Overview of Automatic Focusing Technology of Imaging System

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Abstract: Modern optical system needs to achieve high-resolution imaging through precise focusing, and auto focusing, as a product of modern technology, has become a trend of optical system design. The main approach of auto focusing is to drive the focusing mechanism through the focusing information generated by the relevant methods or algorithms of optical principles and computer science, and adjust the position of the focusing lens group or detector in an automatic way to meet the Gauss imaging formula, so as to make the system ideal imaging. Starting from the imaging principle of optical system, this paper discusses the characteristics of optical system focusing, the reason of defocusing and the structure of auto focusing. Then this paper summarizes the main methods of autofocus, and divides them into four categories according to their characteristics, which are defocusing modeling, focusing based on image detection, focusing based on image processing and Focusing based on artificial intelligence. Through the elaboration and analysis of four kinds of methods, the current trend of autofocus is understood and the future development trend is forecasted.

1. Introduction

In the optical system, in order to obtain a clear image, focusing has become one of the most critical links of the imaging system. According to the difference of focusing mode, it can be divided into manual focusing and automatic focusing [1]. Compared with manual focusing, automatic focusing has advantages including high efficiency, accuracy independent of the professional level of focusing personnel, and it is not affected by the failure of off-axis system. Therefore, the automatic focusing technology has achieved greater development than manual focusing, and a large number of automatic focusing methods have been proposed. Automatic focusing refers to the use of target, environmental and image information to calculate the defocusing amount of the imaging system automatically according to the optical principle and optical structure design, and send the information to the focusing system to compensate for the defocusing. In this way, the target can be clearly imaged on the target surface of the image detector [2]. The automatic focusing combines various technologies such as optics, electronics, computer science, and image processing. It has a variety of application scenarios, and it brings great convenience in various optical instruments such as microscopes, cameras, photoelectric telescopes, scanners, etc. At the same time, it takes into account the characteristics of high precision, strong stability and real-time [3].

This article introduces a series of related knowledge such as the focusing principle of the optical system, summarizes the implementation principles, advantages and disadvantages of various focusing methods, and finally points out the future development direction of the automatic focusing technology.

2. Focusing Principle

2.1. Principle of Optical Imaging

In the optical system, the basic principle of optical imaging [4-6] is shown in Figure 1.

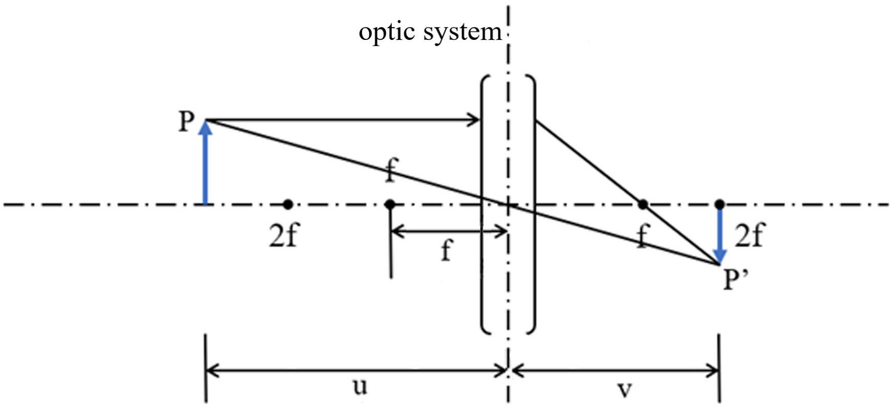


Figure 1: Principle of optical imaging.

According to the principle of geometric optics, when the image point P' is obtained after the object point P is imaged by the lens, there is the following relationship:

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f} \tag{1}$$

Where u is the object distance, v is the image distance and f is focal length. This formula is the Gaussian imaging formula [7]. Ideally, the image obtained by the optical system satisfying this formula is the positive focus image. When the object distance, image distance or focal length changes, the relationship between object and image is no longer satisfied, namely, the image defocus. Focusing is to adjust the defocus image to the focus image. Regardless of the complexity of the optical system, the Gaussian imaging formula can be used for equivalent analysis.

2.2. Depth of Field

In practical applications, optical system focusing is not always ideal. The image point is projected on the target surface before and after the focal point to form a circle called circle of confusion. Due to the limitation of human eye resolution, as long as the diameter of the circle is small enough to be regarded as a point, the image can be considered clear [8]. There are two such circles of confusion before and after the focal point, the distance between them is called focal depth, and the corresponding distance range at the shooting point is called the depth of field [9] (Figure 2). It is generally believed that the imaging within the depth of field is clear. We can calculate the depth of field and the depth of field in front and behind according to Formula 2.

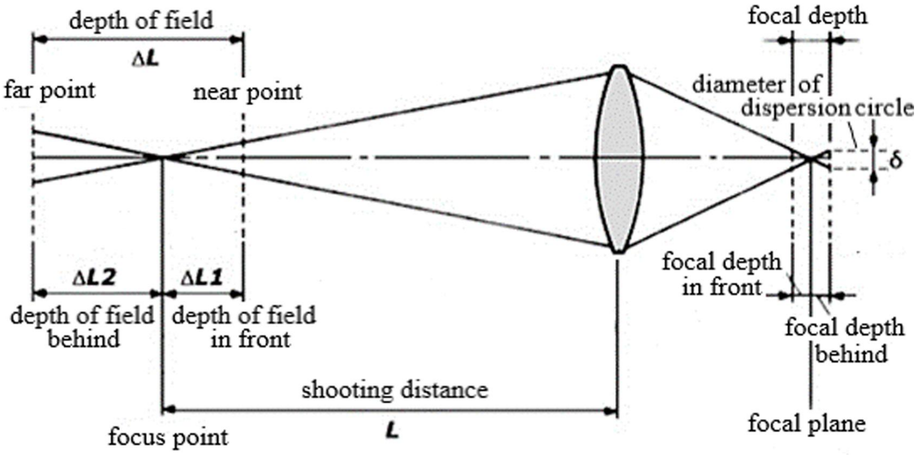


Figure 2: Schematic diagram of the depth of field of the camera lens.

$$\begin{cases} \Delta L = \dfrac{2f^2F\delta L^2}{f^4 - F^2\delta^2 L^2} \\ \Delta L1 = \dfrac{F\delta L^2}{f^2 + F\delta L} \\ \Delta L2 = \dfrac{F\delta L^2}{f^2 - F\delta L} \end{cases} \tag{2}$$

Where δ is diameter of permissible circle of confusion, f is focal length, F is lens aperture value, L is shooting distance, ΔL is depth of field, ΔL1 is depth of field in front and ΔL2 is depth of field behind.

Affected by the depth of field, in engineering applications, there must be some error by using the Gaussian formula to calibrate the positive focus position. And the calibration error will also affect the positive focus position of the auto focus. However, depth of field is also good for autofocus, which reduces the difficulty of autofocus.

2.3. Defocus Reasons

When the camera shoots the target, if the target is not within the depth of field, the image is considered defocus. There are many factors that cause the image to defocus, including the complexity of the optical path of the optical system, the complexity of the shooting environment and the instability of the target motion [10]. Generally, there are two main reasons why the image defocus.

(1) Target movement

It is generally believed that the change of the object distance is one of the important factors for defocusing of the optical system. When it needs to image the target, the movement of the target changes the object distance. If the image distance cannot be changed synchronously, defocus occurs. To get positive focus image, a good-performance focusing system is needed at this time, which can react to the change of the target's object distance in real time. According to the depth of field and the focusing formula (Formula 3 below), for a fast moving target at close range, the focusing amount is relatively large, and the focusing system needs to have excellent performance.

(2) Environmental factors

In the design of optical systems, it is desirable to perform athermalization treatment. Because optical materials and mechanical structures will be deformed by factors such as temperature, gravity and ambient air pressure and humidity, the refractive index and thermal expansion coefficient will change accordingly, which will change the focal length or equivalent focal length of the system. The change of the focal length is an important reason for defocusing of the optical system. According to the Gaussian formula, the focal length changes when the object distance is fixed. If the image distance cannot be changed synchronously, the system will defocus. Normally, given a certain environmental condition, the amount of change in the focal length of the system is controllable. The difficulty of automatic focusing is whether the system can recognize the focal length in real time.

2.4. Focusing Mechanism

The focusing mechanism is an important part of the optical system and an important approach to achieve automatic focusing. Characteristics of the focusing mechanism are different because of different optical systems and designs. During automatic focusing, the focusing of the optical system can be adjusted by the motor moving the focusing mechanism. However, subject to the principles of optical imaging, focusing mechanisms can be divided into the following three categories [11, 12].

2.4.1. Adjust the Lens Group (Adjust Focus)

Adjusting focus is suitable for optical systems with small apertures. The adjustment object is the whole group or part of the lens of the optical system， including the whole lens group movement or internal lens group movement [13]. It is represented in the Gaussian formula as the focal length of the optical system changes. Its working mechanism is to keep the image distance unchanged when the object distance changes and move the lens forward or backward by a certain distance so that the image point falls correctly on the focal plane. During the focusing process, since the equivalent focal length of the optical system has changed, the optical field of view will also change synchronously.

2.4.2. Adjust the Focal Plane Mirror

Adjusting mirror is often used in reflective optical systems. The position of the focal plane can be changed by adjusting the position of the mirror, and then the optical system can realize focusing. The principle diagram is shown in Figure 3.

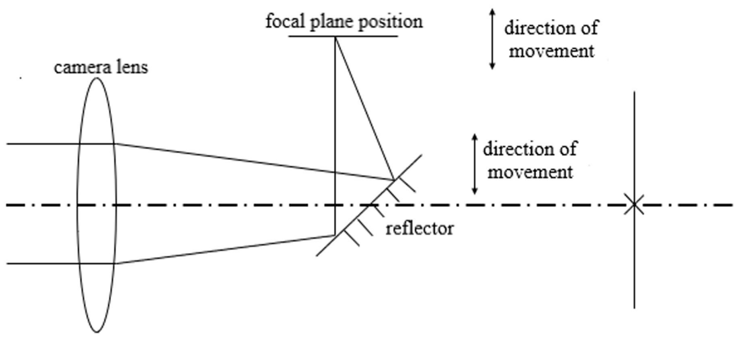


Figure 3: Schematic diagram of focusing of focal plane mirror.

The addition of reflectors in the optical system has two main functions [14, 15]. One is to change the focal plane position. The reflector is usually added to the position of the back of the lens, which affects only the light reaching the focal plane outside the optical system. By adjusting the moving position of the mirror, the position of the focal plane is moved. The other one is to change the optical path. This design shortens the length of the camera, making the optical structure more compact. Therefore, this method is often used for long focal length cameras with long back-intercept lens and high focusing accuracy requirements [13].

2.4.3. Adjust the Image Plane (Adjust Image Distance)

Adjusting the image plane is to move the detection surface of the film or CCD back and forth so that the image is always kept on the detection surface of the film or CCD. As the imaging medium moves, the image distance changes accordingly, so this method is called image distance adjusting. Its working mechanism is that the image distance changes, and the target image is clear by adjusting the position of the image plane (image distance). This method has nothing to do with the structure of the optical system and has a relatively wide range of applications.

No matter which focusing mechanism is used to focus, it is adjusted based on Gaussian formula. But in reality, a variety of focusing mechanisms may be designed in the optical system, and the difficulty of automatic focusing will increase greatly. At the same time, when the optical system is off-axis, focusing will produce a three-dimensional displacement theoretically, and the difficulty of automatic focusing will also increase greatly.

3. Auto Focusing Technology

From the basic principle, auto focusing can be divided into two categories. One is based on the distance measurement method based on distance measurement between lens and object, and the other is based on the focus detection method of the target imaging on the focusing screen [16, 17]. According to the characteristics of auto focusing technology, this paper divides it into four categories, including modeling due to defocus, focusing based on image detection, focusing based on image processing and focusing based on artificial intelligence. The specific classification is shown in Figure 4.

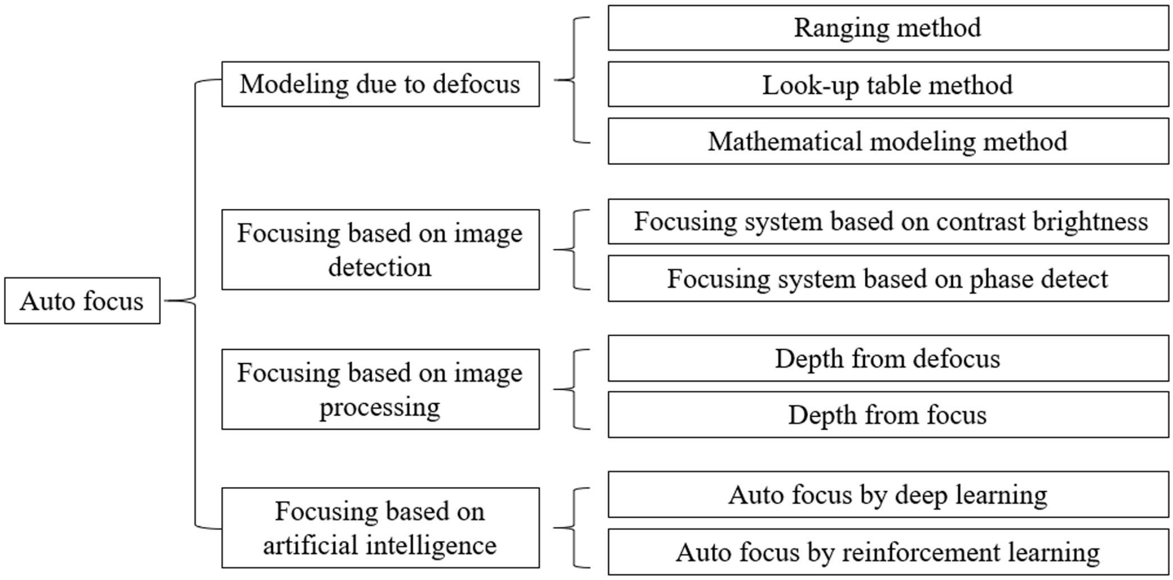


Figure 4: Classification of autofocus methods.

3.1. Modeling Due to Defocus

This kind of method mainly measures the actual situation of factors affecting the focusing process by using sensors and other equipment, so as to analyze and calculate the system model, and establish the corresponding relationship between the factors affecting the focusing and the actual focusing amount [18]. Then the measured data is substituted into the relationship to get the focus information needed by the system. By compensating the influence caused by these factors, the focus is completed. The method can be divided into ranging method, look-up table method and mathematical modeling method. These methods have their own application value.

3.1.1. Ranging Method

Ranging method refers that target imaging can be adjusted clearly by using the distance measured between the target and the optical equipment and combining with the mechanism of optical equipment based on optical Newton formula (Formula 3) [19].

$$\Delta = f'^2 / x \tag{3}$$

Where Δ is focusing amount, x is object distance and f' is focal length. Among them, the object distance can be obtained in many ways, such as external measurement method, radar, autonomous mode measurement method, etc [20-24]. It can also be obtained through more complex optical design, such as double image reproduction method [25, 26] and triangle ranging method [27].

Ranging method can respond to the change of target in real time, and the speed is relatively fast. At the same time, combined with the characteristics of the depth of field, it is also possible to achieve full-focus processing of the target at a small calculation cost. However, the premise of this method is that the focal length of optical system should be kept unchanged, otherwise the amount of focusing calculated by Formula 3 will not be accurate.

3.1.2. Look-up Table Method

Look-up table method [28] is the earliest auto focusing method, which has a very effective application in temperature compensation focusing. Since the Formula 3 can only represent the change of the distance focusing mechanism on the axis, but the system needs to make three-dimensional adjustment, the formula will fail. When the focusing mechanism is off-axis, it is very difficult to establish the focusing formula under off-axis. So technicians can collect the defocusing information, calibrate the relationship between defocusing information and focusing amount in the laboratory, and then make a calibration table. When the defocusing information is obtained again, the corresponding focusing amount information in the table can be queried automatically by the computer. And the focusing amount can be sent to the focusing system to drive the motor to rotate, so as to realize open-loop focusing. Relatively speaking, the look-up table method is easy to operate and performs well in the face of complex focusing system. But because the look-up table method is open-loop method, there will be some deviation when the optical mechanism changes.

3.1.3. Mathematical Modeling

The mathematical modeling method is also the traditional focus compensation method. By establishing the functional relationship between object distance, focal length and focusing amount [29], and sending the focusing information obtained from this relationship to the servo system, driving the step motor to move the focusing lens, auto focusing can be achieved. The difficulty of this method is that there are many errors involved in the factors that affect the focusing amount [30-32]. It is necessary to find all error sources and analyze their influence mechanism on the system, establish the functional relationship between parameters and the focusing amount, and obtain a focusing model with high focusing accuracy and complete system finally. In addition, even if the model is perfect enough, it should be calibrated before use. What's more, the model cannot be updated in time in the process of use. When the device is aging and updating, the model may have errors that cannot be ignored.

3.2. Focusing Based on Image Detection

Although the open-loop method is simple and stable, it cannot improve the accuracy through system feedback. As a closed-loop method, the auto focusing method based on image detection can reduce the deviation through system feedback, has a relatively high precision, and is not sensitive to external disturbance and the changes of system parameters [34]. It is mainly divided into contrast detection method and phase difference detection method, both of which are for point target or analog image generated by parallel light [35].

3.2.1. Focusing System Based on Contrast Detection

This method can automatically focus by detecting the sharpness of the contour edge of the image. The clearer the image, the greater the contrast of the image. Namely, the clearer the contour edge of the image, the greater the contrast between the scene and the background at the edge. Otherwise, the farther away from the focus, the more blurred the image, the more blurred the contour edge, and the lower the brightness gradient or contrast.

The schematic diagram of this method is shown in Figure 5. Two photodetectors are placed at the same distance (the distance is ***l***) before and after the film position. The image of the subject is divided into two detectors (S1 and S2) at the same time, and the contrast of the images is output respectively. When the output contrast of the two detectors is equal, it means that the focusing image plane is just in the middle of the two detectors, that is, it coincides with the position of the negative film. If the contrast is different, the corresponding defocusing amount is calculated by the contrast difference value, and the lens is adjusted to complete focusing. However, this method is easy to be restricted by the light conditions. When the light is dark or the contrast between the target and the background is not obvious, this method has no effect.

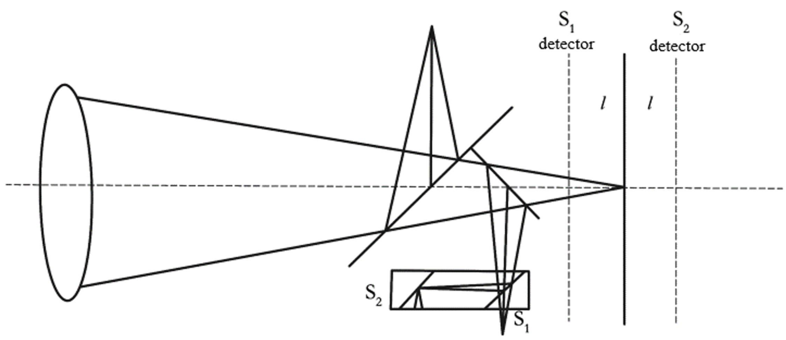
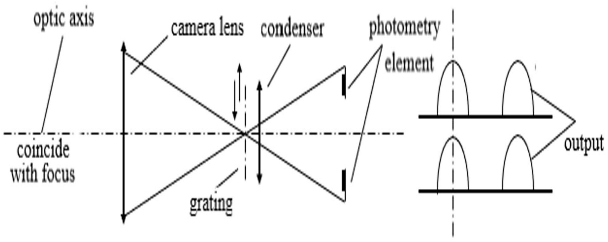


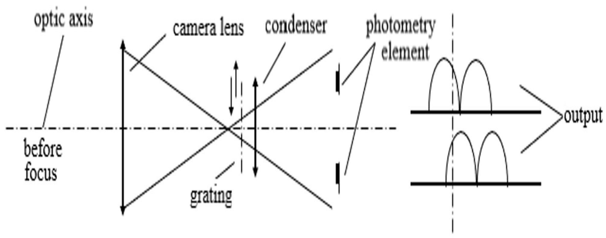
Figure 5: Principle diagram of focusing system based on contrast detection.

3.2.2. Focusing System Based on Phase Difference Detection

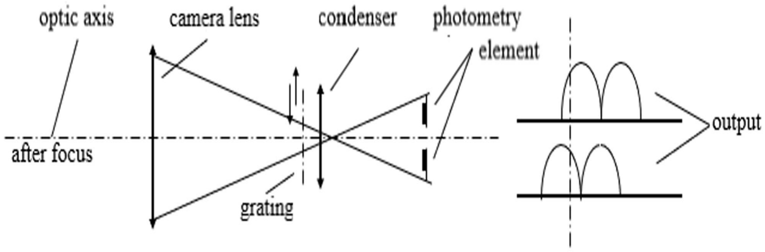
This method realizes auto focusing by detecting the offset of the image [36, 37]. First place a grating in the position of the photographic plate, and two photometry elements are placed symmetrically with the optical axis at a proper position behind the grating. Then the grating vibrates back and forth in the vertical direction of the optical axis. When the focus plane coincides with the grating, as shown in (a) of Figure 6, the light reaches the two photometry elements at the same time. While when defocusing, as shown in (b) and (c) of Figure 6, the beam either reaches the photometry elements first or later, so there is a phase difference between the output signals of the two photometry elements. After the two signals with phase difference are processed by the circuit, the position of the objective lens can be adjusted by the control actuator to make the focus plane coincide with the grating plane.



(a) Positive focus phase.



(b) Defocus phase (Phase lead).



(c) Defocus phase (Phase lag).

Figure 6: Principle diagram of focusing system based on phase difference detection.

3.3. Focusing Based on Image Processing

3.3.1. Principle of Autofocus Technology Based on Image Processing

In order to reduce the complexity and cost of the optical system, the automatic focusing method based on image processing came into being. This method is also a closed-loop method. The optical image of the measured object is collected and processed by computer, and the processing result is fed back to the camera part, and the position of the photosensitive device or the mirror group is adjusted to realize automatic focusing. The image display module can monitor the definition of the image in real time, and the image processing module can process the defocusing situation of the image by analyzing the defocusing situation in Figure 7. Finally, the processing results (control signals) generated by the image processing module are fed back to the camera part to complete the focusing [38, 39].

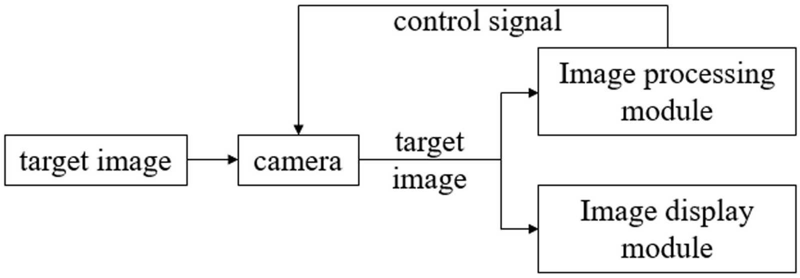


Figure 7: Auto focus principle of image processing.

At present, there are many autofocus technologies based on image processing, but there are two common methods, including depth from defocus and depth from focus. The following two methods are introduced respectively.

3.3.2. Depth from Defocus

It refers to that the system obtains the defocusing information related to the defocusing depth of the focusing target directly through the defocusing image, and calculates the defocusing amount to complete the focusing [40]. In this method, only 2-3 images with different blur degree are needed. By analyzing and processing the images with different imaging parameters, the defocusing depth information of the images is obtained. And then the lens is driven directly to the focus position by the information.

This method can be divided into two categories: defocusing depth method based on image restoration and defocusing depth method based on fuzzy analysis [41-44]. The former mainly uses the image features to estimate the point spread function of the imaging system, uses the image degradation model to carry out inversion calculation, obtains the optical parameters of the best focusing position, and drives the lens to the focusing position according to this parameter. The key of this method is to obtain the representative information in the image. It is not effective for any target and has certain limitations. The latter is to use the principle of defocusing to create a circle of confusion, calculate the radius of the circle of confusion through modeling, and then combine the parameters of the optical imaging system to obtain the positive focus position. The method can be realized in theory. But in practical application, it is necessary to establish an accurate defocusing model in advance, and the accuracy of the parameters of the optical system is also a limiting factor.

3.3.3. Depth from Focus

This method is a focusing method based on search, including image pre-processing, focusing window construction, image quality evaluation and search strategy formulation. It requires that the focusing window should have a proper size and position, which can not only reduce the amount of calculation, but also help to improve the real-time performance of the system, and reduce the impact of background noise on the focusing accuracy effectively; the evaluation function should meet the characteristics of unbiasedness, unimodal, high sensitivity, small amount of calculation and real-time performance [45-47]. It requires to analyze the defocusing information, judge the image clarity accurately, and find the ideal focus position of the system. The commonly used focusing evaluation functions are mainly divided into four categories: gray gradient function [48, 49], spectrum function [50, 51], entropy function and statistical function [52-54]. Users can select appropriate evaluation functions according to different scenes to make the evaluation results meet the requirements; the task of search strategy is to move towards the clear direction of the image and find the positive focus position. The search process should have the characteristics of high accuracy and fast search speed [55-57].

The schematic diagram of depth from focus is shown in Figure 8. Firstly, the images with different defocusing degree are collected, and the evaluation function value of a certain area in the image is calculated by the focusing evaluation function. Then the defocusing degree and defocusing direction of the image are determined. Finally, according to the focusing search strategy adopted, the lens is driven towards the direction of the peak point of the evaluation curve until it reaches the best focusing position.

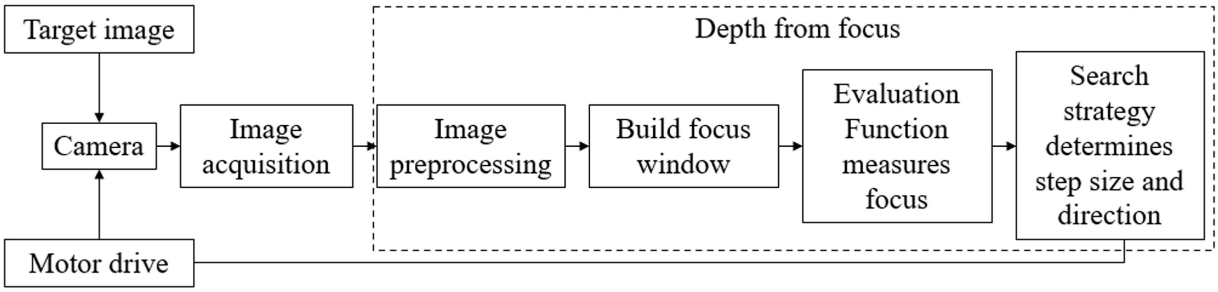


Figure 8: Principle of depth from focus.

The depth of focus method has the advantage of simple algorithm, small dependence on optical imaging system parameters, stable performance and high focusing accuracy. But the performance of its focusing evaluation function is easily affected by background information, and the focusing speed will slow down due to search.

3.4. Focusing Based on Artificial Intelligence

With the rise of artificial intelligence, a large number of automatic focusing methods about artificial intelligence have been proposed by researchers. The biggest difference between this kind of method and the previous method is that the operator lets the machine learn and analyze the data information such as object distance, focal length and image, finds out the internal law and complex corresponding relationship between them, and uses the model solved by itself to complete the automatic focusing of the optical system [58]. There are two main methods about artificial intelligence focusing: auto focus by depth learning and auto focus by reinforcement learning. These two methods play an important role in the requirements of high precision and high speed of automatic focusing of optical system.

3.4.1. Auto Focus by Deep Learning

This method is to use depth learning to establish the mapping relationship between input and output, and to focus automatically through this mapping relationship. The main step of auto focus by deep learning is to design and establish appropriate neuron computing node and multi-layer computing hierarchy, select appropriate input layer and output layer, and establish the relationship between input and output through network learning. Although it is not guaranteed to find the mapping relationship 100%, the network will try to approximate the relationship between them as much as possible. Once the network training is successful, it can meet the complex automation requirements of practical application.

It plays an important role in the field of autofocus for the establishment of complex models. Generally speaking, auto focus by deep learning uses object distance, phase, image and other data to train the relationship between input and output. Once the training is completed, when the neural network receives a new data input, it can quickly reconstruct the required output, so as to realize autofocus [59-61]. This process can be implemented without any iteration, parameter adjustment or user intervention. However, if the amount of training data is so little that it appears a lack of fitting and the neural network layer design is unreasonable, the training effect will be very poor; if the amount of training is so large that it appears an over fitting, the training effect is very good in training set, but it will be very bad in testing set because of including fault-tolerant data [62]. Therefore, the mapping relationship between input and output trained by these two training networks is no longer accurate.

3.4.2. Auto Focus by Reinforcement Learning

This method mainly focuses on the characteristics that reinforcement learning can interact with the environment. Reinforcement learning refers to a kind of machine learning in which agents learn by trial and error. In the process of interaction with the environment, it will use the accumulated rewards at most as a learning mechanism. It mainly includes three important concepts which are environmental state, action and reward [63]. The working mechanism is: the agent selects an action to act on the environment, and the environment is affected by the action to change the current state. At the same time, the environment will feed back a reward or punishment signal to the agent. The agent then selects the next action according to the signal at the moment and the current environment state, and the selection standard is to maximize the reward obtained by the final learning.

Although the working mechanism of reinforcement learning is relatively simple, it also faces a big problem to use reinforcement learning to auto focus. At present, the difficulty lies in how to select the action space of the focusing actuator of the optical system and how to determine the environmental state [64, 65]. At the same time, we should also consider how the system can learn how to make the action execute in the direction of positive reward and how to select the appropriate focusing action according to these values. Although reinforcement learning has the ability of autonomous learning, the complex working environment also makes reinforcement learning auto focus more complex and difficult to realize.

Though auto focus technology by artificial intelligence is emerging in recent years, it has shown great advantages. It has made great progress, but the technology is still not very mature, and it is only common in microscope systems. In the future, there is still a need for greater breakthroughs in auto focus technology by artificial intelligence. Perhaps more complex problems can be solved by combining deep learning with reinforcement learning simply [66].

4. Summary

Now auto focus method has derived many different varieties on the basis of the methods outlined above. The focusing accuracy and speed have been greatly improved compared with the previous ones, and the focusing is also more automated, intelligent and precise. However, there is still much room for improvement in autofocus technology, so the following assumptions are made:

(1) Combining ranging method with method based on image processing

In general, the traditional auto focusing method has better focusing effect and faster focusing speed. But the focusing accuracy cannot be improved to a higher degree due to the addition of additional detection equipment. The auto focusing based on image processing, as a passive focusing method, has high flexibility and wide application range. Because there is no need to add additional ranging equipment, the cost of the optical system is greatly reduced. And the focus adjustment accuracy is significantly improved under the condition of excellent algorithm and adaptation, but it is limited by the search strategy, which slows the focusing speed. In combination with this status quo, it may be possible to improve the overall focus accuracy and speed of the optical system by combining the two in the future, and realize greater application value.

(2) Improve the generality of image focusing algorithm

Although the autofocus algorithm based on image processing has a high focusing accuracy when the target is still or at infinity, it fails in the environment where the target changes in real time or the distance is limited. And most of the algorithms only have a high application value for one system. If the system changes, the algorithm is no longer applicable.

(3) Improve the accuracy of calibration

Depth of field is a range of distance in the imaging system, and the imaging in this range is considered to be clear. However, in the ranging method, there are errors in marking the position of the target surface where the image is clear due to the range. So how to reduce or eliminate this error is also the task of focusing system.

(4) Expand the scope of auto focus by artificial intelligence applicability

Auto focus by artificial intelligence is mainly used in microscope and smart phone, rarely in other fields. Compared with other focusing methods, auto focus by artificial intelligence has great advantages. The neural network involved in it has the characteristics of high computational complexity and fast computing speed. And it can interact with the environment autonomously, which occupies a greater advantage in the task with unclear environment. Therefore, more research on this direction should be put into other optical systems in the future to solve the existing problems of optical system which are greatly affected by the environment and system parameters.

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