Dr Darko Vasiljević
darkov@diginaut.com

Program for Optical System Design and Optimization

Abstract A program for complete design, analysis and optimization of optical systems is described. After general description of the program, selected parts of the program are described in more detail among other optimization algorithms, which represent a vital part of any optical design program. In this paper the following optimization methods are described: classical damped least squares method, adaptive steady state genetic algorithm, twomembered evolution strategy EVOL, multimembered evolution strategies GRUP, REKO and KORR. At the end, the comparative analysis of the program with comercially available programs is given.

key words: Optical design program, optical system design, optical system analysis, optical system optimization

Introduction

Before an optical system can be constructed it must be designed, that is to say, radii of curvature of surfaces, thicknesses, air spaces, diameters of the various components and all types of glass to be used ought to be determined and specified. The process of designing the optical system is partly art, partly science, and plenty of patience. The designer who finds pleasure in the act of designing may well succeed, while the one who loses interest early settles on a lower-quality optical system design. Although the lens designers of 50 and more years ago had an endurance that remains unmatched, the invention of the computer and the development of design programs have enhanced the talent of today's designers. They have also opened the door to novice analyzers of optical systems. Today's technology allows the user to trace millions of rays and seek out design solutions faster than ever before.

While there are differences in details, the fundamental concepts behind most optical-design-software packages are the same. The programs typically have a user interface (either a graphical user interface or a command line based interface), a ray-trace and analysis section, an optimization section, a tolerance analysis section, and a sort of customized programming section.

In this paper a program for optical system design and optimization that was the result of years spent in research and development is described. In the first part of the paper general description of the program and its capabilities is presented. It is similar to other commercially available programs so it is referred to without much description. The main features of the program are various optimizing methods, which belong to both local and global optimization algorithms. All optimization methods are described in the paper together with their implementation in optimization of optical systems. At the end of the paper the limitations of the program for complete design and optimization of optical systems are given and the program is compared with the other commercially available programs such as SIGMA PC, ZEMAX and OSLO. Very interesting is the tabular representation of the main features for all compared optical design programs.

General description of the program

The ADOS (Automatic Design of Optical Systems) program is a proprietary optical design program. Its development started in 1987 with following reasons:

- research in classical and modern optimization methods and their application in optimization of optical systems;

- development of modern optical design program based on PC computer. At that time the state of art optical design programs were defined by large expensive and user-unfriendly programs running on the also large, expensive mainframe computers. Most of those programs were proprietary and they were not commercially available;
- optical design program that can be easily modified to accept new methods of calculation and optimization for classical optical systems and calculation of new types of optical systems. This possibility is very important when the program is used for design of complex optical and optoelectronical systems for military use.

Before starting development of the program the author considered various hardware and software solutions that were available to him. The most important factors in analyzing hardware resources are:

- price/performance ratio which is very good for PC computers because of their low price in accordance with other types of computers (engineering graphical workstations, mainframes and supercomputers).
- speed, which is for optical design programs, characterized by "ray surfaces per second" (RSS). The RSS is the number of rays a computer can trace from one surface of an optical system to the next in one second. The first PC computers in 1984 used a processor capable of about 1000 RSS. This was slower of mainframes of the day but PC computers have been developing very fast and modern PC computers using processors from the Intel Pentium family do more than 1 000 000 RSS.
- availability of computer and software development tools for the chosen computer.

After considering all hardware alternatives, the author decided to develop the program on PC computer. At that time the operating system was the MS DOS and later when the MS Windows was developed the program is redesigned to use the graphical user interface from the Windows operating system. From the start the author's intention was to write a user-friendly program for complete design and optimization of optical systems. The idea was to make integrated environment from which user could easily perform any action that is needed for design or optimization of optical systems. The author's intention was that all commands were available in menus so that user can easily choose it and that the program was error proof, which means that no matter what the user does, the program would display error message and help how to perform correctly this command. This also means that user need not memorize complex sequence of commands any more. The ADOS program has following features:

- design and optimization of various types of optical systems such as different types of objectives, eyepieces, afocal systems, projectors, condensors, collimators;
- different ways of displaying data in tabular or graphical form;
- support for glass databases from well known producers of glasses such as Schott, Corning, Pilkington, O'Hara;
- support for optical system databases from various lens makers such as Melles Griot;
- possibility for user to create a database with all optical systems that are worked on or used in a process of designing complex optical and optoelectronical systems;
- connectivity between ADOS, where user can opticaly design a system to have minimum aberrations, and AutoCAD program for further optomechanical design. This is acomplished by forming script files that can be executed in the AutoCAD.

Once an optical system has been entered into the computer, the user can perform various analyses to determine system quality. Usually, the first thing to do is to trace paraxial rays to determine the first-order properties of the optical system. These are the properties describing the focal length, image distance, numerical aperture, magnification and pupil sizes and locations. It is sometimes useful at this point to perform an analysis of the third-order aberrations of the optical system (also known as Seidel aberrations or Seidel coefficients), which gives the designer a preliminary idea of whether or not the chosen optical system will have a chance of meeting its specifications. For all other analyses it is necessary to calculate ray scheme i.e. set of well defined rays that are passing through the optical system.

The ADOS program incorporates many of the standard methods of analysis that have been used for decades. The traditional ways of describing the image quality of an optical system include:

- calculation of five principal monochromatic aberrations: sferical aberration, coma, astigmatism, field curvature and distortion;
- calculation of transverse ray abberations;
- calculation of chromatic abberations;
- calculation of optical path difference;
- calculation of wave aberrations;
- calculation of spot diagrams and through-focus spot diagrams for finding the best image position;

With the aid of numerical integration and the fast Fourier transforms (FFTs), a host of additional tools for analysis are available such as the modulation transfer function (MTF) which describe the relative image contrast as a function of increasing spatial resolution. The ADOS program provides many types of the MTF analysis, including the MTF as a function of field position, through focus MTF for finding the best image position and the diffraction MTF.

The most important addition to lens-design programs have been the optimization routines, in which starting optical system is modified in order to reduce aberrations. Goal of optimization is to take a starting optical system and change it to improve its performance (the starting optical system should have a necessary number of optical surfaces of sutable types, since optimization can change only the values of the parameters not the number or type of surfaces). Optical systems are defined by the parameters associated with the individual surfaces of the system. These parameters can be divided in two main groups:

- basic parameters which must be defined for each optical system;
- optional parameters which are defined only if these parameters exist, for example if the surface is aspheric, the user must define the aspherical constants.

The basic parameters are the following parameters:

- radius of curvature for each surface of an optical system;
- separation between two surfaces of an optical system;
- glasses of which components of an optical system are made;
- clear radius for each surface of an optical system.

To completely define and analyze the optical system, the user must, besides basic parameters, define ray scheme, which describes rays which all will be traced through the optical system. The user also can define properties of the optical system (for example, radii, element thickness, glass types, and air spaces) that are allowed to vary in optimization. Changing the variables and minimizing the merit function can then optimize the optical system.

Because the optimization of the merit function will find a local minimum, it is up to the designer to bring the starting optical system to a suitable quality before optimization so that the local minimum is close to a global minimum. In other words, it is not possible to choose five plane-parallel plates of arbitrarily chosen glass and expect the program to find an optimum solution.

There have been recent advances in the development of global optimization techniques but the user must be careful with them. Although the global optimization can be a useful tool in the lens-designer's toolbox, it will not satisfy the designer's wish to find the best optical system automatically. In general, the global optimization can produce numerous starting points from which the designer can locally optimize. Optimization is a vital part of the program and will be discussed in the next section.

Optimization

The optimization concept is fairly simple but its implementation can be quite complex. One can define it as the determination of the set of system configuration variables which minimizes the deviation of actual performance from targeted goals without violating boundary limitations. This simply stated problem becomes a complex problem when the number of variables and targets are large, errors are nonlinear functions of the variables, and the errors are not orthogonal to each other with respect to the variables. In the typical optical system optimization case, all of these conditions are true to a certain degree.

When working with various types of optimization methods one usually define a single number, called a merit function, to characterize actual system performance compliance with the targeted system performance. In other words the merit function value is the measure of the effectiveness of the optimization method as it is the goal of the optimization to reduce the merit function value.

The selection of an appropriate merit function for the optimization is fundamental to the successful outcome of the process. From the mathematical point of view the most appropriate merit function is a function in the quadratic form. This type of the merit function is used in all optimization methods in the ADOS program (damped least squares method, adaptive steady state genetic algorithms, evolution strategies EVOL, GRUP, REKO and KORR). The merit function can be defined as a sum of squares of the aberrations:

$$\psi = \sum_{i=1}^{m} \left(\omega_i \cdot f_i\right)^2$$

where is:

ψ - the merit function value;
m - the number of parameters of optimization;
ω_i – the waiting factor for each calculated aberration;
f_i - each aberration that is calculated by raytrace through the optical system.

The waiting factor for each calculated aberration is necessary because, the merit function can consists of different types of aberrations (transverse ray, angular, waveform) that may differ very much. In order to be able to compare aberrations and to reduce their values the program has to bring them to similar values.

Classical damped least squares optimization

The least squares optimization is a modification of the Newton - Raphson method first developed by Levenberg [1]. Rosen and Eldert [2], Merion [3 - 4], Wynne [5] were the first to use it in optimization of optical systems. Damped least squares (DLS) optimization evolved after a period of intensive research and experimentation in late 1950s and mid 1960s. Now almost every optical design program has some kind of the DLS optimization. Experience gained with this method seams to confirm that the DLS optimization is probably very efficient and general method available to the optical designer. The author's implementation of the DLS optimization is based upon works of the researchers from the Imperial College in London (Wynne, Wormell and Kidger [6 - 9]). A detailed description of the DLS applied to optical system optimization can be found in [10 - 11]. The mathematical theory of the DLS optimization is well known and will not be presented here.

The DLS optimization belongs to a broader group of linear optimization models, which do not take any explicit account of the fact that there may be many local minima of the merit function in the space of all variables. The number of local minima depends on the merit function and number of variables. The damped least squares generally drives the merit function to the local minima nearest the starting optical system. The optical designer has several tools besides the optical design program, which allows him to find a satisfactory optical system. These tools are:

- The selection of a promising starting optical system. If one optical system does not give required quality, the optical designer might try another entirely different optical system.
- The choice of optimization variables. A poor choice of variables may even prevent a linear convergence.
- The weights used in construction of the merit function. Good selection of weights is essential in balancing the aberrations.
- The choice of the damping factor (adaptive or multiplicative damping) and the choice of modification of the complete merit function.

These tools are highly dependent on the skill and experience of the designer. Even an experienced designer may have difficulty in searching out a satisfactory solution for a "state of art" design requirement.

Evolutionary optimization

Evolutionary optimization is one of possible ways to improve classical optimization. All classical optimization methods belongs to the local optimization methods since they guaranty finding only the local minimum nearest to the starting point. They do not take any explicit account of the fact that there may be many local minima of the merit function in the search space. Evolutionary optimization is looking for as many local minima as it can find and chooses the best among them. It can be said that evolutionary optimization belongs to global optimization methods.

Evolutionary optimization is based on analogy in the nature. All life in our planet evolved according to the Darwinian theory of the evolution. So we try to apply a simplified Darwinian theory of the evolution in the technical systems optimization. Genetic algorithms emphasize selection process and crossover, while evolutionary strategies emphasize normally distributed mutations.

Genetic algorithms

The basic principles of genetic algorithms (GA) were first laid down rigorously by Holland [12] in general and by De Joung [13] for the GA optimization. The author's implementation of the GA optimization is based on the adaptive steady state genetic algorithm without duplicates (ASSGA) which is described in [14]. A detailed description of the ASSGA applied to the optimization of optical systems can be found in the author's Ph.D. Thesis [15] and in several papers published both in English and Serbian describing theory and implementation of the ASSGA in the optimization of optical systems [16 - 18].

The classical GA such as the simple genetic algorithm (SGA) or the elitist genetic algorithm (EGA) usually uses bit strings, while the ASSGA uses real numbers. It is very important that the genetic algorithm works with real numbers because it is incorporated in the program for the complete design of optical systems. All important information about an optical system are placed in a record and this record represents one individual of the population.

The population of optical systems is initialized randomly. Because of the fact that the designer ca not know a good optical system that will represent the starting point for the optimization in advance, the best way is to start with randomly chosen starting points, and let the GA do the rest. This means that the optical designer ought to have an optical system that fulfills all necessary conditions and that variable construction parameters are varied randomly according to the uniform distribution law or the Gauss normal distribution law. Every optical system that is generated by random changes from the starting optical system must be a valid optical system, which fulfills all paraxial conditions, have a ray scheme and all aberrations calculated and no violations of the geometrical boundary conditions. It is very important to stress that only valid optical systems can be members of the population.

One of the most important things in defining the GA optimization is a proper determination of the evaluation function. The merit function used in the classical DLS, which consists of the sum of the squares of weighted aberrations, is also used the GA.

Because of randomly chosen starting points for the optimization, the merit functions of optical systems usually differ a lot. In order to be possible to compare them it is necessary to introduce the linear normalization, which represents interpolation of the merit function from one starting point to the end point. Values of the starting point, the end point and the step are parameters of our implementation of the GA optimization and can be chosen differently for each optimization run by the optical designer.

The parent selection technique is a roulette wheel parent selection, which gives more reproductive chances to the optical systems that have better merit functions (smaller aberrations).

The GA optimization uses steady state without duplicates for the reproduction technique because each member of the population will be different and the best individuals from all generations will be kept together so no variable genetic information will be lost.

When two different parents are selected only one genetic operator is applied, chosen by roulette wheel operator selection from the following genetic operators:

- uniform crossover;
- average crossover;
- real number mutation;
- big number creep;
- small number creep.

The new offspring competes with all members of population for a place in it. The offspring is accepted, and the worst member is deleted from population if it is better than the worst member in the population, i.e. if it has smaller merit function and aberrations.

Evolution strategies

Evolution strategies (ES) are algorithms, which imitate the principles of natural evolution, such as mutation, recombination and selection as a method to solve parameter optimization problems. Bienert, Rechenberg and Schwefel developed them during 1960s at the Technical University of Berlin in Germany [19]. From that time they evolved from relatively simple ES to a powerful, robust and self adapting tool for mathematical and technical optimization. The main application domain of ES is optimization of high dimensional continuous problems. The strategy performs well in domains where it is impossible, difficult or expensive to find a precise mathematical description of the problem at hand.

The author implemented following evolution strategies in the optimization of optical systems:

- two membered ES called EVOL;
- multimembered ES called GRUP, REKO and KORR.

Description of all those evolution strategies applied to the optimization of optical systems can be found in the author's Ph.D. Thesis [15] and several papers published in English and Serbian [20 - 21].

The most general algorithmic description of ES given in [22] is the following:

1. The problem is defined as finding the real-valued n dimensional vector x that is associated with the minimum of the function $F(x)$.
2. An initial population of parent vectors x_i, $i = 1,...,N$, is selected at random from feasible range in each dimension. The distribution of initial trials is typically uniform.
3. An offspring vector x_i' is created from each parent x_i, $i = 1,...,N$, by adding a Gaussian random variable with zero mean and preselected standard deviation to each component of x.
4. Selection then determines which of those vectors to maintain by ranking the errors $F(x_i)$ and $F(x_i')$, $i = 1,...,N$. The N vectors that possess the least error become the new parents for the next generation.
5. The process of generating new trials and selecting those with least error continues until an optimum solution is reached or the available computation time is exhausted.

Optimization of optical systems is very specific and evolution strategies must be adapted to it. To start the optimization with the evolution strategies one needs a starting point i.e. the initial optical system. This system must be valid i.e. it has to fulfill all necessary geometric boundary conditions. If this initial optical system is valid, then one can calculate aberrations and the merit function and proceed with search for an improved optical system. If this initial optical system does not fulfill all conditions, one has to formulate the auxiliary merit function, which represents the deviation measure from the geometric boundary conditions. This auxiliary merit function is optimized by the same evolution strategies. The process of the optimization is stopped when all conditions are fulfilled i.e. the auxiliary merit function is equal to zero.

After the detailed testing of the starting optical system one has to make the initial population by random changes of the starting optical system according to the Gaussian normal distribution law. Each new optical system must be completely tested:

- calculating all necessary paraxial values;
- calculating ray scheme;
- testing geometric boundary conditions;
- calculating aberrations and the merit function.

If the new optical system is valid it is accepted in the population, otherwise it is rejected. When the whole initial population is completed, the evolution process can start. The first thing is forming a new optical system by application of the genetic operators. Various ES methods have different genetic operators:

- EVOL and GRUP have only one genetic operator – point mutation;
- REKO has two genetic operators:
  - mutation of variable parameters according to the Gaussian normal distribution law;
  - recombination of the optimization step lengths;
- KORR has five different genetic operators:
  - mutation of the variable parameters according to the Gaussian normal distribution law;
  - discrete recombination of pairs of parents;
  - intermediary recombination of pairs of parents;
  - discrete recombination of all parents in population;
  - intermediary recombination of all parents in pairs.

  In KORR all genetic operators can be applied to:
  - variable parameters of optical system;
  - optimization step lengths;
  - rotation angles of the mutation hyperellipsoid.

When genetic operators form a new optical system, the optimization method must decide whether optimization is possible or not. If the optimization is not possible and the search method is looking for the new starting point (valid optical system) then the geometrical boundary conditions of the new optical system are tested. If all conditions are fulfilled then a new valid initial optical system is found and the optimization is stopped. It has to be restarted with this optical system as an initial optical system.

If the optimization is possible then the new optical system is tested. If it is OK, the optical system is accepted in the population. The process of forming, testing and accepting new optical systems is repeated until whole new population is fulfilled. After forming new population, the best optical systems with minimum merit functions are selected to become parents for the next generation. It is important to notice that the optimization method knows in every moment which optical system is the best i.e. with minimum merit function and aberrations.

Various ES methods have different ways of selecting parents for the next generation:

- EVOL has only two individuals parent and offspring and simple comparison between them makes better one (optical system with smaller merit function and aberrations) parent for the next generation;
- GRUP and REKO have the following parent selection scheme: Population is made from μ parents which generate λ offsprings ($\lambda \geq 6\mu$). λ offsprings choose among themselves μ best offsprings to become parents for the new generation. One can see that it is a generational type of ES which means that every individual lives only for one generation.
- KORR has two possibilities of the parent selection for the next generation:
  - Plus strategy – parents and offsprings make population from which are chosen best individuals to become parents in the next generation. Theoretically it is possible that one individual lives for several generations.
  - Coma strategy – parents for the new generation are chosen only from the current generation offsprings. Here every individual lives only for one generation. For coma strategy it is necessary that the number of offsprings must be greater than the number of parents. Schwefel in [19] states that ratio of number of offspring and parents is connected with speed of convergence of the optimization and must be greater then 6 and smaller then 10.

At the end of each generation the optimization method is testing fulfillment of all convergence criteria which are:

- the optimization step length must be smaller than predefined small value;
- the difference in two adjacent merit functions values must be smaller than predefined small value.

For the control of the optimization's step length EVOL uses 1/5 success rule which reflects the theoretical result that, on average, one out of five mutation should cause an improvement of the merit function. The 1/5 success rule states that the ratio of successful mutations to all mutations should be 1/5. If the ratio is greater then 1/5, optimization method should increase the step length, otherwise it should decrease the step length. GRUP, REKO and KORR have no fixed rule to control step lengths. Their step lengths become variable parameters and can be changed along with other variables in the optimization. In this way nature is simulated more precisely.

If any of the criteria is fulfilled, then the optimization is finished and currently the best optical system becomes the optimal optical system. If the convergence criteria are not fulfilled, then the new generation is started and new optical systems are made.

Limitations of the program and the comparison with other commercially available programs for optical design

The ADOS program is developed as a result of research in classical and new-global optimization methods in optical design and as a tool for solving design problems of the complex optical and optoelectronical systems. It is product of research and development of only one man for more then ten years.

Now at the open market there are four types of optical engineering software that covers various different parts of optical engineering:

- Optical design programs also known as classical ray tracers. They alow an optical system to be designed, analyzed, optimized and toleranced. They are ideal for design of various objectives, telescopes and microscopes because they provide powerful optimization methods with strong image analysis features. Typical programs in this category are CODE V from Optical Research Associates, OSLO from Sinclair Optics, SIGMA from Kidger Optics, ZEMAX from Focus software.
- Non-sequential ray tracers which are used for modeling optical systems in which light can follow multiple paths, or in which light suffers multiple reflections. Typical representative of this kind of programs is OptiCAD from OptiCAD Corporation.
- Optical phisics programs that represent light as an elecromagnetic field with the amplitude and phase. They are necessary when the underlying physics of a problem must be understood. Typical applications for this kind of program are laser design, photolitography, diffractive optics for beam control. Representative program for this group is GLAD from Applied Optics Reseach.
- Thin film design programs are used for designing optical coatings which are essential for good optical system. A typical representative is Essential Macleod from Thin Film Center.

The ADOS program can be compared only with programs from the first group. It is very important to notice that almost all programs in this group are results of very long development process (usually longer than twenty years) and large teams of researchers and developers-programmers (usually more then ten). They cover almost everything that one optical designer need in his regular work.

The ADOS program in comparison to those programs has many restrictions and limitations that are results of following factors:

- ADOS program has only features that are neccessary for day-to-day work of an optical designer of military systems. Features neccessary for development of other kinds of optical systems are not included in the program. For example the program supports only spherical and aspherical optical surfaces and does not support difraction gratings, gradient index optics.
- Short time of development in comparison to other commercial programs and only one researcher severely restricted the program development so that whole fields in optical design are not included such as tolerancing of optical systems, various physical optics calculations such as point spread function, line spread function, wavefront analysis, polarization, nonseuential ray trace.

In the field of optimization of optical systems the ADOS program can be compared to any other optical design programs. It has unique global optimization methods such as the adaptive steady state genetic algorithm and evolution strategies that are not available in other optical design programs.

The tabular review of features of the ADOS and three commercially available programs (SIGMA, ZEMAX and OSLO) are given in Table 1.

Table 1 Comparative analysis lens design programs

		ADOS	SIGMA	ZEMAX	OSLO
Surface types	Spherical	Yes	Yes	Yes	Yes
	Aspherical	Yes	Yes	Yes	Yes
	Cylindrical	No	Yes	Yes	Yes
	Toroidal	No	Yes	Yes	Yes
	Diffraction gratings	No	Yes	Yes	Yes
	User defined	No	No	Yes	Yes
Ray tracing	Paraxial	Yes	Yes	Yes	Yes
	Seidel	Yes	Yes	Yes	Yes
	Bucdahl	No	Yes	Yes	Yes
	MIL ray trace	Yes	Yes	Yes	Yes
	aberration calculation	Yes	Yes	Yes	Yes
Analysis (graphics)	aberrations	Yes	Yes	Yes	Yes
	OPD	Yes	Yes	Yes	Yes
	Spot diagram	Yes	Yes	Yes	Yes
	Best image position	Yes	Yes	Yes	Yes
	Geometric MTF	Yes	Yes	Yes	Yes
	Diffraction MTF	Yes	Yes	Yes	Yes
	Gaussian beam	No	Yes	Yes	Yes
	3D Wavefront	No	Yes	Yes	Yes
	Point spread function	No	Yes	Yes	Yes
	Line spread function	No	Yes	Yes	Yes
Optimization	Dumped DLS	Yes	Yes	Yes	Yes
Global	Simple GA	No	No	Yes	No
	Adaptive Simulated Annealing	No	No	No	Yes
	ASSGA	Yes	No	No	No
	EVOL ES	Yes	No	No	No
	GRUP ES	Yes	No	No	No
	REKO ES	Yes	No	No	No
	KORR ES	Yes	No	No	No
Tools	Export to CAD	Yes	Yes	Yes	Yes
	Tolerancing	No	No	Yes	Yes
	Polarization	No	No	Yes	Yes
	Illumination Analysis	No	No	Yes	Yes
	Zoom lenses	No	Yes	Yes	Yes

Conclusions

The ADOS program for optical system design and optimization is the product of years spent in research and development in optical system design and particularly in classical and modern optimization algorithms. It is developed with desire to be integrated environment where an optical designer can do all necessary things to design, analyze and optimize an optical system. It has the graphical user interface, that is now standard for all windows applications, which is very user friendly and intuitive. The ADOS program has similar features as standard commercially available programs for optical design. The real strength and uniqueness are in several optimization methods that are based on:

- Damped least squares method, which represents classical local optimization. It is best suited when good starting point is known in advance and it has very fast convergence to the first local minimum that can be the global minimum if the good starting point is chosen.
- Adaptive steady state genetic algorithms (ASSGA);

- Two membered evolution strategy – EVOL;
- Multimembered evolution strategies – GRUP, REKO, and KORR.

All these optimization methods (ASSGA, EVOL, GRUP, REKO and KORR) represent modern, global optimization algorithms that try to find the global minimum. They can not guarantee to find the global minimum but can find several very good optical systems that represent points near global minimum. Usually these optical systems fulfill all requirements. Global optimization methods have much slower convergence than local optimization methods and usually they need much longer time to find the minimum.

References

[1] K. Levenberg : A method for the solution of certain nonlinear problems in least squares
Q. J. Appl. Math., vol. 2, 164-168 pp, 1944

[2] S. Rosen, C. Eldret : Least squares method for optical correction
JOSA, vol. 44, 250-252 pp, 1954

[3] J. Meiron : Automatic lens design by the least squares method
JOSA, vol. 49, 293-298 pp, 1959

[4] J. Meiron : Damped least squares method for automatic lens design
JOSA, vol. 55, 1105-1109 pp, 1965

[5] C. Wynne : Lens designing by electronic digital computer
Proc. Phys. Soc. London vol. 73, 777-783 pp, 1959

[6] C. Wynne, P. Wormell : Lens design by computer
Appl. Opt., vol. 2, no. 12, 1233-1238 pp 1963

[7] M. Kidger, C. Wynne : The design of double Gauss systems using digital computers
Appl. Opt., vol. 6 , no. 3, 553-563 pp 1967

[8] P. Wormell : Version 14, a program for the optimization of lens designs
Opt. Acta, vol. 25, no.8, 637-654 pp 1978

[9] M. Kidger : The application of electronic computers to the design of optical systems, including aspheric lenses
Ph. D. Thesis, University of London, 1971

[10] D. Vasiljević : Prilog optimizaciji projektovanja optičkih sistema pomoću mikroračunara
Magistarska teza, Mašinski fakultet, Univerzitet u Beogradu, 1990

[11] D. Vasiljević, D. Riđošić : Optomizacija u procesu projektovanja optičkih sistema
Naučno-tehnički pregled, Vol.XLII, 1992, br.2 str. 24-31

[12] J. Holland : Adaption in Natural and Artificial Systems
MIT Press, Cambridge, Massachusetts, USA, 1992

[13] K. De Jong : An analysis of the Behavior of a Class of Genetic Adaptive Systems
Ph. D. Thesis, University of Michigan, 1975

[14] L. Davis, Ed. : Handbook of Genetic Algorithms
Van Nostrand Reinhold, New York, 1991

[15] D. Vasiljević : Mogućnost primene genetskih algoritama u optimizaciji performansi simetričnih objektiva pasivnih nišanskih sprava
Doktorska disertacija, Mašinski fakultet, Univerzitet u Beogradu, 1998.

[16] D. Vasiljević : Teorijske osnove i programsko rešenje genetskog algoritma primenjenog u optimizaciji optičkih sistema
Naučno-tehnički pregled, Vol.XLVIII, 1998, br.3 str. 30-40

[17] D. Vasiljević, J. Golobič : Comparison of the classical damped least squares and genetic algorithm in the optimization of the doublet
Proceedings of the First Workshop on soft computing, Nagoya, Japan, August 1996, pp. 200 – 204

[18] D. Vasiljević, J. Golobič : Analysis of various evolutionary algorithms and the classical damped least squares in the optimization of the doublet
in Second Online World Conference on Soft Computing in

Engineering Design and Manufacturing,
P.K. Chawdhry, R. Roy, R. K. Pand (eds.), Soft Computing in Engineering Design and Manufacturing, Springer Verlag, 1998

[19] H.P. Schwefel : Evolution and Optimum Seeking
John Wiley, New York, 1995.

[20] D. Vasiljević : Teorijske osnove i programsko rešenje evolucionih strategija primenjenih u optimizaciji optičkih sistema
Naučno-tehnički pregled, Vol.XLVIX, 1999, br.1 str. 29-43

[21] D. Vasiljević : Optimization of the Cooke triplet with the various evolution strategies and the damped least squares
Optical Design and Analysis Software, Proceedings of SPIE vol.3780, pp. 207-215.

[22] T. Bäck : Evolutionary Algorthms in Theory and Practice
Oxford University Press, Oxford, 1996.