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Optical System for Industrial Camera That Achieves Both Close Minimum Object Distance and High Resolution

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Abstract

In factories, automatic inspection is performed using images that are acquired using industrial cameras. In these industrial cameras, lenses with various focal lengths are used according to their intended purposes. It is important that the optical systems of industrial cameras have small outer diameters, close minimum object distances and high resolution. In an optical system with a long focal length, the movement of the moving group increases during focusing, and this movement makes it difficult to reduce the minimum object distance. In addition, to achieve higher resolution, it is important to suppress the degradation that occurs because of machining errors or assembly errors. To solve these problems, we developed a floating focus system in which the diaphragm is fixed, and we introduced a moving group that is held using a helicoid and a fitting structure.

Introduction

The progress in digitization (e.g., the Internet of Things, big data) and the technological innovation of artificial intelligence (AI) has caused dramatic change in the industrial environment. To make full use of the technologies, images that are acquired using cameras are now required to have higher image quality.

In factories, automated assembly and automatic inspection are performed using images that have been acquired using industrial cameras. Optical systems that greatly affect the image quality have been developed for each sensor, including the 1 to 1.1 type [1, 2], 2/3 type [3] and 1/2.5 type [4,5]. Optical systems with various focal lengths are available. When taking a picture over a wide range, a lens with a short focal length is selected, and when a larger picture is to be taken, a lens with a long focal length is used. In optical systems for industrial cameras, it is possible to change the focus and the diaphragm by hand. The diaphragm can be changed to adjust the amount of incident light on the sensor [6]. The range over which the object distance and the F number can be changed is determined by each lens.

In recent years, printed circuit boards have been densified considerably. As a result, the spacing between components has narrowed, and imaging with both high magnification and high resolution is required.

Industrial camera

Table 1 compares the properties of consumer cameras and industrial cameras. The term consumer camera refers to the type of camera contained in a smartphone or a single-lens reflex camera. The term industrial camera refers to cameras such as C-mount cameras, in which the lenses can be exchanged.

The optical system for a consumer camera is designed with emphasis on the far distance, where the spatial frequency of the object of interest is high. The optical system of an industrial camera is designed to have higher performance at close distance because these cameras are intended for uses in limited spaces, as in inspection processes. Furthermore, because the position information is important for inspection applications, distortion aberrations are small in industrial cameras and the optical systems basically correct these aberrations. In consumer cameras, there are cases where such aberrations are corrected by image processing [7]. While consumer cameras use auto focusing, industrial cameras are focused manually. Therefore, reduction of the weight of the moving group in the optical system during focusing is necessary to achieve rapid focusing in consumer cameras. However, it is not necessary to reduce the weight of the moving group in industrial cameras. Therefore, it is possible to design the optical system which is higher performance.

Table 1 Comparison of properties of "consumer camera" and "industrial camera"

Property	Consumer camera	Industrial camera
Distance with high performance	Far distance	Close distance
Distortion	Some cases of correction using image processing	Basically corrected by optical system
Focusing	Automatic	Manual
Weight of moving group	Emphasized	Not emphasized

Recently, the features that are required in optical systems for industrial cameras are as follows.

1. Close minimum object distance
   It is desirable to be able to acquire images at high magnification.
2. High resolution
   It is desirable to be able to acquire high-resolution images from infinity to the minimum object distance.
3. Small outer diameter
   The outer diameter is desired to be smaller than the camera body.

Problem

There is a method of focusing in which a specific interval is changed to suppress changes in the aberration, depending on object distance. This method is called the floating focus method. Figure 1 shows an example of a floating focus configuration [8].

The setup consists of a Gaussian-type moving group that includes a diaphragm and a fixed group. When focusing from infinity to the minimum object distance, the moving group moves towards the object side. By varying the interval between the moving group and the fixed group, the aberrations that are generated by the moving group and the fixed group are cancelled out; these aberrations can be corrected over the entire object distance.

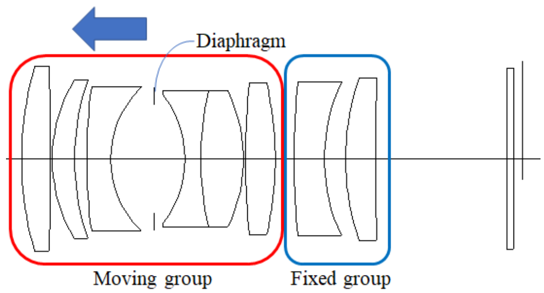


Figure 1 Example of floating focus configuration

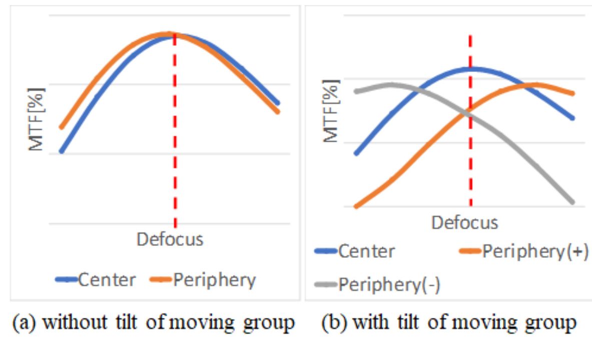


Figure 2 MTF versus defocus characteristics

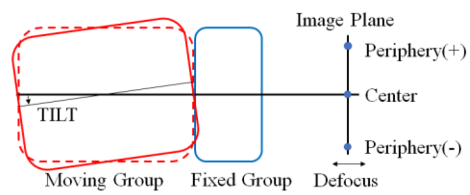


Figure 3 Conceptual figure of center and periphery

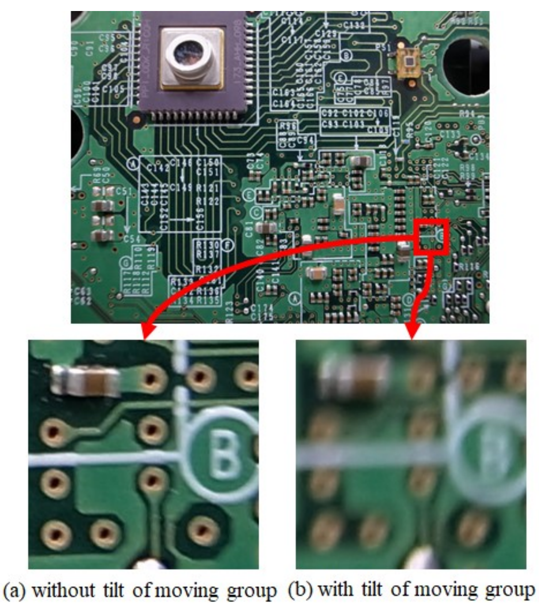


Figure 4 Differences in peripheral image quality

The amount of movement of the moving group is proportional to the square of its focal length. An increase in the magnification of the fixed group reduces the focal length of the moving group, thus allowing focusing with smaller amounts of movement.

However, if the focal length of the moving group is too short, the aberrations that are generated in the moving group will be expanded in the fixed group, and the problem where the resolution degradation increases because of the tilt of the moving group then occurs. This is caused by a decentered aberration [9].

This demonstrates how the system's resolution can be degraded by the tilt of the moving group.

The modulation transfer function (MTF) is used as an index for resolution evaluation [10]. Figure 2 shows the MTF versus defocus characteristics. Figure 2 (a) shows a conceptual figure of the MTF without the tilt of the moving group. Figure 2 (b) shows the conceptual figure of the MTF with the tilt of the moving group. The dotted line indicates the MTF peak position at the center in the optical axis direction, and the MTF is evaluated at this position. Figure 3 shows conceptual figure of center and periphery. The positive periphery (+) and the negative periphery (−) are in point symmetry with respect to the center.

In the case without the tilt of the moving group, the MTF peak positions of the center and the peripheries are aligned, and the MTF is high over the range from the center to the periphery. The positive periphery (+) and the negative periphery (−) have the same value. In contrast, in the case that includes the tilt of the moving group, the MTF peak positions of the positive periphery (+) and the negative periphery (−) move in opposite directions because of the tilt of the moving group. The MTF peak positions of the center, the positive periphery (+) and the negative periphery (-) are not aligned in this case, and the MTF of the periphery is greatly reduced. In addition, the MTF peak value decreases for both the center and the peripheries.

Figure 4 shows the differences in the peripheral image quality. Without the tilt of the moving group, a high-resolution image can be obtained, as shown in Figure 4 (a), but with the tilt of the moving group, the low-resolution image shown in Figure 4 (b) is obtained.

Developed optical system

The system specifications are listed in Table 2. The focal length is 75 mm and the lens is classified as a telephoto lens [11].

Table 2 System specification table

Sensor Size (Image Height)	1" (Y'=8.0mm)
Pixel	9M
Focal Length	75mm
F Number	F2.8
Minimum Object Distance	250mm
Outer Diameter	Φ42mm

When we attempted to achieve the required minimum object distance using the configuration of Figure 1, the focal length of the moving group became too short because the amount by which the moving group could move was constrained. There was the problem that the resolution degradation increased because of the tilt of the moving group.

Therefore, the movement of the diaphragm, which constrains the movement of the moving group, was changed to a fixed state, thus allowing the moving group to move more freely and provide a more appropriate focal length.

When the diaphragm was fixed to the image side of the moving group, there was concern that the periphery would become dark when the F number was high. It was possible to avoid this problem by a narrow angle of view and an appropriate amount of movement for the moving group [12].

Figure 5 shows the optical system configuration developed in this work. The system consists, in order from the object side, of a moving group, a fixed diaphragm and a fixed group. When focusing from infinity to the minimum object distance, the moving group moves towards the object side.

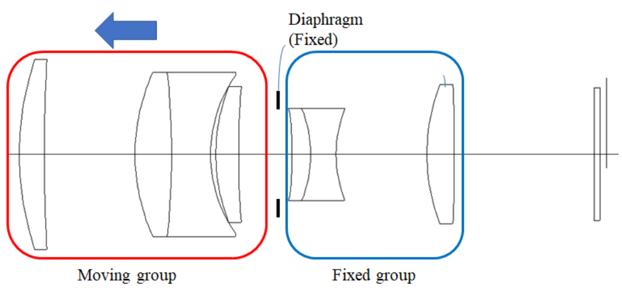


Figure 5 Developed optical system configuration

Figure 6 shows the MTF versus image height characteristics of the system. In Figure 6 (a), the object distance is 500 mm. In Figure 6 (b), the object distances are infinity and 250 mm. The evaluation space frequency is 72.5 line pairs per mm (LP/mm; half the Nyquist frequency of a nine-million-pixel camera [pixel pitch: 3.45 μm]). Using the above optical system configuration, the MTF is high at an object distance of 500 mm. This enabled higher resolution by 20% or more up to the maximum image height of 8.0 mm over the entire object distance.

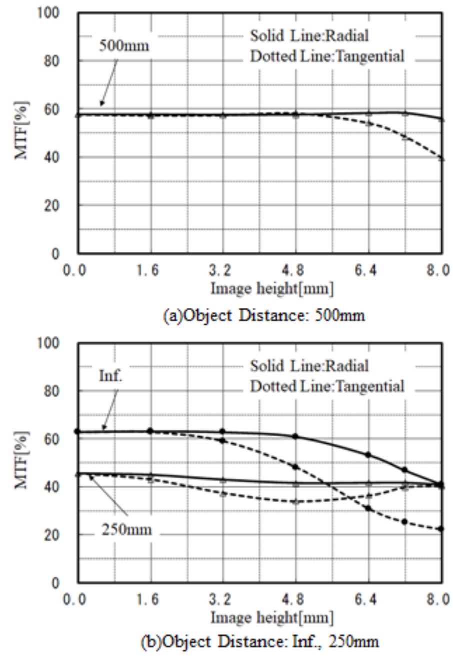


Figure 6 MTF versus image height characteristics

Fixing the diaphragm made it possible to reduce the magnification of the fixed group, the MTF degradation caused by the tilt of the moving group could be suppressed. To provide a further increase in the MTF of the product, the amount of tilt of the moving group was suppressed via the mechanical configuration.

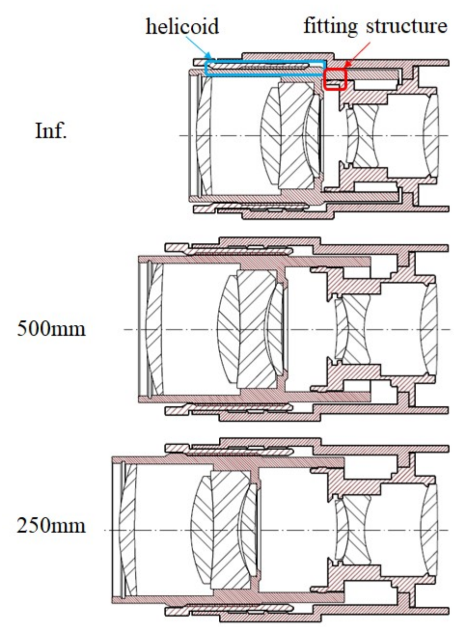


Figure 7 Conceptual figure showing holding structure for the moving group

Figure 7 shows the conceptual figure showing holding structure for the moving group. The object distances are infinity, 500 mm and 250 mm.

The mechanism moves the moving group using a helicoid. When the moving group is held using the helicoid alone, the radial clearance is large and the moving group is tilted strongly.

Therefore, a fitting structure is provided that can be fitted with the frame of the moving group. The fitting structure is fixed with respect to the image plane during focusing. The relationships among the radial clearance of the helicoid, the radial clearance of the fitting structure and the interval between the helicoid and the fitting structure determine the amount of tilt of the moving group, and the amount of tilt can be reduced. The maximum amount of tilt was 20.8' when the moving group was held using the helicoid alone, but the maximum amount of tilt became 11.8' when the moving group was held using the helicoid and the fitting structure. Furthermore, because the tilt center of the moving group is located between the helicoid and the fitting structure, the tilt center of the moving group moves to the image side, in contrast to the case when the helicoid alone was used. This also has the effect of suppressing the MTF degradation.

Figure 8 shows the amount of MTF degradation [object distance: 500 mm] produced by the tilt of the moving group. The periphery [R] is the MTF in the radial direction at an image height of 0.8 Y', and the periphery [T] is the MTF in the tangential direction at the same image height of 0.8 Y'.

The moving group held using the helicoid and the fitting structure suppressed the MTF degradation at both the center and the periphery.

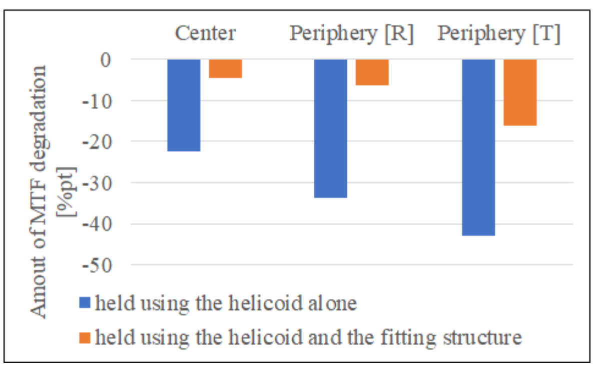
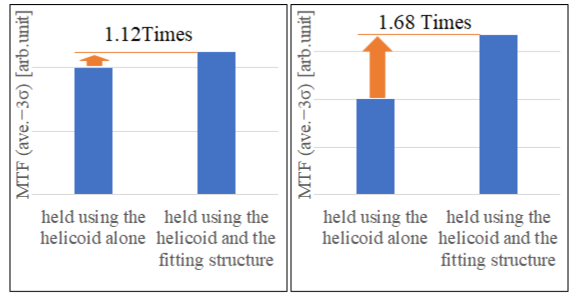


Figure 8 Amount of MTF degradation caused by the tilt of the moving group

Furthermore, Monte Carlo simulations were performed to predict the MTF for the product [13]. Machining errors or assembly errors were used as input values. The average and the standard deviation (σ) were calculated from 500 samples.The results when evaluated with an average −3σ are shown in Figure 9.

The moving group held using the helicoid and the fitting structure had MTF values that were 1.12 times higher at the center and 1.68 times higher at the periphery.



(a)MTF at the center(average-3σ) (b)MTF at the periphery[0.8Y'] (average-3σ)

Figure 9 Results of Monte Carlo simulations

Conclusions

We have developed a floating focus system in which the diaphragm is fixed, and we introduced a moving group that is held using a helicoid and a fitting structure. This system can shorten the minimum object distance and achieve high-resolution imaging.

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Author Biography

Yoshifumi Sudoh received his MS degree in Applied Physics from Hokkaido University in 2004. Since that time, he has worked for Ricoh in Kanagawa. His work has focused on the development and design of optical systems for cameras.