Lenses by design

Problems & Solutions

BY PETER CLARK

Around the world, there are tests of engineering skills that have gained considerable fame: The challenges for chess playing computers and human-powered flight are good examples of efforts undertaken for fun, for education, and because they might lead to innovation and understanding. Also, at universities, students build devices from a strictly limited supply of materials to perform manifestly unimportant tasks.

Members of the optics community may be interested to know that there is also a series of such challenges in the field of lens design. Lens designers look forward to the series of major conferences devoted to optical design known as the International Lens Design Conferences (ILDC, now the International Optical Design Conference, IODC). ILDCs have been held every five years since 1975, and at each conference there has been at least one lens design problem for members of the community to consider.[1-5] Problem descriptions are published before the conference and people are invited to submit solutions. The results are presented at the conference and published in the Proceedings.

The problems are intended to be instructive and enjoyable. Some might feel that working on "impractical" problems is a waste of time, but designers can improve their skills by doing them and by studying the other solutions. Also, it is a rare opportunity to learn about the design process itself by polling the participants. As for enjoyment, the popularity of these problems speaks for itself: As we wrote in 1985, "...optics is one of very few fortunate professions that are so much fun that individuals will devote their spare time to working a difficult problem for just the pleasure of the challenge." This article briefly describes the design process, then discusses lens design problems in general, and the 1985 and 1990 problems, in particular.

THE LENS DESIGN PROCESS

The lens designer's goal is to have every ray from any point on the object intersect the corresponding point on the image. This is rarely perfectly achieved, even on paper, and it is never necessary to reach perfection, because of diffraction or cost limitations. The particular steps that a designer might take varies with the individual and the design. A general description might be as follows:

1. Determine the specifications. Certainly, one must first make sure that the requirements are complete, including wavelengths, object and image size and locations, physical constraints (size, weight, cost), and illumination and image quality requirements. Occasionally the customer is able to translate these into magnification, focal length, field and aperture specifications, but often that is the designer's job.

2. Determine a starting solution. Given the requirements the designer must find a promising starting solution, because today's optimizing lens design programs are not usually capable of drastically changing the form of a lens. For example, they usually don't add or subtract elements, or

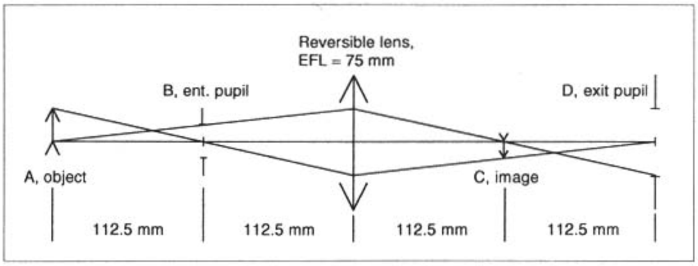


Figure 1. A thin paraxial reversible lens.

change their order within the lens. (However, people are investigating "artificial intelligence" approaches that might!) Starting solutions often are existing designs, scaled and modified appropriately.

3. Optimize the design. Optical design codes allow the computer to automatically improve an existing design. The designer must still participate, though, carrying out several important responsibilities:

- Choose the variables. The designer decides which construction parameters (curvature, thickness, index, aspheric coefficient, etc.) the program may vary.
- Construct the error function. Typically, the program will adjust the variables to minimize a number that reflects the quality of the design. Usually the error function is a sum of squares of ray errors. The designer must make sure that the error function represents performance well; in particular that the wavelengths, aperture and field of the lens are adequately sampled and weighted properly.
- Choose the constraints. If there must be limitations on quantities that do not affect image quality, we may require the program to solve them exactly while improving the error function. Typical constraints might be lens thicknesses or magnification.

4. Iterate, iterate, iterate. One pass is hardly ever enough! The designer inspects the result, looking at layouts of the lens to see if it seems feasible. Image quality is evaluated in the appropriate manner (MTF, encircled energy, wavefront error, etc.), and if improvement is necessary, aberration plots and surface contributions are studied. Our understanding of optics must help us decide what to do next: Alter the error function? Add or delete variables? Change some variables "by hand" to lead the program toward a different local minimum? Abandon this design form for another?

Lens designers often have a "heroic" approach, believing that a lens can be made to perform arbitrarily well by increasing its complexity. For example, if a three element system cannot be designed to satisfy the image sharpness requirement, try four elements (or make a surface aspheric, perhaps). In real life, goals must be set, so that the design process may be stopped when performance is acceptable.

LENS DESIGN PROBLEMS

The 1980 ILDC problem was run by Richard Juergens of Optical Research Associates. It was a test of computer programs. A standard double gauss lens was used as the starting point for two different designs. In one case, the relative aperture was increased and the field reduced. In the other, the field was increased and the aperture reduced. The object was to have the available optimizing routines improve these poor-performing starting points with minimal human intervention. One of the conclusions reached was that "the no human intervention requirement is unrealistic." Exactly how much human help the various programs got became a source of (mostly) good-natured controversy at the 1980 ILDC.

For the 1985 and 1990 problems, we wanted to come up with challenges for the lens designer. They should be unusual, so that nobody would have a design at hand, and so that some thought would be required when determining a starting solution. In fact, they should strive to have no useful purpose at all, absolving their authors of ulterior motive charges! We also decided to minimize the competitive aspect of the problems. We tried (without complete success) to avoid identifying who did which design, and we were not prepared with "Best Lens Designer" trophies. This was a difficult issue: For some, it takes away fun and it denies credit to those who produced outstanding designs, but we felt that participating should be its own reward.

THE REVERSIBLE LENS

The 1985 Lens Design Problem was "the Reversible Lens," stated as follows:

SPECIFICATIONS: FORWARD AND REVERSE

- Object Plane Diameter = 50 mm
- Entrance Pupil Diameter = 25 mm
- Paraxial Image/Object Magnification = -1/2
- Object to Entrance Pupil = 112.5 mm
- Reverse Entrance Pupil = Forward Image Plane
- Reverse Image Plane = Forward Entrance Pupil
- Object, Image, and Pupil Planes must all be Flat and Real
- Monochromatic, 588 nm
- No Vignetting

IMAGE QUALITY CRITERION:

- A simple Merit Function:
  M= 75 mm
  D(0) 1 D(17.5 mm) 1 D(25 mm)
  D(object height) is the minimum diameter (mm) enclosing 80% of the geometrical point spread energy.
- If M is different forward than backward, the smaller value will apply.

Figure 1 illustrates such a lens. Four planes are identified: A, B, C, and D. If plane A is considered the object, then C is its image, and B and D are entrance- and exit-pupils, respectively. It is called a reversible lens because if the lens between B and C were flipped end-to-end, it must still image A to B well. The "merit function" is roughly the number of resolvable points across the image plane, ignoring diffraction.

Unlike most real-life problems, this one had no image quality goal. Designers were encouraged to submit simple designs as well as complex ones. The problem as stated had first-order optical requirements, but minimal non-optical constraints (size, weight, etc.). No restrictions were placed on the use of aspherics, diffractive optical elements or extremely high or low index of refraction.

A fine account of one very experienced designer's approach to the problem was written by Robert E. Hopkins of Optizon Corp.[6] His paper should be read to really understand the challenge presented.

THE IMPOSSIBLE LENS?

The reversible lens was originally chosen because it was unusual and because of its appealing symmetry (in fact, the author went a bit overboard demonstrating its aesthetic appeal), but it was soon pointed out that it was technically interesting as well. Adriaan Walther of Worcester Polytechnic Institute was among those who reminded us that geometrical optics does not permit a lens of finite focal length to have perfect imagery of more than one object plane. Since the reversible lens was supposed to image A to B *and* D to C at −1/2 magnification, there was a limit to the quality of the result that no amount of complexity could overcome.

Here was a challenge for the Heroic Lens Designer! Walther, furthermore, calculated the best result that could theoretically be obtained using an analytic and computational technique that he calls mock ray tracing[7,8] and, not surprisingly, while some of the submitted designs were very good, none of them exceeded that limit.

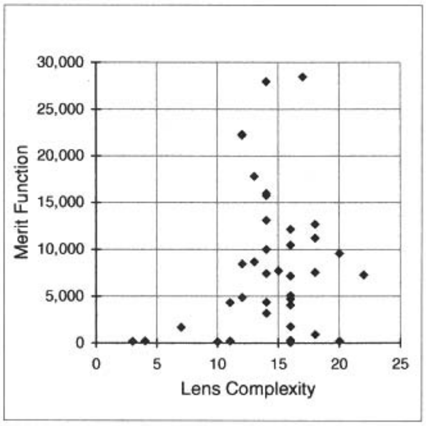


Figure 2. Reversible lens performance.

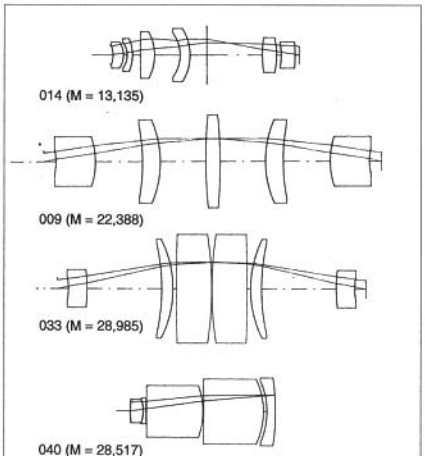


Figure 3. Four reversible lenses.

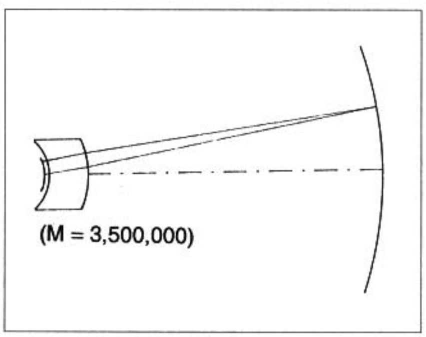


Figure 4. A monocentric reversible lens, showing that it pays to cheat!

The response to the problem was gratifying. Forty reversible lens solutions were received from 28 designers, in 8 countries. Experience ranged from 1 to 40 years, with a remarkable average of 17 years. In Figure 2, the merit functions achieved are plotted as a function of lens "complexity," defined arbitrarily here as the number of surfaces plus the number of non-spherical surfaces or unusual refractive indices. We can see that merit functions reached nearly 30,000. A real system, limited by diffraction, would only reach about 7,700. The merit function ceiling is approximately 50,000, estimated from Walther's mock ray trace aberration plots. Four of the designs are shown in Figure 3.

Most of the designs had a symmetrical arrangement between planes B and C. There are practical reasons for this: The design process is greatly simplified, because with this arrangement, B-D imagery is always identical to A-C imagery, so it doesn't need to be checked in a separate step. Lens design optimizing programs can easily couple surface shapes and thicknesses to ensure symmetry. The natural question arises: Would asymmetric designs have better results? The Heroic Designer's answer is "Of course! I'd have more variables, wouldn't I?", but we're not convinced. Design 014 (M=13,135) (see Fig. 3) is the best of the four asymmetric designs that were submitted, and it sports a diffractive element.

Designs 009 (M=22,388) and 033 (M=27,985) are the two best performing refractive systems. Their forms are similar; quite long, with aspherics on the two negative outer surfaces. Several designers reported that these lenses are unusually slow to optimize. The programs gradually chip away at the error function, without speeding up or slowing down, for many iterations. We don't know exactly why this is; perhaps it is a result of the variable coupling that is needed for symmetry, but it may instead be caused by the merit function ceiling.

It was a surprise that six designs received were catadioptric, systems built with lenses and mirrors. Each was designed with a concave mirror at the plane of symmetry and space for a beamsplitter (usually in a glass cube) to make the image accessible. The best performing of all the reversible lenses was the catadioptric 040 (M=28,517).

THE PETZVAL PROBLEM

How does the problem of aberration correction affect the form of lenses? A strong case can be made that, of the five monochromatic Seidel aberrations (spherical, coma, astigmatism, field curvature and distortion), field curvature-known as the Petzval sum—affects the distribution of optical power most directly. [9] The Petzval sum is the curvature (C=1/radius) of the paraxial image surface in the absence of astigmatism. Each surface contributes to the Petzval sum (P) in a simple way,

$$P = \Sigma C_j (n-n')/nn',$$

where n and n' are refractive index before and after the surface. Field curvature cannot be affected by aspheric surfaces or by the location of the surfaces. However, since lens power *is* affected by surface location, Petzval sum can be corrected. For example, a thin glass lens, n=1.5, has a focal length of 100 mm. Its Petzval sum can be corrected to zero by adding another lens of the same glass, whose focal length is –100 mm. If the two lenses are in contact, the pair has no power, but if they are separated, the power increases but the field curvature remains the same. If the negative lens is placed in a focal plane of the positive lens, as a "field lens," it has no effect upon the system's focal length.

All-refractive reversible lenses must have surfaces with negative power to reduce the Petzval sum. The refractors that performed best placed most of that negative power near planes B and C, where its reduction of the positive power of the system is minimal. Thus the better lenses were all quite long, up to twice the length of the single thin lens solution. Also, for a given power, low index lenses contribute more to Petzval than high, so the negative lenses often were low index and the positive lenses high, reducing the negative power necessary to correct Petzval.

A concave mirror contributes to Petzval with the opposite sign of a positive lens, so the catadioptric systems have an advantage: they can be corrected for Petzval sum with just positive lenses and mirrors. This can reduce length, and avoid other aberrations that may be contributed by the extra power that would be necessary just to correct field curvature.

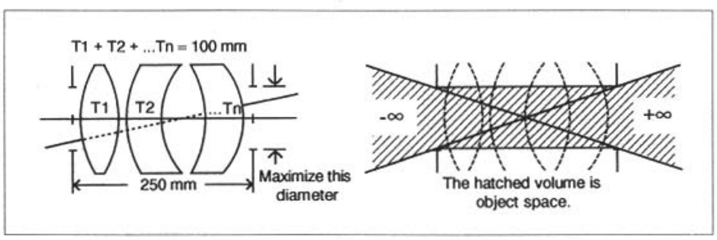
If there was no field flatness requirement, the problem would be very different. It would not have the geometric performance limitation. As an example, a simple monocentric catadioptric system can be designed with curved object and image planes that achieves a merit function more than 100 times the best flat field system! (See Fig. 4.)

THE NONLENS

The 1990 ILDC had two lens design problems: the "Monochromatic Quartet"[5], suggested by David Shafer of David Shafer Optical Design Inc. and run by Donald O'Shea of Georgia Institute of Technology, and the NonLens, which was somewhat related to the reversible lens. The NonLens was suggested by Adriaan Walther and administered by the author and Carmiña Londoño, also of Polaroid Corp. Eighteen people submited 20 solutions. The NonLens problem description was as follows:

A NonLens is a lens that does nothing: Every ray emerges from the NonLens along the same straight line it followed in object space. This is quite different from a window, which causes image shifts and aberrations."

Your task is to design a NonLens between two real circular holes spaced at a distance of 250 mm. The NonLens will be used for a wavelength of 588 nm only.



The axial glass thickness must be 100 mm exactly; refractive indices must be in the range from 1.50–2.00. Any point in the object space that is able to send light through the holes should be imaged on itself with diffraction limited image quality [<0.07 waves root-mean-squared wavefront error (RMS-WFE)]. Within these constraints, the goal is to make the diameter of the input and exit holes, D_{H}, which must be the same, as large as possible.

Like the reversible lens, the NonLens was an interesting and unusual problem. We were confident that nobody would have prior experience with it, but it turned out that "a lens that does nothing" had already been patented![10] The lens in Figure 5 allows introduction of a cube beamsplitter without affecting optical performance.

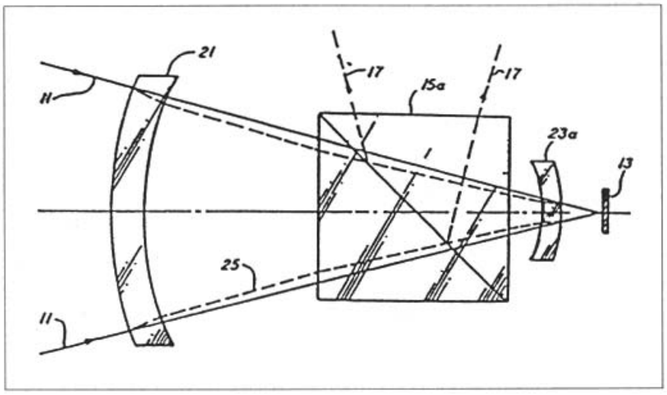


Figure 5. A patented NonLens.

The NonLens problem sounds easy, but some thought is needed to translate it into a lens: To image every object point, onto itself requires that either the object point, the image point or both be virtual. Since no object point is more important than any other, one must not forget all the potential objects to the right of the lens or inside the lens. Also, for object-image planes that are not at the hole planes, there is vignetting. The resultant lens should behave like a 250 mm long cylindrical tube.

Clearly, just air between the two holes does the job perfectly, so the real problem is to overcome the glass thickness. A plane parallel plate (thickness, T, and index, n) images every object point shifted ΔT along the optical axis, where

$$\Delta T = F((n-1),n)\,T.$$

For T=100 mm, if n=1.5, the defocus is 33.3 mm. This limits the acceptable hole size to well under one millimeter unless we reshape and redistribute the glass. Already a design strategy can be seen; the use of a higher n increases the focus shift, making the problem more difficult.

A first-order solution must have three properties. It must have unit (+1) magnification, zero object to image distance, and it must be afocal. If the system is afocal with unit magnification, then its lateral and longitudinal magnification will both be unity. Therefore, if one plane is imaged on itself, all of object space is also imaged on itself. Three design variables are needed to satisfy the first-order requirements.

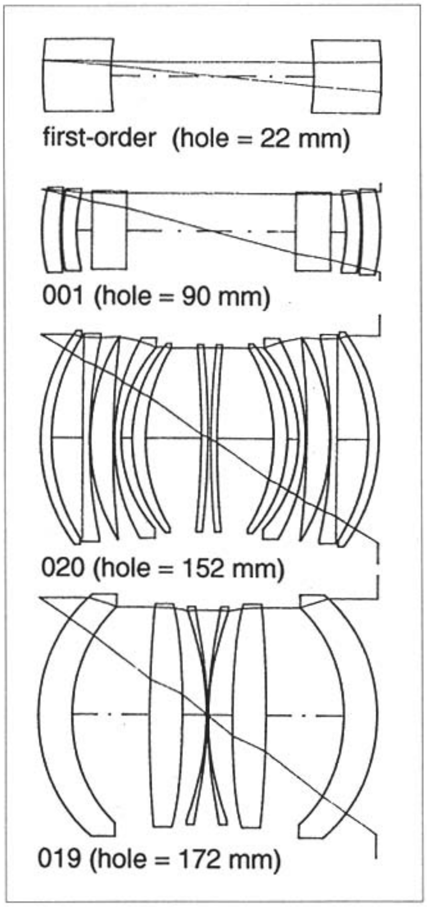


Figure 6. Four NonLenses.

The top lens in Figure 6 is an example of a simple first-order system. It consists of two identical thick elements symmetrically placed about a central plane. The three variables used for the first-order solution were: a) Symmetry forces the magnification to be unity; b) One of the two curvatures is adjusted to make each half of the system an afocal Galilean telescope. The complete system is then afocal with unit magnification; and c) The remaining curvature is varied to change the power of each Galilean to make the object to image distance zero.

IS PERFECTION POSSIBLE?

Like the reversible lens, the NonLens must work well for a multiplicity of object planes. The rule prohibiting perfection, however, does not apply to systems that are afocal, with unit (±1) magnification (called "trivial" systems in some texts!). So perhaps a perfect NonLens would be found.

Demonstrating such perfection seems to be difficult, since every point in the object space volume might need to be examined, but it turns out that if one plane and only one other point are perfectly imaged, then the entire volume is perfect. This principle was used for the design of the lens. Two techniques were described by contributors: In one, the object/image plane was placed at infinity and the pupil was at the center. Then object to image quality was optimized as usual, and image quality of the central point was simultaneously optimized. Distortion would be automatically corrected for infinity if the lens were constrained to be symmetric. The other method used the hole plane as the object/image. If the system were symmetric, then the opposite hole plane would also be optimized. However, distortion must be explicitly controlled.

EVALUATING THE CONTRIBUTIONS

For the NonLens, we did not explicitly state how we would verify the results. Since this is the age of inexpensive computation, brute force was chosen. A selection of seven object planes was made, from the center to infinity, and five points in each plane were checked. The hole sizes were adjusted until the worst wavefront error was 0.07 waves.

So how good could the experts make this "trivial" system? The results can be seen in Figure 7. Hole size is plotted as a function of complexity. This time, there seems to be good correlation of performance of the best systems with complexity. The best NonLens achieved 172 mm, a truly excellent result.

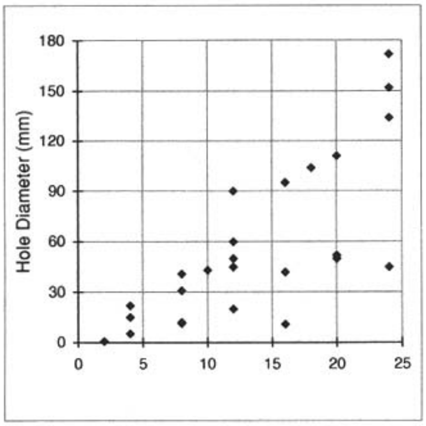


Figure 7. NonLens performance.

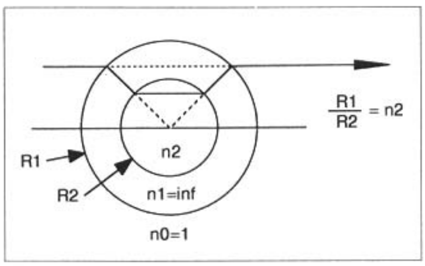


Figure 8. An impossible perfect concentric NonLens.

Concentric-symmetric (C-S) lenses have spherical symmetry about the point half-way between the holes. Every C-S system has unit magnification of the central plane onto itself. If it is afocal, it is a paraxial NonLens. Afocal C-S systems are *almost* automatically perfect NonLenses. Spherical aberration of the central plane is perfectly corrected, as well as every aberration of infinity *except* spherical aberration. The concentric-symmetric systems are interesting because so much correction is achieved automatically. We "only" need to solve the spherical aberration problem to achieve a perfect NonLens. The concentric solutions submitted were solid spheres with a low index core and a high index shell. The best hole size they achieved if the constraints of the problem are honored was only 5.4 mm.

After the conference, David Shafer pointed out that if the refractive index of the shell could be infinite, we would have the elusive perfect NonLens (Figure 8). This is a wonderful result, but aside from being unrealizable, it violates the problem's refractive index limit.

All the symmetric NonLens solutions had the basic back-to-back Galilean telescope form of the paraxial illustration. Here, too, the correction of Petzval curvature affected the form of the result. A simple Galilean telescope has two elements, plus and minus, separated by the sum of their focal lengths. To be realizable, the negative lens must always have the shorter absolute focal length. Therefore, for refractive systems where both lenses are of the same glass, the Petzval sum is positive. The only way to correct it is to change refractive indices. So the best NonLenses have most of their glass thickness in low index glass with thin negative elements of high index, to reduce the Petzval sum.

NonLens 019 achieved the largest hole size, 172 mm. It has only six elements, all index 1.50 except the two very thin negative lenses (1.98). It is a deceptively simple looking design, but every surface of 019 is aspheric. It can be compared with the next largest lens, 020 (152 mm), which has only spherical surfaces, but twice as many elements.

THE FUTURE

The next International Optical Design Conference is scheduled for early of 1994. We expect that lens design problems will continue to be part of the program. In the meantime, the challenge is to identify new and innovative problems, and the volunteers to run them. Suggestions are welcomed.

Perhaps a new direction should be taken: Chromatic correction was not included in the last three problems. A visual system might be interesting, an anamorphic problem, or an illumination problem? Let your imagination go!

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