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AUTOMATED DESIGN OF ZOOM RIFLESCOPE WITH EXTENDED PARAMETERS

Background. Designing an arbitrary afocal zoom optical system is a complex and multidimensional problem. It cannot be solved analytically and requires the essential experience and efforts of the designer.
Objective. The purpose of the paper is to present and verify by simulation the method and means to perform an automated design of complex multi-lens afocal zoom optical systems having variable parameters and characteristics.
Methods. Using the developed specialized software with implemented modification of the adaptive Cauchy differential evolution algorithm for the parametric synthesis of multi-component optical systems of zoom riflescopes with extended functional parameters.
Results. The developed optical system of the riflescope provides the 5Ч magnification ratio and the angular field of view in the object space from 3.26° to 0.83°. It has a reticle located in the first focal plane, the entrance pupil diameter of 60 mm, the eye relief within the range of 106...111 mm, and the maximum system length of 390 mm. The riflescope contains 13 lenses in 10 components. The performed simulations showed that the time interval required for the direct automated design of the riflescope's optical system is about 30–40 hours for the total number of unknown parameters (variables) equal to 91. The root-mean-square values of the angular aberrations of axial beams in all (five) configurations of the synthesized zoom system do not exceed 1.25 arc minute in the whole spectral range. The algorithm helps to determine the prescription data of optical systems, considering the technical requirements and restrictions specified by the designer.
Conclusions. Computer simulations of the development of the zoom riflescope with the magnification of 5-25Ч, the entrance pupil diameter of 60 mm, and the reticle located in the first focal plane have confirmed the effectiveness of the proposed algorithm to design automatically complex multi-lens optical systems with variable parameters. The obtained results proved the high image quality of the generated 13-lens riflescope with the long eye relief. The implemented modification of the adaptive Cauchy differential evolution method can be considered a powerful tool that helps to automate the parametric synthesis of multicomponent optical systems of zoom riflescopes, taking into account the requirements set by the designer. Future research should test the feasibility of the automated design of other riflescopes containing more lenses and providing extreme performances.
Keywords: automated optical design; zoom riflescope; optical system; parametric synthesis; global optimization; aberration.

Introduction

Due to its complexity and variety, the design procedure for multi-element optical systems is usually a lengthy and iterative process. It requires significant designer experience and must consider many technical requirements and design constraints [1–4]. The design procedure becomes more complicated for afocal zoom optical systems since, throughout the range of used magnifications, all images must be at infinity, the position of the exit pupil is to be practically unchanged, and the system must provide a high image quality.

The design process is reasonably divided into separate stages to simplify the task in practice. Only the first-order parameters of individual components are determined in the first stage [5, 6]. Then, zoom system components are often implemented as achromats to decrease chromatic aberrations. However, even this does not help the designer correct the

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residual chromatism in the entire range of the component movements.

A serious number of works were devoted to zoom systems design (for example, [7–13]). However, no 'universal' approach was found for obtaining optimal solutions.

Brief review of methods for designing zoom optical systems

An analytical solution to the problem of parametric synthesis for an arbitrary zoom optical system is not possible due to the complexity and multidimensional nature of the problem. In this regard, the following common approach is often applied to design zoom optical systems. According to it, the first-order properties and the trajectories of component movements (loci) are first determined [7–13]. All components are synthesized based on the 3rd-order aberration theory. Then the whole optical system is 'assembled' from the obtained elements, and a local optimization algorithm is launched. The local optimizer improves the existing starting solution by introducing relatively small changes in variable prescription data. It involves the computation of the first and second derivatives at each step. The iterative process continues until the algorithm finds an optimal solution or an offered time limit expires. Despite the advantages, the design approach has several drawbacks, the main of which are the following: the design procedure is quite lengthy; it requires the active participation of the designer; the solution is limited to lower-order aberrations, and the starting optical system must provide high image quality.

Global optimization methods have been increasingly used in different fields of science and technology to overcome (or at least reduce) design difficulties [14–17]. They determine a pseudo-optimal solution in a multidimensional set of possible solutions satisfying the designer's requirements. The merit functions are often compound mathematical functions containing individual components with different weights. Thus, global optimizers reduce the dependence of the result on the designer's experience and can provide (although not guarantee) a desired or acceptable solution to complex technical problems.

Various global optimization algorithms have been actively used also for the design of optical systems in recent years [18–32]. Thus, Young introduced a point-by-point design algorithm that allows obtaining free-form imaging systems with improved characteristics [22]. Paper [23] presented a multi-objective approach of evolutionary memetic optimization dividing the process into three different phases: selection of optical glasses, analysis of possible solutions, and the detailed study. In papers [24–26], a genetic algorithm helped to develop classic lenses and zoom systems with linear and mechanical compensation of image plane shift. Two versions of the ant colony optimization algorithm were implemented and tested for optical design problems [27]. A method of automatic design of a medium-wave infrared zoom system was described in papers [28, 29]. Similar global search algorithms were successfully applied for the developments of varifocal lenses, aspherical lenses, X-ray lenses [30–33], or finding the starting schemes of zoom systems [34, 35].

Despite the above-mentioned, to date, there are few publications devoted to partial or complete automation of the procedure of aberration design of zoom optical systems (and, in particular, riflescopes).

Problem statement

The aim of this work is to test the effectiveness of automated parametric aberration synthesis of a complex multi-lens optical system of riflescope with variable parameters. Such verification is done by computer simulation of the developed procedure using one of the modern global optimization algorithms.

In particular, for the parametric aberration synthesis of the optical system, it is proposed to apply a modified version of the adaptive Cauchy differential evolution method [36, 37]. In this method, each point of the current population stores its numeric values of the scaling and crossover factors specific to classic differential evolution. The algorithm generates new random values of these parameters using the Cauchy distribution at each iteration. These random values have mean values obtained by averaging parameters within the population at the previous iterations. Compared with the Gaussian (normal) distribution, the Cauchy distribution function provides wider deviations of random values, which allows a more detailed study of the given merit function in the multidimensional parameter space. New values of specific parameters are saved for a generated trial point only if the merit function is improved. Thus, the algorithm adjusts its parameters for a current task. In general, the algorithm delivers fast convergence, the high quality of a solution, and is efficient when searching optimum values within the multidimensional functional space.

Earlier [38–43], the developed computer program implementing the modified versions of differential evolution has helped the authors to obtain the prescription data of different optical systems with fixed parameters in an automatic mode. Any surface radius, axial lens or air thickness, edge thickness, or glass parameter can be an optimization variable. In more complex cases, the optimization variables may include aspheric coefficients, specific parameters of optical surfaces (e.g., parameters of different diffraction gratings), and mediums data (including gradient mediums) [44]. In this work, however, such specific parameters are not involved. Due to the requirements of manufacturability and cheapness, all surfaces in the developed optical system must be spherical, and ordinary glasses only should be selected from the given catalog(s) for all lenses.

The proposed approach

The procedure of the parametric synthesis of an arbitrary optical system starts with setting the main functional parameters (like the spectral range, the field of view, and the relative aperture) and determining the overall component structure of the optical system. In this case, all lenses are distributed (by numbers) between the components.

Next, the optimization variables are to be selected. When designing optical systems containing only flat and spherical optical surfaces, such variables include surfaces' radii, axial lens thicknesses, and optical glass parameters. The designer should indicate the ranges of acceptable values and practically arbitrary initial values of all variables.

By freezing the marginal ray's exit angle at the rear optical surface of the system, one can ensure the desired fixed value of the effective focal length of the system. Obviously, for all configurations of the telescopic optical systems, this angle must be equal to zero, and thus their effective focal length will be infinite.

For the parametric synthesis of the optical systems, one can set a widely-used merit function minimizing the RMS sizes of light spots at the image surface for specified object field points of view. This approach does not require any level of image quality from the initial optical system, but it is significant to have the rays passing through the system from all object field points. Therefore, the initial optical system may be simply defined as a set of plane-parallel plates.

In the case of the synthesis of diffraction-limited optical systems, other merit functions can minimize the wavefront deformations for all specified beams or maximize the modulation transfer function values at different spatial frequencies and field points. Such merit functions are rational to use in the final stages of designing optical systems with high image quality.

When establishing the merit function, it is rational to set the limits for the total axial length of the optical system, acceptable ranges for axial and edge thicknesses, the maximum values of light heights, and other restrictions necessary for the physical implementation of the system.

The default elements of the merit function are often generated automatically by the developed software to simplify the merit function setup. Additionally, it is possible to restrict the maximum values of individual aberrations (e.g., spherical aberration, relative distortion, longitudinal or lateral chromatic aberration).

Then, the main design phase launches one of the global optimization algorithms implemented in the program. This automatic process does not require any participation of the designer. Because global optimization algorithms require essential computational power, this phase will be the longest in time. Therefore, it is rational to apply software providing concurrent calculations to shorten the time interval required for the optimization process.

In most practical cases, the global optimization procedure results in an acceptable final solution (of course, if such a solution exists under specified restrictions). If the algorithm is prematurely interrupted by the designer, a local optimization tool can be engaged to 'fine-tune' the image quality of the optical system.

Example of zoom lens design

As a numeric design example, a zoom riflescope optical system was chosen with the magnification of 5–25$^{\times}$ and the entrance pupil diameter of 60 mm. Its reticle is to be located in the first focal plane. The total number of lenses should not exceed 13. The angular field of view in the image space in all zoom configurations of the system should be at least 32° in the wide-angle mode and 40° in the narrow-angle mode. The riflescope should operate in the visible spectral range (0.47...0.656 μm) with the primary wavelength of 0.555 μm. Table 1 includes spectral data used in the simulation.

Table 1. Wavelength data used in the design

Wavelength, μm	0.41	0.51	0.555	0.61	0.656
Relative weight	1	2	3	2	1

Vignetting of rays is allowed in the wide-angle mode only when the exit pupil diameter exceeds 8 mm.

Fig. 1 illustrates a general schematic structure of the optical system of the zoom riflescope. From a functional point of view, the riflescope includes a two-component telephoto lens, a reticle plate, a two-lens fixed focusing component, a two-lens zoom module, and a four-lens eyepiece. The fixed focusing component with positive optical power reduces the light diameters of the next following zoom module. The zoom module itself contains two moving lenses to change magnifications. Notably, in this research, they are implemented as single lenses (not achromatic cemented doublets).

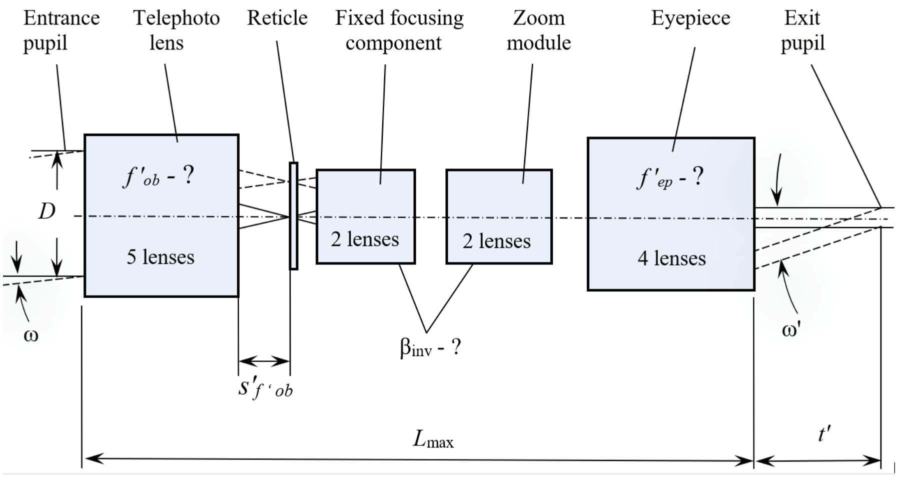

Fig. 1. General layout of the zoom sight optical system. Question marks indicate unknown parameters which are to be determined by the program

In the simulation, five zoom configurations were considered to achieve high image quality in the entire magnification range (5-25$^{\times}$). In each zoom configuration, the numeric values were pre-determined for the angular fields both in the object and image spaces, as well as the exit pupil diameters. Table 2 presents the established values of external functional parameters.

During the parametric synthesis of the riflescope, the minimum acceptable values for axial and edge lens thickness were set to 2.8 mm and 2 mm, respectively. The distance from the last surface of the telephoto lens' second component to the reticle plane should be between 10 and 80 mm. In all zoom configurations, the eye relief was within the range of 106 to 111 mm. For riflescope mounting reasons, the maximum surface light diameters were restricted to 23 mm for the inverting sub-system and 40 mm for the eyepiece. The total length L_{max} of the optical system (i.e., the distance from the front surface of the telephoto lens to the rear surface of the eyepiece) was limited to 390 mm.

The overall merit included several additional items to reduce the field curvature and provide a better quality of the real image formed by the telephoto lens at the reticle. These items forced the algorithm to correct transverse aberrations of a few meridional rays of the peripheral beam at the reticle's plane.

During the synthesis, almost all radii of optical surfaces and axial thicknesses were indicated as optimization variables. Besides, all glasses were selected by the program automatically from the glass catalog CDGM. The refractive indices for the primary wavelength were observed in the range of 1.45...1.85, while the Abbe numbers were from 20 to 88. The total number of unknown parameters (variables) was 91.

The initial optical system of the zoom riflescope was set identically in all zoom configurations. Fig. 2 shows its schematic view.

In principle, at any intermediate zoom configuration of the optical system of the riflescope, its angular magnification Γ can be determined by the formula:

$$\Gamma = \frac{f'_{ob}}{f'_{ep}} \beta_{inv},$$

Table 2. External parameters of the zoom riflescope

Zoom configuration	Magnification Γ, $^{\times}$	Angular field of view in the object space 2ω, degrees	Angular field of view in the image space 2ω′, degrees	Entrance pupil diameter *D*, mm	Exit pupil diameter *D*′, mm
1	25	0.83	41.2	60	2.4
2	20	0.98	39	60	3
3	15	1.22	36,8	60	4
4	10	1.74	34.6	60	6
5	5	3.26	32.4	42	8.4

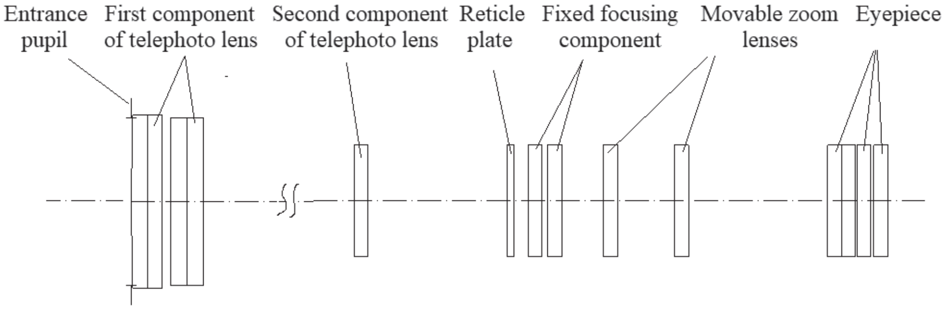

Fig. 2. Scheme of a starting optical system of the zoom riflescope specified as a set of plane-parallel plates identically in all zoom configurations

where f'_{ob} is the effective focal length of the telephoto lens; β_{inv} is the lateral magnification of the inverting subsystem which itself contains the fixed focusing component and the zoom module; f'_{ep} is the effective focal length of the eyepiece. Here it is important to note that the designer may not specify the numeric values of f'_{ob}, β_{inv}, and f'_{ep}, and the optical powers of the positive and negative components of the telephoto lens. In this research, all these parameters were not pre-determined in any form, and their optimum values were found exclusively by the global optimizer.

The simulation results show that the procedure of global optimization with 91 variables requires approximately 30–40 hours of work on a computer with an Intel Core i9-9900K processor (8 cores, 16 threads) operating concurrently. Fig. 3 illustrates the optical layout of the developed riflescope for different intermediate zoom configurations.

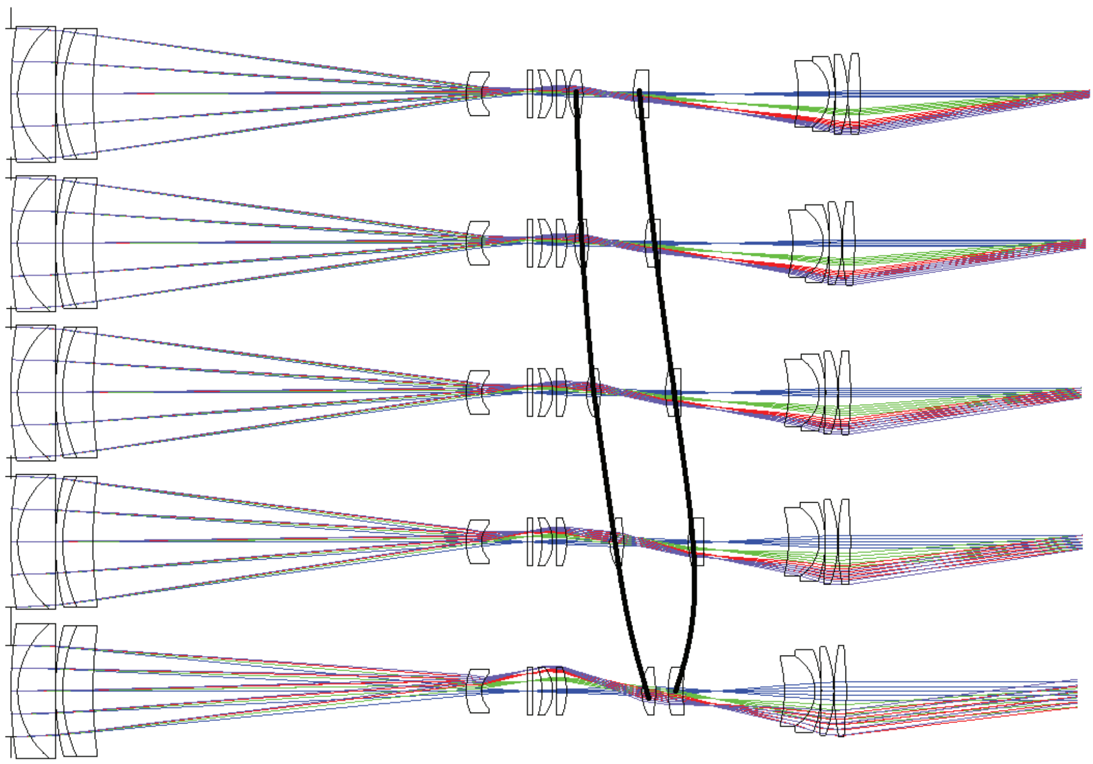

Fig. 3. Schematic diagram of the obtained zoom riflescope. The diagram shows the system in different configurations for magnifications Γ (from top to bottom): 25×, 20×, 15×, 10×, and5×.Thick curves indicate zoom lens trajectories. This optical system was synthesized automatically solely by the global optimization algorithm without applying the local optimizer

The program met all restrictions specified earlier by the designer for the prescription data of the lens system. The image quality of the obtained optical system can be estimated by the root mean square (RMS) values of the angular aberrations of the output axial beams. Table 3 includes their numeric values for five zoom configurations.

Table 3. Values of found angular aberrations of the developed zoom riflescope

Spectral range in which aberrations were evaluated	RMS values of angular aberrations in [arc. minutes] evaluated for axial field points at different visible magnifications Γ				
	$\Gamma = 25^{\times}$	$\Gamma = 20^{\times}$	$\Gamma = 5^{\times}$	$\Gamma = 0^{\times}$	$\Gamma = 5^{\times}$
The primary wavelength (0.555 μm)	0.61	0.49	0.35	0.28	0.65
Wide spectral range (0.47...0.656 μm)	1.21	1.00	0.77	0.64	0.97

As it is clear from Table 3, the RMS values of the angular aberrations of the axial beams in all configurations of the developed zoom riflescope system do not exceed 0.7 angular minute for the primary wavelength and 1.25 angular minute in the whole visible spectral range. It proves the high image quality achieved by the global optimization algorithm.

Future research should verify the feasibility of the considered approach for the automated design of high-quality zoom riflescopes, which will contain an increased total number of lenses, an extended magnification range, and improved functional characteristics.

Conclusions

Computer simulations of the development of the zoom riflescope with the magnification of 5-25$^{\times}$, the entrance pupil diameter of 60 mm, and the reticle located in the first focal plane have confirmed the effectiveness of the proposed algorithm to design automatically complex multi-lens optical systems with variable parameters. The obtained results proved the high image quality of the generated 13-lens riflescope with the long eye relief. The implemented modification of the adaptive Cauchy differential evolution method can be considered a powerful tool that helps to automate the parametric synthesis of multicomponent optical systems of zoom riflescopes, taking into account the requirements set by the designer. Future research should test the feasibility of the automated design of other riflescopes containing more lenses and providing extreme performances.

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Сокуренко В.М., Сокуренко О.М.

АВТОМАТИЗОВАНИЙ РОЗРАХУНОК ПАНКРАТИЧНОГО ПРИЦІЛУ З РОЗШИРЕНИМИ ПАРАМЕТРАМИ

Проблематика. Проектування довільної афокальної панкратичної оптичної системи є складною і багатовимірною задачею, яка не може бути розв'язана аналітичним способом та вимагає значного досвіду та зусиль конструктора.

Мета дослідження. Подати та перевірити за допомогою моделювання метод автоматизованого проектування багатолінзових афокальних оптичних систем зі змінними параметрами та характеристиками.

Методика реалізації. Використання розробленого спеціалізованого програмного забезпечення з реалізованою модифікацією адаптивного диференціального еволюційного алгоритму Коші для параметричного синтезу багатокомпонентних панкратичних прицілів з розширеними функціональними параметрами.

Результати дослідження. Розроблена оптична система забезпечує 5-кратний перепад збільшень та кутове поле зору в параметрах простору від 3,26° до 0,83°. Вона має прицільну сітку, розміщену в першій фокальній площині, діаметр вхідної зіниці 60 мм, видалення вихідної зіниці в діапазоні від 106 до 111 мм та максимальну довжину системи – 390 мм. Приціл містить 13 лінз у 10 компонентах. Проведене моделювання показало, що інтервал часу, необхідний для проведення безпосереднього автоматизованого розрахунку оптичної системи прицілу, становить близько 30–40 годин при загальних пошукових параметрах (змінних) 91. Середньоквадратичні значення кутових аберацій осьових пучків у всіх (п'ятих) станах синтезованої панкратичної системи не перевищують 1,25 кутової хвилини у всьому спектральному діапазоні. Алгоритм дозволяє визначити конструктивні параметри оптичних систем з урахуванням технічних вимог і обмежень, заданих конструктором.

Висновки. Комп'ютерне моделювання, проведене на прикладі розробки панкратичного прицілу з видимим збільшенням 5-25$^{\times}$, діаметром вхідної зіниці 60 мм та сіткою в передній фокальній площині, підтвердило ефективність запропонованого способу до автоматизованого розрахунку складних оптичних систем зі змінними параметрами. Отримані результати підтверджують високу якість зображення згенерованого 13-лінзового прицілу з віддаленою вихідною зіницею. Реалізовану модифікацію адаптивного методу диференційної еволюції Коші можна вважатися потужним інструментом, який дозволяє здійснювати автоматизований параметричний синтез багатокомпонентних оптичних систем панкратичних прицілів з урахуванням вимог, заданих конструктором. Наступні дослідження доцільно направити на перевірку здійсненності автоматизованого розрахунку інших прицілів, які мають більшу кількість лінз та забезпечують екстремальні характеристики.

Ключові слова: автоматизований розрахунок; панкратичний приціл; оптична система; параметричний синтез; глобальна оптимізація; аберація.

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