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Optical Design Using an Expert System

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ABSTRACT

We present, as a different perspective on optimization, an expert system for optimization of optical systems that can be used in conjunction with damped least squared methods to find minima for specific design forms. Expert system optimization differs from global optimization in that it preserves the basic structure of the optical system and limits its search for a minima to a relatively small portion of the design space. In general, the high density of local minima obscures the general trend of the merit function in the region of interest for systems with a large number of variables and constraints. Surprisingly, there may be a potential decrease of an order a magnitude in the merit function for a region of solution space. While global optimization is well-suited to identifying design forms of interest, expert system optimization can be used for in-depth optimization of such forms. An expert system based upon such techniques was used to obtain the winning entry for the 2002 IODC lens design problem. The expert system used is discussed along with other design examples.

1. INTRODUCTION

The modern desktop computer and readily available optical design software packages have made lens design accessible to the non-expert. This paper offers one perspective on the ability of both the expert and non-expert to contribute to the lens design process. We begin by offering context and perspective on the definition of the term expert system. Essentially, we use a practical definition of an expert system. -macro programming is used as a tool to guide the optical design process. The utility of expert system optimization will be demonstrated with the examples of an f/1, 10 degree field of view objective and the 2002 IODC design problem.

A little later in this paper we'll let the computer loose, but first some context. Below, figure 1 shows a triplet designed without a computer by Rudolf Kingslake. The optical design and optimization took 6 weeks. The design was optimized by making small trial changes to the design variables and then tracing a few rays by hand to determine the primary aberrations. Solving a few equations such that the design satisfied key constraints reduced the number of variables for optimization[1]. Without the computational ability of the computer, the design methodology needed to be very efficient. Understanding of the task was critical (as is still is). The value of this analytic approach should not be forgotten.

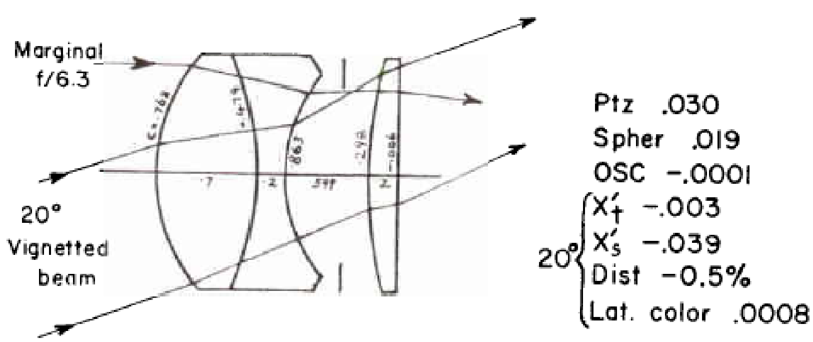


Figure 1. Triplet designed without a computer by Rudolf Kingslake.

Thirty years ago, the lens design program was beginning to mature. Computing power enabled a numerical optical design approach. The high cost of computing time did however limit the availability of optical design programs. Although the lens design programs have matured, the following observations by R. E. Hopkins seem equally valid today[2].

- "a skilled, experienced person was far more effective than an inexperienced person [at using a lens design program]."
- "It takes a great deal of experience with a given program to really learn how to use it well."
- "all lens design of the future would be done on large computers in remote batch."
- "only the professionals willing to dedicate their career to it could make much of a contribution from hereon in."

So where do we stand today? The computational gain in ray tracing speed since the 1950s is ***30 million!*** R. R. Shannon presented a paper at the 2002 IODC conference that gives context on the modern lens design process[3]:

- "lens designers are very inefficient … the apparent lack of efficiency is striking."
- "Integration of concepts, knowledge and basic theory in the computational tools would be adventitious."
- "The designer [has become] even more dependent upon the actions and vagaries of the computer and its program."

For better and worse, it is my opinion that the modern lens design program enables the professional with little knowledge of optical design to design well-corrected lenses. That being said the expert remains critical when considering real world constraints such as packaging, cost, and as-built performance.

So what is this expert system then? An expert system is a computer program that simulates the judgment of a person that has expert knowledge. In this case, the expert is the lens designer and the expert system is the macro language program that interacts with the lens design program to guide optimization. The work presented here is a small step towards a mature expert system. These techniques should not be seen as global optimization and do not replace an experienced lens designer. A strength of this approach is that fast and inexpensive computer time allows the designer's time to be used more efficiently. Expert system optimization is implemented as a remarkably simple macro that relieves the lens designer of monitoring optimization minute by minute. The macro language programs discussed in this paper utilize existing optimization techniques[4].

The expert and the expert system work together as a team and balance each others strengths and weaknesses. The expert's strengths include intuition, knowledge, experience, and efficiency. The expert system's strengths include computational speed and persistence. The lens design process has long teamed the persistence of a non-expert with the knack of an expert. W. T. Plummer commented on the lens design process before computers[5]:

> "Confronted with a lens design problem, a few men with a genius or a knack could sense the direction to take. Then it was a matter of the laborious application of Snell's law over and over again as designs were checked out by tracing the paths that rays of light might take from the object to the image. Few outside the profession could comprehend the magnitude of the task ... The key to a successful outcome was persistence."

Today, the key to a successful outcome remains persistence.

2. EXPERT SYSTEM OPTIMIZATION

This lens design process that I am describing teams an expert with an expert system consists of four stages: initial system layout done by the lens designer, expert system definition, expert system optimization, and analysis and optimization by the lens designer to produce a final design. For a complex design, most of the time in the design process should be spent in expert system optimization. This allows the designer's time to be used more efficiently. The lens designer uses intuition and knowledge to produce the initial system design. The goal is to obtain an initial design form for which damped least squares optimization algorithms are well-behaved such that they can be applied repeatedly by an expert system. After definition by the lens designer, the expert-system is used to "walk" the initial design to a lower minima by a combination of intelligent choices and brute force. The lens designer then analyzes the results of the expert system macro and may further optimize to produce a final design. This final design may give the lens design intuition about the design space and may inspire a new initial design for expert system optimization. So, not only does the expert impart knowledge to the expert system, but also the expert learns from the results of expert system optimization.

Expert system optimization consisted of four parts: choosing optimization parameters, damped least squares optimization, analyzing the design, and modifying the design by simulating the judgment of a lens designer. A schematic of the process is shown below in figure 2. The expert system optimization cycle begins by choosing the optimization parameters. These parameters include: optimization variables, design constraints, merit function weighting, and the ray grid for optimization. Damped least squares optimization is then used to find a local minima. Note that optimization speed is proportional to the square of the number of variables. For complex design forms convergence may be very slow and optimization may stagnate. The results of the damped least squares optimization are analyzed to calculate the merit function and determine if the design constraints are satisfied. Then based on the analysis the expert system then makes an educated guess as to the direction that the design should take. The design is then modified based on this educated guess.

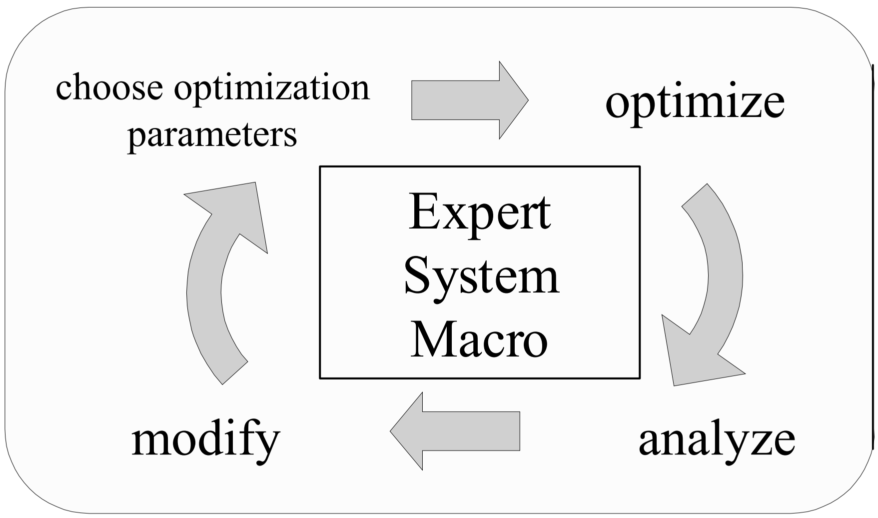


Figure 2. Schematic of expert system optimization macro

By modifying the design the expert system simulates the judgment of a lens designer. Modification of the design is done in several discrete steps. If the design convergence is too slow then the design is discarded for a previous design. This gives the macro the ability to recover from incorrect choices. Note that a controlled number of uphill steps may be allowed in the design process. The lens is modified to meet design constraints such as for positive edge thickness. Lenses may be split, added, deleted, and flipped. Glass types may be varied. The system is perturbed out of local minima is necessary. My experience is that the difficult choices in design direction are in the initial layout of the design and that for detailed optimization persistence is the key...

For expert system optimization randomness is a key ingredient. One definition of finite probability claims that, "an infinite number of monkeys typing on an infinite number of typewriters will (eventually) produce the complete works of Shakespeare." So too, given enough computing speed and power an expert system will (eventually) produce a well corrected lens design. In defining the expert system parameters there is a balance between determinism and randomness. If there is too little randomness very little of the design space will be explored and optimization is likely to stagnate. Too much randomness makes the optimization unstable. One tool for introducing randomness into the design process is catalysts. Examples of catalysts that I have found useful include: the variation of the system back focal length, random scaling of the design, and the introduction of an asphere with later removal.

One useful tool for use in conjunction with an expert system, especially one with many design parameters, is Sparse Optimization. Sparse Optimization is defined as using a subset of optimization variables and parameters for a give number of cycles. As optimization speed is proportional to the square of the number of variables, each optimization cycle takes less time. By changing the variable subset after one or more optimization cycles, generality is maintained. My experience is that Sparse Optimization allows the merit function to converge more rapidly and prevents stagnation. We illustrate this with an example of an f/1, 10 degree field of view objective. The initial design of the objective along with the design after optimization is shown in figure 3. In figure 4, we graph the merit function versus optimization time. Sparse Optimization with 25-50% of the variables shows rapid convergence when compared to optimization with 100% of the design variables.

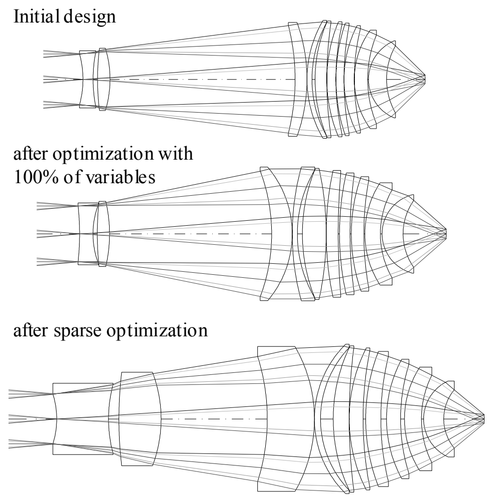


Figure 3. Initial design for an f/1 objective along with the optical layout after optimization with 100% of the variables and sparse optimization. Note that the design form is maintained.

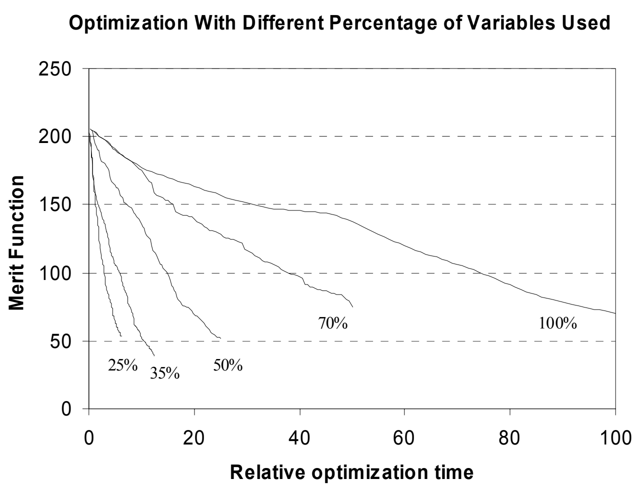


Figure 4. Merit function versus time for optimization with different percentage of variables used. Sparse Optimization with 25-50% of the variables shows rapid convergence when compared to optimization with 100% of the design variables.

One application of an expert system is to obtain initial design forms when the lens designer has little knowledge or intuition about the design. The initial designs are produced by walking the starting point step by step to a well-corrected design that satisfied the requirements. We shown in figure 5, an example of an f/1, 10 degree field of view objective designed by an expert system starting with plane parallel plates! Additionally, by repeating the process several times with the introduction of randomness an expert system can be used to coarsely sample the design space. Shown in figure 6 are several initial designs generated by the expert system.

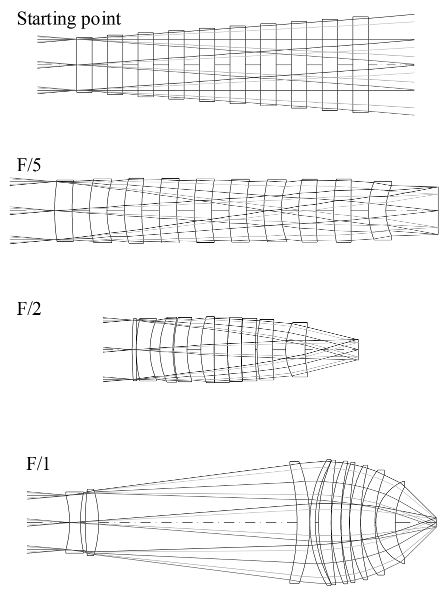


Figure 5. An f/1, 10 degree field of view objective designed by an expert system starting with plane parallel plates. The system is walked step by step to a design that meets the requirements.

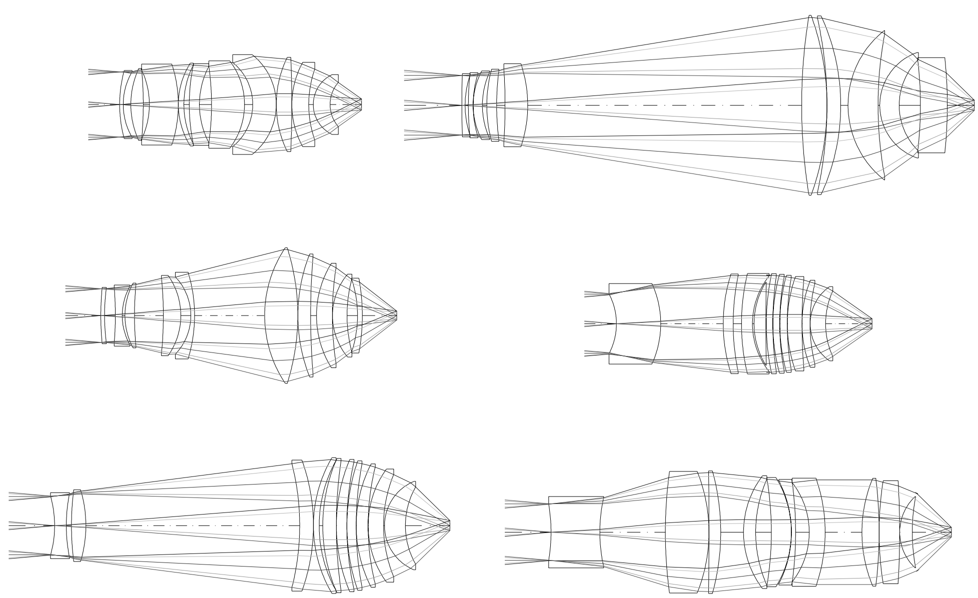


Figure 6. Randomness allows a coarse sampling of the design space for an f/1, 10 degree field of view objective. The sampling is done by repetition of the process shown in figure 5.

3. IODC 2002 LENS DESIGN PROBLEM

R. E. Hopkins remarked, "Lens design on large computers can become a disease. Otherwise useful people can be sucked into a useless life of playing games on computers by designing paper lenses.[2]" That being said, we further demonstrate the utility of expert system optimization with the example of the 2002 International Optical Design Conference lens design problem. The design requirement was to design an f/8 100 mm focal length lens which simulates the chromatic nature of a diffractive optical element over the wavelength range 400 to 750nm. A graph[6] of the solutions for the design problem are shown in figure 7. The application of expert system optimization enabled an incredibly small merit function.

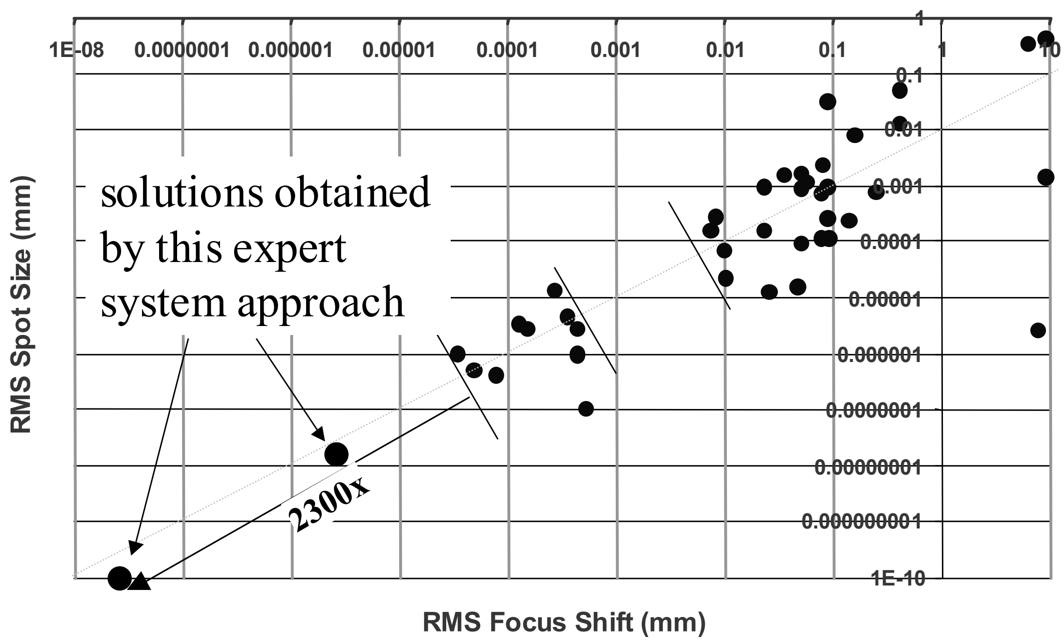


Figure 7. Graph of solutions for 2002 IODC lens design problem. The solutions obtained by this expert system approach had incredibly small merit functions.

For the 2002 lens design problem, design was done in three phases: initial layout , interactive optimization, and finally expert system optimization. The initial layout produced a starting point that met a few key design requirements, but not necessarily all. In the interactive design phase, with the help of damped least squares optimization, the starting point was interactively "walked" to a well-corrected design form that met all design requirements. The problem did not limit the number of optical elements nor the overall length. By only varying the surface curvatures and thicknesses, the design theoretically had sufficient degrees of freedom obtain a perfect merit function value of zero. Due to the complex design space and the large number of variables, damped least squares optimization stagnated in local minima. Hence, glass choice was not used as a variable. This simplified the design space and allowed the design to converge more rapidly. The goal was to obtain an initial design form for which damped least squares optimization algorithms were well-behaved such that they could be applied repeatedly by an expert system. The expert-system was used to "walk" the initial design to a lower minima by a combination of intelligent choices and brute force. The expert system operated by perturbing the design from a local minima and then re-optimizing to find a new local minima. Repeating this process for several days resulted in a final design with a merit function several orders of magnitude lower than the initial design. We note that although the final designs had merit functions several orders of magnitude lower than their corresponding initial designs, they were remarkably similar to their initial designs in form.

The layout, ray aberration plots, and the chromatic focal for a "chromatic doublet" solution to the lens design problem are shown below in Figure 8. The starting point for this first design consisted of cascaded afocal doublets. The diffracted focal shift curve was approximated by using overcorrected achromatic crown/flint doublets. The starting point had second order correction for the chromatic focal shift and used a combination of aspheric surfaces and perfect lenses to satisfy imaging requirements. During interactive optimization I removed the perfect lenses and replaced the aspheric surfaces with spherical surfaces. I added lenses with special partial dispersion characteristics to give the degrees of freedom for chromatic correction. At this point, I added an intermediate image and field lens to compensate the high-order spherical aberration that was present in the design. The initial design had a merit function of 453 nm, had 6^{th} order chromatic correction and 10^{th} order spherical correction. The initial design was then given to the expert system for further optimization. The expert system optimization stalled with a merit function of 20 nm after 7 days of optimization. Surfaces were then added to the lens by me including a 1 kilometer relay at the front. After changing the expert system parameters, optimization continued. The final design had a merit function of 3 nm, 20^{th} order correction for spherical aberration, and 8^{th} order chromatic correction. To achieve 20^{th} order correction for spherical aberration required such a fine balance that the "expert system" optimization stalled.

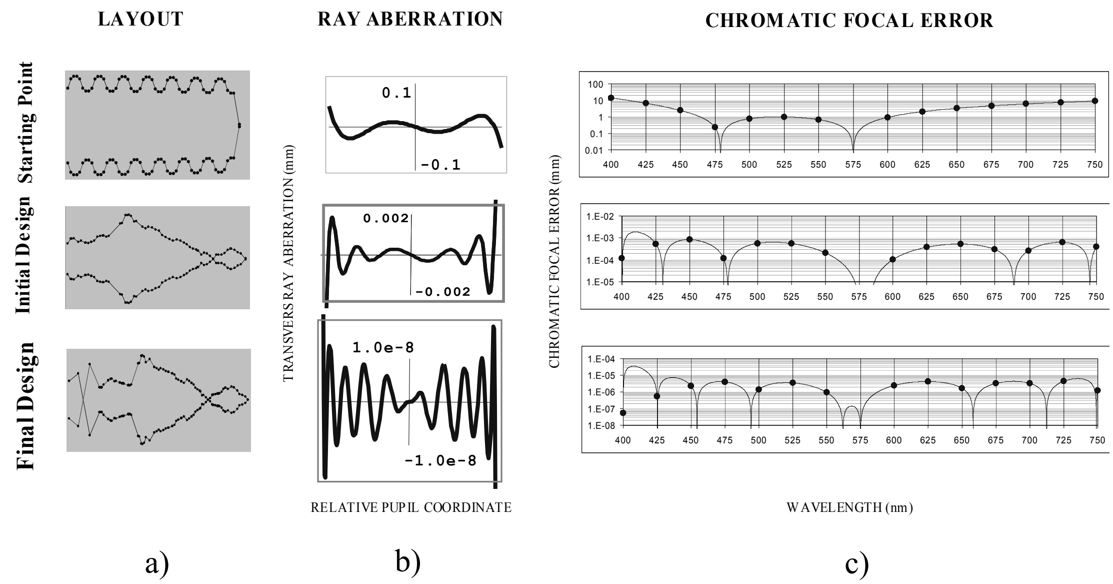
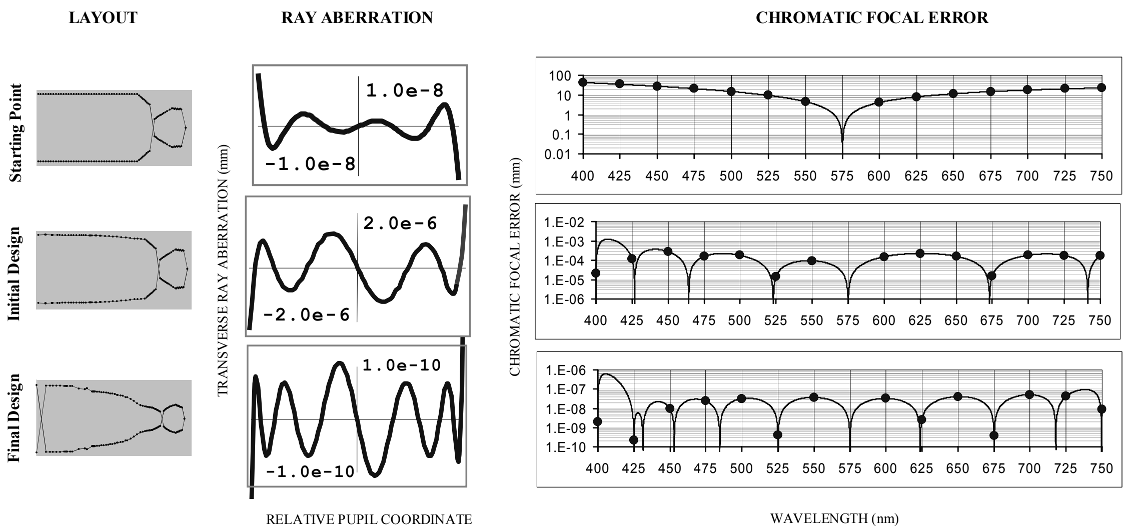


Figure 8. a) Layout of the "Chromatic Doublet" design at each design stage. The vertical axis plots the aperture at each surface. The horizontal axis plots a compressed surface vertex location, $\tilde{z}$, according to the equation: $\tilde{z}_i = \sum_{j=1}^{i} \ln(z_j - z_{j-1} + 1)$, where z is the absolute vertex location. b) Transverse ray aberration as a function of relative pupil coordinate is given for each design phase. Note that the final design is corrected for 20^{th} order spherical aberration. c) Chromatic focal error versus wavelength plotted on a logarithmic scale.

After analyzing the results of expert system optimization of the "chromatic doublet" design I had the following conclusions. The design was limited by higher order spherical aberration and a large number of glass types did not appear to be necessary. This inspired a second design approach using matched index triplets (buried surfaces)[7] such that very high order spherical aberration was not introduced. The design also included an intermediate image to control high order spherical aberration. With the expert system was already developed, optimization of a second design form could proceed with little investment of my time.

The layout, ray aberration plots, and the chromatic focal for the "matched index triplet" design are shown below in Figure 9. In introducing the chromatic focal shift, the chromatic doublet design also induced 22^{nd} order spherical aberration that could not be compensated in the design. The matched index triplet design minimized 3^{rd} order spherical aberration in each of the triplets such that induced higher-order spherical aberration was minimized. The starting point for the matched index triplet design had well-corrected imaging properties and did not consider the focal shift. It consisted of an objective using the glass SF59. Buried surface triplets were added that would be used to introduce the focal shift. The glasses F4, TIF6, and SSK4A have nearly the same index at 575 nm and together are a buried surface triplet that has little effect on the imaging properties of the lens. I walked the starting point to the initial design by introducing the chromatic focal shift. The initial design had virtually no power in the buried surface triplets and maintained good imaging. This initial design was then used as the initial design for expert system optimization. After 500 hours of expert system optimization, the aberrations for the triplet design were two orders of magnitude lower than for the doublet design and it was only necessary to correct spherical aberration to 10th order.



a) b) c)

Figure 10. a) Layout of the "Matched Index Triplet" design at each design stage. The vertical axis plots the aperture at each surface. The horizontal axis plots a compressed surface vertex location, $\tilde{z}$, according to the equation: $\tilde{z}_i = \sum_{j=1}^{i} \ln(z_j - z_{j-1} + 1)$, where z is the absolute vertex location. b) Transverse ray aberration as a function of relative pupil coordinate is given for each design phase. Note that the final design is corrected for 12th order spherical aberration. c) Chromatic focal error versus wavelength plotted on a logarithmic scale.

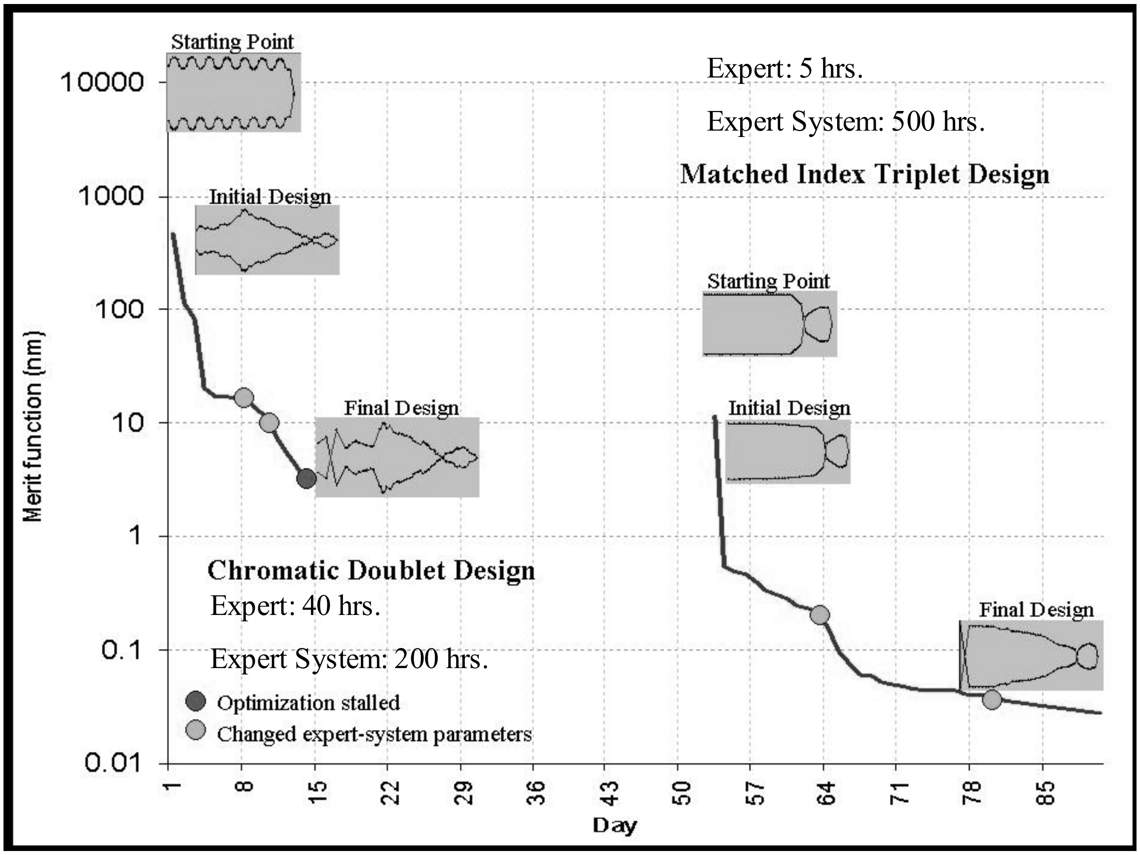


Figure 9. Graph of Merit function versus day for two solutions to the 2002 IODC design problem.

4. CONCLUSIONS

The expert system used for optimization of the 2002 IODC lens design problem was relatively simple at first. As optimization proceeded, I developed a more sophisticated expert system macro using my experience and intuition.. In figure 10, we graph the merit function versus day for both the chromatic doublet design and the matched index triplet design. The importance of choosing ones initial design is illustrated by examining how quickly the matched index triplet design was optimized to a lower merit function than the chromatic doublet design. The lens designer's thought, intuition, and experience are critical in choosing the design starting point. The utility of persistence in the design process is also illustrated. Expert system optimization resulted in a two order of magnitude improvement in each of the design forms. This improvement was accomplished without me needing to invest a large amount of time to the process. In generating the two designs and the expert system, I spent a total of 45 hours. The use of an expert system enabled a total design time of over 700 hours. So in effect my efforts were multiplied by over twenty times. It was surprising how much the designs improved. After over a month of optimization the match index triplet design improved by a few percent per day!

In design optical systems using expert system, we are essentially doing lens design in remote batch executions. Recall that thirty years ago R. E. Hopkins said that "all lens design of the future would be done on large computers in remote batch.[2]" I have found the expert system concept to be most useful for complex design tasks including exploration of new design forms, tolerance loosening of systems, and trade studies. The expert and computer can be seen as a design team. Computers are now a virtually free resource with stunning speed. By using expert system optimization to multiply our design efforts we more fully realize the advantages of the computers computational ability. In conclusion, the expert system combines the lens designer's intuition with the computer's persistence.

5. ACKNOWLEDGEMENTS

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