Tutorial

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Trends in optical design from 1988 to 2018… where to from here?

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Abstract: Much experience in practical optical systems design (over 40 years for each author) gives us the perspective to discuss recent trends in advanced optical technologies. We give an ontology of its development and try to make a forecast for the near future, which will be useful for beginners as well as professionals in this complex field.

Keywords: automatic design; computer revolution; optical design.

1 Introduction

This paper is a brief review of the progress made in the field of optical systems design from 1988 to today. These dates were not chosen occasionally, but as a way of continuing 'the dialog' with Professor Robert E. Hopkins, who presented his review paper 'Optical design 1937 to 1988…Where to from here?' [1]. In this publication, he analyzed the development of optical design methods over the 50 years of his experience in the field.

We take into consideration the period of 30 years: from 1988 (where Professor Hopkins had stopped his review) to 2018 (30 years), because the technology revolution has been most impressive in this period, spurred by the computer revolution.

As optics is a key enabling technology, it takes many new roles in various spheres of research, production, monitoring, illuminating, and more [2–4].

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The most important market applications for optics-photonics innovation are [4] laser material processing, machine vision, medical technologies, optical communications, lighting, flat panel displays, solar energy, defense and optical systems.

2 The results of the computer revolution after 1988

Progress in lens design, mostly due to the computer revolution, has made it possible to design and evaluate almost any kind of imaging or non-imaging system, including gradient index, holographic element, nonrotational surfaces, tilted components, freeform elements [5, 6] and more.

This computer revolution started in the 1950s, and optical designers were one of the first to utilize the new tools. Along the way they needed, and achieved, more speed, more memory and cheaper computing costs. Ray-tracing speed increased from one meridional ray surface per minute to thousands of skew rays per second, and it continues to grow.

The computer revolution has indeed changed the optical design process during the approximate period of 50 years from 1937 to 1988.

2.1 A brief history of computer-aided lens design (CAD)

Newcomers to the field of CAD are likely familiar with but two or three commercial programs, which are the survivors of a long development effort by many researchers at many institutions. The author's career has spanned over 50 years and utilized a wide variety of computers, operating systems and programming languages. Here we mention briefly the development of the SYNOPSYS™ program during the last 30 years [7]. As extra capabilities were provided, additional needs were discovered, which led to yet more capabilities.

From the early 1960s to about 1987, most lens design programs utilized an algorithm known as 'damped least squares' (DLS), which worked well enough to launch the computer revolution in this field. But that method suffered from very slow convergence in most cases, and numerous attempts were made to find mathematical enhancements. Most of these involved methods for finding and adjusting the damping factor, which is a constant added to the diagonal of the Jacobian matrix before the solution vector is calculated. A technique known as orthonormalization was also tried, which involved linear algebra manipulations of the matrix with the aim of faster convergence. Some of these techniques worked better than others, or worked on some problems better than on others – but none addressed the real problem, which arises because of the inherent nonlinearity of lens design. In 1987, Dilworth published a method of approximating the effect of higher-order derivatives by observing the changes in first-order derivatives from one iteration to the next, and in its current incarnation, this method, which he termed the Pseudo-Second-Derivative (PSD) algorithm, has proved to be far superior to the DLS method. Indeed, an optimization task that requires about 2 h on a popular DLS program can be completed in about 1 s on the current PSD III algorithm [8].

More recent enhancements to the lens design software armada include what are called 'global optimization' methods [9]. One can improve an existing lens design with DLS or PSD and drive the design to a local minimum. Then one can try to escape from that minimum using a process called 'simulated annealing', a method that makes small random changes to the design variables and optimizes over and over, and which is surprisingly effective and widely used. But the more general problem of finding a whole different lens construction requires yet more tools, the best of which are the DSEARCH and ZSEARCH programs of Dilworth. These create candidate configurations for either fixed-focus or zoom lenses according to a deterministic algorithm, and then optimize those with the PSD method. This combination often returns lens constructions that are superior to what a human designer can produce and has reduced the development time required from days to minutes.

Another recent enhancement to the software armament is the ability to determine the best place to insert a new element into a lens with the Automatic Element Insertion tool or to remove an unnecessary element with the Automatic Element Deletion tool. Using these features, one can change the overall lens construction in stages, always improving the performance, in a deterministic manner that greatly exceeds what a human expert could do using classic methods. It is now possible to automatically determine where in a lens system an aspheric surface would be of most benefit, which higher-order aspheric terms will be most useful and even where a diffraction optical element could best be used.

Numerous schemes have been devised to optimize image quality, using rules for adjusting the relative weighting factors on each of a grid of rays, or by controlling the optical path differences (OPD) of selected rays and even by giving targets to the diffraction modulation-transfer function (MTF) in the merit function [10]. One of the most powerful of these schemes controls the difference in the OPD as calculated at a set of sheared pupil points, thereby maximizing the MTF at a selected frequency [11, 12].

1987: The PC became available, which, with a version of Unix installed, could do interactive lens design.

1992: SYNOPSYS was ported to DOS, programmed in Fortran.

1999: The first native Windows version, fully interactive, programmed in both C++ and Fortran.

To present: vigorous development of novel techniques, primarily in the direction of automatic search methods for finding and optimizing starting designs with minimal user intervention.

Of course, we were not the only ones developing lens design software. Other programs were developed by other authors and are listed below; yet, others were written for proprietary use in industry.

Slams (C.G. Wynne); Ordeals (Tropel); Flair (Radkowski); COP (Grey); Lead (Kodak); Father (B & L); Spade (Sperry); Optik V (Texas Inst.); Alsie (Osaka, Suzuki); SIGMA (Kidger); Bathos (Blandford); ACCOS (Spencer); CERCO (French); Cool Genii (Genesee); CODE n (Harris); Oslo (Sinclair); ZEMAX (Moore); SYNOPSYS (Dilworth).

These programs employed a variety of optimization methods, of which the following are noteworthy [3, 8, 13, 14].

Correction (Itek); Orthonormalization (Grey, Unvala); Damped least-squares (Levinberg); Steepest descent; Simplex (Bathos); Random search (Texas Instruments); Adaptive (Glatzel); Metric schemes; Solution scaling; PSD (Dilworth).

All these programs were effective when used by an advanced optical designer, and sometimes, it is difficult to explain why some prefer this or that software; it could be because of exposure to advertising or the history of the company. But the most recent techniques seem to be adequate for the design of most optical systems.

As new problems appear in lens design, every optical design software program has to add new features to respond to them.

2.2 The technological revolution powered by the computer revolution

A technological revolution occurs when one technology (or a set of technologies) is replaced or enhanced so as to greatly accelerate process.

So, in optical manufacturing, there were great changes from grinding and polishing technology to injection molded plastic lenses (1950), molded glass lenses (1980) and up to printed lenses (2010s). It provides a new level of capability for increased productivity and efficiency. It includes new optical materials, manufacturing and design enabling new innovations and also changes in management, financing, methods of research, social interactions and so on. The technology development cycle for digital image sensor is outlined in Figure 1.

At one time, sensors and the lenses forming images were produced in separate factories, and nobody thought to consider the design inter-relationships with an eye to the total product. Progress was achieved in several areas:

2.3 Camera revolution powered by the computer revolution

2.3.1 Camera revolution

1. In regular cameras with resolution of 0.3 MP, using simple lenses with all-spherical surfaces. In the period 1984–1985 in Japan, Ataritel (a division of the Atari Video Game Company) began to develop their first Videophone, known in the market of America as the Luma LU-1000 design (was sold under the brand Mitsubishi Electronic).

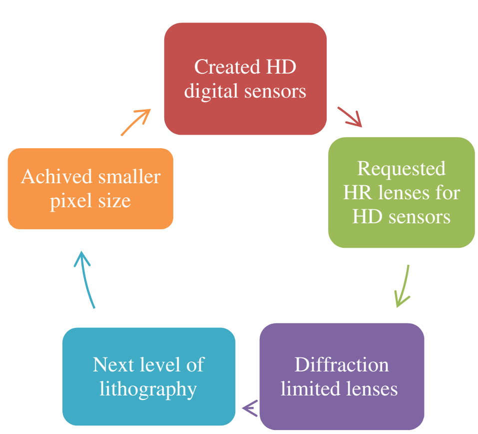

Figure 1: The technology development cycle for digital sensors. HD, high definition digital sensor; HR, high resolution lenses.

2. Modern digital receivers may have 36 MP, and the associated lenses became very complex. During the next 25 years, there was strong competition in camera construction and quality. Some examples:

In March 2015, Samsung GS6 became the winner, which had a camera with a record aperture f 1/1.9. And from that moment on, the race to increase the resolution stopped, because users stopped bribing marketing move with large numbers in the 'camera resolution'. In addition, SGS6 could record 4K video, which also became a trend in mobile cameras.

Less than 2 months later, LG for the first time began to compete with the flagships in terms of the camera, presenting LG G4 with a new record aperture f 1/1.8.

Samsung GS7 became a little more interesting. The aperture is now f 1/1.7, and a new focusing technology – Dual Pixel – was introduced. The bottom line is that each pixel, as the company claims, has two photodiodes instead of one, which allows you to focus more quickly on different objects.

Later LG presented its G5. The smartphone had on the back two cameras with different viewing angles, and it is good that they were not used to blur the background. The first camera had a higher resolution and served for everyday tasks and for artistic photography. The second camera was needed to capture the rest of the objects that are impossible to capture with the first camera.

The Huawei P9 also has two cameras and uses optics from Leica. This model is interesting because the optics and sensors are the same, but with a special filter increasing the dynamic range.

Another famous leader is the Lenovo 2 Pro. It is the first to get the Tango technology from Google. It is equipped with four cameras that measure the exact distance from the camera to the object, allowing you to create a model of the space around.

And yet, at the end of 2015, Samsung announced its intention to release a camera sensor technology Britecell. So, one can see what kind of new ideas help to increase the brightness of the image. The color remains as natural as the green filter. And the pixel size can be reduced without loss of quality of light.

3. Progress in materials (gradient materials, graphene, liquid lenses, nano-technologies, etc.) as outlined in Figure 2. This progress supports to change size and shape (and aberration) of lenses.

Developments in materials and processing lead to the possibility of producing new surface types that better correct aberrations. If lenses are better corrected, we can use them with higher-resolution sensors. Each advance creates a need for the next one.

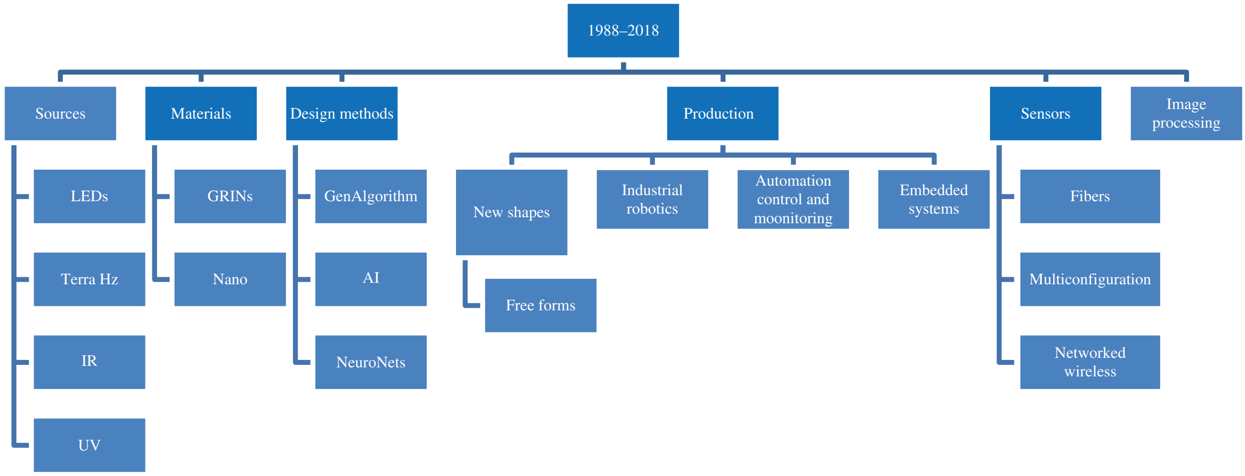

Figure 2: Illustration of important stages in optics in the recent 50 years.

4. Another option of getting better images is image processing. Where hardware and software share their functions to improve image quality.
5. Automation and process control; industrial machinery and new machine tools; machine tools with numerical control; industrial robots.
6. Data processing and information technology:

Recent trend is that an optical system stops being a separate independent element and becomes a part of embedded systems.

Embedded systems are now commonly used in consumer, cooking, industrial, automotive, medical, commercial and military applications.

Telecommunication systems employ numerous embedded systems from telephone switches for the network to cell phones at the end user. Computer networking uses dedicated routers and network bridges to route data.

A new class of miniature wireless devices called ‘motes’ are networked wireless sensors. It makes use of miniaturization made possible by advanced integrated circuit design to couple full wireless subsystems to sophisticated sensors, enabling people and companies to measure a myriad of things in the physical world and act on this information through information technologies monitoring and control systems.

7. Light-emitting diodes (LEDs) are highly efficient and long lasting. Here is an important combination of primary and secondary optics in one set. LEDs in general emit light at a 120° viewing angle. Secondary optics which is used over the LED transforms light into a spot or elliptical illumination patterns depending on applications.
8. During this period, the fiber optical revolution happened: optical fiber started its industrial applications in 1953, and now achieved high transmission and became a medium for telecommunication and computer networking because it is flexible and can be bundled as cables. It is especially advantageous for long-distance communications, because light propagates through the fiber with little attenuation compared to electrical cables. This allows long distances to be spanned with few repeaters. As an example, 1 Pb per second over 50 km over a single fiber was achieved by Nippon Telegraph and Telephone Corporation in 2012.

So, in optical design, a simple two-element air-spaced lens has nine variables: four radii of curvature, two thicknesses, one air space thickness and two glass types.

Nowadays, a multi-configuration lens corrected over a wide spectral band and field of view over a range of focal lengths and over a realistic temperature range can have a complex design volume having over 100 dimensions.

In the late 1990s, Harvey Pollicove founded and led the Rochester Center for Optics Manufacturing to automate fabrication of spherical and rotationally symmetric aspheric surfaces under computer numerical control.

Now this technology is moving forward to fabricate surfaces without rotational symmetry, so called freeform surfaces [5, 6]. Using this shape for the surface offers an opportunity to introduce three-dimensional packages while simultaneously correcting more directly the limiting aberrations.

These surfaces not only enhance performance to the maximum extent but also increase depth of field and field of view.

They simplify system structure with fewer surfaces, lower mass, lower cost and reduced stray light.

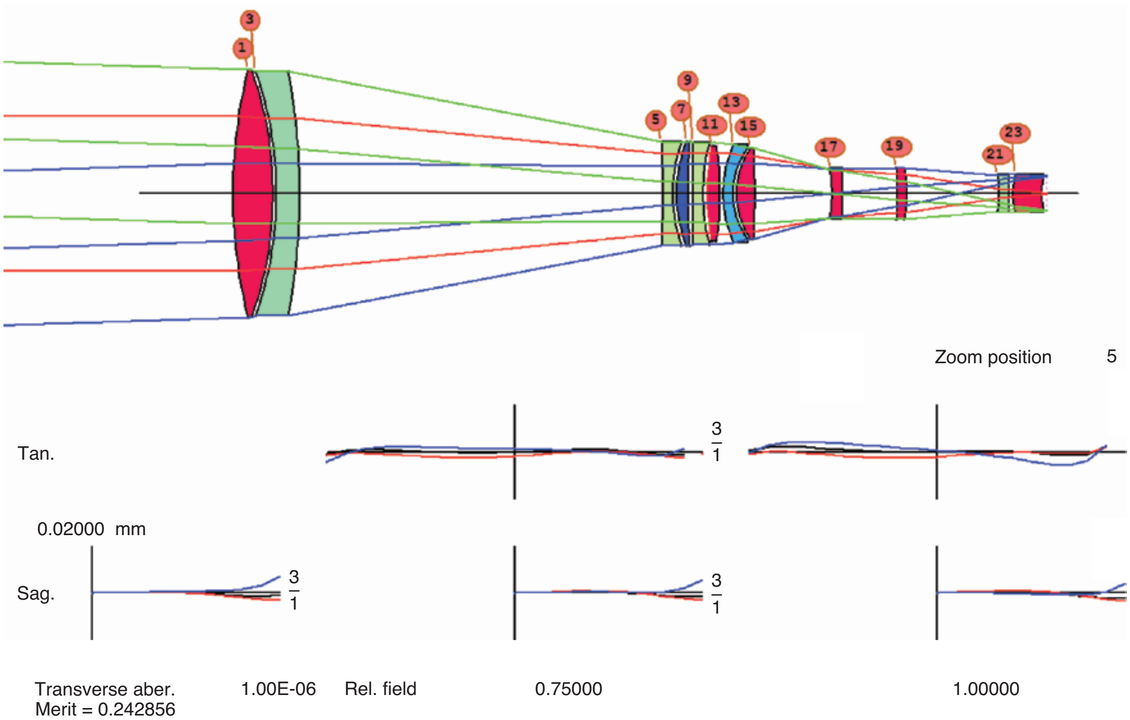

Figure 3: A zoom lens found by an automatic search algorithm.

2.4 Progress in lens design resulting from the technology revolution powered by the computer revolution

In parallel with these advances, the role of optical design software has also grown, since devices have become so complex and consist of so many elements that it is impossible to design them by any other means than with specialized software.

Optical design software has to meet the requirements of being very user-friendly and must respond quickly to technology changes. New problems regularly emerge in optical design, and the optical programmer has to be ready to add appropriate features to the program. An example of the latter, in the SYNOPSYS program [7], is the ability to find zoom lens construction automatically, given just the design requirements. Figure 3 shows an example of such a lens.

In this method, the software first creates a set of candidate lenses, assigning element powers according to the value of each bit in a binary number whose size equals the number of elements. Then each candidate is optimized in two stages, first with a merit function consisting of only first-order targets and third- and fifth-order aberrations plus very few real rays, and then a final merit function with many grids of real rays. All the while, the program monitors and controls a selection of boundary conditions such as maximum and

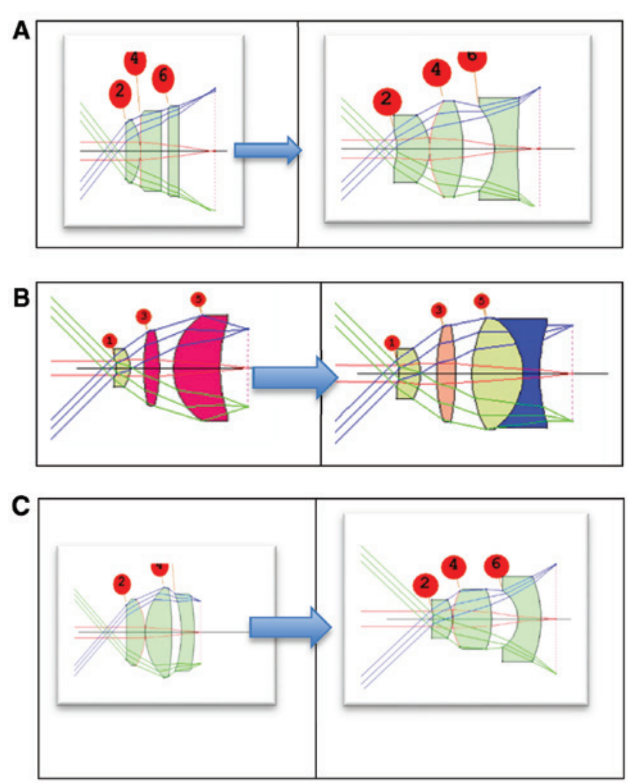

Figure 4: Comparison of the three methods of starting point selection. A) A simple way to start, using a positive lens and two plane parallel plates (CAD); B) the fastest way to get a starting point: using DSEARCH from [7]; C) the logical way to start using surfaces with well-known properties to start.

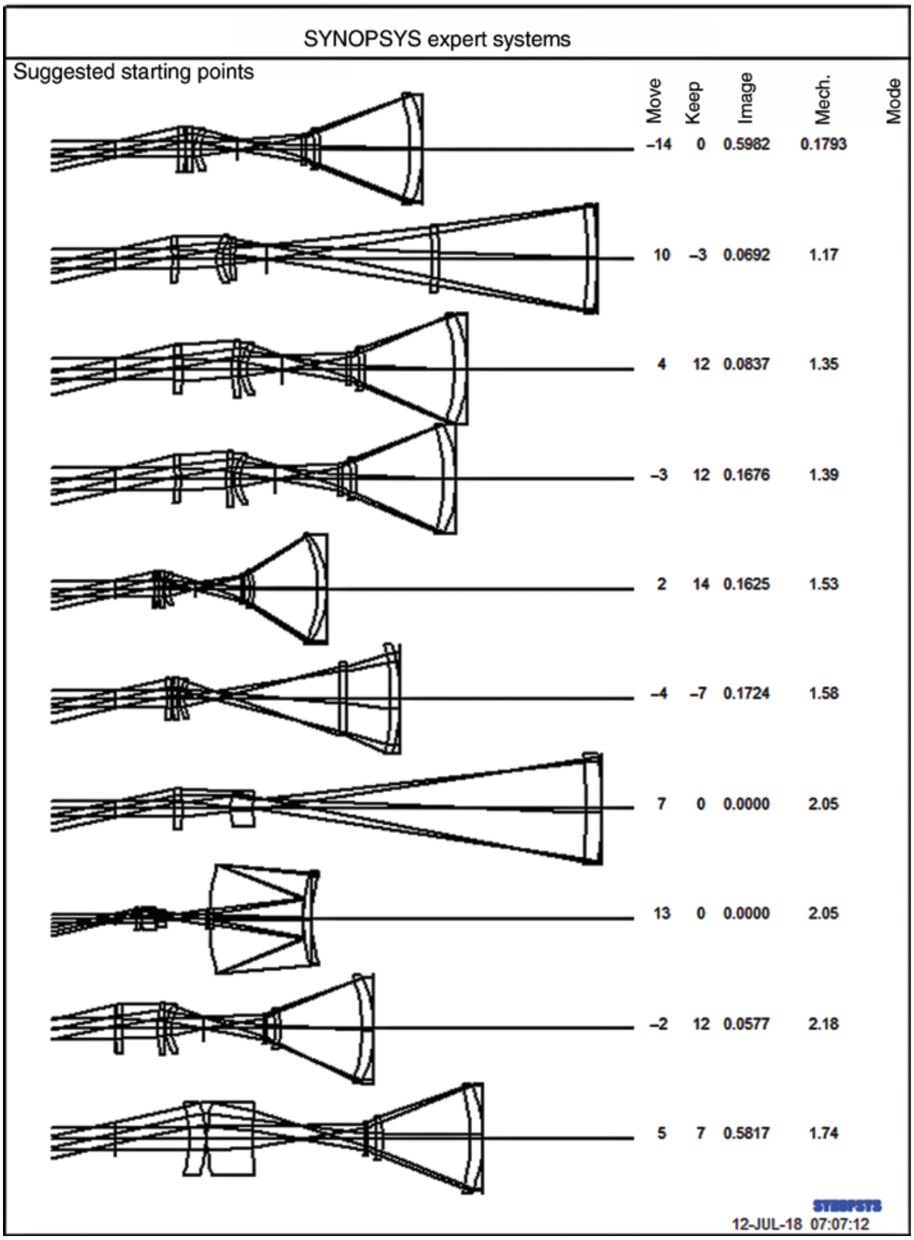

Figure 5: Example of the expert system method of SYNOPSYS. Focal magnification 0.2; total length 300 mm. Knowledge is embodied in a database.

minimum element thicknesses, steepness of ray angles and surface slopes, and the like. The result is a practical lens configuration with excellent performance, suitable for final optimization. Then the software can automatically match the model glasses to real glass types, match the radii to a selected vendor's test-plate list, calculate a tolerance budget so that the desired image quality is obtained to a desired statistical confidence level and even prepare shop drawings with dimensions and tolerances.

2.5 CAD for design process – could the design process be automatic?

The question of when a computer will replace a human designer remains a very popular topic of discussion at optical conferences. Professor Hopkins, along with many other optical designers of previous generations, often answer 'NO!' when addressing this question. In reference [1], he says: 'Automatic computing – here now; automatic design – never!'

Irina Livshits also shared this position until approximately 2013. She worked as a 'classical optical designer' using third-order aberrations for analysis and optimization. But then, she decided to compare different methods of lens design and to understand recent developments.

In reference [15], she presented three ways of selecting a starting point, illustrated in Figure 4. Analyzing the results, we can say that a computer program that uses artificial intelligence (AI) or automatic search methods for starting point selection works much faster than a human designer and achieves very interesting results [7].

So, now answering the question: Is automatic design possible? We can reply –YES! We now have abundant examples of lenses found by automatic search methods that are as good as or better than those found by a human expert. And because computers are now so fast, these designs can be developed, from start to finish, with real-glass selection, test-plate matching and tolerance calculations in a matter of minutes instead of the many days required by an older generation.

2.6 Further needs of lens designers

Anticipating the future needs of the next generation of optical designers, we can say that for progress in this field to continue, a number of items come to mind:

– New ideas for starting point selection, including, but not limited to, genetic algorithms (GA) and AI.

Figure 5 shows a selection of designs found by the expert-systems algorithm in SYNOPSYS. This technique first examines a set of well-designed lenses and analyzes all of the first-, third- and some of the fifth-order properties of each one. Then, it creates a database containing this knowledge in a form that can be utilized when a new problem requires a solution. At that point, it can substitute, remove, scale up and down and refocus portions of the example lenses and determine what changes would most benefit the lens under development. The result is often an improved design, one that benefitted from the expert knowledge embodied in the reference data set. The new designs usually contain portions of the original lens and portions of one of the example lenses.

– Improving automatic design and optimization;
– Mount design and tolerancing for housing;
– Virtual prototyping and preliminary testing of optical systems in a real environment, including dust, fog, high pressure, temperature, etc.

3 Conclusions

The development of optical design software has been, and continues to be, a demanding and immensely rewarding profession, at the same time anticipating future needs and finding mathematical solutions suitable for programming in a user-friendly environment. The software we have today has automated most of the tedious analysis and design tasks and has freed the designer to explore creative ideas and evaluate a wide range of possibilities that were never available to the previous generation, using tools that were then available. Modern lens design techniques can:

– correct for ray failures
– improve tolerance sensitivity
– find the best glass combination [9]
– locate strained elements
– generate a complete tolerance budget automatically.

Referring again to reference [1], we can predict the next technology revolution connected with a new computer revolution within next 15–20 years. We think that this will be oriented to create new materials and manage material properties.

We hope to be still alive at that time and ask future lens designers: *Optical design 2018 to 2038…Where to from here?*

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