Zoom Lens Design of Mobilephone Camera with Global-Explorer Optimization

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Abstract: Unlike the designs of common zoom lenses in literature, mobilephone applications demand an extremely short total track length (TTL), less around 10 mm. This short TTL request makes the zoom lens design of mobile phones unique. Also in viewing the cost advantage of CMOS sensor, we explore the mobilephone camera zoom lens with typical CMOS sensor format by global explorer (GE) optimization as well as the fundamental limitations. The basic lens forms for initial designs are deduced. Physically different merit functions have been developed to investigate how the best performance could be achieved. Furthermore, we also identify the improvements that could be achieved by GE optimization.

Key words: Lens design, Camera zoom lens , CMOS sensor , Optimization , Global explorer, Mobilephone camera lens

1. INTRODUCTION

Recently, global optimization algorithm is widely applied in optical design, regardless of fixed focal lens or zoom lens system. The design parameters of optical system are typically to form a complicated multidimensional parameter space. By constructing a merit function that expresses the departure of individual configuration from ideal required performance, it is possible to determine all of the possible configuration in this space and hence, to yield the best solution for the design problem. Using conventional design procedure, an optical designer chooses an initial design and with the help of an automatic optimization algorithm, the configuration is modified around the design space to achieve a best, or, at least workable performance. Unfortunately, in general, even the optimization routine is the best, it still can't find the global optimum. In order to efficiently and effectively get the local minima in the design space, a lot of global optimization algorithms have been proposed since tens years ago. Most popular optimization routine which could be accepted is the Damped Least Square (DLS) method [1] and others that related to it are based on systematic descent principles that accept only steps that decrease the merit function. However, these methods are not able to, almost always, find the best solution universally and they easily

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get trapped in a local minimum [2]. Thus, some of the global optimization techniques are necessarily applied in finding the best solution. A lot of proposed global optimization techniques have further the advantage of having deterministic sequence of operations that lead to the final solution set [3]. The conventional design is not deterministic and involves heuristic information in the determination of the final solution. Because of the absence of global view, the verification of the relative quality of a solution is very difficult and often leads to excessive number of iterations of the local search procedure.

On the other hand, camera lens design has been a long standing issue in geometrical optics, where the progress of consumer optics renews the interest and applications. Current mobile phones implement various new kinds of application such as taking photos and move shooting by using embedded camera and memory devices, while zooming requirement is always in demanding. It is interesting to note that current application of mobile phone camera lens demands high-quality performance, even up to the limit of diffraction-theory [4]. Although the initial design can be deduced by common paraxial optics, extensive use of optimization has been necessary to achieve the desired performance. Hence, it is always worthwhile to evaluate the role of optimization in lens design, particularly for the zoom lens, which remains a challenge in lens designs. Hence, in order to verify the capability and feasibility of global optimization algorithm, it is worthwhile to look over the zoom lens design for the camera device which plays an important role in the modern imaging taking applications, especially for the various field angle has been demanded in three years with the attention on high quality image.

For the extreme performance of a zoom lens, aberration correction such as astigmatism or distortion in multiple configurations is necessary. The reason for much of the zoom lens complexity, and for the difficulty in understanding how they function, is that generally both the object and pupil conjugates change during zooming. Spherical surface cannot be used to selectively correct high order aberration, for this reason that almost all examples of aspheric zoom lenses are comprised of more than one aspheric element. Therefore, we may use three aspheric plastic elements to ensure the smallest spot size and least in optical path difference.

In this paper, in viewing the application needs, a newly developed zoom lens is proposed with very short overall length by using aspheric surfaces, which is designed with mechanically compensated zoom lens system that have only one moving optical element to accomplish the zoom function and make image-shift stable.

2. More on zooming in mobile phone camera lens

A fixed-focal length lens with“zoom”function is generally handled by an electronic zoom system. Normally mobile phone lenses are designed with a fixed focal length because this makes the design manufactured much simpler and the total size compact. A simple optical lens for a mobile phone, in general, might be a very simple triplet with aspherical elements. The design of zoom lens is arguably more difficult than the fixed focal-length lens system and generally has a smaller solution space.

Normally a zoom lens contains two basic units, a vari-focal unit and a compensation unit. The vari-focal unit works linearly, but compensation unit doesn't. Classical mechanically compensated zoom lens design theory required that more than one group pf optical elements move relative to one another to produce the zoom function and no image shift. Optically compensated zoom lens have at least one moving group that comprised two lens elements spatially fixed relative to one another, with a fixed element that is located within the moving group. This means that the overall length of zoom lens is much larger than that of a normal fixed focal length and it doesn't perform so well as one may expect. Therefore, it is a great challenge to design a zoom lens for a mobile phone.

From the point of view of aberration, it is much easier to control aberration in a fixed focal lens due to no movement unit inside the lens. Some common aberrations could be easily controlled. But on the contrary, zoom lens system could perform well at certain specific focal length but would not perform at the best throughout the zoom range. Normally a mobile phone lens can zoom from wide angle to telephoto angle. At the wide angle end, the field of view is about ~60 degrees and is difficult to correct the aberration related to the incident angle without adding the element. At the telephoto end, the spherical aberration and chromatic aberration become serious, depriving the lens of some of its best performance at a specific focal length.

The ability of the designer to desensitize a lens is directly tied to the TTL (total track length) and, for shorter form, the BFL (back focal length) constraints. The longer the TTL, the more modest the refraction needed at each surface, the weaker each lens can be and the less sensitive the performance of the system is to build tolerances. The more constrained the lens system in length, the more refractive power is needed at each surface, and the more sensitive the lens becomes to tolerance-induced image degradation.

3. Global Optimization Scheme and Approach

In order to prevent optimizer trapped in a local minimum surrounded by steep, several methods, such as saddle point method [5], tunneling method [6], trajectory method [5], and the Global Explorer (GE) with an escape function proposed by Isshiki [7-9], had been released.

For a practical and complicated case of optical design, the surface of merit function constructed by the parameter space is extremely intricate. In addition, the definition of merit function is not easy to describe all the views of requirements especially for the cost and manufacturing considerations. Multiple local minima are needed for a global optimization problem and they have to be re-examined for the further consideration. Thus, the GE is a very good candidate to be utilized to find multiple local minima in the merit space and even more, the exposed solution are able to be proceeded to the further optimization with another optimization method or alternative merit function [9].

For global explorer, the optimizer flee from a local minimum instead of being trapped inside it due to the assistance of escape function, f_E , as following:

$$f_E = \sqrt{H}\exp\{-\frac{1}{2W^2}\sum_j \omega_j(\chi_j - \chi_{jL})^2\}, \quad (1)$$

where x_j denote the components of the coordinate of present position lying on the j^{th} parameter, x_{jl} is the coordinate of the current local minimum, ω_j is the weight imposed on parameter x_j ,and H and W represent the height and width of escape function, respectively.

Although the escape function can throw optimizer out of current local minimum, however, the determinations of height (*H*) and width (*W*) of the escape function will be an issue when the program is running. Too large values of *H* and *W* might induce an unexpected ignorance of the potential optimal solution if several local minimum cluster around the vicinity, on the contrary, too short and narrow escape function will also waste computational resources in repetitiously trying to escape by magnifying its values of height and width in case the valley is deep, wide or a steep around. Hence, the performance of GE is determined not only by the algorithm for local minimum approach but also the parameter of escape function.

4. Lens Design Specifications

A summary of the specification is shown in Table 1. As a simple example of illustration, the optical zoom ratio is demanded to be 2X with the resolution of 640X480 pixels as well as only moving one group to achieve zoom function and stable focal plane. The overall size must be reduced to a minimum in order to accommodate into the portable devices such as mobile phone or PDA. It is very difficult for lens designers to reduce the length of the system by improving usual optical zoom system. For cost consideration and weight-reduction, optical plastics, such as E48R or OKP4HT are no doubt applied for our lens material rather than glass in this case. One of the keys to a compact zoom lens is size and weight reduction by using aspherical lens.

In addition, the purpose of the maximum chief ray angle value is to maximize the light collection efficiency. The relative illumination is the level of light energy incident at the image plane for a given field point relative to that at the center of the image. Lens specification usually requires a value greater than 50% at the edge of the field. Relative illumination is required to be higher simply because of the elimination of noise at the image corners.

We have focused on N-P type zoom lens, the power of the 1st lens group is Negative and the 2nd lens group is

Positive.. It is because “negative-lead” is much smaller and has more robust sensitivity than “positive-lead” in 2X zoom lens design. In this case, we choose N-P-P type which has a good balance in size for our initial design and optimize from the basic lens form to achieve final result.

The expected optical performance is shown below. The image height is 1.44mm according to its CMOS sensor size, which constrains the chief ray height .With regard to the field of view (FOV), at the wide angle end 60 degrees can be reached. At the tele angle end is around 28 degrees. The Modulation Transfer Function (MTF) is required to meet central 20% or larger at 160 lp/mm while, the outer 20% at 120 lp/mm. Distortion in multiple configuration must be less than one percent to ensure the image quality. The details is shown in Table 1.

Table 1. The VGA CMOS camera with 2X optical zoom specification

ITEM		TARGET
System		
Optical zoom ratio		2X
Power arrangement		N-P type (Three groups)
Total Tract Length		<10mm
Back Focal Length		>2mm
Field of view		28~60 degrees
Image height		1.44mm
Chief ray angle		<25 degrees
Spot size		<3.2μm
Materials		Optical plastics (PMMA, E48R, etc.)
Optics		
Distortion		<2%
Lateral color		<10μm
Relative illumination		>50%
MTF	(center)	160 lp/mm @0.2
	(outer)	120 lp/mm @0.2

5. Zoom Lens Design

A mechanically compensated zoom lens with three elements can be moved only one element to achieve the 2X optical zoom ratio. The moving element functions for both zoom and compensation. Therefore, the back focal length and the overall length wouldn't change while zooming. Its advantage is to simplify the mechanics and to prevent the damage while zooming if the overall length changes. (see Fig.1 and Fig.2)

As a case of simple demonstration, we consider a three elements design with aspheric surface which can be describe as eq.(2). The lens elements have aspherical surfaces which coefficient is up to the 10^{th} order. For the first order parameters, please check Table 2.

$$z = f(x,y) = \frac{cs^2}{1+\sqrt{1-c^2s^2}} + A_2 s^2 + A^4 s^4 + ... + A_j s^j \, , \qquad (2)$$

where A_i is the ith-order aspheric coefficients and z is the longitudinal coordinate of a point on the surface which is a distance s from the z axis. And c is curvature.

In the preliminary stage, we adopted variables including the lens thickness, CV, AS2, AS3, AS4 and AS5 of each surface to drive the merit function to the lowest value by global explorer algorithm. For the requirement of the minimum spot size for multiple configurations, the definition of merit function was determined as the summation of root-mean-square geometric spot size.

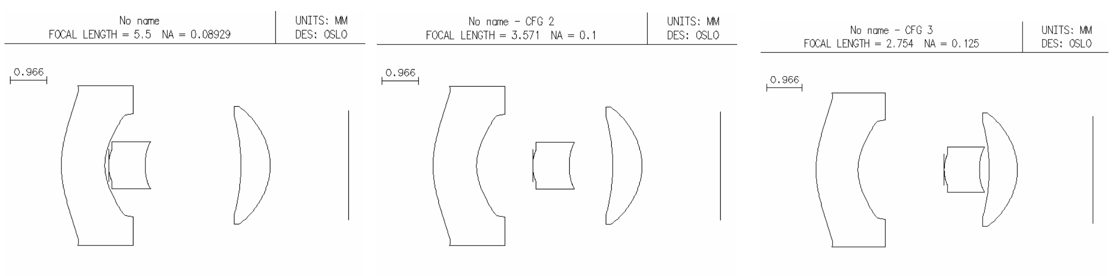

Fig.1. Zoom lens layout

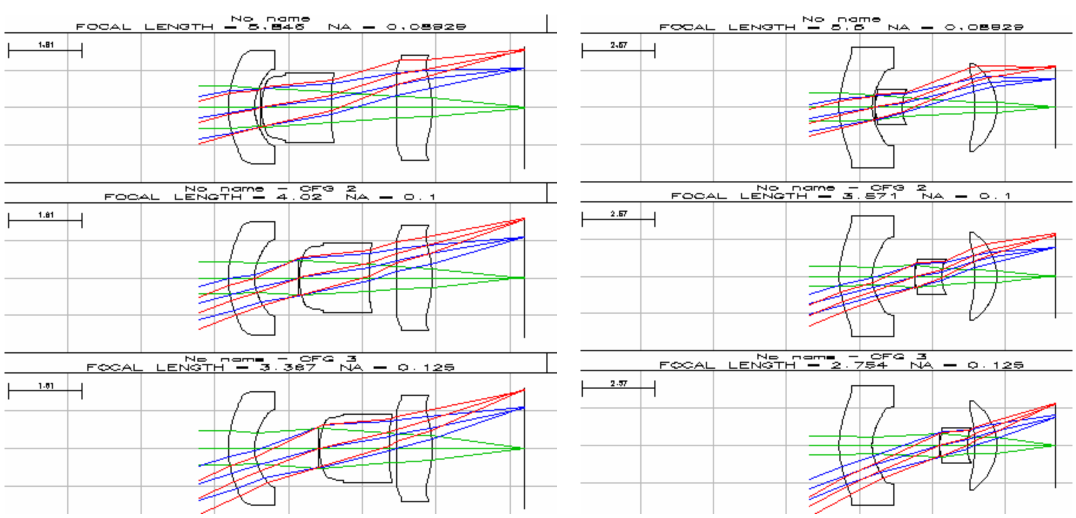

Fig. 2. The best two designs generated by the Global Explorer (GE)

Table 2. First-order optics parameters

	CFG1	CFG2	CFG3
Effective Focal Length (mm)	5.50	3.57	2.75
Back Focal Length (mm)	2.08	2.08	2.08
Total Track Length (mm)	7.64	7.64	7.64
F-number (F/#)	5.6	5.0	4.0
Field angle (degrees)	29.5	44.0	57.0
Image Height (mm)	1.44	1.44	1.46
Chief ray angle (degrees)	4.68	12.79	19.99

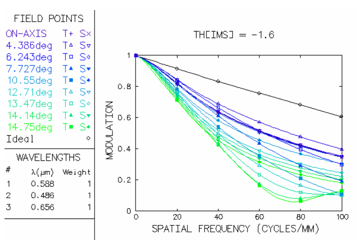

Fig.3. Zoom 1 MTF plot

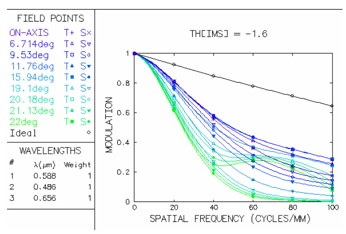

Fig.4. Zoom 2 MTF plot

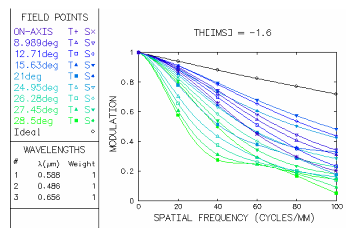

Fig.5. Zoom 3 MTF plot

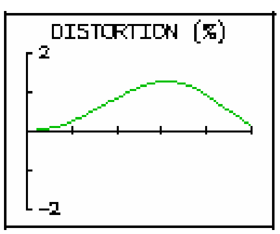

Fig.6. Zoom 1 Distortion Curve

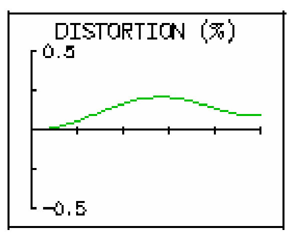

Fig.7. Zoom 2 Distortion Curve

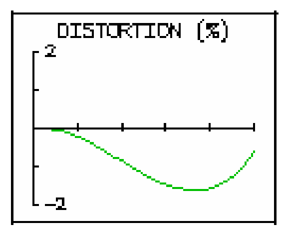

Fig.8. Distortion Curve

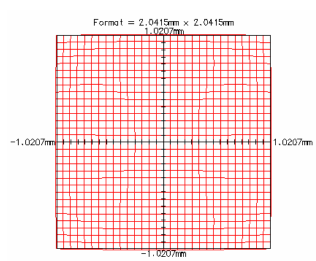

Fig.9. Zoom 1 Distortion Plot

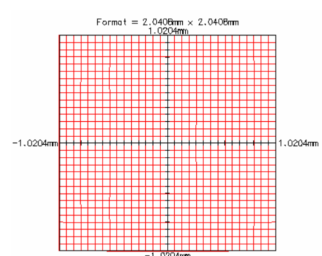

Fig.10. Zoom 2 Distortion Plot

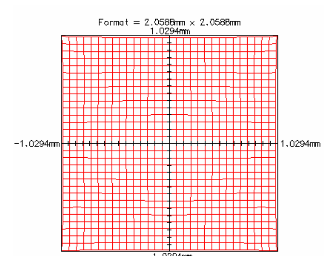

Fig.11. Zoom 3 Distortion Plot

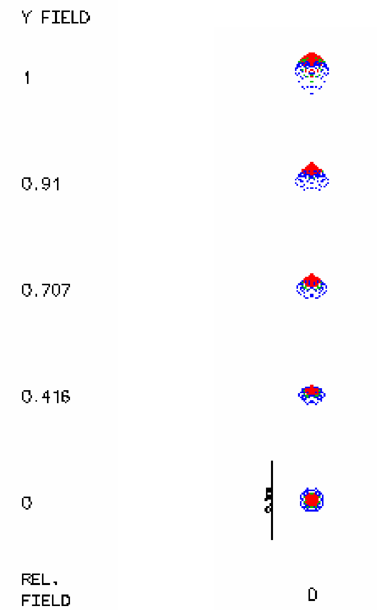

Fig.9. Zoom 1 Spot Diagram

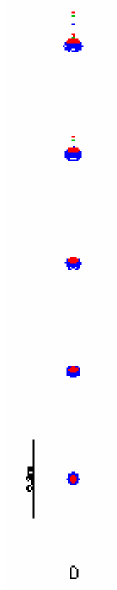

Fig.10. Zoom 2 Spot Diagram

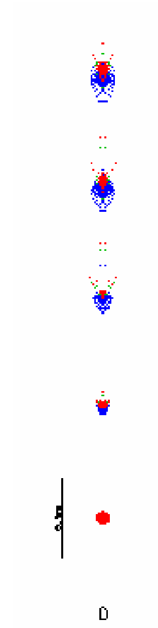

Fig.11. Zoom 3 Spot Diagram

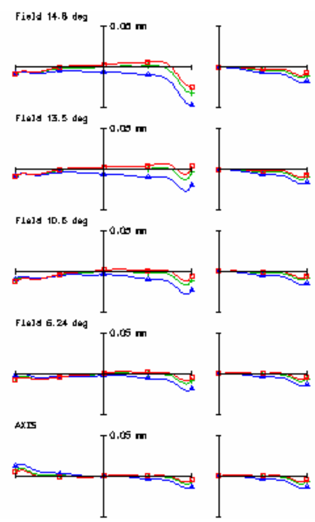

Fig.12. Zoom1 Ray-Fan Plot

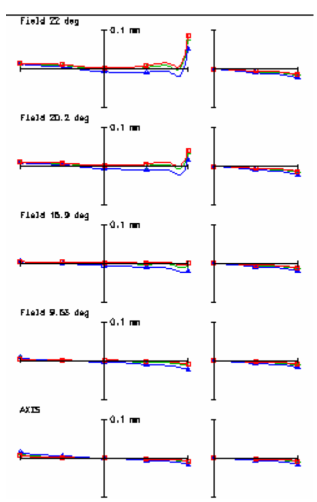

Fig.13. Zoom2 Ray-Fan Plot

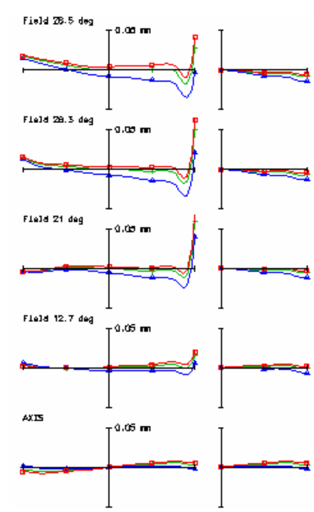

Fig.14. Zoom3 Ray-Fan Plot

6. Conclusions

Two zoom lenses have been designed by means of Global Explorer, which performance reaches most of the design target (Fig 3 to 14). The layout shows that the zoom lens with extremely short and fixed total track length which simplify the mechanism which might be suitable for cases where total length is the priority for the optics on a mobile phone. The thickness of lens group has been greatly reduced by utilizing aspheric elements .It is expected that mobile phone will be much thinner and more complicated in the future.

The global explorer can be utilized as a powerful optimization tool to provide better design as we demonstrate in this paper. Despite utilizing the global explorer, it seems very difficult to improve MTF higher than 20% at 120 lp/mm unless more aspherical lens or diffraction element are used. This design might represent maximum performance with these requirement.

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