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TITLE: Development of an Autonomous Design Program

AUTHOR(S) I. O. Bohachevsky, WDP/AWT, F668
T. P. Cotter, S-DOT, F607
V. K. Viswanathan, P-5, E523

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Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

DEVELOPMENT OF AN AUTONOMOUS DESIGN PROGRAM

I. O. Bohachevsky, T. P. Cotter, V. K. Viswanathan

Los Alamos National Laboratory

ABSTRACT

Presented is a general approach to the development of an "intelligent" computer program that designs technical devices and systematically improves its capability without human intervention. The methodology is based on the recognition that effective use of computers requires employment of clearly defined concepts and precise language, therefore significant effort is devoted to the formulation of the design problem in mathematical terms. This formulation is based on the introduction of metrizable performance and configuration spaces and on the representation of the design process as a mapping from the performance into the configuration space; the inverse of this mapping represents the design evaluation. An essential part of the design mapping, as we define it, is design optimization. For that purpose we developed a generalized simulated annealing method capable of locating global extrema of multidimensional functions that have numerous local extrema and may not be differentiable. The optimization method is interesting in its own right, for its applicability transcends the original intent. The exploitation of the concept of the design mapping and the optimization algorithm are illustrated with an application to the design of optical lenses. This application was chosen because it offers the possibility to evaluate each design solely by computation and thus validate the program's capability without the need for a physical realization.

I. Introduction

The objective of our research is the development of an "intelligent" computer program able to design technical devices and to improve that capability with repeated usage without human intervention. We are developing such a program in the context of the design of image forming optical lenses because this application offers the possibility to evaluate each design solely by computation and thus validate the "intelligence" and the capability of the program without the need for physical realization and experimental verification.

Our approach is based on the interpretation of technical design as a mapping of a performance specification into a device configuration determination. In general, this mapping is defined by the optimization of a suitable performance objective function.

In the next section we illustrate the concept of the design mapping with a specific example and discuss the difficulties encountered in its automation. In Section III, we indicate and illustrate a way of overcoming the implementation difficulties, in Section IV we summarize briefly the global optimization procedure that we use to specify the design mapping, and in Section V we discuss the current and future work.

II. The Design Mapping

The description of the design mapping requires a definition of the performance and configuration spaces. These are the spaces spanned by all the variables necessary to specify the performance and configuration of the technical device being designed. The recognition that these spaces must be defined compatibly with the performance objective function is one of the crucial elements of our approach. In that approach the performance variables are the coefficients in an expansion of the performance objective function in terms of basis functions each of which represents some performance characteristics. The design mapping assigns to each point in the performance space that represents a reasonable set of requirements one or more configurations representing one or more designs that meet these specifications in some prescribed sense. We illustrate this concept with a simple example in which the performance and configuration spaces are one-dimensional. Let us design a slender column with a uniform solid circular cross-section using the least amount of the structural material to support a load L at a specified height h. In this case the performance space is spanned by the coordinate L and the configuration space by the cross-section radius, r. The design mapping is given by the well known Euler relation:

$$r = \sqrt{\frac{2h}{\pi}} \sqrt[4]{\frac{L}{\pi E}} \qquad (1)$$

where E is the Young's modulus. Its inverse, the expression for the buckling load L,

$$L = \frac{\pi^3 E}{4h^2} r^4 \qquad (2)$$

characterizes the performance of the design configuration specified by the cross-section radius r. The design mapping and the evaluation of the configuration are indicated schematically by arrows in Fig. 1.

In most practical applications severe difficulties preclude straight-forward algorithmic implementations of the design mapping. The first difficulty stems from the fact that the performance and configuration spaces encountered in engineering designs are multidimensional (100 to 200 dimensions are not unusual), therefore the design mapping and evaluation are composed of numerous interconnected steps that express complex relationships among the many variables.

The second, fundamental, difficulty stems from the fact that, in general, the design mapping cannot be represented by explicit algorithms. Algorithms that constitute design evaluations can be expressed explicitly relatively easily; many exist and are used for that purpose, however, very few can be inverted to obtain an explicit representation of the design mapping.

Therefore the determination of the image in the configuration space of a given preimage in the performance space usually requires iterations. This is the place in the design process where either the human or the "artificial" intelligence must enter.

The third difficulty is partly a cause and partly a consequence of the first two; it is the fact that the design mapping is seldom unique and it does not cover the configuration space completely. In general, there are several configurations that result in the same or nearly the same performance and there are many configurations that do not correspond to meaningful performances. Practical, aesthetic, or even arbitrary considerations are used to select among the several available design alternatives.

III. <u>An "Intelligent" Design Mapping</u>

The difficulties outlined above, albeit serious, are not fatal; to circumvent them we exploit the anticipated continuity and regularity of the design mapping in certain regions of the spaces on which it is defined. Because of the continuity and regularity f the physical world it is plausible to expect that neighboring configurations will have approximately similar performances except possibly across isolated boundaries corresponding to different types of discontinuities. If the continuity of the mapping can be established and the boundaries across which it breaks down determined, then suitable metrics can be introduced and interpolation/extrapolation used to predict the location of the image in the configuration space of a specified point in the performance space. The coordinates of that anticipated image (in general not unique) provide "good" initial configurations to start the design optimization. The points needed for the interpolation/extrapolation will be obtained from previously determined successful designs retained in the computer's memory.

Successive applications of the program will continuously increase the number of successful configurations and their preimages stored in the memory; these will provide an increasingly dense covering of the relevant regions in the performance and configuration spaces which, in turn, will improve the prediction of "good" initial configurations for the design optimizations. Such a learning process is the computer analogue of the process by which human designers gain experience. Expressed mathematically, the process is equivalent to the determination of the inverse of the design evaluation algorithm from a sparse sample of known images. The increasing density of the covering will also improve predictions of the locations across which the design mapping is discontinuous.

We illustrate the characteristics of a realistic mapping with the example of two-element lens systems. The objective is to investigate the design of two-element lens systems with the effective focal length of 1 inch, back focal length greater than 0.75 inches, f-numbers ranging between 5 and 10, and the fields of view ranging between 10° and 30°. To make the graphical presentation of the results possible, we condense the performance and the configuration spaces to two dimensions each; in the actual design calculations these spaces were appropriately multidimensional.

The condensed performance space, shown in Fig. 2, is spanned by the f-number and the field of view and the condensed configuration space, shown in Fig. 3, is spanned by the optical powers of the first (P_1) and of the second (P_2) element. The design of the two-element lens systems, as formulated in this paper, is equivalent to the determination of the image of the region R (in the performance space) in the configuration space. The image under the design mapping is to be determined with the optimization of the "optical quality" of the lens system.

We designed [1] a sample of 44 lenses with specifications in the region R using the optical design code CODE V[2] interactively; its optimization algorithm is capable of finding local optima near reasonable starting configurations. The result, presented in Fig. 3, shows that the image of the region R consists of two disjoint rectangles in the performance space: $1.60 < P_1 < 2.70$, $-1.70 < P_2 < -0.60$, and $-1.60 < P_1 < -0.80$, $1.90 < P_2 < 2.5$, depending on the order of the positive and negative power elements. (Of course, the boundaries of these regions are not sharp, but fuzzy.) With that experience, the code knows that initial configurations in the above two regions lead to designs that meet the specifications with acceptable image quality; conversely, attempts to design to specifications in region R beginning outside of either region C_1 or C_2 end up in their interiors after guided optimization as indicated by the designs labeled 1, 2, 3, and 4 in Fig. 3.

It is worthwhile to note that the only analytically derivable specification of the image regions C_1 and C_2 is the condition $P_1 + P_2 = 1$ (focal length of 1 inch) and the additional limitations are consequences of the optimization of image quality.

The results of this simple example confirm the expected continuity of the design mapping in restricted regions and indicate that the boundaries of these regions and the topological structure of the mapping may be inferred from a moderately large sample of design calculation and configuration evaluations. The current efforts to exploit these properties are indicated in the last section. Prior to that we outline the global optimization method developed for the application in "intelligent" design programs.

IV. Design Optimization

The autonomy and robustness of intelligent design programs are enhanced significantly with a design optimization method capable of locating global extrema of objective functions of many variables that have numerous local extrema and may not be smooth (differentiable). We developed a method with these properties by generalizing the standard simulated annealing algorithm; the generalization was introduced in Ref. 1 and described in detail in the paper recently submitted for publication [4]. In this section we indicate the nature of the method only very briefly for the sake of completeness and illustrate its characteristics with one result.

The search for the global optimum is conducted with a biased random walk that favors the beneficial directions. However, the probability of accepting some detrimental steps is not zero unless the global extremum has been reached. Thus the walk meanders in and out of local extrema but is always trapped at the global one. A representative solution of a 2-dimensional optimization problem obtained with this method is shown in Figs. 4 and 5. Fig. 4 is an isometric representation of a function of two variables with many local extrema and one global extremum located at the origin x = y = 0. The biased random walk toward the origin is shown in Fig. 5 on the contour plot of that surface. Solid dots represent the accepted steps and open squares those rejected as too detrimental. The circular pattern of points around the origin (approximately) illustrates the inability of the algorithm to walk out of the global extremum. We terminate the computation when an uninterrupted sequence of trials of a specified length (depending on the dimensionality of the problem) fails to find a direction in which an acceptable step may be taken The method has been used successfully to solve multidimensional optimization problems (10 to 40 variables) in mathematical biology [(4)], crystallography, and military planning.

We have investigated the applicability of the generalized simulated annealing method to the optimization of optical lens designs on the simple example of a single element "landscape" lens. For this lens the performance space may be spanned by the focal length (or lens thickness) and the field of view and the configuration space by the mean lens curvature and the stop location (for a fixed index of refraction). The appropriate objective function whose minimization defines the design mapping is the wavefront variance. For the landscape lens this function has two minima as shown in Fig. 6 [(5)]. We implemented the design with the commercially available code ACCOSV [(6)] in which the generalized simulated annealing was the optimization algorithm. A preliminary result that demonstrates the method's ability to climb away from the shallower minimum and to migrate into the deeper one is shown in Fig. 7.

V. Current and Future Work

The discussion and the results presented in this paper indicate that we have developed a general approach and validated the elements needed to realize an "intelligent" optical lens design program. Our current efforts are aimed at the integration of these elements into an autonomous program. In particular, we are streamlining the interface between the available optical design and analysis code, ACCOSV, and the generalized simulated annealing algorithm and devising useful "universal" performance objective function. We will use the resulting program to exhaustively explore the structure of the design mapping for one- and two-element lenses and to determine suitable metric functions on the performance and the configuration spaces. Having validated the performance of the program on one- and two-element systems, we will proceed to the more complex applications

The evaluation of sufficiently general and satisfactory performance objective functions (for example, the Modulation Transfer Function) may be computationally expensive, therefore we are exploring ways to improve the efficiency of the generalized simulated annealing algorithm. Several possibilities appear promising; the results will be reported when they become available.

ACKNOWLEDGEMENT

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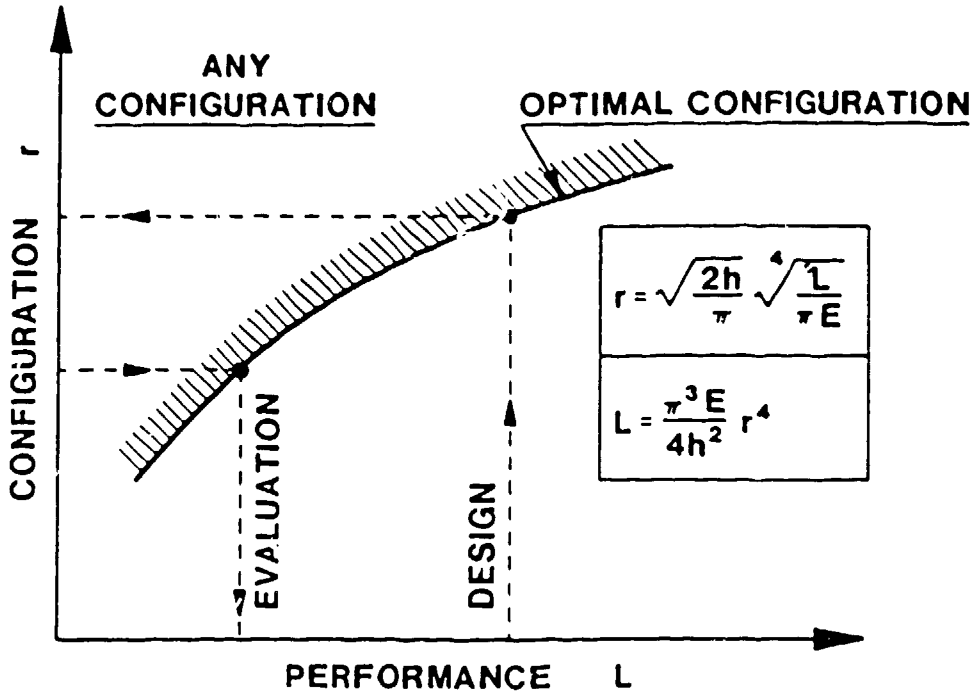

Fig. 1 Design Mapping and Evaluation (Schematic)

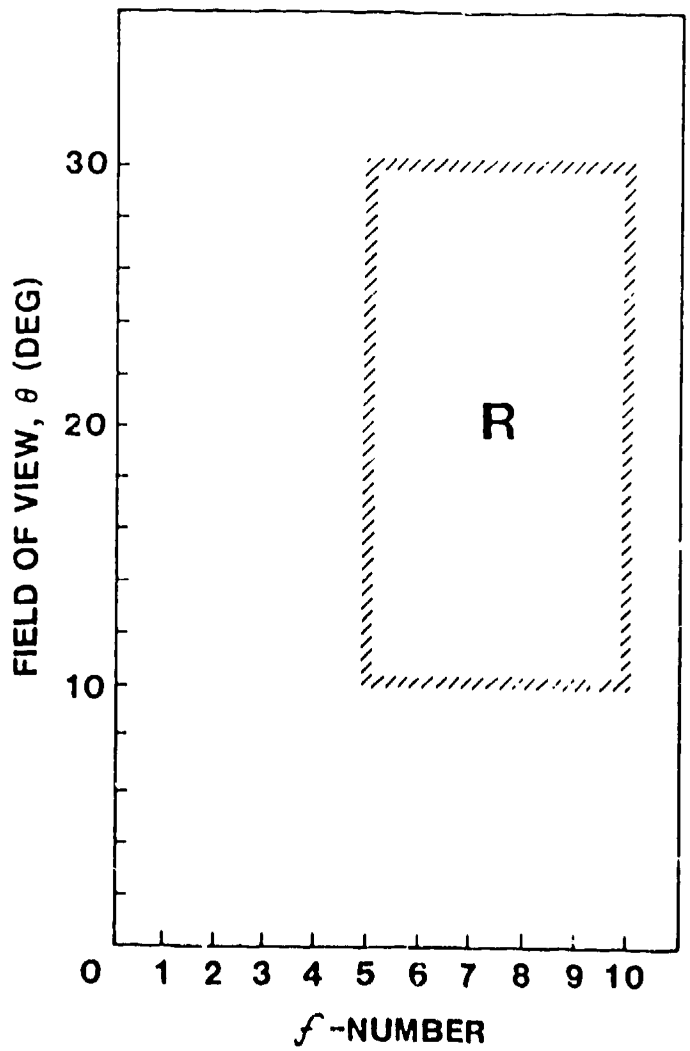

Fig. 2 Condensed Performance Space

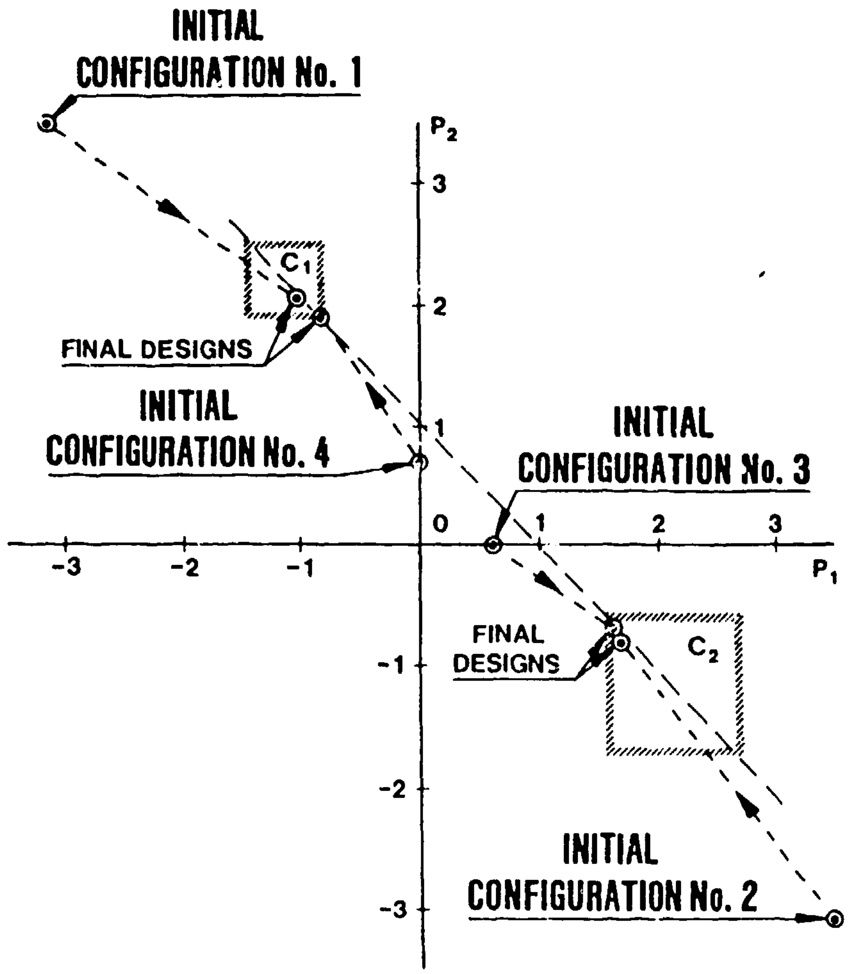

Fig. 3 Condensed Configuration Space

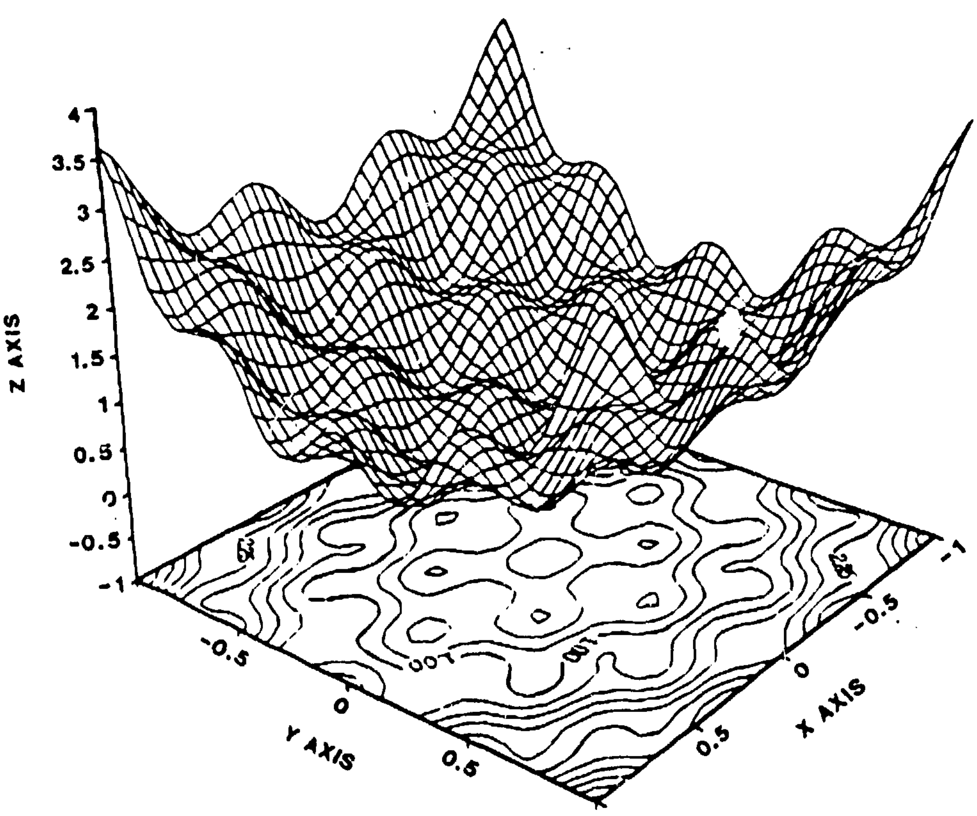

Fig. 4 Isometric View of the Surface $z(x,y) = ax^2 + by^2 - c(\cos\alpha x)(\cos\gamma y) + c$; $a = 1$, $b = 2$, $c = 0.3$, $\alpha = 3\pi$, $\gamma = 4\pi$

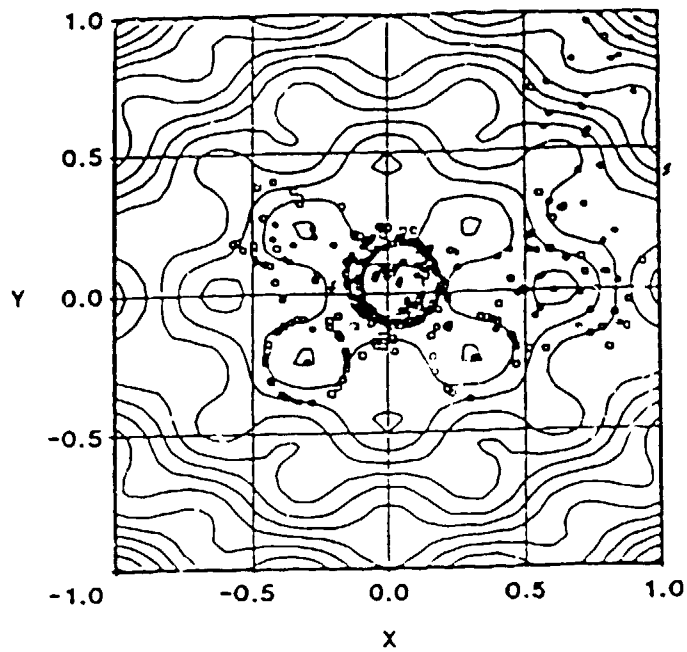

Fig. 5 Generalized Simulated Annealing Method With g = -1, Δr = 0.15, β = 3. The function is that of Fig. 4

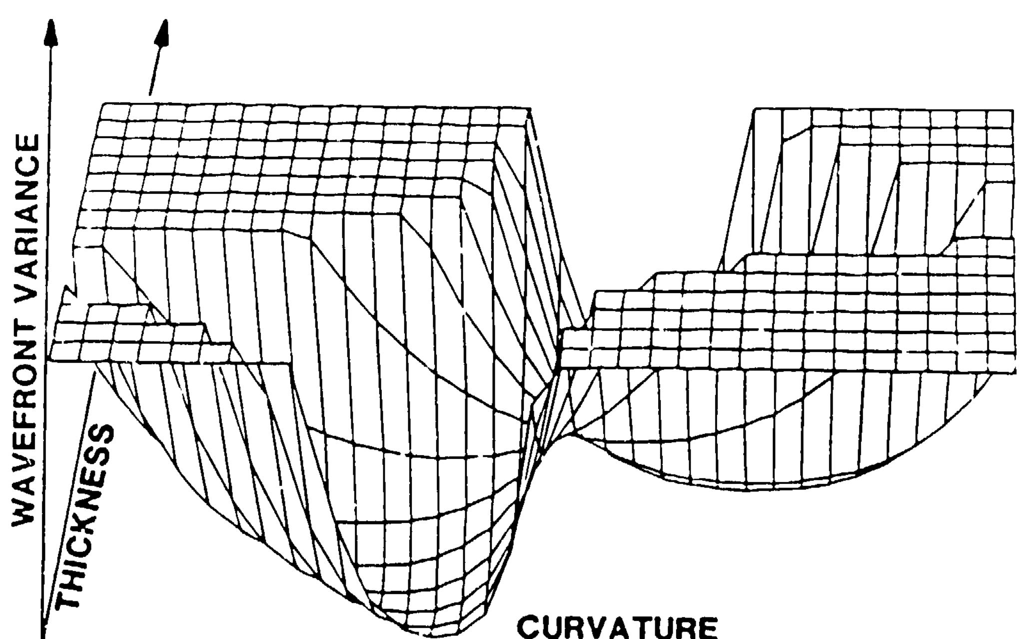

Fig. 6 Performance Objective Function for the Landscape Lens

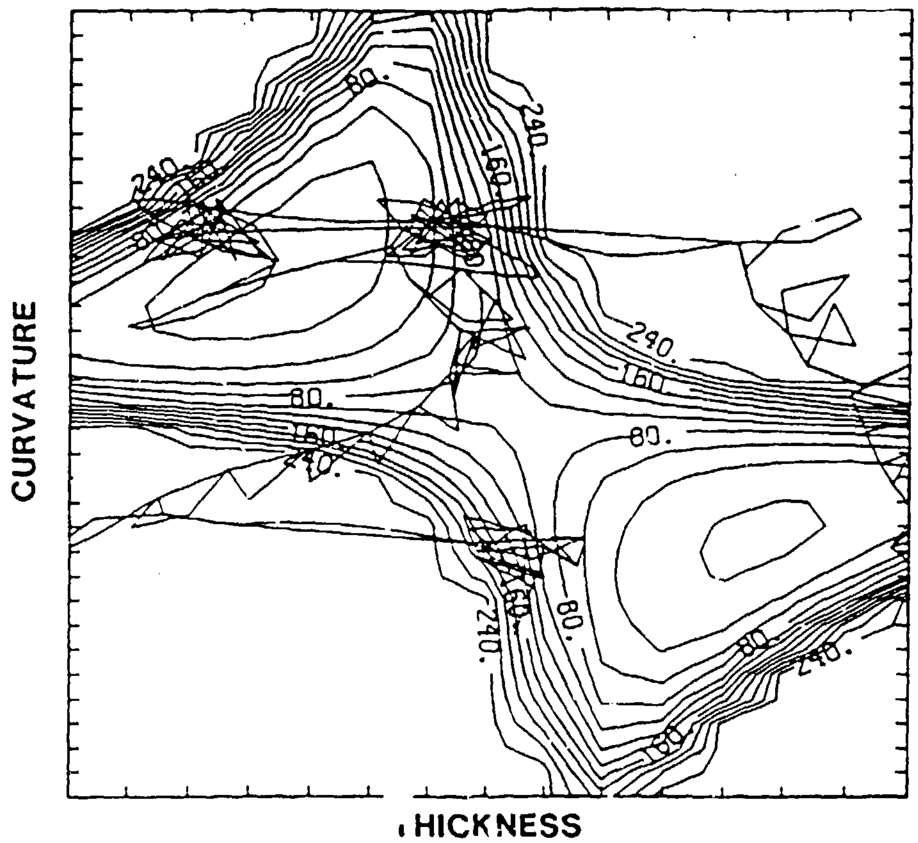

Fig. 7 Optimization of the Landscape Lens Design
with Generalized Simulated Annealing