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PRODUCIBILITY ANALYSIS OF LENS SYSTEM DURING OPTICAL DESIGN STAGE

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Abstract

Subject of Research. The paper presents the idea of combining various stages of production of optical devices in a single logical sequence from the design of optical elements, through the mechanical and technological production stages, to the calculation of their manufacturing cost. This idea is all the more attractive because it is possible to control the entire process and save time and budget to decide on the most suitable production option already during the design stage. The information is important to be objective, related to the specific type and volume of production, and easily verified and controlled at the initial design stage. **Method.** The method consisted in combination of all stages for optical device creation on a "turnkey" basis, including the analysis and visualization of options for the device optical scheme, taking into account mechanical and technological aspects and calculation of the "project-product" cost, depending on the volume of production, with recommendations for its optimization. It is known that there are several alternative circuit solutions when designing optical elements, especially for image quality assurance approaching to the resolution diffraction limit: options for lenses containing only spherical surfaces or having different quantity of optical elements in the scheme, or lenses with non- spherical surfaces. At the design stage the choice is difficult. In this case, the decision is made taking into account the lens production technological processes. **Main Results.** The choice of the optimal lens optical scheme is performed. Evaluation of an optical device manufacturing possibility at the earliest stage is carried out, when the designed variants of its optical scheme, the manufacturing tolerances for optical elements and the volume of production are known. The manufacturing cost for optical elements of the given device for various variants of its optical scheme is determined. The study of alternative circuit solutions is carried out, for example, lens variants that contain only spherical surfaces or have a various number of optical elements in the scheme, or use non-spherical surfaces. At the design stage, the right choice is difficult. In the case presented in this paper, the solution is developed taking into account the technological processes of lens production. Aimed at this, a new software tool, called PanDao, has been applied providing a preview to producibility, fabrication technologies needed and production cost to be expected at the early design stage of optical systems. To illustrate the use of the PanDao software, two pinhole lens schemes have been developed and compared with a forward-facing input pupil that coincides with the aperture of the lens; the design of the first lens is consisted of the three spherical components, the second lens is a combination of four aspherical optical components. **Practical Relevance.** The possibility of manufacturability analysis for the lens system at the stage of optical design is shown, and determination of the optimal technological sequence of an optical device manufacturing is performed within the conditions of its production given volume. Modeling of the manufacturing process for various optical components gives the possibility to choose the optimal production chain and evaluate the need and cost of manufacturing, assembly and equipment testing. An additional advantage is the calculation of the device cost at an early design stage, which serves to optimize its optical scheme in some cases, and sometimes even avoid the prototyping stage. This approach is first implemented in PanDao software and is now available to a wide range of researchers.

Keywords
optical design, optical manufacturing, artificial intelligence, optical technology, lens, aberrations, tolerances, manufacturing cost, manufacturing cost analysis

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АНАЛИЗ ТЕХНОЛОГИЧНОСТИ ЛИНЗОВОЙ СИСТЕМЫ НА ЭТАПЕ ОПТИЧЕСКОГО ПРОЕКТИРОВАНИЯ

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Аннотация
Предмет исследования. Представлена идея объединения различных стадий производства оптических приборов в единую логическую последовательность от проектирования оптических элементов, через механическую и технологическую стадии производства, до расчета себестоимости их изготовления. Решение привлекательно тем, что можно контролировать весь процесс и экономить время и бюджет, чтобы выбрать наиболее подходящий вариант производства. Важно, чтобы эта информация была объективной, связанной с конкретным видом и объемом производства, и легко проверялась и контролировалась на начальном этапе — стадии проектирования. **Метод.** Предложено объединение всех этапов создания оптического прибора «под ключ», включая анализ и визуализацию вариантов оптической схемы прибора, учет механических и технологических аспектов и расчет стоимости «проект-продукт», в зависимости от объема производства, с рекомендациями по его оптимизации. Известно, что при проектировании оптических систем, особенно для обеспечения качества изображения, приближающегося к дифракционному пределу, существует несколько альтернативных схемных решений — например, варианты линз, содержащие только сферические поверхности и имеющие разное количество оптических элементов в схеме, или линзы, использующие поверхности, отличные от сферических. **Основные результаты.** Выполнен выбор оптимальной оптической схемы объектива и оценка возможности изготовления оптического прибора на самом раннем этапе, когда известны расчетные варианты оптической схемы, допуски на изготовление оптических элементов и объем производства. Определена стоимость изготовления оптических элементов данного устройства для различных вариантов оптической схемы. Проведено исследование альтернативных схемных решений — например, варианты линз, содержащие только сферические поверхности, имеющие различное количество оптических элементов в схеме или использующие поверхности, отличные от сферических. На стадии проектирования выбор затруднен, и в этом случае решение разрабатывается с учетом технологических процессов производства линз. Для иллюстрации использования программного средства PanDao разработаны и сопоставлены две схемы объективов с вынесенным входным зрачком, совпадающим с апертурной диафрагмой линзы: конструкция первого объектива состоит из трех сферических компонентов; второй объектив — комбинация из четырех оптических компонентов асферической конструкции. **Практическая значимость.** Показана возможность анализа технологичности линзовой системы на этапе оптического проектирования, а также определение оптимальной технологической последовательности изготовления оптического прибора в условиях заданного объема его производства. Моделирование технологического процесса изготовления различных оптических компонентов позволяет выбрать оптимальную производственную цепочку и оценить необходимость и цены изготовления, сборки и испытаний оборудования. Дополнительным преимуществом является расчет стоимости устройства на ранней стадии проектирования, что помогает в ряде случаев оптимизировать его оптическую схему, а иногда даже избежать стадии прототипирования. Этот подход впервые реализован в программном обеспечении PanDao и теперь доступен широкому кругу исследователей.

Ключевые слова
оптическое проектирование, оптическое производство, искусственный интеллект, оптические технологии, линзы, аберрации, допуски, производственные затраты, анализ затрат на изготовление

Introduction

Computer technologies are taking up more and more space in various fields of science, production and life, penetrating into areas where previously their implementation would have been difficult to imagine. One of these recent examples is a multidisciplinary project at the intersection of optical systems design, manufacturing processes of optical elements, and the cost of their production.

Optical design consists of starting point selection, where the number of optical elements and their position is selected. The next designer controls technical specification and image quality.

The design of optical devices characteristically exhibits the presence of several technical solutions [1]; the difference between them is not obvious. It is possible to choose the best one, for example, by determination of their optimal production chain, and comparison of production costs for alternative variants.

These issues are successfully solved by using the recently developed PanDao software tool[1]. In brief, PanDao is a software which analyses optical layout and tolerances prepared by an optical designer. Subsequently, it recommends a technological fabrication chain and calculates production cost for the selected technologies.

[1] www.pandao.ch

Up to the present, existing software tools have been working separately to solve the problems of optical and mechanical design and create the technological chain of its production. So, software programs SYNOPSYS, OSD[1], CODEV[2], OPTICS STUDIO[3] gave to user an option to implement ray tracing, analyze optical elements and prepare optical layout with tolerances for optical elements which were never combined with technology of its production. After an optical designer, another specialist using different software, such as MOLDEX 3D[4], presents the process of lens technology chain and production of plastic optics by applying injection molding only. As a rule, these engineers are not connected and often work in contradiction. This fact slows down the process of optical device production and increases its cost.

During the generation of optical systems, three different entities are involved subsequently:
1) initially, optical system designers are translating performance parameters into optical system parameters such as types of glass used, lens geometries, surface shape accuracies, roughness and mid-spatial frequency errors as well as types of coatings applied;
2) subsequently, optics manufacturing designers translate optical system parameters into a well-designed production chain employing machinery with optimized sets of fabrication parameters such as abrasives being used [2], machining kinematics, resonance frequencies, or sputtering rates being applied;
3) finally, production managers use the installed optical fabrication chain to manufacture the optical system applying optimized batch sizes and well-trained operators at high atomization levels.

Traditionally, it is the optical designers who are negotiating with customers about the "optical system" product including specifications, prices and issues concerning manufacturing, coating, mounting and delivery of product.

While optical system designers are well supported by software tools to design the optimum set of optical elements, there are no such tools existing to design the optimum fabrication chain needed for production. As far as optical fabrication is concerned, optical designer's decisions are restricted to their personal experiences from the earlier negotiations with their company or their suppliers' optics workshop. The reason is that optical fabrication technologies are not a part of optical designer's training, such as material science, machine tool metrology, mechanical engineering, abrasive machining, fabrication process parameters control, chemical engineering and a profound understanding on the science behind the "golden hands of the opticians".

Background and problem statement

The process of any optical device production is quite complex and contains several necessary steps, and not all of them have already been computer-integrated. Fig. 1 shows a general sequence for an optical device production, including all steps, from the technical requirements when an optical designer creates an optical system and calculates tolerances. Optical parts cannot "hang in the air", they must have housings and other mechanical parts, which are implemented on the step two by another person (a draftsman). The third step consists in preparation of technology process by a team of specialists. Finally, an optical device is produced in a workshop, and after testing it is ready. All these steps were traditionally separated. It seems logical to create links between existing software programs and unite various software tools using special algorithms. PanDao program, being discussed in this publication, has created the tool, which is first of all useful for an optical designer to go through the following steps to estimate many things, such as: complexity of optical system, drawing works, check of tolerances, determination of the approximate production cost for various variants. For example, step one in Fig. 1 does not lend itself to algorithmization, and despite a fairly large number of computer-aided design programs, the selection process of the final version to be manufactured is far from unambiguous. It seems very attractive to solve this problem in conjunction with the subsequent steps 2–4. Then, having the estimated cost of each of the options, the choice becomes easier.

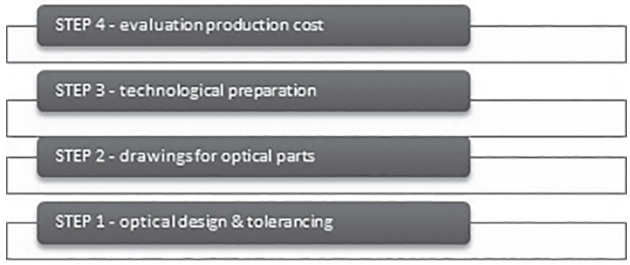

Fig 1. General sequence for an optical device production

Thus, among the above steps, one can select the design procedures, such as: design of optical components, design of optical circuits and mechanical components, or production preparation process, optical and mechanical parts and, finally, actual production and assembly of the device and, if needed, marketing (estimated cost of production of various variants of optical design). The steps presented in Fig. 1 are responsible for most of cost input.

Until now, the software has been developed for the design and construction stages, while the technological, production, and, especially, marketing aspects have not been sufficiently prepared for their algorithmization.

Thanks to the research of a group of scientists[5] [1, 3–5], this problem was solved as an Expert System, which provides knowledge unification within development of optical devices. The Expert System is the first step to start an artificial intelligent approach to this complex engineering field. The target of this research is to "explain" to a computer, not only how to design a lens, but also how

[1] http://www.osdoptics.com/
[2] https://www.synopsys.com/
[3] https://www.zemax.com/
[4] https://www.moldex3D.com/
[5] https://schott.com/

to make it. This is a very hard work, where optical experts in neighboring optical specializations have to be attracted.

Recently, within the PanDao software project, such tool has been developed, capable of predicting producibility, fabrication technologies required and expected production cost within the design stage.

PanDao method

Based on the know-how gained from decades of academic and industrial state-of-the-art manufacturing and experiences, an expert system like software tool has been developed.

PanDao is based on several databases as well as on the optical-expert know-how of designers, mechanical, electrical and chemical engineers, and optics fabrication technology specialists, who are working together to generate the information about manufacturing effect on optical element shapes to give optical designers an input data for optimum choice of parameters and tolerances on the early design stage.

PanDao includes expanded information sources, knowledge databases in the field of design, production and testing of optical devices. That way, optical designers can test their projects for producibility and find out the essential optical fabrication technologies needed for production. Furthermore, fabrication cost-impact analysis of optical design parameters is possible and design parameters can be optimized for minimum fabrication cost. Therefore, PanDao describes the whole fabrication chain including fabrication cost, coating cost, testing cost and centering cost during the optical design process. Aimed at this, PanDao creates a special algorithm to input lens parameters, calculate technological parameters depending on reasonable tolerances and find out prices depending on the above data and desired volume of production.

The PanDao algorithms contain know-how which is not opened in this publication, whereas we present an optical design case where we applied PanDao for optimization and as a decision-making tool for the best optics design. In the following, we give the examples how to use PanDao.

PanDao is user's friendly software. First, we download information files from[1] as well as tutorials from YouTube, contact PanDao manager, register, receive an access and start working.

Before starting PanDao we need to prepare an optical layout for an optical system planned for production with all parameters, specifications and tolerances. We get this information from OSDOPTICS[2], SYNOPSYS[3], ZEMAX[4] software, and some other software applications used for optical design. Depending on the type of software used for optical design, he/she inputs requested information into PanDao.com. The volume of production has to be input obligatory.

Working in a dialog with PanDao we get optical drawings for all optical elements and reports on technological chains for their production. In addition, costs are estimated.

[1] www.pandao.ch
[2] http://www.osdoptics.com/
[3] https://www.synopsys.com/
[4] https://www.zemax.com/

Design and analysis of a wide angle pinhole lens

Let us discuss the manufacturing of pinhole lenses for mobile phone cameras as they are booming now. Pinhole lens is a special objective, which is often used for safety and security applications because of small size of its entrance pupil. This lens has a variety of optical solutions, which fit to a wide range of technical specifications.

In the following, the optics designs of two optical systems for the same purpose are presented and they are produced in 10 000 lenses overall. Their producibility and the optimum optical fabrication technologies and fabrication cost are analyzed. The first system was designed of three spherical lenses presented as example 1 in Fig. 2 and the second lens is made of four all aspherical lenses, example 2, (Fig. 5). The system specifications are shown in Table 1, and they are the same for both examples. So, we have got two variants for the same technical requirements.

Where:

Note: All linear dimensions, such as: focal length, paraxial focal point, image distance, cell length, Gaussian image height, marginal ray height, chief ray height, entrance and exit pupil semi-apertures, entrance and exit pupil locations are given in millimeters.

Wavelengths (WAVL).

Angular dimensions chief ray angle is in angular degrees.

F/NUMBER has no dimension as it is a ratio of two linear values focal length and lens diameter.

Example 1. All spherical pinhole lens

The optical scheme of all spherical pinhole system is presented in Fig. 2. As one can see, the lens consists of three separated optical elements: two positive and one negative in between of them. This is a scheme of modified triplet with aperture stop in front of the lens. The lens was designed and optimized using software[5]. This lens quality is geometrically limited, which is confirmed by the numbers in Table 5 of modulation transfer function (MTF).

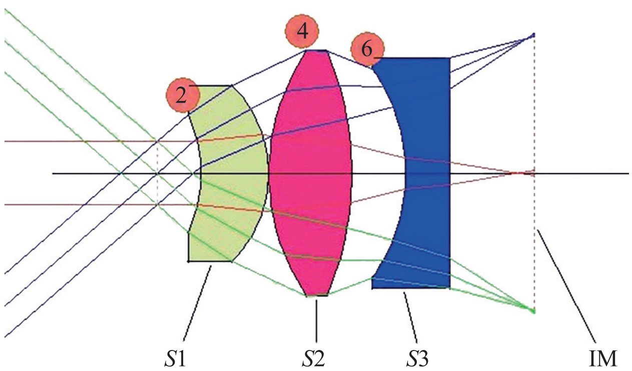

Fig 2. Pinhole triplet featuring three spherical lenses *S*1, *S*2 and *S*3; lenses form an image in the image (IM) plane

[5] http://www.osdoptics.com/

Table 1. System specifications for both design examples

Specification	Value, mm	Specification	Value, mm
OBJECT DISTANCE (TH0)	INFINITE	FOCAL LENGTH (FOCL)	1.6000
OBJECT HEIGHT (YPP0)	INFINITE	PARAXIAL FOCAL POINT	0.6683
MARG RAY HEIGHT (YMP1)	0.2500	IMAGE DISTANCE (BACK)	0.6683
MARG RAY ANGLE (UMP0), angular degree	0.0000	CELL LENGTH (TOTL)	2.3243
CHIEF RAY HEIGHT (YPP1)	0.0000	F/NUMBER (FNUM)	3.2000
SEMI-CHIEF RAY ANGLE (UPP0)	41.0000	GAUSSIAN IMAGE HT(GIHT)	1.3909
ENTR PUPIL SEMI-APERTUR	0.2500	EXIT PUPIL SEMI-APERTURE	0.3425
ENTR PUPIL LOCATION	0.0000	EXIT PUPIL LOCATION	–1.5238
WAVL	0.0006562700 0.0005875600 0.0004861300		

Table 2. Selected specifications and aberration values for example 1 and 2

Number field point	Relative field of view in angular degrees	Distortion for example 1, %	Distortion for example 2, %	Lens specification	Lens quality/quantity	
					for example 1	for example 2
1	0	0	0	Presented in Table 1	Geometrically Limited/3	Diffraction Limited/4
2	9.8	–0.047	–0.050			
3	16.4	–0.218	–0.167			
4	32.8	–1.680	–0.760			
5	49.2	–5.387	–0.888			
6	65.6	–11.897	–1.190			
7	82.0	–23.000	–1.440			

In this type of optical systems, the size and the structure of image are limited by geometrical aberrations. Aberration of distortion is not corrected in a pinhole lens with an aperture stop in front of optical system (OS). For this type of the lens it is one of the most critical aberrations. The values of pinhole distortion for all spherical and all aspherical lenses are presented in Table 2.

All spherical pinhole triplet (Fig. 2) consists of a meniscus *S*1 and is formed by surfaces 2 and 3; a biconvex lens *S*2 is formed by surfaces 4 and 5, and a negative concave, flat lens *S*3, is formed by surfaces 6 and 7. Numbers of surfaces 3, 5 and 7 are not shown in Fig. 2, where lens *S*1 has a yellow color, which corresponds to glass model with refractive index $n = 1.800$ and Abbe coefficient $v = 46.63$. Lens *S*2 is made from crown material with $n = 1.63323$, $v = 61.65$, it is colored in red and lens *S*3 is made from heavy flint glass with $n = 1.800$ and $v = 25.05$, which is colored in blue.

A drawing of lens *S*2 is presented in Fig. 3 in accordance with standard[1].

All lenses have been analyzed using the PanDao software tool and presented due to ISO 10110 standards. As a typical example, we take the biconvex lens *S*2 (Fig. 3).

PanDao identifies a three step fabrication chain (Fig. 4) featuring curve generator CNC (Computer Numerical Control) [6] grinding with a final full-aperture CNC polishing step to be the optimum fabrication chain for production. In addition, dedicated testing equipment needed to manufacture this lens is listed. Total fabrication cost per lens is about 6.4 € comprising of 5.26 € fabrication

[1] ISO 10110-1 1996. Optics and optical instruments — Preparation of drawings for optical elements and systems — Part 1: General. 01.03.1996. 23 p.

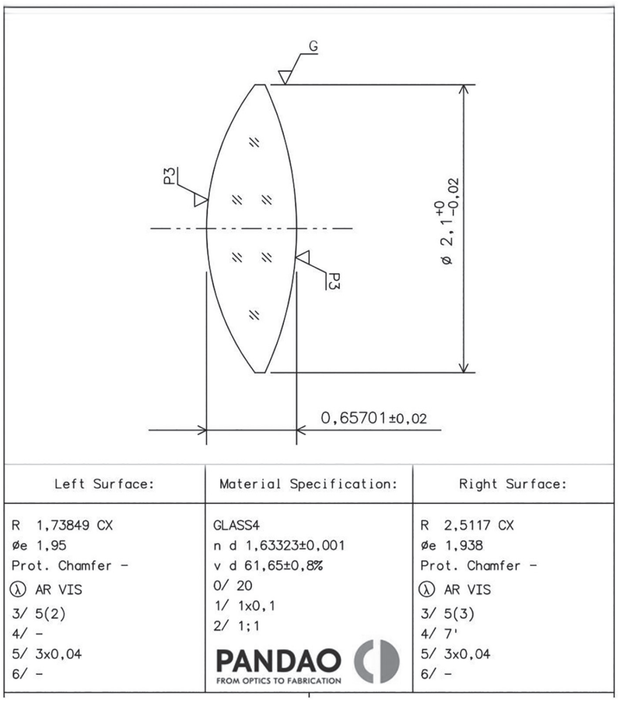

Fig 3. Optical drawing of lens (*S*2) from example 1

Best fabrication chain:

Side 0:	Side 1:
curve generator rough grinding	curve generator rough grinding
fabrication price 1.15€	fabrication price 0.33€
curve generator grinding	curve generator grinding
fabrication price 1.14€	fabrication price 0.31€
cnc full aperture polishing	cnc full aperture polishing
fabrication price 1.83€	fabrication price 0.50€

Total fabrication cost for this lens: 5.26€
Investbudget for installing machinery for this fab-chain: 380000€

Centering:
best centering process: centeringCNCTransferMandrel
centering cost for this lens: 0.11€
investbudget for installing centering machinery: 100000€

Coating:
coating cost for this lens: 0.52€
investbudget for installing coating machinery: 1000000€

Testing:
testing cost for this lens: 0.52€
Minimum testing equipment needed for this lens: Micrometers, flowboxes, ring-spherometers, microscopes with size-analyzing software, hand-hold Profilometer, various testing equipment (magnifying glasses, skale, heating tables, USB-microscopes, pH-value testing device, etc), laser sheet diameter testing device, Refractometer, CMM. wavefront testing interferometer, white light interferometer, standard Profilometer, Nomarski microscope, ScratchDig-detection apparatus, MTF testing device

Disclamer:
cost calculations representing an average-sized European fabricating company, including: machining, tooling, operator, centering, testing, coating, setting-up, machine's invest cost, bank payback time, interest, operators salaries, two-shift fabrication, etc; excluding: material cost, companies' overhead, assembly and delivery cost

Fig. 4. PanDao analysis of lens *S*2 (Fig. 3) with per lens 5.26 € fabrication cost.
Required production volume is 10 000 lenses

cost plus 0.52 € coating cost plus 0.52 € testing cost plus 0,11 € center grinding cost (taking an average sized Central-European company into account: without company overhead cost and material cost). The costs for all technological chain depend on the country of manufacturer. In our example we use the average prices for Swiss manufacturer.

PanDao producibility analysis for all spherical pinhole objective is summarized in Fig. 4 and Table 3.

CNC is an abbreviation for Computer Numerical Control in Fig. 4 [6], and CCP is an abbreviation for Computer Controlled Polishing [7–9]. PanDao analysis of example 1 is presented in Table 3, where fabrication cost, grinding cost, coating cost, testing cost are calculated. Lens design and material costs are not included.

Example 2. All aspherical pinhole lens

All aspherical pinhole lenses (Fig. 5) have same applications as all spherical, but are used in mass production, for example, as a lens for mobile cameras [10], but for this case it must have perfect quality. If we compare optical schemes of these lenses, example 1 looks more simple and attractive, but it is not obvious which one is better. PanDao analysis of all aspherical pinhole lens is presented in Table 4.

Let us check image quality, the results of its calculation in accordance with the MTF are presented in Table 5. This lens is a diffractive limited over almost the whole field of view, which is 82 angular degrees. We compare values in columns *X-Y* Perfect MTF and MTF shown over the field. These values are almost equal. Aspheric lens has more parameters for optimization rather than spherical, this is why, it is possible to correct additional aberration –distortion. Parameters for optimization are radii, thicknesses in both examples, and aspheric coefficients and conic constants in all aspherical design. Materials of lenses in our examples are not recommended to use as optimization parameters, we just select suitable glasses and do not change them. The attention should be paid that all aspherical design usually requires all plastic material [11], but we assume to select glass because, at this moment, plastic materials are not included into PanDao materials catalogue. This is a significant drawback, which will be fixed this year. Materials, which we have picked up from Schott glass catalogue1 are: BK1 and F2 and they have refractive index close to plastic materials.

[1] https/schott.com/

Table 3. PanDao analysis of all spherical pinhole triplet

PanDao analysis of example1	fabrication cost, €	center grinding cost, €	coating cost, €	testing cost, €	optimum fabrication chain
lens1 (*S*1)	11.90	0.40	0.52	1.17	left side and right side: (1) curve generator rough grinding (2) curve generator grinding (3) CNC full aperture polishing
lens2 (*S*2)	5.26	0.11	0.52	0.52	left side and right side: (1) curve generator rough grinding (2) curve generator grinding (3) CNC full aperture polishing
lens3 (*S*3)	3.70	0.10	0.52	0.36	left side: (1) curve generator rough grinding (2) curve generator grinding (3) overarm polishing right side: (1) curve generator rough grinding (2) CNC full aperture flats grinding (3) CNC full aperture flats polishing
Total	20.86	0.61	1.56	2.50	Total for three lenses – 25.53 €
Total	For 1 000 000 pieces to be produced				for three lenses – 1.68 €

Table 4. PanDao analysis of all aspherical pinhole lens

PanDao analysis example 2	fabrication cost, €	center grinding cost, €	coating cost, €	testing cost, €	optimum fabrication chain left side and right side:
lens1 (*A*1)	6.88	0.05	0.52	0.67	(1) CNC sub aperture rough grinding (2) CNC sub aperture grinding (3) CCP fluid jet polishing
lens2 (*A*2)	3.94	0.04	0.52	0.39	(1) CNC sub aperture rough grinding (2) CNC sub aperture grinding (3) CCP fluid jet polishing
lens3 (*A*3)	4.53	0.04	0.52	0.44	(1) CNC sub aperture rough grinding (2) CNC sub aperture grinding (3) CCP fluid jet polishing
lens4 (*A*4)	3.99	0.08	0.52	0.39	(1) CNC sub aperture rough grinding (2) CNC sub aperture grinding (3) CCP fluid jet polishing
Total	19.34	0.21	2.08	1.89	for four lenses — 23.52 €
Total	For 1 000 000 pieces to be produced				for four lenses — 4.13 €

Let us now calculate production costs for the same volume, 10 000 lenses sets. PanDao analyses the production of the aspherical pinhole lens objective for surface roughness requirements of 1 nm RMS (Root Mean Square) [12].

A drawing of all aspherical pinhole objective is presented in Fig. 5, which consists of a biconvex lens (*A*1) formed by surfaces 1 and 2, a negative meniscus lens (*A*2) formed by surfaces 3 and 4, a biconvex lens (*A*3) formed by surfaces 5 and 6 and biconcave lens (*A*4) formed by surfaces 7 and 8. Numbers of surfaces 2, 4, 6, 8 and 10 are not shown in Fig. 5. The rays are traced from left to right and produce an image on the surface called IM. PPP is a plane-parallel plate protecting CCD-receiver from damage. Parameters of PPP element is necessary to take into account when we design a lens, because the system is diffraction limited and each optical element input is essential.

In Fig. 5 lens *A*1, *A*3, PPP have pink colors, which correspond to crown BK1 from Schott glass catalogue1. Lenses *A*2, *A*4 have blue color, they are made from flint material F2 also from Schott glass catalogue.

To illustrate the complexity of optical elements shape, the attention should be paid to equation (1), which describes the shape of conic and power series asphere. In this example we have enough parameters to correct distortion, which in this lens has the value less than 1.5 % along the whole image field. So, this lens can be used for measuring and testing applications.

$$z(r) = \frac{cr^2}{1 + \sqrt{1 - (1 + k)(cr)^2}} + G_3 r^4 + G_6 r^6, \qquad (1)$$

where: z — aspheric sag; k — conic constant; c — surface curvature; G_3 — first aspheric coefficient for even asphere; G_6 — second aspheric coordinate for even asphere; r — radial coordinate.

Parameters for optimization are: radii, thicknesses in both examples, and aspheric coefficients and conic constants in all aspherical design. Materials of lenses in our examples are not recommended to use as optimization parameters, we just select suitable glasses and do not change them. The attention should be paid that all aspherical design usually requires all plastic material, but we assume to select glass because, at this moment, plastic materials are not included into PanDao materials catalogue. Materials which we have picked up from Schott glass catalogue are: BK1 and F2 and they have refractive index close to plastic materials.

Conclusion

In conclusion, a new optical design software tool, called PanDao, has been presented for the design of optimum fabrication chain depending on optical design parameters and tolerances. By applying this software tool, fabrication cost can be minimized already at the design stage of optical systems.

Two pinhole lens optical designs have been presented and compared in terms of optical system performance demonstrating that the aspherical objective has substantially

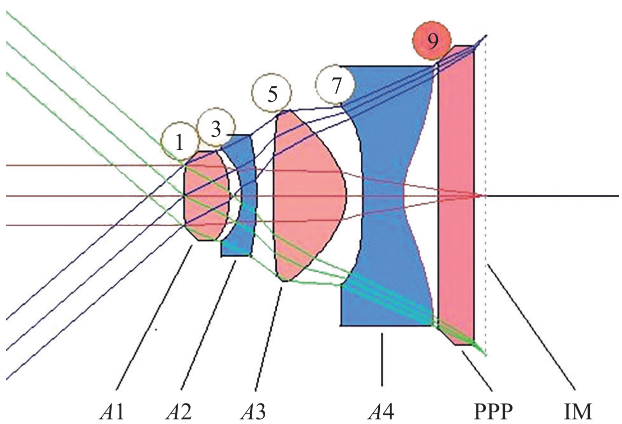

Fig 5. All aspherical design of four lenses *A*1, *A*2, *A*3, *A*4 and plane-parallel plate (PPP)

[1] https/schott.com/

Table 5. Convolution MTF for all spherical (**) and all aspherical designs (*)

Frequency, mm^{-1}	*X-Y* Perfect MTF	XMTF, $X = 0$ For axis — sagittal		YMTF, $Y = 0$ For axis — meridional		XMTF, $X = 1.0$, $Y = 0$; sagittal		YMTF, $X = 0$, $Y = 1.0$ meridional	
		*	**	*	**	*	**	*	**
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
27.261	0.936	0.935	0.865	0.935	0.865	0.918	0.870	0.885	0.742
54.535	0.873	0.870	0.661	0.870	0.661	0.847	0.653	0.777	0.284
81.795	0.809	0.805	0.445	0.805	0.445	0.765	0.410	0.668	0.115
109.061	0.747	0.743	0.256	0.743	0.256	0.682	0.197	0.562	0.072
136.255	0.685	0.681	0.117	0.681	0.117	0.614	0.049	0.464	0.063
163.595	0.623	0.620	0.033	0.620	0.033	0.542	0.028	0.381	0.068
190.855	0.563	0.560	0	0.560	0	0.471	0.051	0.296	0.059
218.124	0.504	0.501	0.007	0.501	0.007	0.416	0.047	0.211	0.046
245.383	0.447	0.444	0.001	0.444	0.001	0.355	0.028	0.139	0.032
272.651	0.391	0.389	0.037	0.389	0.037	0.293	0.002	0.075	0.014
299.915	0.337	0.336	0.074	0.336	0.074	0.244	0.035	0.025	0.007
327.186	0.285	0.284	0.113	0.284	0.113	0.187	0.078	0	0.030
354.447	0.235	0.234	0.136	0.234	0.136	0.134	0.116	0	0.043
381.711	0.188	0.187	0.133	0.187	0.133	0.093	0.132	0	0.031
408.975	0.144	0.143	0.097	0.143	0.097	0.052	0.116	0	0.090
436.242	0.104	0.103	0.063	0.103	0.063	0.019	0.081	0	0
463.507	0.068	0.067	0.031	0.067	0.031	0.002	0.044	0	0
490.778	0.037	0.037	0.019	0.037	0.019	0	0.017	0	0
518.033	0.014	0.014	0	0.014	0	0	0	0	0
545.309	0	0	0	0	0	0	0	0	0

better performance and is even cheaper than the spherical objective for a production sizes of 10 000 lenses, for example.

On the other hand, if production numbers go up to millions, PanDao identifies precision glass molding, PGM [13], to be the most suited fabrication technology for the application aimed at reducing cost down to 6 % for the spherical and to 17 % for the aspherical system.

From the performance point of view, the aspherical system is always preferable. Nevertheless, if we take fabrication cost into account, two different regimes are identified. While for smaller quantities (e.g. 10 000 pieces), the aspherical system is more cost effective than the spherical system, things change for high volume fabrication (e.g. 1 000 000 pieces), where the spherical system is cheaper than the aspherical system.

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