaging effect of the camera. At the same time, different spatial positions of camera, light source and measured object will result in different imaging effects, so special consideration should be taken into account in the design.

2.2 Defect Types of Solar Cells

The causes of defects in the production and preparation of solar cells are complex, and there are various types of defects \(^{[7,8]}\). Therefore, it is necessary to study and summarize all types of defects and find out their respective characteristics, so as to design the corresponding defect detection algorithm.

In every process of solar cell production, some defects are likely to occur, among which screen printing, sintering and transmission of solar cells account for a large number of defects \(^{[9]}\).

In general, defects generated in the production and preparation of monocrystalline silicon solar cells can be divided into four types according to their different locations: edge defect, front defect, back defect and grid defect. Common defects of solar cells are shown in Fig. 2.
The common appearance defects of solar cells are edge breakage, edge collapse, surface contaminants, back electric field defect, back electrode defect, sub-grid breakage, sub-grid heavy dot, scratch and so on. These defects seriously affect the photoelectric conversion efficiency and appearance quality of solar cells \cite{10}. Therefore, in the research and design of detection algorithms, this paper mainly focuses on the above types of defects.

2.3 Design of Image Acquisition System

Image acquisition provides high-quality sampled images for image processing. Reasonable layout and sampling process of image acquisition system are the prerequisite to ensure the accuracy and reliability of the detection system \cite{11}.
(1) Layout of Image Acquisition System

The defects on the surface of solar cells will have different visual effects when viewed from different angles. For example, the broken grid defect on the grid line and the slurry leakage defect on the coating surface are more obvious when viewed from the front. In order to clearly and accurately reflect the characteristics of all kinds of defects of the cells, the detection system designed in this paper uses three cameras to shoot the front image, side image and back image of the cells for comprehensive processing.

At the same time, the position of the light source in the image acquisition system has a great influence on the image acquisition effect. Experiments show that low-angle illumination can effectively highlight the grid characteristics of cells in the front image acquisition, and the color features of the front defect can be better restored to facilitate defect classification; diffuse reflection illumination method can greatly reduce the reflective effect of the cell surface in the side image acquisition, ensuring that the gray level of side image changes evenly without white stripes due to local unevenness. Back image acquisition using high angle illumination can effectively restore the characteristics of the back electrode of the cells, and the back defects, especially the scratch defects on the back can be highlighted for convenience of image processing. Therefore, the layout of camera and light source in the detection system designed in this paper is shown in Fig. 3.

![Fig. 3 Schematic Diagram for the Layout of Camera and Light Source](image)

(2) Image Acquisition Process

In order to obtain a stable and reliable image acquisition effect, it is necessary to ensure the same lighting effect in each photograph. The flashing mode of system light source instead of continuous mode can effectively avoid the inconsistency of illumination effect caused by the intensity attenuation of the light source after power-on, and also greatly increase the service life of the light source. The system uses external trigger method to control the industrial camera to take photos, and the flash control output interface equipped on the industrial camera is used to control the flash of light source, in which the external trigger signal is provided by the motion control unit. The schematic diagram for the connection of the motion control unit, industrial camera and light source controller of the system is shown in Fig. 4.

![Fig. 4 Schematic diagram for the connection of camera control line](image)

The camera parameters need to be initialized before the system detection starts, including setting the...
photographic mode, flash delay, photographic delay, exposure time and so on. When the cell reaches the designated position, the motion control unit sends the image acquisition signal to the industrial camera, the camera controls the flash of the light source, and starts the frame sampling. In order to avoid the mutual interference between frontal image acquisition and side image acquisition, side camera adopts the method of delayed photographing (300ms). Since the front and back images of the same cell are not captured at the same time, the captured images should be stored in the image queue, and then processed sequentially to ensure that after each image processing, the detection results of the front and back images correspond to the same cells. The flow chart of image acquisition is shown in Fig. 5.

![Flow Chart for the Image Acquisition](image)

2.4 Software Design of Detection System

The design of software system is an important part of the development of the detection system. The intelligence, efficiency, reliability and human-computer interaction friendliness of the software system directly affect the comprehensive performance of the detection system [12, 13].

(1) Design of General Software Framework

The general block diagram of software system functions is shown in Fig. 6. The designed software for the appearance detection of solar cells is mainly composed of parameter setting module, image processing module and data processing module. The main flow of the system for appearance detection is that the user first sets relevant parameters and takes a certain amount of cells as samples for comparison and calculation in image processing. After detection, when each cell is transmitted to the designated position by the transmission mechanism, the system automatically triggers the corresponding camera to take photos through the hardware, and the software system processes, compares, analyses and judges the collected images to identify the color of the cell and find out the defects of the cell. Then, according to the set standards, the software system will implement calculation according to the grade and box number of cells, and sends the box number information to the motion control system through the serial port for sorting. Finally, the software saves the test results to the database to generate the test report.
Fig. 6 General block diagram of software system function

(1) Overview of Software Modules

a). Parameter setting module

The parameter setting module mainly realizes the system parameter setting, including hardware parameter setting, detection parameter setting and sorting parameter setting. The designed detection system uses multi-camera for image acquisition, so the exposure time of each camera and the flash delay time of the corresponding light source need to be set separately. Serial communication is used between the upper computer and the motion control system, and parameters such as serial number, baud rate, data bit and stop bit need to be set. The parameters and thresholds of defect detection in image processing can be set in the detection parameter setting to obtain the optimal defect detection effect. The cells of different batches, different specifications or different periods may have different requirements for cell detection. By setting the sorting parameters, the test items, the evaluation criteria of cell grade and the corresponding sorting box numbers of different efficiency grades and colors can be set.

b). Image processing module

Image processing module is the core component of visual inspection system. When the detection starts, the detection system first acquires the front image, back image and side image of the cells to be detected through the image acquisition system and stores them in the image queue for processing. In the course of processing of each cell image, the software system extracts the front, back and side images of the corresponding cell from the image queue for detection of front defect, back defect and grid defect. In the detection process, the software interface will display the working status of the detection system, the color information and defect information of each cell in real time, and output the image processing results of each cell in order to facilitate the subsequent battery grading calculation. After each cell is processed, the software automatically deletes the detected cell images to ensure the effectiveness of the image queue.

c). Data processing module

Data processing module is mainly used for database operation and further analysis and processing of image processing results to determine the cell grade. Cell grade determination is to classify the cells into five grades: A, B, C, D and NG according to the appearance classification grade standard. Defects affecting the appearance quality of cells are called surface defects. Surface defects can be classified into different types according to their characteristics and causes. Quality inspection departments can grade cell according to the types of defects and the severity of defects (quantity, area, length, etc.). Among them, A, B and C are the three common grades in appearance classification. After determining the grade of the cells, the sorting box number should be calculated according to the color and grade of the cell. The designed detection system has 48 sorting boxes, which correspond to different grades, colors and appearance.

The function modules of the software system are independent of each other to realize different functions, and at the same time, they complement each other to ensure the efficient operation of the system. One of the advantages of using modular software architecture is that users can copy the set detection parameters related to image processing to multiple detection systems for use, and set different grading standards according to actual needs to meet different sorting requirements.

3. Design and Analysis of Cell Defect Detection Algorithms

In view of the four main kinds of appearance defects which are edge defect, front defect, back defect and
grid defect in the process of solar cell preparation, different detection algorithms are designed to complete the corresponding defect detection because of the different defect characteristics. For the edge defect of cell, the least square fitting method combined with edge detection algorithm is used; for the front defect of cell, the geometric transformation method, image enhancement method, image filtering method, local adaptive threshold segmentation method and MLP classifier are combined for detection and classification. For the back defect of cell, morphological open-close operation method and image segmentation method are combined, and for the grid defect of the cell, Fourier transform extraction grid and local adaptive threshold segmentation method are combined.

3.1 Edge Defect Detection Method

The edge breakage defects of solar cells occur at the edge of the solar cells, which are mainly the short corners, notches and edge collapse defects occurred during the transmission or the workers’ handling of the solar cells on the production line [14]. The location characteristics of edge damage defect are obvious, and the location and type of defect can be determined by detecting the edge area of cells separately. The flow chart for edge defect detection algorithm designed in this paper is shown in Fig. 7.

![Flow chart of edge defect detection algorithm](image)

In the image acquisition part of the detection system, the background plate structure is designed and installed, which ensures that the background color of the image outside the cell area is uniform and single, and has a large contrast with the cell color. Therefore, the image binarization method with fixed threshold can be used to remove the background area directly. In this paper, the actual outline effect of the cell is extracted as shown in Fig. 8.

![Extracted actual outline effect of cell](image)

(1) Fitting Standard Outline and Defect Detection

The defective defect of solar cell is mainly the notches and short corner on the edge of the cells, which will lead to the incomplete shape of the cell appearance. Defective defects can be extracted by fitting the standard outline of the cell and comparing the fitting outline with the actual outline of the cell. The sketch of defect detection by the detection algorithm designed in this paper is shown in Fig. 9. The solid outline in Fig.9 is the actual outline of the cell, and the dotted line is the standard outline of cell restored by fitting.
The appearance of monocrystalline silicon solar cells studied in this paper consists of 4 straight lines and 4 rounded chamfers. After extracting the actual outline of the cell, four edges of the standard cell outline can be obtained by the straight line fitting method, and four chamfers of the standard cell outline can be obtained by circular fitting method. The least square method combined with Tukey weight function can accurately fit straight lines and circles. The test system designed in this paper can obtain ideal results by using this method to fit and restore the standard outline of cells. The fitting and restoration effect of cells with short corners and notches is shown in Fig. 10.

(a) Fitting and restoration effect of short corners (b) Fitting and restoration effect of notches

Fig. 10 Effect picture for the fitting and restoration of standard outline of cells

(2) Extraction of edge collapse defects by edge detection

Like the defective defects, the edge collapse defects occur on the edge of solar cells. The difference is that the edge collapse defects appear as the falling off of silicon from the cell surface, but the solar cells are not damaged, so the appearance of solar cells is complete. Only the edge area of the cell needs to be detected in the detection of the edge collapse defects. The designed detection algorithm takes the area whose edge width is 1 mm as the edge detection area of cells. The edge detection algorithm can be used to extract the edge collapse defect area because of the high color contrast between the edge collapse defect and the background area of the cell coating as well as the clear boundary.

The visual detection system designed in this paper uses Canny edge detection operator to detect the edge of the image in the cell edge detection area to extract the edge collapse defect and obtain a more rational defect extraction effect. The detection effect of edge collapse defect is shown in Fig. 11.

(a) Original drawings of edge collapse defects (b) Edge detection

Fig. 11 Diagram for the edge collapse defect detection effect
3.2 Detection and Classification Method of Front Defects

Front defects of solar cells are common types of defects in the production and preparation of solar cells, including dirt, oil, slurry pollution, slurry leakage, white spot, bright spot, watermarking, suede pollution and so on. The causes of different front defects are different, so it is necessary to classify the front defects correctly so as to facilitate statistical analysis and guide the improvement of production process. Because there are many types of defects contained in front defect of cells, it is a lot of work to find their own characteristics by analyzing them one by one. In this paper, a defect recognition and classification method based on multi-layer perceptual classifier is designed, which can easily and quickly obtain the ideal defect classification results. The flow chart of the detection algorithm for the front defect of the cell is shown in Fig. 12.

\[ H = -\sum_{i=1}^{M} \sum_{j=1}^{M} p_{y} \log_{2} p_{y} \]  

\[ p_{y} = \frac{f(i, j)}{\sum_{i=1}^{M} \sum_{j=1}^{M} f(i, j)} \]

(1) Defect Classification by MLP Classifier

Pattern classifier is a method to distinguish different types of objects according to the different feature information of the extracted detection objects. The pattern classifier quantitatively analyses the input image by computer, and classifies the input image or the designated area of the input image into one of several categories, which can replace the human eye for intelligent judgment \(^{[15, 16]}\). The steps of using the classifier are shown in Fig. 13.

(2) Local Entropy Image Processing

In order to clearly show the details of the image (such as the geometric shape of the object, the spatial distribution of the pixels, etc.), local entropy image processing is carried out when processing the image with front defects. For the image with size of M*N, considering the local neighborhood centered on (i, j), the local entropy value H is defined as \(^{[17]}\):

\[ H = -\sum_{i=1}^{M} \sum_{j=1}^{M} p_{y} \log_{2} p_{y} \]  

\[ p_{y} = \frac{f(i, j)}{\sum_{i=1}^{M} \sum_{j=1}^{M} f(i, j)} \]

Where, \( f(i, j) \) is the gray value of the pixel (i, j), and \( p_{j} \) represents the probability of gray distribution at the point (i, j). The size of H reflects the amount of information contained in the local area of the image, that is, the larger the value of H, the higher the degree of chaos of gray distribution in the region; the smaller the value of H, the higher the orderly degree of gray distribution in the region. Therefore, the local entropy H can represent the discreteness, noise intensity and signal intensity of the distribution of pixels of each gray level on the image, which also reflects the richness of the information contained in the image \(^{[17]}\). The advantage of image local entropy processing lies in:

①The size of local entropy depends on the gray value of all the pixels in the local image window and it is not sensitive to a single noise point, so the local entropy processing has a certain filtering ability.

②Local entropy represents the total gray discreteness of the corresponding window image, and it is difficult to represent the specific distribution of a single pixel. Therefore, if the target object occurs local geometric deformation, the statistical characteristics of its gray level remain unchanged, and the corresponding
local entropy value will not change. Therefore, the local entropy processing has excellent anti-geometric distortion performance, and the larger the selected window, the better the anti-geometric distortion effect.

③ If there is a target object in the image and the target object is smaller than the selected image window, the texture features of the corresponding region in the image will change, and the local entropy value will also change. In the image window, the gray level change caused by the target object may lead to a great change in the local entropy value, which is helpful to the detection of the object. In this design, the effect of local entropy processing for dirt defect of cells is shown in Fig. 14.

![Original image of dirt defect and image after local entropy processing](image)

**Fig. 14** Original image of dirt defect and image after local entropy processing

(3) Extraction of front defects by local adaptive threshold segmentation method

The local adaptive threshold segmentation method is to determine the local gray threshold according to the gray value distribution of the neighboring pixels [18]. Local adaptive threshold segmentation method is used in image processing to obtain distinct feature extraction effect.

Therefore, for the pre-processed front and side images, this paper uses the local adaptive threshold segmentation method to segment the image, which achieves a better effect of front defect extraction, as shown in Fig. 15.

![Original image of oil dirt defect and extraction effect of oil dirt defect area](image)

(a-1) Original image of oil dirt defect  (a-2) Extraction effect of oil dirt defect area

**Fig. 15** Original image of oil dirt defect and extraction effect of oil dirt defect area
3.3 Back Defect Detection Method

Back defects are easy to occur in the screen-printed electrode and coating film during transportation. Back defects mainly occur on the back electrodes or back coating film of cells, and they are divided into back electrode defects and back electric field defects. In this paper, morphological open-close operation \cite{19, 20} algorithm is used to detect back defects, and the flow chart of its detection algorithm is shown in Fig. 16.

When detecting the defect of back electric field, the color of defect area on the acquired back image is different from that of back coating film, so when detecting the defect of back electric field, it is necessary to eliminate the influence of back electrode on the defect area extraction of back electric field, and then detect the defect of back electric field in all areas of the back image of cells.

In this paper, the detection steps of back electric field defects are as follows: 1. image preprocessing; 2. extracting back electrodes; 3. removing back electrodes; 4. image segmentation to extract back electric field defects. The extraction effect of back electric field defects is shown in Fig. 17.
3.4 Grid Defect Detection Method

Grid is the current transmission channel on the solar cell, which occupies a large part of the space on the front image of the cell. The common defects on the grids are broken grids, scratches and rough points on the grids. When detecting grid defects, it is necessary to accurately extract grid of cells for analysis. In this paper, Fourier transform method is used to detect grid defects, and the flow chart of the detection algorithm is shown in Fig. 18.

On solar cells, grid can be seen as periodically arranged textures. If the points corresponding to the low-frequency region and the points near the horizontal center line are filtered out from the Fourier transform frequency domain image of the cell, the grid image of the cells can be extracted after the inverse Fourier transform. The effect of the method designed in this paper on the extraction of grid defects is shown in Fig. 19. As can be seen from the Fig.19, only the grid image is retained in the inverse Fourier transform image, and the background image of the coating film of cells is removed. Using this method to extract grid of cells can effectively eliminate the influence of non-grid area image on grid detection, while retaining useful information on grid in a better way, and also can ensure the accuracy of grid defect detection.
(1) Extraction of grid defects

Different defect extraction methods should be adopted according to the different characteristics of broken grids, scratches and rough points of grids.

a) Extraction of broken grid

The broken grids on the grid will cause the broken circuit of cells, which is a serious defect of cells. The following steps can be taken to detect grid breakage defects: (1) Closed operation of morphological gray level in the direction of grid line is performed on the extracted grid images of cells; (2) Difference operation between the output image obtained from (1) and the grid image is performed; (3) The broken grid area is extracted by using local adaptive threshold segmentation method. The image processing procedures of step 1 and 2 are also called the bottom-hat operation of gray level. In this paper, the system is designed to extract grid breakage defects as shown in Fig. 20.

b) Extraction of scratches

It is easy to scratch the solar cells in the transmission process on the production line, leaving long strip marks on the grid and blue coating film of the solar cells, thus affecting the appearance quality of the solar cells. When detecting the scratch defect, it is necessary to conduct comprehensive processing of the grid and coating background.

For scratch defect detection, the following steps can be taken: 1) extract the scratch area on the coating background by local adaptive threshold segmentation method; 2) extract scratch area on the grid by local adaptive threshold segmentation; 4) connect the scratch area on the coating background and grid to obtain a complete scratch defect area. The system designed in this paper can detect scratch defects as shown in Fig. 21.
(a) Scratch defect  (b) Local adaptive threshold segmentation of coating background

(c) Local adaptive threshold segmentation of grid  (d) Connection of points in the scratch area

Fig. 21 Diagram for the extraction effect of scratch defect

c) Extraction of coarse dots on the grid

The main reason for the coarse dot defect of grid is the abnormal local width of the grid caused by the excessive pulping of the equipment when printing the grid line, which is shown by the brighter white dots on the grid than the grid line. The detection of this kind of defect can be based on the difference between the grid line and the cells.

The following steps can be taken to detect the coarse dot defect of grid line: (1) Fourier transform is used to remove the grid line; (2) local adaptive threshold segmentation treatment is applied to the image after removing the grid line, so as to extract the area with high brightness of the grid line position as the coarse dot defect area of grid line. In this paper, the principle and method of extracting grid line by Fourier transform are introduced. On the contrary, if the points near the vertical center line are filtered out from the Fourier transform frequency domain image of cells, the image after removing grid effect can be obtained by inverse Fourier transform. The detection effect of the system designed in this paper for coarse dots of grid is shown in Fig. 22.
4. Statistics and Analysis of Experimental Result

According to the above design method, a prototype of the solar cell appearance defect detection system is developed in this paper, and the field diagram is shown in Fig. 23.

Implementation of experiment: In this paper, the surface appearance defects of 10000 pieces of monocrystalline silicon solar cells with specifications of 156×156 are detected by the prototype, and the results of defect detection of the prototype are compared by the method of manual re-inspection. The data such as the number of mistakenly reported defects, omitted defects and misreport defects as well as the detection missing rate, etc are counted.

The misreport and detection missing situation of defects is shown in table 1

<table>
<thead>
<tr>
<th>Item</th>
<th>Misreport</th>
<th>Detection missing</th>
<th>Misreport rate (%)</th>
<th>Detection missing rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge defect</td>
<td>76</td>
<td>4</td>
<td>0.76</td>
<td>0.04</td>
</tr>
<tr>
<td>Front defect</td>
<td>232</td>
<td>6</td>
<td>2.32</td>
<td>0.06</td>
</tr>
<tr>
<td>Back defect</td>
<td>32</td>
<td>2</td>
<td>0.32</td>
<td>0.02</td>
</tr>
<tr>
<td>Grid defect</td>
<td>28</td>
<td>0</td>
<td>0.28</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>368</td>
<td>12</td>
<td>3.68</td>
<td>0.12</td>
</tr>
</tbody>
</table>

As can be seen from Table 1, the misreport rate of defects is 3.68%, and the detection missing rate is 0.12%. It can be seen that the designed defect detection algorithm can achieve very low defect detection missing rate and low defect misreport rate, and the defect detection algorithm is accurate and effective.

At the same time, the detection efficiency of the designed system is tested with a prototype in this paper. Implementation of experiment: According to the testing process, 10000 cells shall be firstly taken from the previous process of the appearance quality testing of the cells, and 300 pieces shall be put into the feeding box of the testing system according to the capacity of the feeding box of the system; then the solar cells are automatically transferred to the imaging position of the testing system through the conveyor belt, triggering the camera to take pictures and immediately transfer the cells to the next position, and waiting for sorting instructions; at the same time, the detection software automatically detects the acquired image, and then sends the test results to the sorting motion controller, sorting the cells to the designated feeding box to complete the sorting. The statistical results of detection efficiency are shown in Table 2.
From Table 2, it can be calculated that the detection duration of a single cell is about 1.35S, and the production rhythm of the solar cell on the production line is 1.6s per piece. It can be seen that the visual inspection system designed has high detection efficiency and can meet the efficiency requirements of cell production.

5. Conclusions

In this paper, an integrated automatic detection system for the appearance defects of solar cells is designed, and the innovation of this system lies in:

(1) The surface defects of solar cells are divided into four categories: edge defects, front defects, back defects and grid defects. Different detection algorithms are designed for different types of defects. Therefore, the detection system designed in this paper can detect all the common appearance defects of solar cells in an all-round way.

(2) In the design of image acquisition system, we innovatively use multiple cameras to take pictures and obtain the imaging effect of the cells at different angles, which can clearly and accurately reflect the color and shape characteristics of various major defects for subsequent image processing. We design a lighting system composed of multiple light sources to obtain the imaging effect of the cells under different lighting conditions, which can effectively highlight the imperceptible defect and improve the detection rate of the detection system. Controlling the light source by external trigger can improve the stability of the imaging effect and prolong the service life of the light source.

(3) In the software design of the designed visual inspection system, developing the system software according to the modular design idea is conducive to further improvement according to production demand; designing data processing module is conducive to providing intuitive product quality information for production managers to guide process improvement and reduce or eliminate defects; adopting multi-threading technology to realize synchronous implementation of color recognition, front defect detection, grid line detection and back defect detection can effectively utilize computer system resources and improve detection efficiency.

(4) In the design of edge defect detection algorithm, the least squares fit method is used to cooperate with Tukey weight function to detect edge defect, and Canny edge detection algorithm is used to detect edge collapse defect. They cannot interfere with each other, so the accuracy of edge defect detection is high.

(5) In the design of front defect detection algorithm, geometric transformation, image enhancement and image filtering are used to pre-process the image. Meanwhile, the concept of local entropy is innovatively introduced to process the image. The obtained defect image has abundant information and good anti-jamming performance. Meanwhile, MLP classifier is innovatively used to effectively classify the front defects, so the detection accuracy of front defect is high.

(6) When designing the back defect detection algorithm, morphological open-close operation combined with image segmentation algorithm is adopted, so the accuracy of back defect detection is high.

(7) In the design of grid defect detection algorithm, Fourier transform combined with local adaptive threshold segmentation algorithm is used, so the accuracy of grid defect detection is high.

The experimental results show that the system can automatically detect many common appearance defects of solar cells at the same time, and the system is accurate and reliable, with high detection accuracy and efficiency. Therefore, the detection system designed in this paper can meet the requirements of cell production practice, and has a certain guiding role for the research in related fields.
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