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An "Intelligent" Optical Design Program

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Abstract

Described is a general approach to the development of computer programs capable of designing image-forming optical systems without human intervention and of improving their performance with repeated attempts. The approach utilizes two ideas: 1) interpretation of technical design as a mapping in the configuration space of technical characteristics and 2) development of an "intelligent" routine that recognizes global optima. Examples of lens systems designed and used in the development of the general approach are presented, current status of the project is summarized, and plans for the future efforts are indicated.

Introduction

This paper describes the current status of the development of an "intelligent" computer program capable of designing image-forming optical systems without human intervention and of improving its performance with time. In the description, we formulate a general approach to the development of "intelligent" design programs, present an example that illustrates the approach, and outline the plans for future efforts.

The design of image-forming optical systems was selected as the specific vehicle for the development of the general approach because these systems can be designed and their performance determined and evaluated with reliable design codes without resort to time consuming and costly experimental verification. However, these codes require intelligent human guidance and can find local optima only. We believe that the design program which we are developing will be useful in current optical design procedures and practices.

The general approach

Our approach to the development of intelligent design programs is based on the interpretation of the design process as mapping of a subspace of characteristic parameters into its complement; in general that mapping is required to extremize some objective function. The subspace being mapped may be viewed conveniently as the set of the prescribed characteristics of the device to be designed and the image subspace as the set of the derived characteristics; the union of these sets forms the configuration space of all technical characteristics that must be known to manufacture the device. Design optimization establishes a correspondence between the prescribed and the derived characteristics of any device; that correspondence is the design mapping.

In general, the specified characteristics do not provide the information needed for device realization, i.e. manufacturing. The characteristics that provide this information must be derived subject to some constrained optimization. For example, for optical lens systems, the specified characteristics may be the f-number, back focal length, the field-of-view, the total power of the system, the geometric envelope, etc. The surface radii of curvature, element thicknesses, indices of refraction, relative positions of the elements, etc., are needed for manufacturing; these quantities must be derived subject to image quality requirements. The task of the human designer is to select initial values of the derived characteristics in such a way that the design optimization will lead to a system which satisfies the specified characteristics. This is equivalent to the knowledge of the properties of the inverse of the design mapping.

Commercially available design codes (for example: ACCOS V(1), CODE V (2), and others) are capable of determining the optimal values for all derived characteristics provided an initial point in the configuration space is chosen intelligently and the code performance is monitored to prevent computation of physically unacceptable values of some parameters (for example lenses that are meters thick or hundreds of meters apart).

In the program being developed, we strive to eliminate the need for human involvement by inferring the properties of the inverse mapping from the calculation of a large num-

ber of images under the direct design mapping. These calculations establish regions in the subspace of derived characteristics that correspond to given regions in the subspace of specified characteristics. The computer program will store the descriptions and correspondences of these regions and thus will be capable of suggesting an initial configuration for each set of specified characteristics (requirements) without the need to retain in the memory every design previously calculated. A metric will be introduced to interpolate or extrapolate to design points outside of the well determined regions.

The above scheme for information storage approximates the concept of the content addressable memory because it makes it possible to retrieve general information (e.g. ranges of values in which the derived characteristics lie) pertaining to a specified set of devices.

The "intelligent" design code will improve its performance with time (learn) in two ways. First, the boundaries of corresponding regions in the specified and in the derived subspaces of the configuration space will be determined with increasing precision as more design points are calculated and the results assimilated. Second, the technique for locating the best starting preimage in each region will be refined. The goal is to determine the inverse mapping with such accuracy that the machine's first suggestion of a configuration results not only in the achievement of the specified performance requirements but also generates a system that is close to optimum in some sense.

We close this section by indicating the reason for developing the above described approach instead of following the standard artificial intelligence (AI) approach to the development of "expert" programs. Employing the concepts of regions in mathematical spaces and of mappings makes it possible to better utilize the large flawless memory and the manipulative speed of computer than is possible with the "if-then" production rules that are commonly employed in standard AI programs.

The general considerations presented in this section are made specific and illustrated in the next Section.

Two-element lens systems

As stated previously, the general approach described above is being developed for application to the design of optical image-forming devices. In this section we present the details and the results of the applications to simple two-element lens systems. For these systems, the dimensionality of the subspace of the specified and the derived characteristics is sufficiently low to allow representation in two dimensions. This facilitates the exposition.

We employed CODE V(2) to design a sample of approximately 40 lens systems. The details of the design and the performance calculations are presented in the Appendix. Here, we summarize the results relevant to the present application.

We use the effective focal length (equal to one inch), f-number and the field-of-view, θ , as the specified characteristics and the optical powers of the two elements, P_1 and P_2 , as the derived characteristics. The results are illustrated in Figs. 1 and 2; they show that to the region in the subspace of specifications described by the inequalities $5 \leq f \leq 10$, $\theta \leq 30^\circ$ there correspond two regions in the subspace of derived characteristics ($1.60 < P_1 < 2.70$; $-1.70 < P_2 < -0.60$, and $-1.60 < P_1 < -1.80$; $1.90 < P_2 < 2.50$) depending on the order of the positive and negative power elements. (Of course, the boundaries of these regions are fuzzy, not sharp.) An initial configuration in the above two regions results in a design that meets the specified requirements with acceptable image quality. Conversely, an attempt to design to specifications beginning outside of these regions ends up in their interiors after optimization, as shown in Fig. 2 and demonstrated in the Appendix. Consequently, we need to store in the memory only the description of and the correspondence between the regions shown in Figs. 1 and 2 instead of the 40 or more designs.

The performance of the designed systems is measured with an average value of the modulus of the optical transfer function whose evaluation is described in the Appendix. This quantity is normalized to the value that obtains for diffraction-limited systems and subtracted from unity so that the objective function to be minimized ranges between zero and one. The results of the performance evaluation are shown in Figs. 3 and 4 as functions of the powers of individual elements for the (+)(-) combination; similar plots obtain for the (-)(+) sequence. We see that the departure of the image quality from diffraction-limited ranges between 10 percent and 80 percent in an apparently random fashion. This variation may be caused by the fact that the optimization procedure used by CODE V employed to arrive at these designs does not minimize the same objective function that we use to evaluate their performance. The combination of a larger field angle and smaller f-number may also play a role as there may not be enough degrees of

freedom to design a better system. The behavior of the objective function shown in Figs. 3 and 4 indicates that it is futile to attempt development of an analytic procedure that would lead to an optimum design in the regions of Fig. 2. Instead, we developed for that purpose an "intelligent" search routine that is a generalization of the simulated annealing method. It is described in the next Section.

Generalized Simulated Annealing

Optimization by simulated annealing has been described previously and applied effectively to problems containing large numbers of parameters and global optima surrounded by many local optima (3). The method is based on the observation that optimization with a large number of variables is analogous to the relaxation of a physical system with a large number of degrees of freedom (e.g. many-body system at a finite temperature) to the state of minimum energy.

The computational algorithm based on this analogy is a random walk at each step of which the objective function is evaluated. If the step leads to a decrease of the objective function (when optimization means minimization), it is accepted and its endpoint used as the starting point for the next step. If the step leads to an increase of the objective function, then the probability $p = \exp(-\beta \Delta z)$ is calculated (Δz is the positive increment of the objective function and β is a parameter) and a random number, ρ , is chosen from the uniform distribution $0 \leq \rho \leq 1$. When $\rho > p$, the step is rejected and a step in a different direction is tried; when $\rho \leq p$, the step is accepted and its endpoint used as the starting point for the next step. In this way, the method of simulated annealing accepts some positive increments of the objective function, z , and consequently can walk out of local minima (with proper values of step size and β); however, it is biased toward the decreasing values of z . The amount of bias is determined by the value of the parameters β and the size of the attempted increment Δz .

Our generalization of the simulated annealing method uses the knowledge that in the present application the objective function vanishes by definition at the global optimum. We generalize the expression for the probability to $p = \exp(-\beta g \Delta z)$, where g is a nonpositive number at our disposal. Because of this modification, the algorithm rejects an increasing number of (positive) increments as a global minimum (there may be several locations where $z=0$) is approached. Therefore, its tendency to wander away diminishes. However, at any local minimum where z is bounded away from zero, the probability of accepting (positive) increment remains significant and the algorithm may walk out of it as intended. The exponent g controls the rate at which the probability p diminishes as a global optimum is approached; for $g=0$ we recover the standard method of simulated annealing.

We are using several objective functions to assess the performance of the generalized simulated annealing method. The analysis and the results will be published elsewhere; here we present one example to illustrate the effectiveness of the generalization.

The objective function on which the location of the minimum value is to be found is given by:

$$z(x,y) = ax^2 + by^2 - c \cos ax - d \cos y + c + d, \\ -1 \leq x \leq +1, -1 \leq y \leq +1. \text{ It is shown in Fig. 5 for } a=1, b=2, c=0.3, d=0.4, \\ \alpha=3\pi, \text{ and } \gamma=4\pi; \text{ it's global minimum } (z=0) \text{ is at } x=y=0 \text{ and it has many local minima.}$$

Numerical experimentation with the standard simulated annealing method ($g=0$) indicated that the most favorable values of the parameters are $\beta=4.50$ and step size $\Delta r = (\Delta x^2 + \Delta y^2)^{1/2} = 0.15$. One walk of 150 steps with the starting point at $x_0 = 0, y_0 = 0.90$ is shown in Fig. 6; here the solid circles indicate the accepted steps and the open squares the rejected tries. We see that the algorithm finds the global minimum readily but does not remain there because of the low value of β ; however, if β is increased (in the analogy with the physical many body problem this implies lowering of the temperature) then the algorithm gets stuck at a local minimum. Therefore, a satisfactory optimization strategy requires an increased value of β after the biased random walk reaches the neighborhood of a global optimum.

In the spirit of our work, aimed at the elimination of human intervention in computer operations, in the generalized simulated annealing method β is effectively increased in the neighborhood of a global minimum, $z=0$, through the dependence of the probability p on a negative power of z . Figure 7 shows the biased random walk with $g=-1.00$, $\Delta r=0.15$, and $\beta=3.00$; we see the inability of the algorithm to walk out of a global minimum after finding it. In this calculation, the initial point was again at $x_0=0, y_0 = 0.90$ and the total number of attempted steps was 150.

Summary and Conclusions

We have proposed a new general approach to the development of intelligent design programs. This approach is based on the interpretation of the design process as a mapping of the configuration space onto itself in which the subspace of specified characteristics is mapped into the subspace of derived characteristics. The point and its image in these subspaces represent a complete description of a specific design. The design mapping is usually accomplished with some constrained optimization. Our researches thus far have demonstrated the feasibility of the proposed approach with the application to the design of simple two-element image-forming optical lens systems. We have also devised a generalized simulated annealing method for use in the "intelligent" design programs and demonstrated its capability to locate and recognize global optimal by trapping the biased random walk there.

Future Work

Our task for the immediate future is to complete the integration of the design mapping, an optical design code (e.g. CODE V, ACCOS V, or other), and the generalized simulated annealing method into one "intelligent" computer program. We will then utilize this program to more fully explore two-element systems: the exploration will reveal if additional corresponding regions exist in the relevant subspaces of the configuration space and will thus improve our insights into the design mapping.

Following significant progress in the above two tasks, we will extend the scheme to multi-element systems; this will include calculations of design points in the configuration space and the determination of suitable characterizations of the subspaces of the specified and the derived characteristics.

We fully realize that there exist a variety of systems with differing performance requirements. Our approach is to not attempt to solve all the complexities of the design problem at once, but to proceed it in a systematic fashion. Because the image forming systems have fairly well defined characteristics in terms of the optical transfer function properties, we intend to study these systems first. Fortunately, most optical codes with optimization routines also heavily favor such systems.

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Appendix

The Optical Design of Examples

In this Appendix, we present the details of the design calculations used to obtain the various examples for this study. We chose the two-element systems not only because they are easy from the optical design point of view, but also because the distribution of powers between the two elements appears to be a suitable choice for parameter studies.

The specified characteristics for each design were:

- 1) The effective focal length (E.F.L.) equal to 1 inch
- 2) The back focal length (B.F.L.) exceeding 0.75 inch
- 3) The f-numbers ranging from F/5 to F/10
- 4) The field angles ranging from 10° to 30°

The image performance of each system was calculated as follows:

We calculated the polychromatic modulation transfer function at 10 equally spaced spatial frequencies to a maximum of 179.5 lp./mm (cut-off frequency for F/10 system at $\lambda = 557.1$ nm) for an incoherent beam. These values were normalized to the performance of a diffraction limited system at the corresponding f number and averaged with equal weights. The objective function to be minimized is defined to be one minus the above average value; it represents the performance of the system in terms of the MTF. The polychromatic M.T.F. was calculated following the prescription of E. I. Betensky⁴ for photographic lenses. This means that the optical wavelengths were weighted as follows:

Wavelength(nm)	Weight
433.9	0.1324
482.8	0.2739
557.6	0.2848
633.7	0.2110
686.1	0.0979

This estimate of the polychromatic optical transfer function is equivalent to an estimate using nine equally spaced wavelengths and any standard numerical quadrature rule and represents the best practical spectral distribution for daylight combined with average lens transmittance.

The specifications related to constructional parameters were:

- 1) The edge thickness for a positive lens (or the center thickness for a negative lens) shall be at least 10 percent of the center thickness (edge thickness for a negative lens) for the full beam size.
- 2) The air spaces between lenses have to be positive so that lens surfaces do not cross inside the full aperture involved.
- 3) The glasses used in the design have to be real catalogue glasses currently manufactured by well known glass manufacturers.

The design procedure was as follows:

The starting point for each design was an example based on patent literature. These are the examples 1, 2, 3 and 4 in Table 1. The examples 1, 3, and 4 have the positive element first and example 2 has the negative element first. From these starting points, the cases 1.1 thru 1.8, 2.1 thru 2.8, 3.1 thru 3.9, 4.1 thru 4.8 were generated. CODE V was allowed to optimize from these starting points using the optimization routine with the constraints imposed by the specifications. Initially the glasses were allowed to vary but later in the design process the code reoptimized the systems with catalogue glasses close to the ones the program chose.

These designs resulted in the boundaries shown in Fig. 2 and Table 2 for the two cases (positive element first and negative element first).

To prove that these indeed are the boundaries, we attempted to design specified systems from initial configurations well outside of the two regions. Table 3 summarizes these results. Start number 1, thru start number 4 are designs that start outside the boundaries. As shown in Table 3, after optimization, they all fall within the boundaries of Fig. 2. The other claim to be verified is whether the systems after optimization fall within the boundaries if the starting system itself is within the boundaries. Examples 1, 1.1; 2, 2.1; 3, 3.1; and 4, 4.1 illustrate that this is indeed so (Table 1). 1 is the starting system and 1.1 is the optimized system and this is the case for starting systems 2, 3, and 4 also.

Thus, we have shown that whether the starting system is inside the boundaries or outside, the optimized system always falls within the boundaries established in Fig. 2, for the two-lens systems that have been considered. Thus, the choice of the powers of the two elements appears to be appropriate for the two-element case. We hope to derive similar description of the boundaries for multi-element systems also, in the future.

References

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2. CODE V - A proprietary optical design and analysis code of Optical Research Associates, Pasadena, CA.
3. S. Kirkpatrick, C. D. Gelatt, Jr. M. P. Vecchi, "Optimization by Simulated Annealing", Science, Vol. 220 pp 671-680 (13 May 1983)
4. E. I. Betensky - Photographic Lenses - Vol VIII - Applied Optics and Optical Engineering, Page 6. Published by Academic Press. 1980.

TABLE 1 - Description of 2 Element Optical Systems

SYSTEM NO. MERIT	F NO.	SEMIFIELD (DEGREES)	P1 (POWER OF FIRST ELEMENT	P2 (POWER OF SECOND ELEMENT	AVG. M.T.F.	FIGURE FMT=(1- AVG. MTF)
1	10	5	2.0	-1.1	.36	.64
1-1	10	5	1.8	-0.8	.87	.13
1-2	10	10	1.9	-0.9	.77	.23
1-3	10	15	2.2	-1.2	.60	.40
1-4	7.5	5	1.9	-0.9	.81	.19
1-5	7.5	10	2.2	-1.2	.64	.36
1-6	7.5	15	2.1	-1.1	.41	.59
1-7	5	5	2.1	-1.1	.70	.30
1-8	5	10	2.0	-1.0	.33	.67
2	10	5	-1.0	+2.1	.29	.71
2-1	10	5	-1.2	2.3	.88	.12
2-2	10	10	-1.2	2.2	.79	.21
2-3	10	15	-1.6	2.5	.66	.34
2-4	7.5	5	-1.2	2.3	.85	.15
2-5	7.5	10	-1.2	2.2	.60	.40
2-6	7.5	15	-1.2	2.2	.43	.57
2-7	5	5	-.9	2.0	.75	.25
2-8	5	10	-.8	1.9	.40	.60
3	10	5	2.7	-1.7	.45	.55
3-1	10	5	2.0	-1.0	.89	.11
3-2	10	10	2.1	-1.1	.81	.19
3-3	10	15	2.5	-1.5	.58	.42
3-4	7.5	5	2.0	-1.0	.85	.15
3-5	7.5	10	1.9	-0.9	.61	.39
3-6	7.5	15	1.9	-0.9	.32	.68
3-7	5	5	2.0	-0.9	.68	.32
3-8	5	10	1.7	-0.7	.31	.69
3-9	5	15	1.7	-0.6	.17	.83
4	10	5	1.9	-1.0	.50	.50
4-1	10	5	1.8	-0.8	.90	.10
4-2	10	10	1.9	-0.9	.80	.20
4-3	10	15	2.3	-1.3	.58	.42
4-4	7.5	5	2.1	-1.1	.88	.12
4-5	7.5	10	1.9	-0.9	.62	.38
4-6	7.5	15	2.1	-1.1	.42	.58
4-7	5	5	1.9	-0.9	.69	.31
4-8	5	10	2.0	-1.0	.32	.68

TABLE 2 - The Boundaries of Power Distributions
For examples in TABLE 1

DESCRIPTION	FIRST ELEMENT		SECOND ELEMENT	
	UPPER BOUND(P1)	LOWER BOUND(P1)	UPPER BOUND(P2)	LOWER BOUND(P2)
POSITIVE ELEMENT FIRST	2.7	1.6	-0.6	-1.7
NEGATIVE ELEMENT FIRST	-0.8	-1.6	2.5	1.9

TABLE 3 -Description of the 4 cases in FIGURE 2 which had
starting points outside bounds of TABLE 2
which end inside bounds of TABLE 2

SYSTEM NO	FNO	SEMIFIELD ANGLE (DEGREES)	P1 (POWER OF FIRST LENS,	P2 (POWER OF SECOND LENS)	(AVG. M.T.F.)	FIGURE MERIT FMT =(1-avg. MTF)
START NO 1	6.67	5	-3.1	+3.5	.03	.97
FINISH NO 1	6.67	5	-1.0	+2.1	.37	.63
START NO 2	6.67	5	+3.5	-3.1	0.01	99.99
FINISH NO 2	6.67	5	+1.7	-0.8	.60	.40

TABLE 3 (cont'd)

START NO 3	6.67	10	+1.60	0	0*	1
FINISH NO 3	6.67	10	1.63	-0.7	.45	.55
START NO 4	6.67	10	0	+0.7	0*	1
FINISH NO 4	6.67	10	-0.81	+1.9	.56	.44

* The M.T.F. computation for this case does not matter, as the starting point has a focal length too far away from the value of 1, (which is needed for the effective focal length system).

FIG. 1 THE SUBSPACE OF SPECIFIED CHARACTERISTICS

FIG 2

FIG. 2 THE SUBSPACE OF DERIVED CHARACTERISTICS

FIG. 3

FIG. 3 NORMALIZED IMAGE QUALITY

FIG. 4

FIG. 4 NORMALIZED IMAGE QUALITY

FIG. 5

FIG. 5. AN OBJECTIVE FUNCTION USED
IN ALGORITHM TESTING

FIG. 6

FIG. 6. STANDARD SIMULATED ANNEALING

FIG. 7

FIG. 7. GENERALIZED SIMULATED ANNEALING