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Tutorial

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Q and A tutorial on optical design

Abstract: There are many good books for optical designers, so we decided not to repeat basic and classical issues, but to answer frequently asked questions which students have put to us during our long-time teaching experience in optical design on different levels – from very beginners to advanced professionals from the EU who came for the project SMETHODS to improve their design skills. This tutorial is divided into two parts: general questions and examples, when students ask how to design some popular schemes.

Keywords: optical design; optical system; tutorial.

OCIS codes: 220.0220.

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1 General questions

Q1: What is optical design?

A1: There are many discussions on the definition of optical design [1–3], we understand it as:

'Optical design is a process of selecting optical elements and putting them into a special order to satisfy the customer's request, this process includes estimation and optimization of system parameters with tolerance for their manufacturing. Optical design is a COMBINATION of many entities: art, science, inspiration, good luck, hard job, sleepless nights, routine, trial and errors, ability to make decisions, correct choice, failures and success, which results in customer satisfaction, and brings more new projects to the optical designer'.

Q2: 'How to succeed?'

A2: The English proverb, which states 'Good beginning is a half of ending', fits perfectly to success in optical design.

Thus, we consider that success in optical design is a suitable starting point strengthened by the ability of the optical designer to make decisions, supported by appropriate optical design software.

A configuration, presented in Figure 1, shows the main steps of the optical design process. This confirms that one of the most important keys to success is a suitable starting point.

Q3: What necessary knowledge is required for an optical designer to start?

A3: The answer is in Table 1.

Q4: 'What can an optical designer expect from optical design software?'

A4: In Table 2, one can see the distribution of the roles between a designer and a computer. The steps are the same as in Figure 1. For more information, please see [4, 5].

Q5: What is the routine in the optical design process and what is the creative part of the job?

A5: Staring point selection and creation of merit function are the most creative parts of the optical design job, as well as making any decisions, see Table 2, and also [6, 7].

Q6: How do you classify an optical system (OS) type depending on its object-image position?

A6: There are only four large classes (or OS types) described by this classification, see Table 3.

Q7: What other classifications of OS are recommended in aiding the design process?

A7: This question is important for any optical designer when he/she gets a new project and tries to find out how to start.

The definition of system complexity could be a problem, especially for a beginner, and it strongly depends on what type (class) of optical system we have to design, see Table 3.

First of all, we have to continue to classify OS in more detail and we separate the definition of technical and general classifications [4]:

- Technical classification operates with physical values. It is also important to know what type of OS it is due to the classification presented in Table 3. Depending on this, the technical specification has separate units for items of the specification, thus if infinite object size is angular, but in the case of finite object it is linear, etc., for '01' OS type is given in Table 4.
- General classification operates with provisional numbers: 0, 1, 2 and show the complexity of the system.

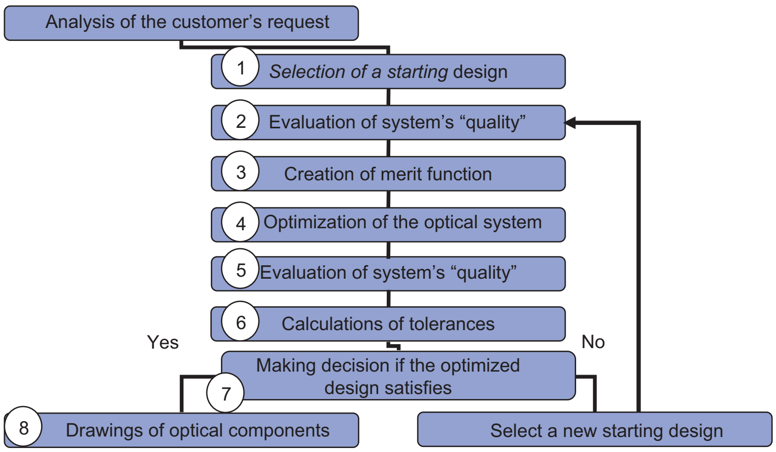


Figure 1 Main steps of the optical design process.
Steps 1, 3, 6 are the main responsibilities of the optical designer, which will also be explained later.

Table 1 Necessary knowledge required for an optical designer.

N	Minimum knowledge to start optical design
1	Refraction and reflection laws
2	Stops, pupils
3	Rays, raytracing
4	Aberrations
5	Optical design software

Table 2 Distribution of the roles between a designer and a computer.

Step N	Step description	Input, %	
		Designer	Computer
1	Selection of a starting point	95	5
2	Evaluation of system quality (preliminary)	50	50
3	Creation of merit function	95	5
4	Optimization	20	80
5	Evaluation of system quality (preliminary)	50	50
6	Making a decision if a system satisfies a customer's request	95	5
7	Calculations of tolerances	50	50
8	Drawings of optical components	5	95

Table 3 Classification of OS due to object-image position.

	Position: 0 – at infinity; 1 – finite distance		
	Object	Image	Name of OS class (type)
1	0	0	Afocal, telescope
2	1	0	Microscope
3	0	1	Photo-objective
4	1	1	Relay, projector OS

For both classifications, we use the same seven characteristics, which we consider are the most important for lens designers, these are: J, W, F, L, Q, S, D – the meaning of each is explained in Table 4.

The link between the classifications for aperture, field, and focal length for '01' OS type is presented in Table 5, for other links see [4, 5].

More detailed explanations with regard to general classification are presented in Figures 2 and 3 and in publications [4, 5, 8].

Thus, '0' corresponds to small aperture, small field, etc.; '2' corresponds to super fast aperture, super wide field, etc.; and '1' has an average value (between 0 and 2).

Q8: How to estimate a complexity for optical system type '01' – photographic objective?

A8: The index of complexity is estimated by Eq. (1):

$$R=J+W+F+L+Q+S+D=0\text{–}14 \quad (1)$$

where J, W, F, L, Q, S, D are explained in Tables 4 and 5, and in [4, 5].

Examples of estimation of index of complexity are presented in Table 6. It is known from experience that OS with R>7 are considered as complex.

Q9: Where is the best position for aperture stop in OS?

A9: See Figure 4 and Table 7, where three possible positions of the aperture stop in OS are explained and recommendations for its usage are given.

Q10: How to define OS specification and OS parameters?

A10: This is also one of the most important questions – the answer is presented in Table 8.

Q11: How many parameters does a singlet lens have?

A11: It has six parameters: two radii of surface curvature, one lens thickness, two parameters from lens

Table 4 Definition units in technical classification for all OS types.

Items of specification	OS '01'		OS '10'		OS '00'		OS '11'	
	object	Image	object	Image	object	Image	Object	Image
J (aperture)	Linear	Angular	Angular	Linear	Linear	Linear	Angular	Angular
W (field)	Angular	Linear	Linear	Angular	Angular	Angular	Linear	Linear
F (magnification)	Focal length – linear		Magnification[a], focal length		Magnification[a]		Magnification[a], focal length	
L (spectral range)	Linear – nm							
Q (quality)	Angular	Linear	Linear	Angular	Angular	Angular	Linear	Linear
S (back focal length)	Angular	Linear	Linear	Angular	Angular	Angular	Linear	Linear
D (position from the 1st surface)	Linear – mm from the surface							

[a] Magnification – it is the ratio of two linear (angular) units, it has no dimensions.

Table 5 Links between general and technical specifications.

Characteristics (specifications)	General	Technical	Description
J-FN	0	FN > 2.8	With small aperture
	1	1:2.8 > FN > 1:1.5	Fast
	2	FN < 1.5	Super fast
W-field	0	2w < 15°	Narrow field
	1	15°< 2w < 60°	Wide angular
	2	2w > 60°	Super wide angular
F-focal length	0	f < 50 mm	Short focal length
	1	50 < f < 100 mm	Ordinary focal length
	2	f > 100 mm	Long focal length

material, one more parameter – aperture stop position from the singlet.

Q12: How many parameters are enough to succeed?

A12: It strongly depends on OS complexity, but the 'rule of thumb' states that one parameter is enough for one correct function, if they are not working in contradiction with each other. From this point of view, it is clear that all seven elementary aberrations could not be corrected in a singlet, which is true.

Q13: How do you increase the number of parameters in OS?

A13: There are several options to increase the number of parameters in OS:

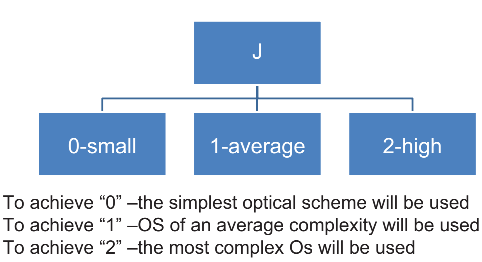


Figure 2 Example of general classification for F-number.

– Add components.
– Add more parameters to lens (mirror) shape: aspheric coefficients, holographic optical element (HOE), diffraction optical element (DOE).
– Add more parameters to material: use gradient index Lens (GRIN).

Q14: How do you select a starting point?

A14: There are two main approaches for starting point selection: 'bottom-up' and 'top-down', see Figure 5.

The steps for the bottom-up approach are described in Table 9.

The bottom-up strategy of starting point selection is mostly based on design experience and a logical approach; for more detail, please see [4, 5, 8].

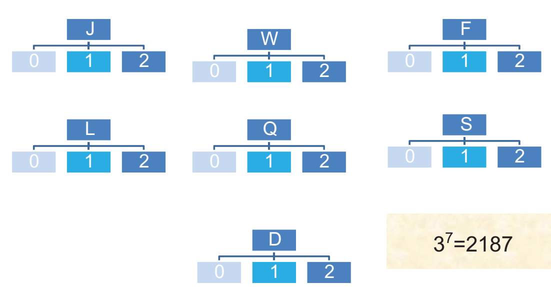


Figure 3 Explanation of general classification for all items of classification.
The total number of classes described by this classification is 2187 OS classes.

Table 6 Examples of calculations of OS complexity.

OS name	J	W	F	L	Q	S	D	R
Singlet	0	0	1	0	0	0	0	1
Triplet	0	1	1	1	0	1	0	4
Planar	1	1	1	1	0	1	0	5
Fish-eye	1	2	0	1	0	1	1	6
Pinhole for mobile phone camera	1	2	0	1	2	1	2	9

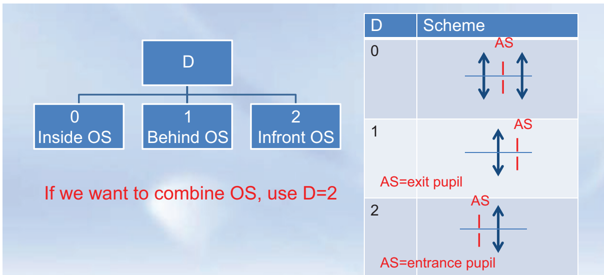


Figure 4 Possible location of the aperture stop in OS.

With regard to this approach, we first produce a structure of OS, then estimate parameters and input them into the computer together with technical requirements.

The main advantages and disadvantages of this approach include:

– understanding of function of each element in OS;
– easy to select parameters (as we know how they work);

Disadvantage:

– requires experience in optical design.

The composition of the elements used for structural synthesis of OS in the bottom-up approach is presented in Figure 6, where *B* is a basic element; *Y* is an element to develop field in OS; *V* is an element to develop aperture in OS; and *C* are elements to correct the residual aberrations of all other types of elements. The types of optical elements for this approach are presented in Table 10.

An example of the bottom-up design of pinhole lens is presented in Table 11.

Q15: How do you select a correction element?

A15: To select a correction element, it is necessary to understand what aberrations will correct and then select a design strategy to use one of the options presented in Figure 7.

As seen from Figure 7, one can use the following correction options:

Table 7 Recommendations for aperture stop position in OS.

N	Situation, when needed	Recommendation		
		D=0	D=1	D=2
1	Simplest OS	+		
2	Shortest OS		+	
3	Smallest entrance pupil			+
4	Combining different OS		+	+

Table 8 Explanation of specification and parameters (constrains) in OS design.

Specifications (FUNCTION, TARGET)	Parameters (ARGUMENT)
Image, object position, aperture, field	Surface data: radii, other shape data
Magnification (focal length)	Thickness, distance between optical element (OE) in OS
Wavelength range	Material data: index of refraction, dispersion, law of gradient index
Quality specification	Position of the aperture stop
Working distance (or back focal length)	

– Compensation – when aberration of one sign is compensated by an aberration of an opposite sign – an example is a doublet, where negative spherical aberration introduced by positive lens is compensated by positive spherical aberration of a negative lens.
– Splitting – when large aberration introduced on a single surface is decreased by using few surfaces of the same sign of optical power instead of one – aberration is shared between several surfaces, its becomes smaller on each surface and in total – an example is to design OS for minimum of spherical aberration.
– Increasing number of parameters – similar with step 2, but lenses added to increase parameters have different signs of optical power.
– Symmetry is an important tool to simplify OS, because the symmetrical system is automatically free of odd aberrations: coma, distortion.

Q16: What is the 'top-down' approach in lens design?

A16: It is a way of starting point selection when input data are taken from patents, the literature, etc.

The steps for the top-down approach are described in Table 12.

Q17: Is it possible to combine 'bottom-up' and 'top-down' approaches?

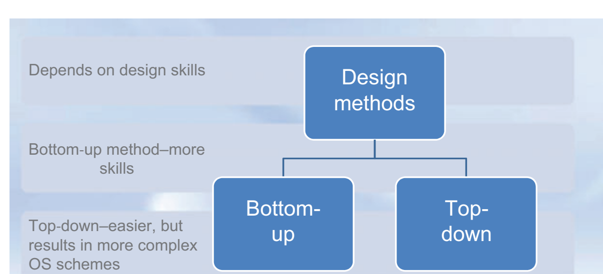


Figure 5 Design methods for starting point selection.

Table 9 Steps for the bottom-up approach for starting point selection.

Step N	Step content
1	Analyze the customer's request;
2	Estimate OS type and complexity;
3	Implement a structural synthesis of OS: select a basic, correction, fast, and wide-angular elements, depending on OS type and complexity (preferably an OE where surfaces have well-known properties [4, 5]);
4	Implement parametric synthesis, input parameters and specification into the computer using special optical design software [7];
5	Analyze system quality and create a merit function for optimization;
6	Optimize OS, changing merit function and parameters if necessary to achieve the goal;
7	Analyze OS after optimization, if we achieve the result then we complete the project with tolerances and drawings, if not – we select an alternative starting point solution.

A17: Yes, we have to define composition elements in the patent and then estimate basic, fast, wide-angular and correction elements, after that try to analyze the purpose of each element and try to decrease the number of elements.

2 Examples

Q18: What is the additional value of pinhole lens? What are the best applications of this type of lens?

A18: Pinhole lens is the construction when aperture stop is removed forward and coincides with the entrance pupil of the lens. Such a construction provides the smallest possible diameter of the entrance pupil, which is a very useful option for many cases, such as underwater applications, covert video surveillance, mobile phone cameras, and eyepieces. Another useful property of this lens is its ability for combination, see Figures 8 and 9.

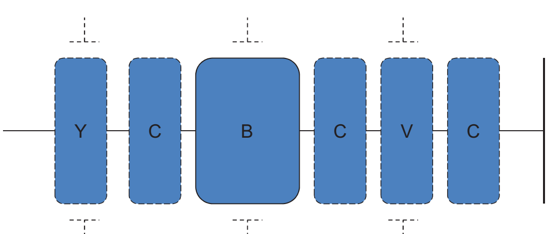


Figure 6 Composition of optical elements for selection of OS starting point using the bottom-up method.

Making a telescope system from two pinhole lenses is easy, see Figure 9.

Q19: How do you design an eyepiece?

A19: It is easy to design an eyepiece as a reversed pinhole lens.

Q20: How do you design a symmetrical system?

A20: It is easy to design a symmetrical system as a combination of pinhole lens and reversed pinhole lens. Reminder: put together both aperture stops of direct pinhole lens and reversed pinhole lenses, see Figure 10.

Another example of a symmetrical system is presented in Figure 11.

Q21: How do you design relay lens, projection lens, lithography lens – OS class '11'?

A21: An example is presented in Figure 12 – a relay lens is a combination of two reversed pinhole lenses when they coincide by the planes of their entrance pupils.

Q22: What is an example of effective application of aspheric surfaces?

A22: An example is presented in Figure 13 – an objective for a mobile phone camera.

The general number of parameters of triplet used as a starting point of this design was 11 (six radii, three lens thicknesses, and two distances between the lenses). It did not allow to change lenses materials and aperture stop position.

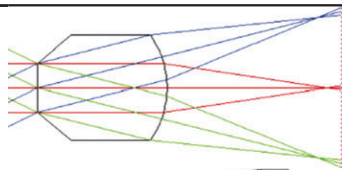
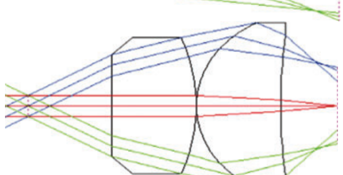
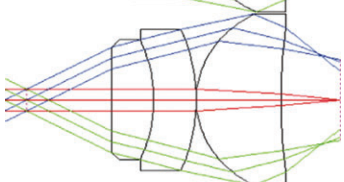
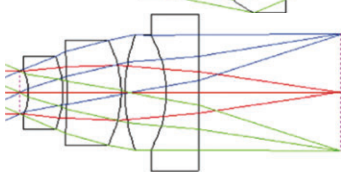
As the system has to be diffraction limited there were not enough parameters to achieve the customer's request. Using aspheric surfaces on all lenses surfaces, we have increased the number of parameters on each surface for four parameters: conic constant + three aspheric coefficients of power-series aspheric, see Eq. (2).

Thus, the total number of parameters for a three-aspheric lens objective for a mobile phone camera is minimum 23 (11+12=23).

Table 10 Types of optical elements for structural synthesis of OS in the bottom-up approach.

OE number	Name	Sign of optical power	Function in OS	Possible quantity in OS
1	Basic	Positive only	Produce optical power in OS	Only one
2	Correction	Positive, negative, afocal – depending on type of corrected aberrations	Correct aberrations	Three on every position
3	Wide angle	Negative or afocal	Develop field	Three
4	Fast	Only positive	Develop aperture	Three

Table 11 The bottom-up design of pinhole lens.

N step	Structure	Explanation
1		One basic lens: first surface is aplanatic[a]; second is concentric[b] about chief ray
2		basic + fast lens: fast lens – first surface is concentric about marginal ray; second surface is concentric about chief ray
3		Basic + fast + correction elements Correction element introduced into the basic element – to correct spherical and chromatic aberrations
4		Wide-angular element (also correction) + basic + fast element together with correction element, optimization: Basic and correction elements were uncemented to increase the number of parameters, correction element took a function of wide-angular element; Second correction element was introduced into fast element to correct chromatic aberrations; Final scheme – after optimization

[a]Aplanatic surface is a special surface for which both the object and image are located in aplanatic conjugates [1, 2,], for object at infinity this surface is flat.
[b]A surface concentric about chief ray is a special surface, which is free of astigmatism and coma, because chief ray goes along the normal to the surface and does not refract [1, 2].

$$z=\frac{ch^2}{1+\sqrt{\{1-(1+k)c^2h^2\}}}+G_3h^4+G_6h^6+G_{10}h^8 \qquad (2)$$

where z is aspheric sag, c is surface curvature, k is conic constant, h is current coordinate, G_3, G_6, G_{10} are power-series aspheric coefficients. Aspheric coefficients were added gradually during the optimization.

Q23: How do you design a fish-eye lens, what is its suitable starting point?

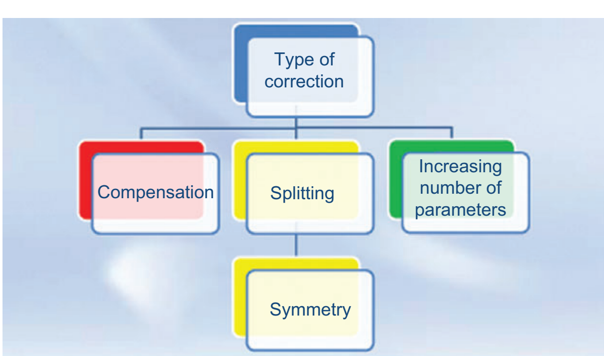


Figure 7 Design strategy for aberrations correction.

A23: Many different fish-eye lenses could be designed from a combination of the surfaces with well-known properties, see an example in Figure 14.

Q24: How do you design freeform surface and what is its value?

Table 12 Steps for the top-down approach for starting point selection.

Step N	Step content
1	Analyze the customer's request;
2	Estimate OS type and complexity;
3	Select a patent with specification closest to the customer's request
4	Input parameters and specification into the computer using special optical design software [7];
5	Analyze system quality and create a merit function for optimization;
6	Optimize OS, changing merit function and parameters if necessary to achieve the goal;
7	Analyze OS after optimization, if we achieve the result then we complete the project with tolerances and drawings, if not – we select an alternative starting point solution.

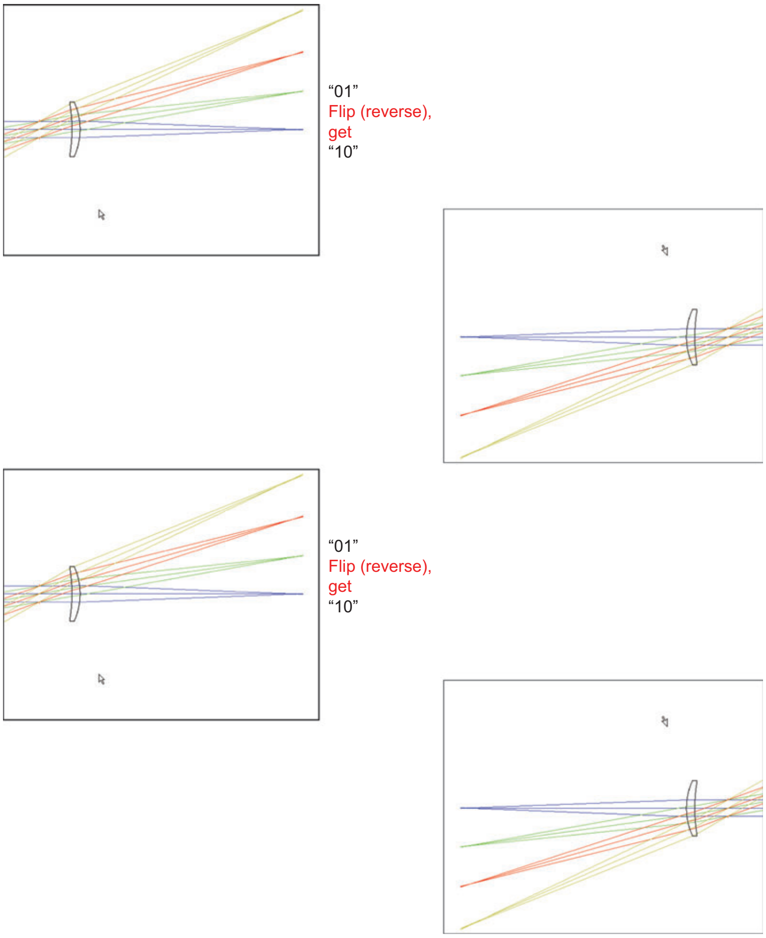


Figure 8 Use of pinhole lenses for combinations.

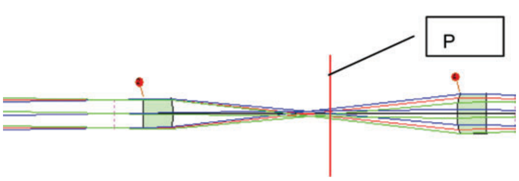


Figure 9 The telescope system is a combination of two pinhole lenses. Red line (P) shows the plane where both focal points have to coincide.

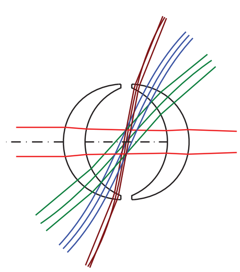


Figure 11 Hypergon, 2w=136°, free of coma, distortion, and lateral color because of symmetry, designed using [10].

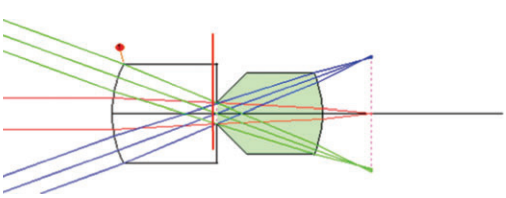


Figure 10 Symmetrical system design, red line (P) is a common plane for aperture stops of both lenses: first radius is equal to the last one with opposite sign: r1=-r2; thickness of both lenses are equal: d1=d2, P is a dummy surface where aperture stop is located.

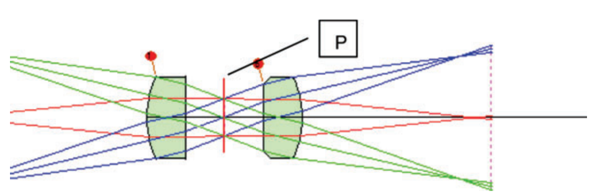
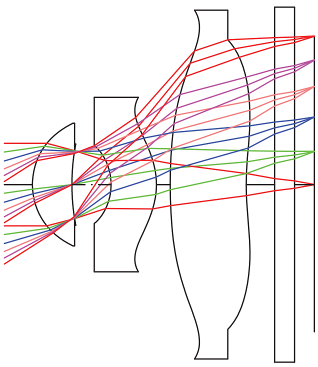


Figure 12 An optical system class '11' as a combination of two reversed pinhole lenses, where red line (P) shows a plane of location (and coincidence) for two entrance pupils of pinhole lenses.



	Technical	General
J	F2	1
W	2w=65	2
F	4 mm	2
L	Visual	1
Q	Diffract	2
S	1	2
D	Inside	0
R		10

Figure 13 Objective for mobile phone camera, designed using optical design software [10].

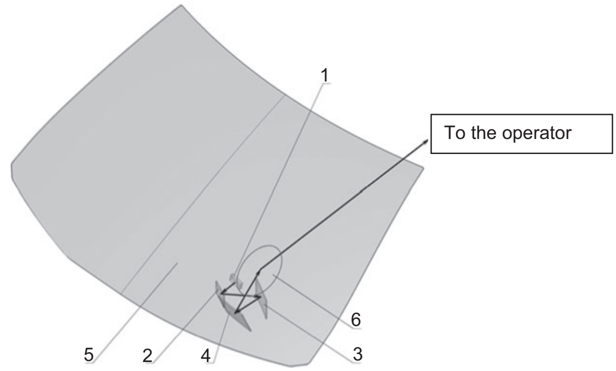


Figure 15 Head-up display with freeform mirrors, where 1 is object (information display); 2, 3, 4 are freeform mirrors; 5 is windshield; and 6 is real view zone.

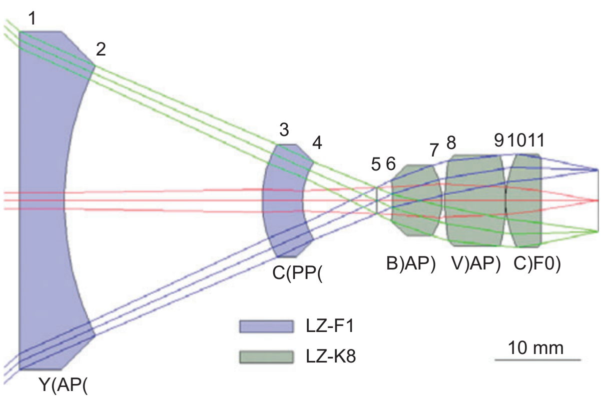


Figure 14 Starting point for fish-eye lens built with concentric and aplanatic surfaces; F1.8, 2w =84°, f′=4.5 mm.
C)F0), correction element with 1st surface concentric about marginal ray, 2nd - flat; V)AP), fast element - 1st surface aplanatic, 2d -concentric about chief ray; B)AP), basic element - 1st surface aplanatic, 2d - concentric about chief ray; C(PP(, correction element - “biconcentric meniscus” - both surfaces are concentric about chief ray; Y(AP(, wide-angular element with 1st surface aplanatic and 2d - concentric about chief ray; ((, if element is located before the aperture stop;)), if element is located behind the aperture stop.

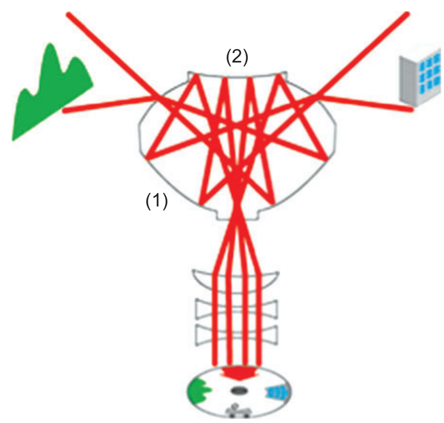


Figure 16 Compact wide-angle (360°) imaging system with axisymmetrical freeform surfaces; (1), (2) are reflecting surfaces.

A24: The first freeform surfaces are used in imaging and nonimaging optics to increase the number of parameters in OS and to produce more compact design. Two examplesarepresented:head-updisplay,whichcombinesreal view and information display, see Figure 15, [11] and wide-angle imaging lens system, see Figure 16, described in [12].

All mirrors in this display have aspheric surfaces to correct aberrations in the system, compactness is provided by freeform shape. This type of design could be used both for aircraft and automobile applications.

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References

[1] M.M. Rusinov, in ‘Technical Optics’ (Leningrad, Mashinostroenie, 1979) (in Russian).
[2] D. Shafer, Proc. SPIE 237, 234–241 (1980).
[3] B. R. Irving, Proc. pp. SPIE 554, 2–9 (1985).
[4] I. L. Anitropova, Proc. SPIE 1603, 154–162 (1993).
[5] I. L. Anitropova, Proc. SPIE 1780, 188–196 (1992).
[6] S. W. Weller, Proc. SPIE 1780, 118–126 (1993).
[7] D. C. Dilworth, ‘SYNOPSYS. OSD, Inc.: User’s Manual’ (2012). pp. 18–25.
[8] I. L. Livshits, D. I. Mouromtsev and V. N. Vasilev, in ‘Ontology Approach in Lens Design. Information System’, Ed. by C. Kalloniatis (InTech, 2012). ISBN: 978-953-51-0647-0.

[9] SMETHODS (available at: http://www.smethods.eu/).
[10] CODEV, in 'SYNOPSYS. User's Manual' (2012).
[11] A. A. Bagdasarov, R. V. Anitropov, O. V. Bagdasarova and I. L. Livshits, in 'Systems for the Indications and Display of Secondary Information in Avionics and Autobasing Complexes'. (Izvestiya Vyzov, Priborostroenie, Aviation Technoque, Kazan, RF, 2011) pp. 48–52 (in Russian).
[12] Chen-Cheng Liao, in 'Compact wide-angle imaging lens system' (Asia Optical Co. Inc. Taichung, Taiwan), US Patent 7508597.

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