



Research



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Optical design of an inner focus type telephoto lens with a large aperture

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As consumer demand for high-performance lenses increases, lenses with a large aperture of F/1.2 are being developed in the auto-focus (AF) market. As the F-number decreases, the diameter of the lens increases, which increases aberration as well as the weight of the lens. Those used in photography cameras must be very small and thus have relatively weak torque. Although motors with stronger torque, such as ultrasonic motors, are available, they generate noise when the lens moves, which is fatal in filming video content. To solve this problem, a design using a floating system that moves two lens groups has also been proposed. However, this becomes more complicated in terms of mechanical and electronic control compared with the method of moving a single lens group. Therefore, in this study, we propose a novel design for an F/1.2, $f = 85$ mm large aperture telephoto lens that uses one AF group and consists of a single lens to lighten the moving lens group for quiet and precise focusing. Even at the maximum aperture of F/1.2, the modulation transfer function (MTF) performance was maintained at 80% in the center and 69% at the periphery. By reducing the weight of the moving lens group by using a single focusing group, the proposed system was able to operate quickly and quietly without any significant degradation in performance, even in the minimum object distance. Therefore, our results demonstrate that an internal focusing structure based on a single focusing group is feasible even in an F/1.2, with an 85 mm large-aperture prime lens.

[†]These authors contributed equally to the study.

1. Introduction

Market demand for zoom lenses that can cover various angles of view with a single lens has increased in recent years, and research on zoom lenses is also continuing accordingly [1,2]. Although zoom lenses offer high convenience, achieving high resolution and shallow depth of field can be difficult when open like prime lenses. For this reason, there is still a high demand for fixed-focus lenses among users who value performance and openness. Lenses with F/1.2 specifications are being released to achieve a very shallow depth of field and fast shutter speed, even in low-light environments like indoors, so the camera can capture more light, enabling faster shutter speeds. This significantly improves the stability and usability of low-light shooting. The depth of field refers to the depth of the range in focus. The shallower the depth of field, the narrower the area that is clearly expressed before and after the focus, which makes the subject stand out more [3]. Currently, F/1.2 lenses have the largest aperture value among auto-focus (AF) lenses. Although lenses with large apertures like F/1.0 or F/0.95 do exist, they are designed exclusively for manual focus. Therefore, F/1.2 has the lowest F-number available that supports auto-focus. F-number is defined as the ratio of the effective focal length (EFL) to the entrance pupil diameter (EPD) [4]. At the same focal length, the larger the aperture, the smaller the F-number value, which allows more light to enter. Therefore, the design of an F/1.2 lens requires a large-aperture lens, which increases the aberration and overall weight of the optical system [5].

Yamamoto proposed a fixed-focus lens design that simultaneously achieved a lightweight focusing lens group and miniaturization of the entire optical system while maintaining a small F-number [6]. Achieving both aberration suppression and a lightweight and compact design is a key challenge in the design of large-aperture lenses. The inner focusing method is widely applied for this purpose. It sets a specific lens group as a focusing group and drives it with a motor. This method applies not only to interchangeable lenses but also to optical inspection systems and enables stable focus adjustment even when the subject distance or optical data change [7]. This method enables stable focus adjustment even when the magnification changes owing to changes in the distance to the subject or changes in optical data. In environments where focus movement is continuous, such as in shooting videos, this approach is mainly used to determine the contrast of the image by repeatedly moving the focusing lens group by a small amount. Of note, a stepper motor with low driving noise and precise control is advantageous. A stepper motor provides smooth and quiet movements when driven at low speed. However, stepper motors have low driving torque, which makes them unfavourable for driving heavy focusing lens groups. Let us consider a state-of-the-art optical system with a lens with the same specifications as that used in this study, $f = 85$ mm and F/1.2 [8]. The focus group is driven in a different way than using a single stepper motor. Figure 1 shows a representative optical layout developed by Maetaki [9].

According to the optical layout (figure 1), they are driven by an inner focusing method using the second group as the AF groups. A total of seven lenses are used in the moving lens group, so a strong torque must be used to drive them. They used a ring-type ultrasonic motor (USM) with a driving method that can drive a heavy and large-aperture lens with strong power by moving the lens group with ultrasonic and rotational motion [10]. However, according to the driving principle of the ultrasonic motor, the vibration of the stator is transmitted through frictional contact with the rotor. In this process, physical noise is generated owing to frictional noise and structural vibration. Autofocus speed is not simply defined by maximum drive speed or instantaneous lens movement speed, but rather is evaluated in terms of the total response time required to accurately reach the target focus position [11]. Stepping motors have discrete step-based control characteristics, and each step contains absolute position information, enabling direct positioning relative to the target position. This reduces repetitive fine-position corrections near the focus point, resulting in efficient response characteristics in terms of actual autofocus completion time. Conversely, ultrasonic motors, while capable of rapid initial lens movement based on high torque, may require additional fine-tuning near the target focus point owing to their continuous drive nature [12]. Therefore, for lightweight focusing lenses and limited travel stroke conditions, a stepping motor-based drive system offers advantages in terms of practical autofocus response time [7]. Figure 2 shows a representative optical layout developed by Machida [13]. Figure 2 shows the optical layout from a patent for what is expected to be the Nikon Z 85 mm F/1.2 S product [14].

Based on the optical layout (figure 2), we can observe that the AF group uses the second and third lens groups and adopts the floating system method of movement. To apply this method to an optical system with a large magnification change and to enable sufficient aberration correction, a large number of moving lens groups are required. In this case, a system in which two or more lens groups move

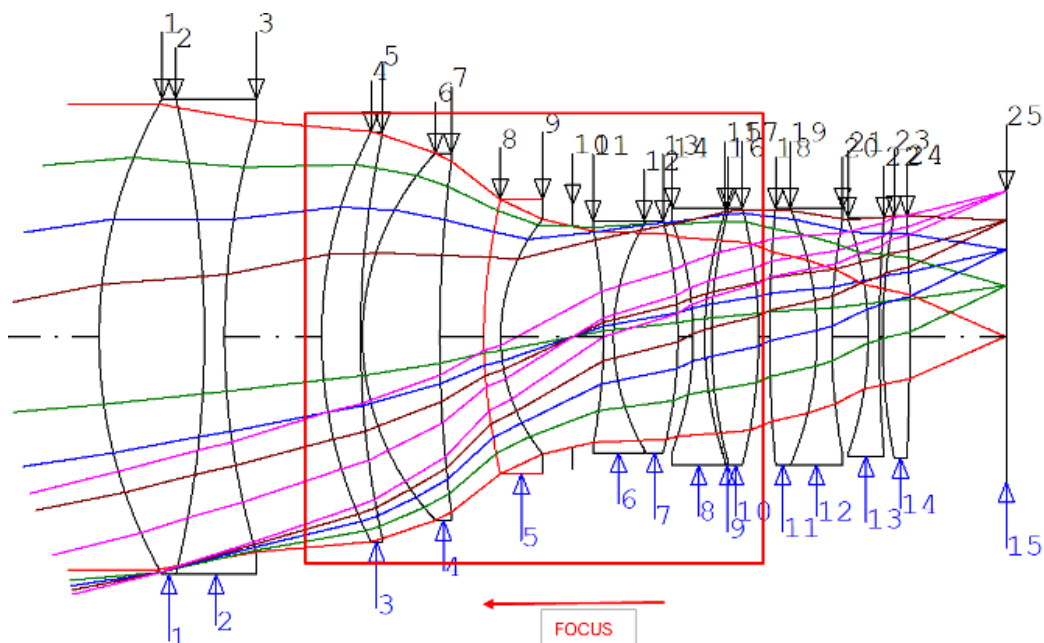


Figure 1. Optical layout of Canon RF 85 mm, F/1.2L USM DS product [9].

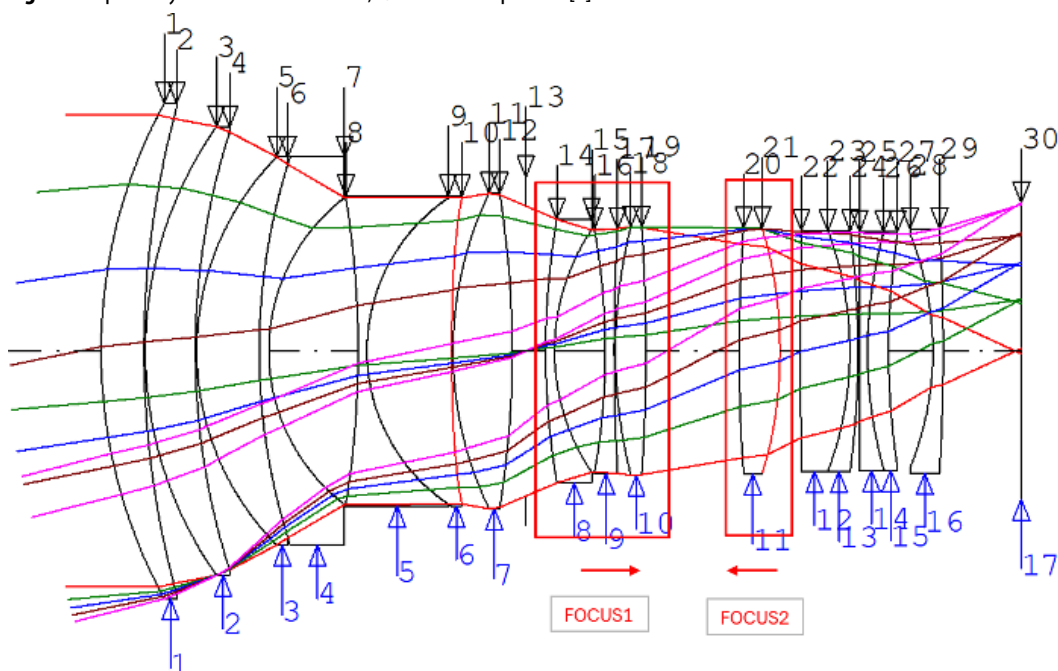


Figure 2. Optical layout of Nikon Z 85 mm F/1.2 S product [13].

during focusing is called a floating system [15]. Focusing was achieved by using a multi-focus method with two stepper motors mounted on an AF actuator. This method has the advantage of being able to operate quietly and quickly, even with large-aperture lenses. However, it complicates the structure by requiring two stepper motors and additional components for the floating system, which increases the development time and cost, as well as the weight of the product. Udagawa *et al.* also proposed a floating method for moving two or more lens groups together to properly correct aberrations in the entire field when moving the focus from infinity to a close distance in a large-aperture F/1.2 lens [16]. In contrast, to solve the problem of complexity and increased weight of the floating method, Ryu *et al.* configured a focusing lens group in a large-aperture telephoto lens as a single element and applied an internal focusing method [17]. This method improves dust and water resistance and is easy to use because the overall length does not change during focusing. It also minimizes the weight of the focusing lens group, which enables high-speed AF even with a low-torque stepping motor.

Although the single-lens AF method was proposed in the F/1.4 specification, Ryu *et al.* expanded its application to a low F-number (F/1.2) large-aperture lens. They achieved high-performance AF and excellent optical performance even with a single, lightweight focusing lens. Meanwhile, Shiota proposed a method to simultaneously correct chromatic aberration and reduce weight by optimally arranging crown and flint glass in a large-aperture lens design [18]. Thus, an appropriate selection and combination of lens materials is essential to satisfy optical performance and manufacturability simultaneously in the design of actual large-aperture lenses. Therefore, research is also being conducted on methods for selecting such materials [19].

In this study, the target performance was achieved by suppressing chromatic aberration through an optimal combination of crown and flint glass in a large-aperture F/1.2 lens, and a lightweight lens was placed in the second group to simultaneously achieve AF performance and weight reduction for mass production in the factory. This design enables high-speed and precise focusing using only a single stepper motor drive. It also reduces the weight of the focusing lens group while maintaining the internal focusing structure. Thus, our proposed approach resolves the problem of insufficient motor torque, which inevitably occurs in conventional large-diameter lens designs.

2. Method

Our research goal was to design a full-frame prime lens with a focal length of $f = 85$ mm and a maximum aperture of F/1.2 for mass production in a factory. In particular, the second group is designed to be lightweight with a single focusing group and implement an internal focusing structure that enables high-speed and precise focusing, even with a stepper drive. The image sensor was set based on the full-frame standard of 35 mm film. The proposed optical system consists of a total of 15 lenses, including two aspherical lenses and one extra-low dispersion (ED) lens. Design and optimization were performed using the CODE V software package (v. 2023.03, Synopsys Inc., Sunnyvale, CA, USA). The wavelength conditions applied were C- (656.27 nm), d- (587.56 nm), e- (546.07 nm), F- (486.13 nm) and g-lines (435.83 nm) in the visible light region, and the central wavelength was set to the e-line. Optimization was performed to suppress major aberrations (spherical aberration, chromatic aberration and field curvature) that commonly appear in telephoto lenses and to maintain high resolution.

For optical performance verification and analysis, we compared two products, the Canon RF 85 mm F/1.2 L USM DS and the Nikon Z 85 mm F/1.2 S, which are previously developed F/1.2 single focus lenses, as shown in figures 1 and 2. Both products support a low F-number of F/1.2. However, the focusing method used in the two is distinctly different. Maetaki [9] used an internal focusing method that moved seven elements in the second group and included a USM motor, while Machida [13] applied two stepper motors based on a floating structure that moves the second and third groups together. Unlike conventional methods, the proposed approach uses only a single element of the second group as the focusing group and implements internal focusing using a stepper motor.

Our approach offers the advantages of structural simplification, lighter focusing groups and low-torque operation. We compared the performance of the latest optical systems developed by competitors, starting with Canon's RF 85 mm F/1.2 L USM DS and Nikon's NIKKOR Z 85 mm F/1.2 S. Table 1 lists the main specifications of each product.

The design goal was determined by comparing the specifications of two existing optical systems, and the design began with Nikon's specifications as the comparison target. As shown in figure 1, Canon's patented optical system comprises the first group of doublets. If the first group is designed as a doublet, chromatic aberration, which tends to increase in telephotos, can be controlled efficiently. However, this structure further increases the diameter of the front lens in large-aperture lenses. In particular, the thickness of the first lens is designed to be approximately 15 mm or more, which can lead to increased manufacturing difficulty and cost, as well as an increase in the unit price of parts. In addition, as the lens located in front of the aperture increases in size, the weight of the entire optical system increases. In our study, the first group of lenses was configured as a single lens rather than as a doublet to reduce the aperture of the front lens. This effectively reduces the aperture of the lens in front of the aperture, thereby securing advantages in terms of manufacturing cost and weight. Therefore, in our study, the number of lenses was designed to be the same as that of the Nikon products, with a total of 15 lenses (including 2 aspherical lenses). The shooting angle (angle of view) was determined based on the focal length and size of the imaging element. In interchangeable camera lenses, the angle

Table 1. Currently developed product specifications.

products	RF 85 mm F/1.2 L USM DS	NIKKOR Z85 mm F/1.2 S
lens configuration	9 groups and 13 elements (1 aspherical element)	10 groups and 15 elements (2 aspherical elements)
minimum focusing distance	0.85 m	0.85 m
maximum shooting range	0.12X	0.11X
filter size	82 mm	82 mm
length	117.3 mm	141.5 mm

of view is usually determined by the focal length because the sensor size is usually fixed [20]. A lens with a focal length of approximately 50 mm on a full frame (35 mm film size) is called a standard lens. A lens with a focal length of 35 mm or less that provides a wider angle of view than a standard lens is called a wide-angle lens, whereas a lens with a focal length of 70 mm or more is called a telephoto lens. To increase the focal length, the telephoto lens was designed with an optical system in which the lenses were arranged such that the front group had a positive power and the rear group had a negative power, as shown in figure 3.

The ' f ' shown in figure 3 does not represent the focal length of an individual lens, but rather EFL of the entire optical system. This diagram is presented to illustrate the fundamental construction principle of a telephoto optical system, which consists of a group of lenses with positive refractive power at the front and a group of lenses with negative refractive power at the rear.

Our design makes it possible to achieve a long focal length while reducing the overall length of the lens by making the EFL longer than the back focal length (BFL). Figure 4 shows the optical layout of the proposed design.

Our designed optical system was also adopted in the telephoto method, with lenses arranged in the front group having positive power, and those in the rear group having negative power. The lens in front of the aperture is composed of large aperture elements, so it is not cost-effective to use aspherical elements [21]. Two aspherical elements were used on the lens right behind the aperture and on the last surface. When photographing a subject, we do not simply photograph subjects that are infinitely far away; therefore, we need to design our camera to stay in focus, even when the subject gets closer. When the object distance changes, the magnification changes as well, and the image plane of the optical system becomes defocused [22]. In this case, to align the image plane, the imaging element must move, or the entire optical system must be moved to focus. However, for interchangeable lenses, the position of the sensor cannot be changed. The entire optical system is too heavy to move, which makes it difficult to control using the motor used in interchangeable lenses, and the focusing speed is also very slow [23]. Therefore, the design must move a specific group rather than the entire optical system to focus on the image plane.

The fixed-focus lens methods are largely divided into three techniques [24]: the front focusing method, in which the front group of the optical system moves to focus; the rear focusing method, in which the last group of the optical system moves to focus; and the inner focusing method, in which a specific group inside the optical system moves to focus. In the front focusing method or rear focusing method, not only is the moving lens group heavier than that in the inner focusing method, but the overall length of the optical system also changes as the lens group moves. In comparison, the inner focusing method moves a specific group inside the optical system; therefore, there is no change in the total length of the optical system. Thus, the focusing method is widely used because of its environmental resistance.

Figure 5 shows the optical path for the internal focusing method of the floating system. The floating system uses an inner focusing method that moves two or more lens groups inside to focus [25].

As a distant object approaches, two or more internal lens groups move to compensate for the movement of the image plane. In the inner focusing method, as shown in figure 5, the total length of the optical system does not change with the movement of the AF lens group. If there is no focusing group according to the change in the object distance, the image plane moves and the desired resolution is not obtained because focus is not achieved. Therefore, it is necessary to move the focusing group to compensate for the occurrence of defocusing on the image plane according to the change in distance to the subject. Figure 6 shows an optical path diagram showing that the focus is not on the image plane when there is no focusing group moving owing to the change in the object distance.

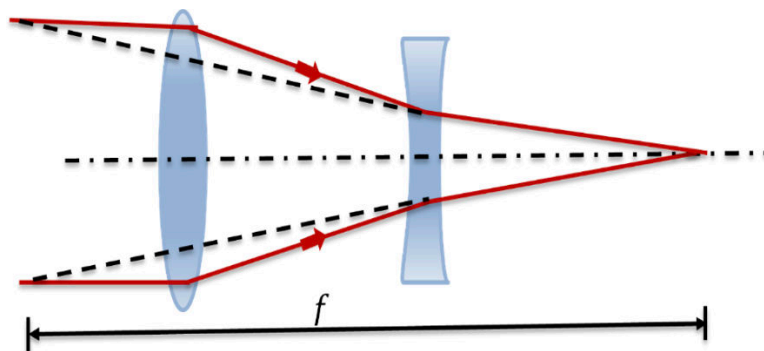


Figure 3. Telephoto configuration.

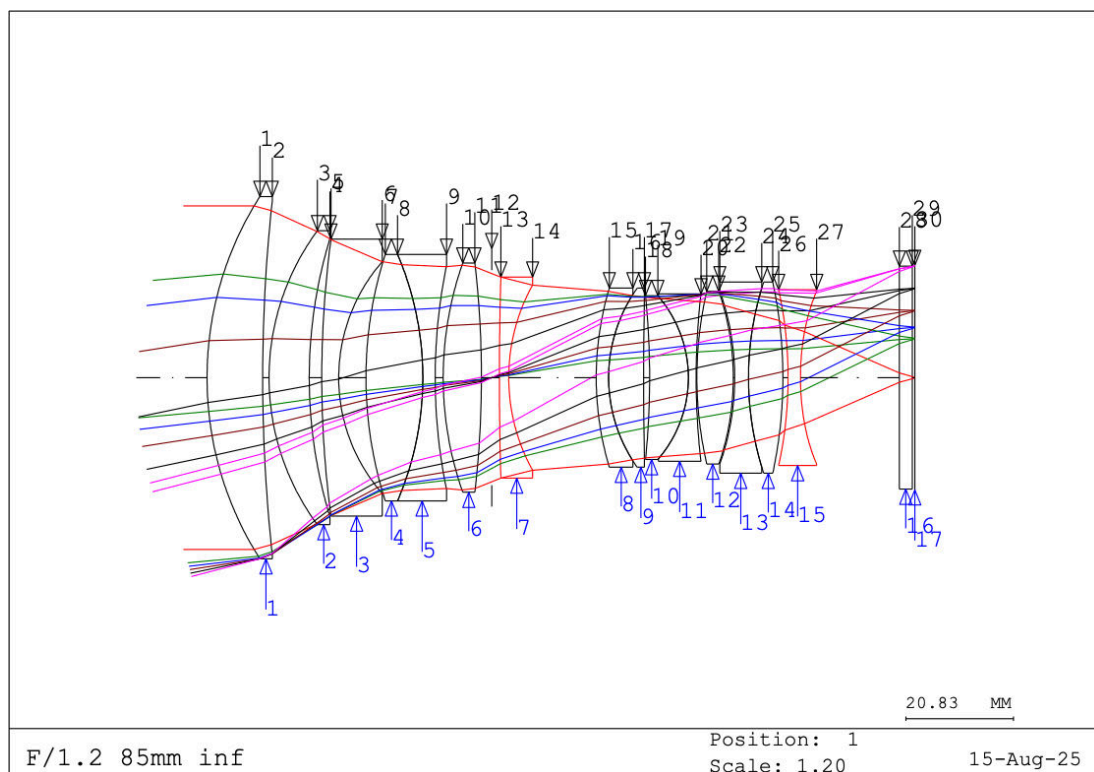


Figure 4. Our designed optical path.

In the focusing group, the change in aberration between movements was not significant, and the lens group that changed the BFL was selected [26]. The amount of change in the BFL according to the movement of the lens group is called longitudinal sensitivity or pint sensitivity [27]. The amount of change in the image plane according to the movement of the lens group can be calculated using the longitudinal sensitivity.

As shown in figure 7, this is a diagram for an arbitrary lens for which longitudinal sensitivity is calculated according to lens movement. Figure 7 is not intended to represent actual ray tracing results or the detailed optical path of a physical optical system. Rather, it is a conceptual schematic illustration, intentionally simplified to theoretically explain the concept of longitudinal sensitivity owing to lens group movement.

For an arbitrary lens, the object-image distance L can be defined as the sum of the object distance s from the image formed by the previous lenses to the object and the image distance s' to the image formed by the arbitrary lens, as in equation (2.1) [28].

$$L \equiv s + s'. \quad (2.1)$$

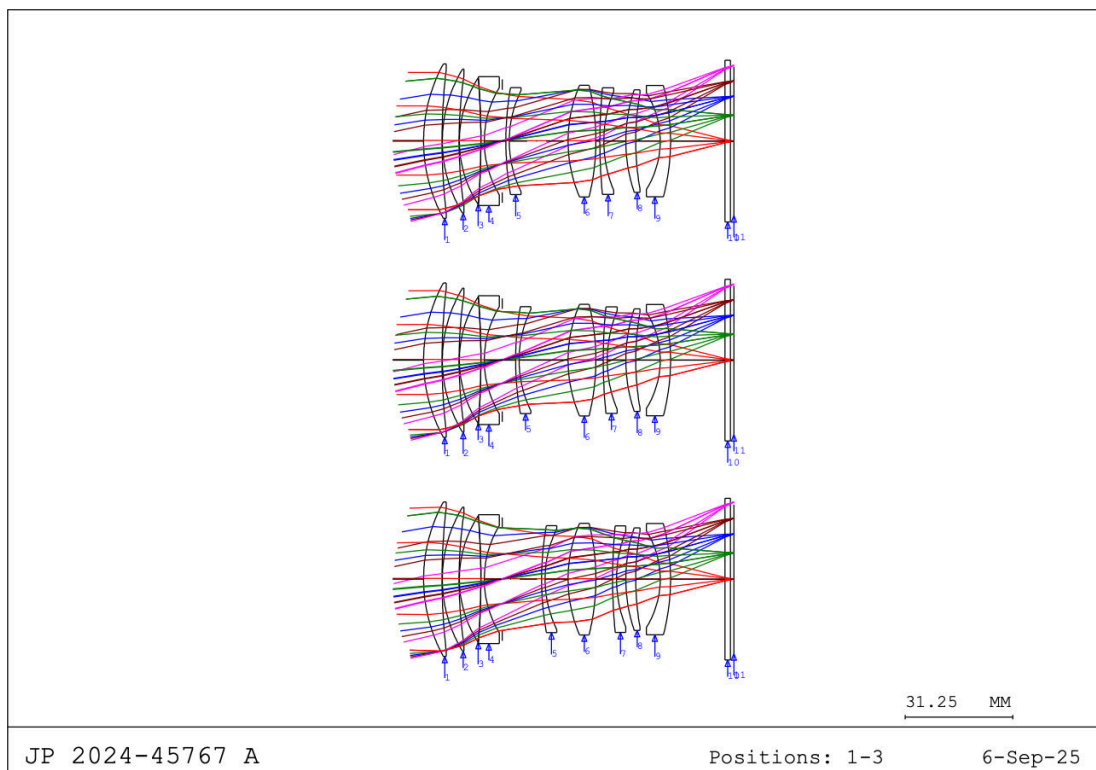


Figure 5. Movement of the focusing group according to changes in object distance.

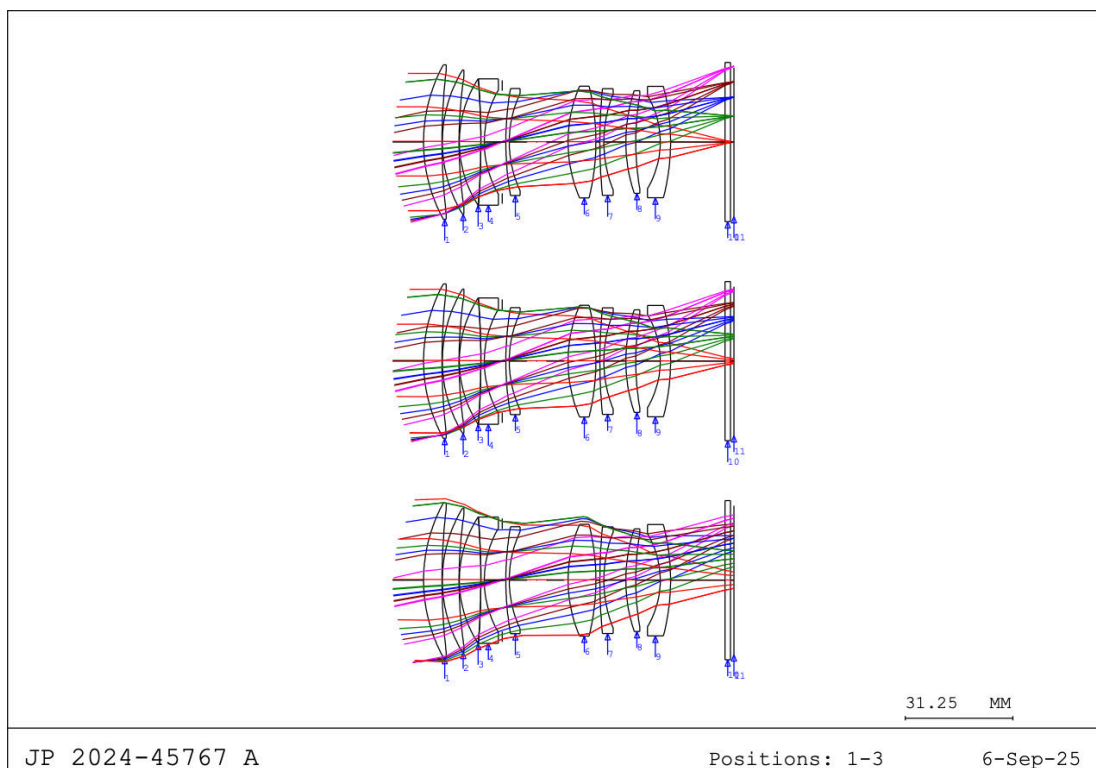


Figure 6. Optical path when no group moves owing to changes in object distance.

The sign convention is based on the origin of the light ray. Let f be the focal length of any lens group, and the object distance s and image distance s' satisfy the following imaging (equation (2.2)) [28]:

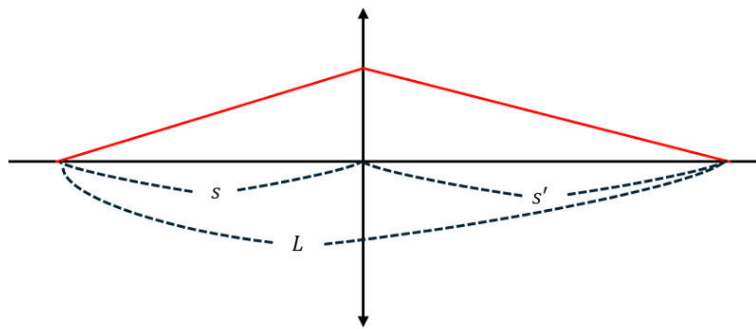


Figure 7. Optical path representing light refraction for any group of lenses.

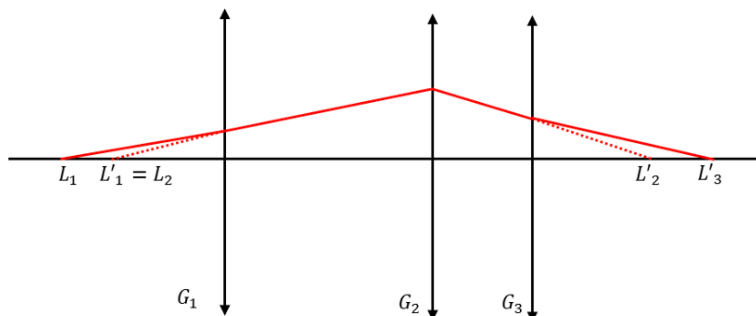


Figure 8. Optical path representing light refraction for any number of lenses.

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}. \quad (2.2)$$

Transverse magnification m of the optical system is defined as the ratio of the phase distance s' to the object distance s , as expressed in equation (2.3). If equation (2.2) is differentiated for the distance to an object s and phase distance s' , it can be expressed as equation (2.4). The moving $\Delta s'$ of the image plane with respect to the moving Δs of the object surface can be expressed as given in equation (2.5) [28].

$$m \equiv -\frac{s'}{s}, \quad (2.3)$$

$$-\frac{\Delta s}{s^2} + \frac{\Delta s'}{s'} = 0, \quad (2.4)$$

$$\Delta s' = -\left(\frac{s'}{s}\right)^2 \Delta s = -m^2 \Delta s. \quad (2.5)$$

When an arbitrary lens group moves by Δs in the optical axis direction, the change amount ΔL of the object distance can be expressed as equation (2.6). This represents the amount of movement of the image plane with respect to the movement of the lens.

$$\Delta L = \Delta s + \Delta s' = \Delta s(1 - m^2). \quad (2.6)$$

Equation (2.6) corresponds to the calculation of the amount of movement of the image plane based on the movement of a single lens group. However, given that this optical system is composed of several groups, it is possible to calculate the amount of movement in the image plane when any group of lenses moves. Figure 8 shows an optical path diagram for a lens composed of any number of groups.

In figure 8, when the first lens group G_1 moves, the change in the object-image distance ΔL_1 can be expressed as described in equation (2.7). Δs represents the amount of the movement.

$$\Delta L_1 = \Delta s(1 - m_1^2). \quad (2.7)$$

When G_1 moves, the object distance of the second group also changes by ΔL_1 . Accordingly, the object-image distance to G_2 according to the movement of G_1 is as in equation (2.8).

$$\Delta L_2 = m_2^2 \Delta L_1 = \Delta s(1 - m_1^2)m_2^2. \quad (2.8)$$

If there is a third group, the change in the object–image distance to G_3 for the movement of G_1 can be expressed as in [equation \(2.9\)](#).

$$\Delta L_3 = m_3^2 \Delta L_2 = \Delta s (1 - m_1^2) m_2^2 m_3^2. \quad (2.9)$$

If there are several groups instead of one group, the $\Delta L'_N$ of a change in the object–image distance according to the movement of a specific group may be expressed as in [equation \(2.9\)](#).

$$\Delta L'_N = p_i \Delta s_i p_i \equiv (1 - m_i^2) \prod_{k=i+1}^N m_k^2 \quad (2.10)$$

where p_i is defined as the longitudinal sensitivity of the i th group. If we calculate p_i by setting the value of Δs_i to 1, we can calculate the change in BFL when the i th lens group moves 1 mm. The transverse axis m of each group can be expressed using a Lagrange invariant preserved before and after refraction [29]. Its definition is described in [equation \(2.10\)](#). Therefore, the transverse magnification can be expressed as the product of the refractive index n before refraction and angle u of the axial light divided by the product of the refractive index n' after refraction and angle u' of the axial light.

$$\begin{aligned} nuh &= n'u'h', \\ m &= \frac{h'}{h} = \frac{nu}{n'u'}. \end{aligned} \quad (2.11)$$

[Figure 9](#) shows an optical path diagram based on the change in the distance to the object in the optical system that we designed.

In our design, the focus was designed to move the seventh lens, which is located just behind the aperture, and the longitudinal sensitivity was calculated. In addition, the minimum object distance or maximum magnification of the optical system was determined using the developed optical system with the same specifications as previously described, and the object distance input was entered using [equation \(2.10\)](#). If f is the focal length and m is the magnification, the object distance relative to the magnification can be obtained.

$$l = f \left(1 - \frac{1}{m} \right). \quad (2.12)$$

As shown in [figure 10](#), zoom 2 entered the object distance at a magnification of 0.025 $\times$, and zoom 3 entered the object distance at a magnification of 0.12 $\times$.

In [figure 10](#), the object distance represents the distance from the first surface of the optical system to the object. When comparing the performance of interchangeable lenses, it represents the distance from the image sensor to the object. Therefore, the minimum object distance (MOD) of the optical system in this study was 867 mm because we added the total length of the optical system to 137 mm. In general, the higher the maximum magnification, the better it is for capturing pictures of close-up subjects, and the more the out-of-focus effect is maximized. The total length of the Nikon NIKKOR Z 85 mm F/1.2 S is approximately 141.5 mm from the mount surface to the front lens. However, in the proposed design, if an actual mount surface thickness of 3 mm is reflected, excluding the flange back of 18 mm, the length from the mount surface to the front lens is formed to be shorter at approximately 122 mm. The Nikon design, unlike the design of this study, which moves only one lens group, uses a composite focusing structure in which two or more lens groups move. Therefore, it requires mechanical space and a drive unit, which increases the overall length and weight. The MOD in this study was approximately 17 mm longer than the previously developed model, Nikon's NIKKOR Z 85 mm F/1.2 S; however, it had a magnification of 0.12 $\times$, allowing for a larger subject to be captured. Thus, we designed the optical system to implement stable resolution and a background blur effect simultaneously.

3. Results and discussion

In this study, a mid-range lens with a focal length of 85 mm with a large aperture value of a maximum open F/1.2 for a full-frame sensor was designed for mass production in the factory. To compensate for the shortcomings of the existing developed focusing method with the same specifications, the focus group was designed to implement a quiet and high-speed AF, and the lens was designed to meet the target performance by suppressing optical aberration even when moving. The modulation transfer function (MTF) is the most fundamental indicator that can strategically evaluate the resolution of an optical lens and represents the contrast transmission ability according to the spatial frequency [30].

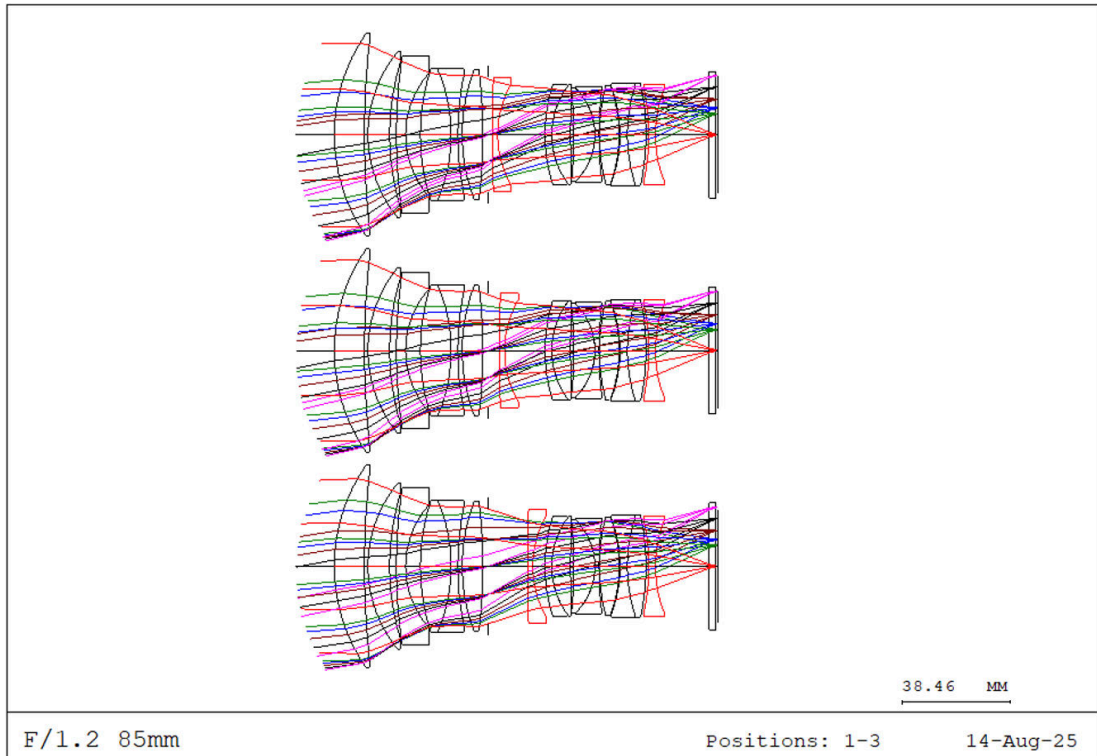


Figure 9. Optical path diagram according to the change of object distance.

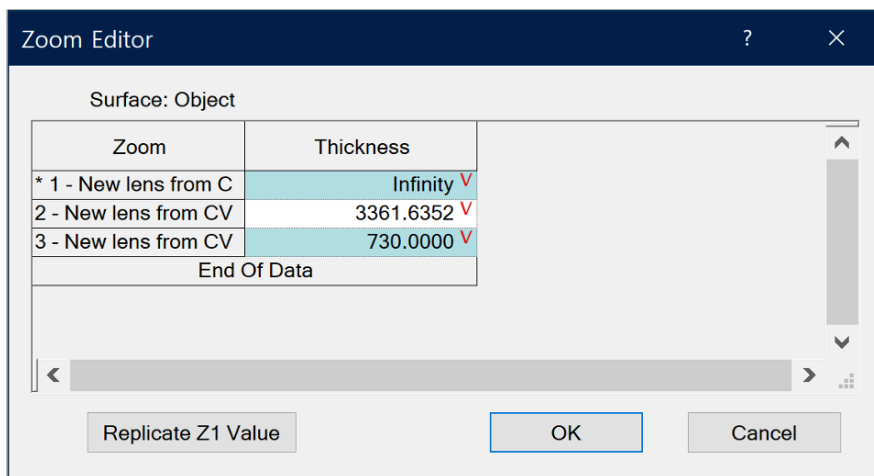


Figure 10. Object distance in this design in the CODE V software.

Therefore, it is considered a standard for evaluating the performance of an optical system. Figure 11 shows the through-focus MTF performance when the object distance of the designed optical system is infinite. The right part of figure 11 is weighted in this design based on the opposite angle size of 21.63 mm of the full-frame photographing device and shows the designed field. The solid and dotted lines indicate the angular, tangential and sagittal directions [31]. The MTF was confirmed to be 30 line pairs (lp) mm^{-1} , which is the spatial frequency provided by the exchange lens.

The results show that the performance was close to 80% from the centre, and the performance was roughly 69% in the last field, that is, at the edge of the screen. When designing the optical system in this study, three zooms were added to achieve the performance of each infinite object point of 0.025 $\times$ and 0.12 $\times$. Figure 12 shows the MTF at 0.025 $\times$ and 0.12 $\times$.

When moving the AF group from an infinite point at a magnification of 0.025 $\times$, we observed that the performance degradation was insignificant, as shown in figure 12a. Therefore, if only one lens is moved, the sensitivity to aberration is low, and sufficient AF performance can be achieved. In

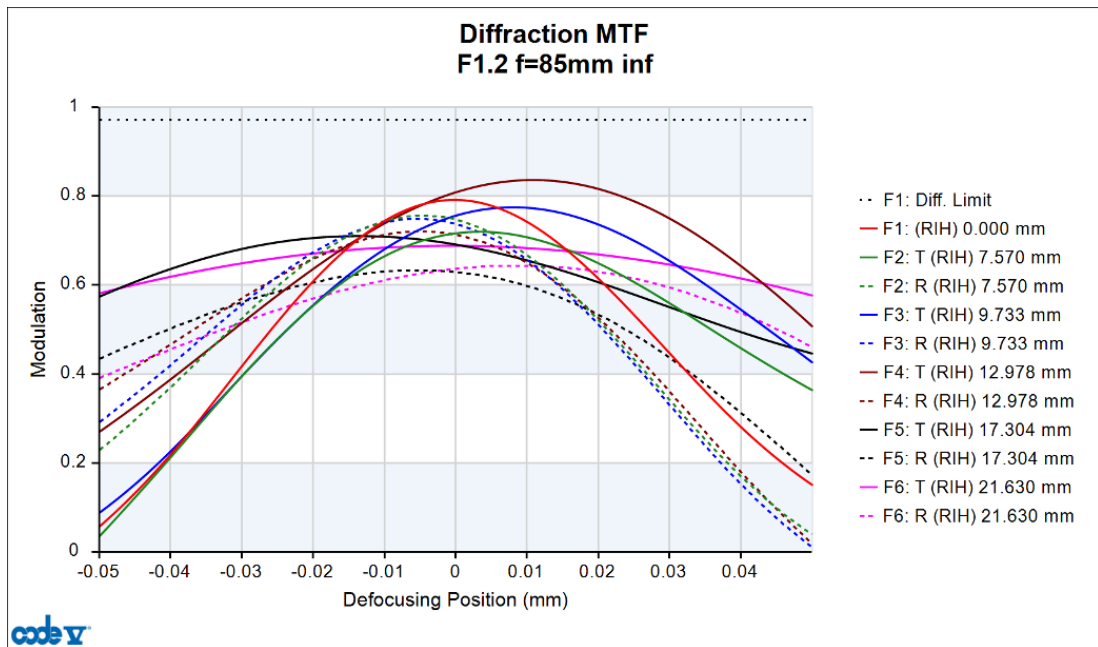


Figure 11. Zoom1 MTF at 30 lp mm^{-1} .

addition, the MOD in figure 12b induces background blurring out of focus; therefore, it does not set the peripheral performance high. Therefore, in fields F6 and F5, which are the edges of the screen that do not matter if the performance collapses, the performance was intentionally not achieved. Thus, higher performance could be achieved in other areas. For MOD-centred performance, more than 60% was secured, and the target resolution performance was satisfactory. The MTF allows the evaluation of the resolution of the optical system [32]. However, no matter how high the resolution is, if the aberration is not properly captured, the quality of the image is affected. Therefore, both resolution and aberration controls are required when designing an optical system. Figure 13 shows the longitudinal aberration diagram at an infinite object point.

The spherical aberration can be confirmed by looking at the first figure of the longitudinal aberration, where the vertical axis is the incident height of the light beam, and the horizontal axis is the focus position. Spherical aberration is the basis of all aberrations and is considered important when obtaining high resolution because it affects the screen-centred performance. In general, wide-angle aberration, astigmatism, magnification, chromatic aberration, top curvature and distortion aberration tend to increase when wide-angle lenses are used. Meanwhile, as the telephoto lens is expanded, the effects of the spherical and axial chromatic aberrations tend to increase. In addition, in a lens with a low F-number and a large aperture, such as in the design of this study, the height of the light beam, i.e. the longitudinal axis of the spherical aberration, is lengthened so that the spherical aberration is likely to increase accordingly. However, in the proposed design, we can observe that spherical aberration was corrected well despite the large aperture of F/1.2. Axial colour refers to the difference in BFL according to wavelength and is an aberration that appears at the centre of the screen [28]. Because the lens can change its angle of refraction depending on the wavelength of the light, the position of the focus is misaligned. As a result, chromatic aberration occurs, and a specific colour may spread, or colour smudging may be observed in the centre. The longitudinal aberration can be seen when looking at the difference in the focal position at an incident height of 0.00 (i.e. near the optical axis) for each wavelength.

In the case of the optical system of this study, the target was set to $65 \mu\text{m}$, and ED lenses, crown materials and flint materials were appropriately used in the bonding lens to achieve the target longitudinal aberration. The spherical and longitudinal chromatic aberrations explained above are aberrations that indicate the performance of the centre of the image; however, field curvature is an aberration of the periphery of the image. That is, when the focus is on the centre during shooting, the surrounding images appear blurry if the field curvature is large. The curvature of the surface is expressed in the sagittal and tangential directions, and the difference between the two is called astigmatism [33].

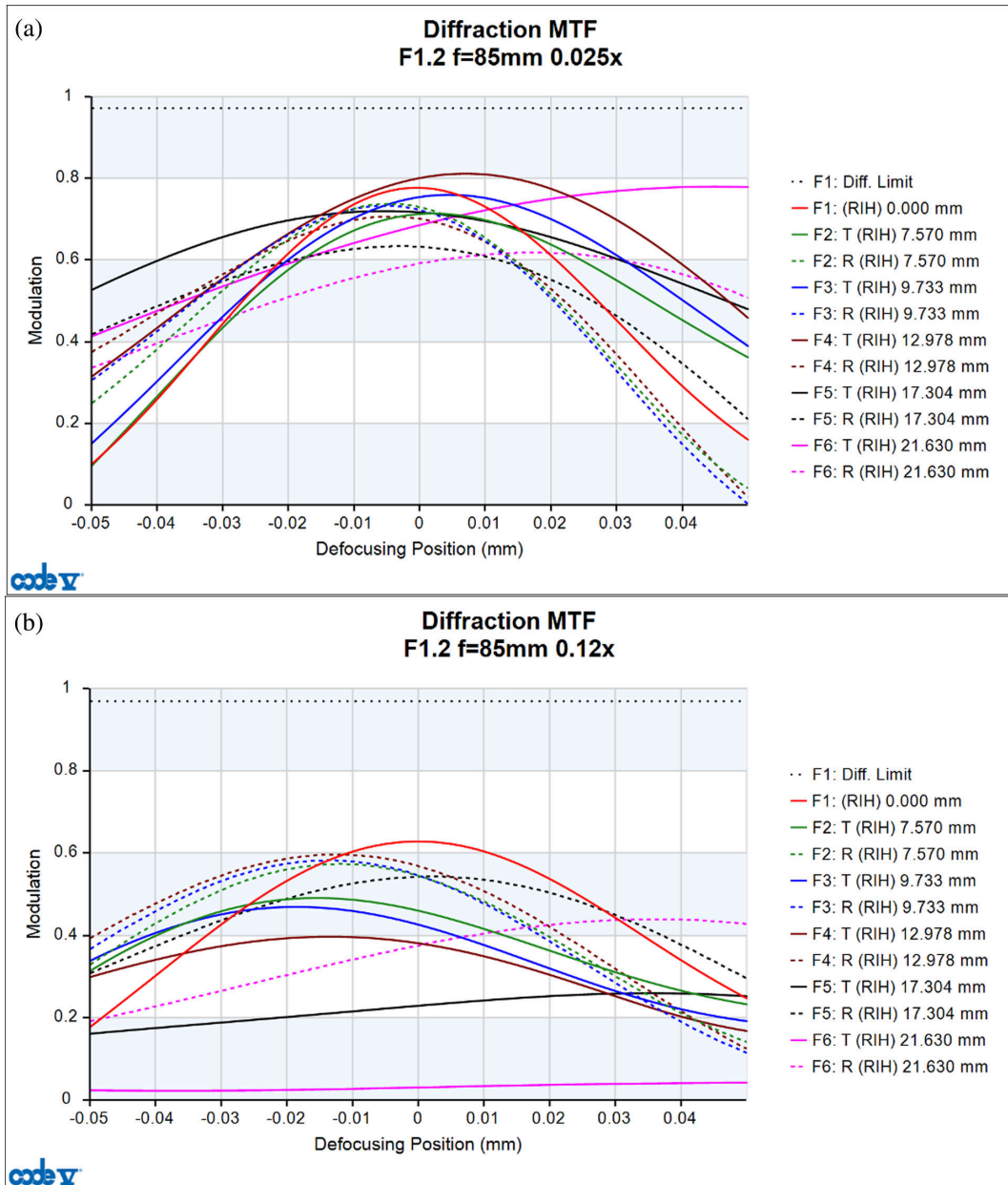


Figure 12. Diffraction MTF at (a) 0.025 $\times$ and (b) 0.12 $\times$

In the upper surface curvature of the optical system in this study, as shown in the second graph in figure 13, we can observe that the difference between the sagittal and tangential curves was not large in all fields up to the maximum height, which means that the difference in focus across the entire image area was not large, and the performance in the periphery was appropriately captured. The last graph in figure 13 illustrates this distortion. Distortion is the difference between the root-axis calculated value of the main light line and the finite-light calculation value [34]. Unlike other aberrations, this is not an aberration that degrades the quality of the image, but an aberration that changes the shape of the image. In the case of distortion, depending on the sign of distortion, (–) and (+) appear to be a barrel and a pincushion type, respectively. In telephoto lenses, the distortion mainly appears as a pincushion type and is controlled to a level that was not noticeable at 1.5%.

Figure 14 shows the field curvature of a single lens. Field curvature refers to a phenomenon in optical systems in which the plane of the image is not actually flat but rather has a curved shape, as shown in the figure. While the central rays focus on the right positions, the surrounding rays focus on a relatively shorter position, leading to an out-of-focus periphery of the image. This can be expressed as a decrease in the image quality at the periphery of the optical system.

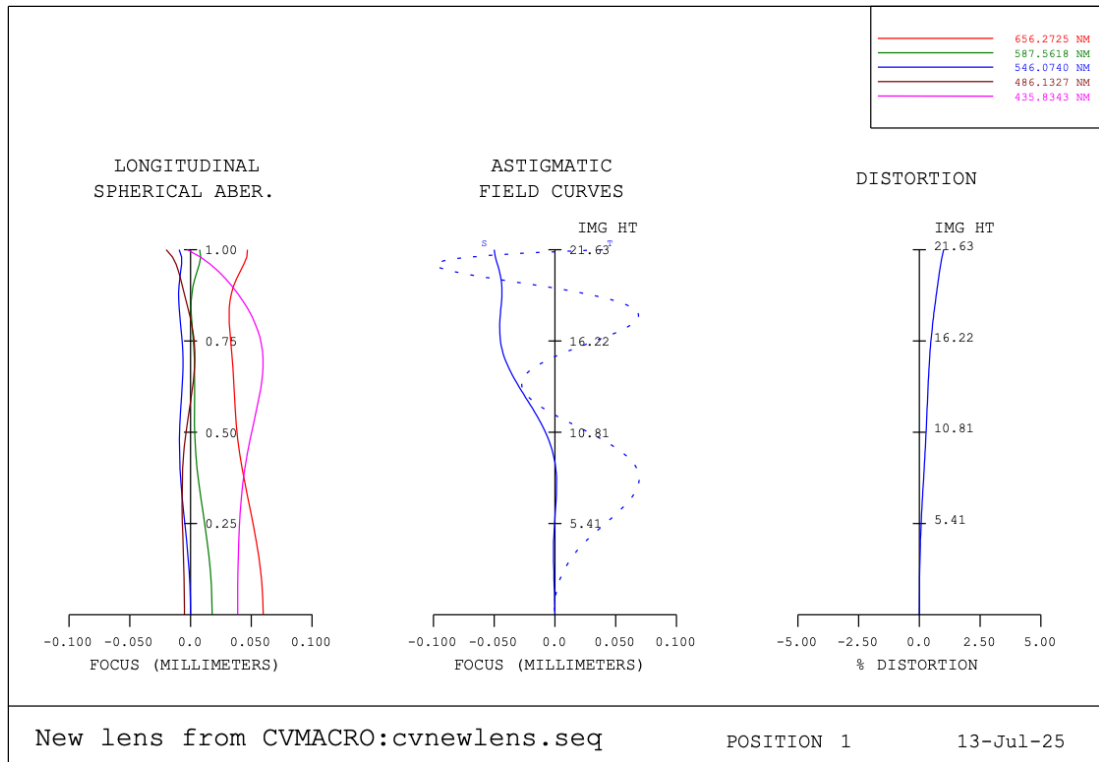


Figure 13. Longitudinal aberration at an infinite point.

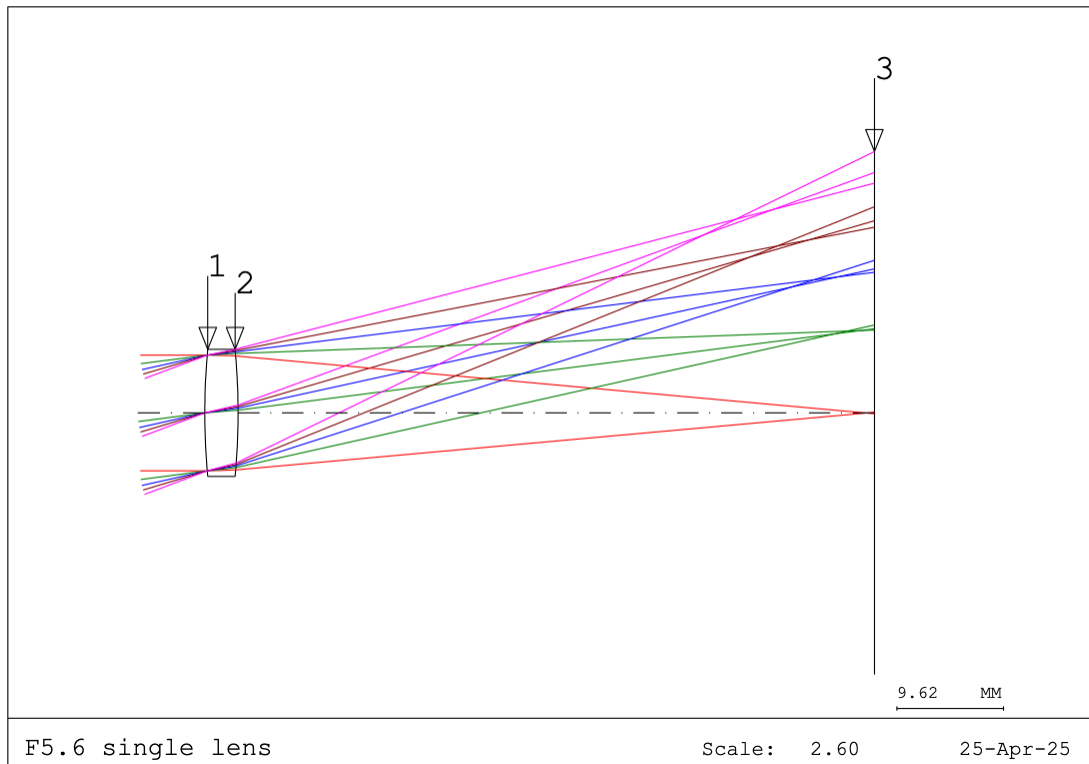


Figure 14. Field curvature in a single lens.

Figure 15 shows a longitudinal aberration diagram when the magnification was 0.025 $\times$. Looking at the following aberration diagram, we can observe that even when the magnification was changed by moving the AF lens group, the aberration owing to the movement of the AF lens does not decrease significantly compared with the infinity point and was corrected well.

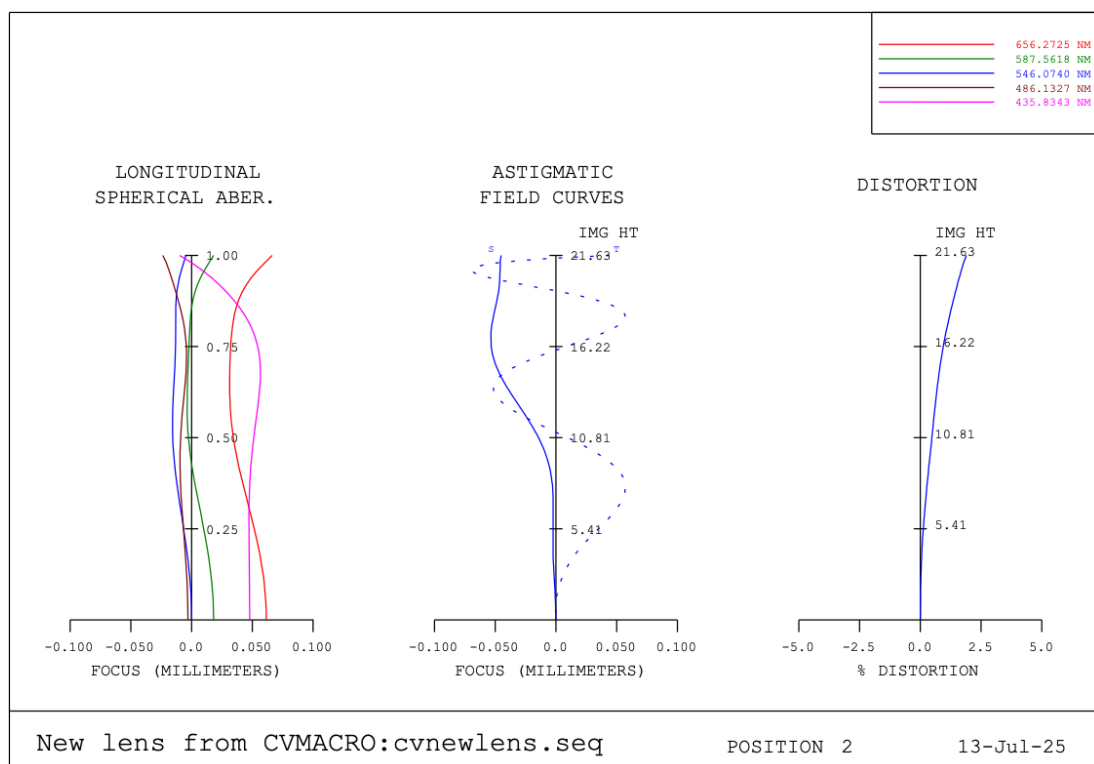


Figure 15. Longitudinal aberration at 0.025 $\times$.

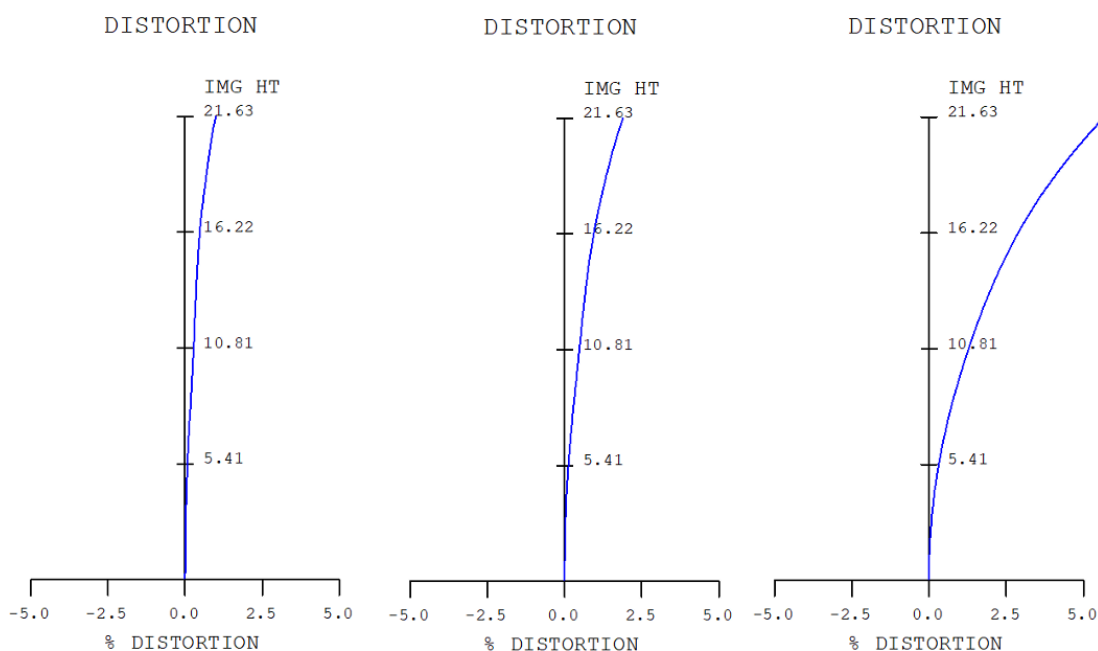


Figure 16. Distortion graph by object distance.

Figure 16 shows the distortion values at infinity, 0.025 $\times$ and 0.12 $\times$ positions. At infinity, the distortion was suppressed to less than 1.0% and was barely noticeable. It increased to approximately 5.0% at the maximum magnification (0.12 $\times$). However, because the out-of-focus effect is often intentionally used to create a peripheral blur effect owing to the nature of medium telephoto lenses, this level of distortion does not lead to a real decrease in image quality. Additionally, the distortion curve was designed to increase in only one direction without reversing in the middle to minimize the visual discomfort caused by changes in the distorted shape.

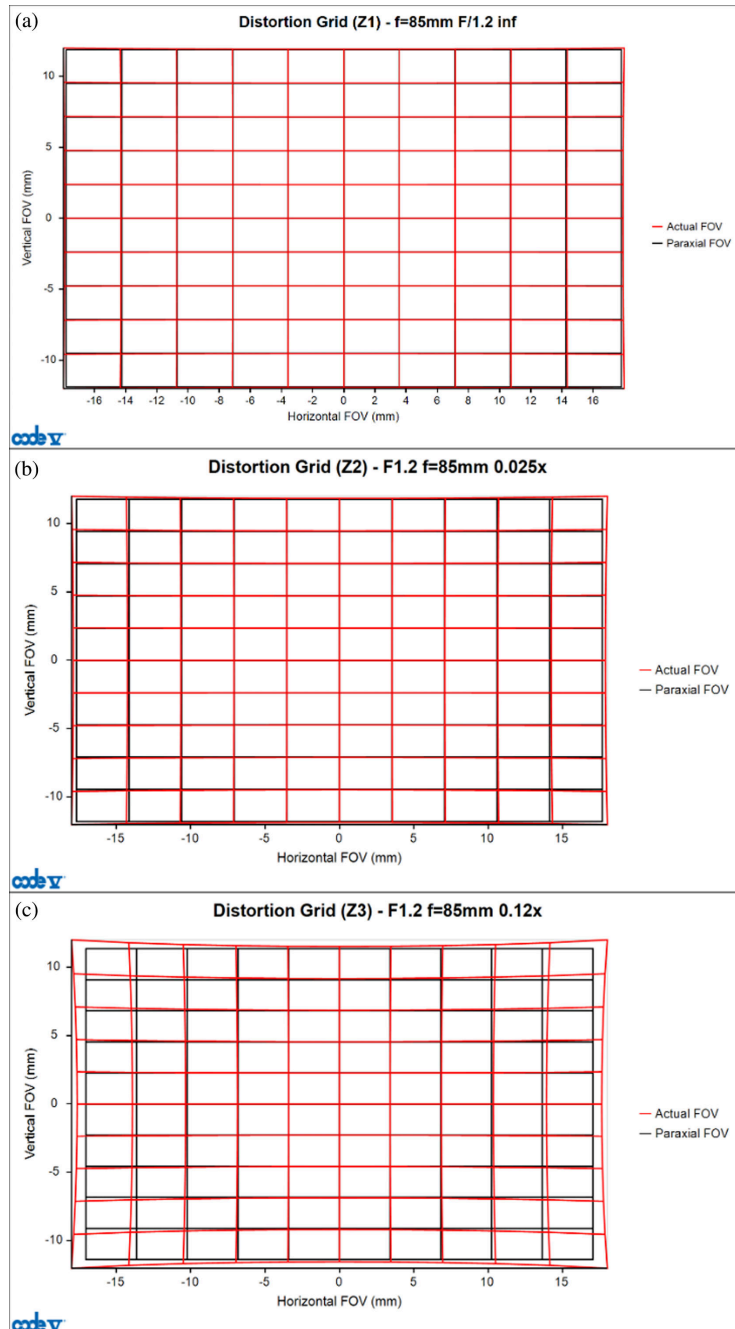


Figure 17. (a) Distortion grids at zoom 1 (infinity), zoom 2 (0.025 $\times$) and zoom 3 (0.12 $\times$) positions.

Figure 17 shows a distortion grid from infinity to the near field, to allow visualization of the distortion pattern. The black and red lines represent ideal and actual image positions, respectively. We can observe that the grid spreads outward toward the periphery, and a distortion of the pincushion type (needle-shaped, +) shape occurs. This phenomenon is common in telephoto lenses.

Figure 18 compares the MTF data for each field at 10 and 30 lp mm^{-1} at the infinite object distance, which was set as the initial design goal, between the proposed optical system and the optical system. Figure 18a,b shows the MTF performance data of the designed optical system and the NIKKOR Z 85 mm F/1.2 S optical product, respectively. The solid and dotted lines represent the sagittal (radial) and meridional (tangential) directions. In figure 18 the x - and y -axes represent the image height and the MTF values, respectively. In figure 18a, the upper and lower curves represent the MTF at 10 and 30 lp mm^{-1} , respectively. In figure 18b, the red and blue lines represent the MTF at 10 and 30 lp mm^{-1} , respectively.

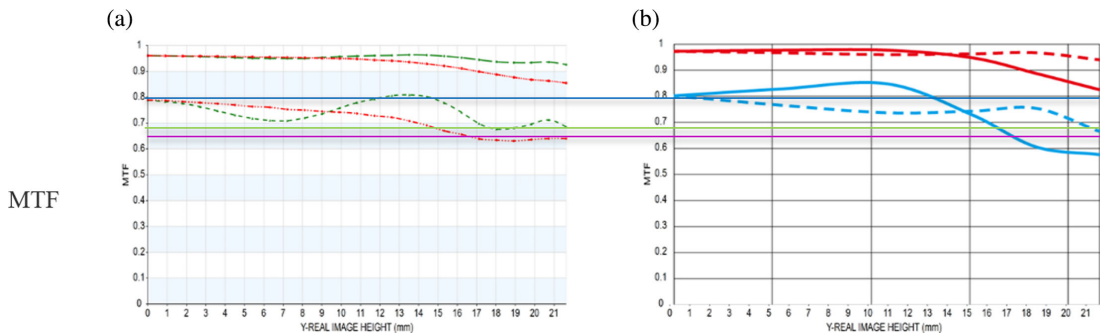


Figure 18. MTF versus field of (a) our design and (b) NIKKOR Z 85 mm F/1.2 optical lens product. The x -axis and y -axis represent the field's position and MTF, respectively.

Table 2. Performance parameter comparison between our optical system and the NIKKOR Z 85 mm F/1.2 product.

products	our optical design	NIKKOR Z85 mm F/1.2 S
lens configuration	10 groups and 15 elements (2 aspherical elements)	10 groups and 15 elements (2 aspherical elements)
focus type	inner focus	floating type
minimum focusing distance	0.86 m	0.85 m
maximum magnification	0.12×	0.11×
filter size	82 mm	82 mm
length	117.3 mm (up to the last surfaces of the design standard)	141.5 mm (from the filter to the mount surface)

The MTF at 10 lp mm^{-1} reflects the contrast characteristics of the image, whereas the MTF at 30 lp mm^{-1} reflects the resolution in the high-frequency range, i.e. the sharpness characteristics. In [figure 18a](#), the difference between the sagittal and meridional direction curves is not large; therefore, stable performance is maintained without sudden aberration changes across the entire field. In particular, a high resolution of approximately 70% is maintained at 30 lp mm^{-1} from the image centre to the last field point, indicating that astigmatism is well suppressed. However, [figure 18b](#) shows very good MTF performance of approximately 85% at 10 lp mm^{-1} near the 10 mm image height. As the field position increases, the meridional direction curve decreases relatively quickly, and the performance tends to decrease to less than 60% at the image periphery. In comparison, the proposed optical system exhibits an overall flat and balanced MTF distribution. Thus, excellent optical performance is achieved, especially in terms of high-frequency performance. Therefore, the data shown in [figure 18](#) go beyond a simple numerical MTF comparison and demonstrate that the proposed inner-focusing structure based on single lens group movement can maintain uniform and stable MTF performance across the entire field of view, even in the high-frequency range of 30 lp mm^{-1} .

To improve the readability of the comparison, [figure 18](#) shows a reference line based on the performance of the optical system proposed in this study. The comparison was made at 30 lp mm^{-1} , which evaluates the resolution, and the blue line is a line set based on the centre MTF performance of the design in this study. The green line is a line based on the meridian direction full-field MTF performance of the design in this study under the same conditions, and the purple line was used as a reference line indicating the sagittal direction full-field MTF performance of the design in this study, allowing for intuitive confirmation of the performance change of the optical system to be compared with the proposed optical system.

In [figure 18b](#), the floating design, which simultaneously moves two lens groups, is advantageous in terms of aberration correction, but inevitably increases structural complexity and weight. In this study, despite the large-aperture telephoto optical system with an F/1.2 aperture, an inner focusing structure was adopted, which moves only a single lens group.

As compared in [table 2](#), our designed optical system could provide a higher magnification than the NIKKOR Z85 mm F/1.2 S optical product and also shortened the overall length of the optical

system. While the commercial optical system being compared adopted a floating focusing structure in which two lens groups move simultaneously, this study applied an inner focusing structure in which only a single lens group moves. Although floating focusing structures may have advantages in terms of aberration correction, they may increase computational complexity and structural complexity because two lens groups must be precisely controlled simultaneously during the focusing process. Additionally, using two motors increases the weight, and the overall length may be longer to ensure movement space. Even if we add 3–4 mm of mount length to compare it under the same conditions as NIKKOR Z85 mm F/1.2 S, we can show an optical system overall length that is about 20 mm shorter. This has enabled the implementation of a lightweight focusing structure of the inner focus type, while reducing the overall length of the optical system and effectively suppressing aberration changes owing to lens movement, achieving both fast AF performance and high-resolution image quality.

4. Conclusion

In this study, we have proposed a movable internal focusing structure that overcomes the technical limitations of the existing method in the design of an F/1.2 large-aperture 85 mm single-focus lens and satisfies all high-performance, lightweight and high-speed AF for mass production in a factory. Existing 85 mm and F/1.2 optical systems have adopted a complex floating structure that moves multiple lenses, uses a high-torque motor, or moves two or more lens groups. Moving multiple lenses increases the weight of the focusing group, which makes it difficult to secure sufficient speed and precision with a stepper motor. Moving two or more groups also involves various problems, such as mechanical and electronic control complexity. We also designed a stepper motor-based focusing method that moves only one lens. This simplifies the design of the instrument, improves productivity and enables the fast and precise AF performance required by mirrorless cameras in mass production. In the design process, the Nikon NIKKOR Z 85 mm F/1.2S product was set as the main comparison target, and the purpose was to simplify the structure while satisfying the same F/1.2 specifications.

Our final design was completed in 15 pieces, including two aspherical lenses and one ED lens, effectively suppressing spherical and axial chromatic aberrations, which are particularly susceptible to telephoto design. Aspherical lenses contributed to spherical aberration control, whereas ED lenses contribute to chromatic aberration correction. As a result, high resolution could be maintained not only at the infinite object point but also at the MOD.

As a result of the MTF analysis, this design achieved very high resolution in the centre and uniform and stable performance in the periphery. It exhibits excellent response characteristics even in high-frequency regions. It also showed excellent MTF performance compared with the Nikon NIKKOR Z 85 mm F/1.2 S product.

Our design secures a high resolution of approximately 80% in the centre and at least 68% in the periphery, although it did not significantly reduce the performance across the entire range. As may be observed in [figure 18](#), unlike the Nikon NIKKOR Z 85 mm F/1.2 S product, which was set as a comparison target, whose performance deteriorated sharply to less than 60% in the periphery, the proposed optical system maintained stable and uniform performance throughout the entire range.

Unlike a floating structure that moves a large number of lens groups, this design also reduces mechanical complexity by moving only one lens group, thereby alleviating the difficulty of designing the instrument and the burden of electronic control. As a result, the goals of lightweight and improved AF speed were achieved simultaneously. This work presents a practical alternative that can maintain high performance while minimizing the problem of lightening the focusing group in large-aperture lens design.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. All the data presented in this study are included in the article, so there are no additional data. Datasets for this research work are available from the Dryad Digital Repository: [35].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. Y.N.: conceptualization, data curation, investigation, methodology, writing—original draft; Y.J.J.: conceptualization, data curation, investigation, methodology, writing—original draft; J.R.: conceptualization, data curation, investigation, methodology, project administration, writing—original draft; H.C.: conceptualization, data curation, investigation, methodology, project administration, writing—original draft.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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