Optics beyond Optical Barriers - General Approach

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Abstract

Existing standard optic design methodologies enable to produce high-quality optical systems. However, these systems are limited by the limitations of physical optics such as depth of field, diffraction limit resolution, etc. In this paper, we demonstrate an innovative optical design method, - Dblur's Software Lens™, which enables to produce optical systems beyond the barriers of physical optics. In contrast to existing techniques, Dblur's design flow does not optimize intermediate targets such as point spread function of optical systems, but rather optimizes, as part of the design process, both the optical system as well as its complementing software lens image processing, to achieve maximum image quality. As a demonstration of our design method, we present an enhanced depth of field camera based on a standard two-megapixel mobile CMOS sensor and simple cylindrical symmetry plastic lens.

Introduction

With the development of digital cameras, innovative digital techniques have been used to enhance the quality of images acquired by digital cameras. Some of these techniques even attempt to address problems with existing optical systems. The suggested design approach presented in this paper is unique as it considers both the lens and image processing as one whole system. This paper demonstrates this new optical design methodology that takes in account digital processing abilities during the design of optical elements. As a result, we can design optical systems that are not limited by existing optical systems design barriers.

Standard optical design methods are limited by different physical barriers such as total track, F#, focus length, diffraction limitations, etc. These limitations are caused by physical limitation such as size of optical elements, amount of light required for acquiring a high quality image, physical limitation in convergence of electromagnetic waves, etc. In mobile cameras, these physical barriers prevent camera developers from designing sufficiently small and functional cameras that meet standard image quality requirements. Essentially, our methodology allows extending the performance boundaries of classic optics. It enables us to produce various optical solutions for different purposes such as enhanced depth of field (EDoF) optical systems, simplified optical zoom, short total track, and even optical systems with resolutions beyond the diffraction limit. No additional exotic optical components are needed. Moreover, our optical systems can be produced on standard manufacturing lines with standard processes. Our method is demonstrated here with tests produced with an EDoF camera.

Dblur's Optical Design Methodology

Digital techniques that address optical problems, especially digital methods that perform de-blurring of blur images, are scientifically known as image restoration. Usually, these techniques are considered by camera designers as unrelated to the camera optical design. However, we assert that the role of restoration techniques in image quality is similar to the role of other optical element. To demonstrate this, we show a used SLR digital camera based prototype in which the optical system was replaced by a large pin-hole with no lens - a lens-less camera. We then applied restoration process on the blurred images, as captured on the sensor, for the purpose of correcting the blur. The results as presented in Figure 1 demonstrate how restoration is completing a lacking optical system.

Figure 2 shows another pair of images. The image on the right was acquired by conventional VGA mobile camera with two optical elements; the VGA image on the left was acquired by a Dblur camera module featuring only one optical element combined with Dblur's Software Lens™ restoration algorithm.

It is possible to see that the final quality of both images is the same: two physical lenses without any restoration on one hand and only one physical lens complemented with the Software Lens™ on the other. Hence, a similarity can be identified in the role of digital restoration processes and additional optical elements in the improvement of final image quality and once this is established, the value of restoration could be gained by the mutual optimization of optical system and the restoration process. Moreover, using a Software Lens™ "optical" element achieves greater optical performance than just the addition of a conventional optical element. In [1] we describe in detail our approach to the common design of optical method and restoration processes. In this approach, we formulate a final target according to the desired customer specification. Accordingly, the optical designer can design optical system with standard optic design tools (ZEMAX, Oslo, Code Five, etc.). The true value of the restoration element emerges when an extended optical/imaging design system optimizes the physical optics with the Software Lens™ simultaneously. This can be achieved by calculating the theoretical Point Spread Function (PSF) in different field points. We produce it based on Zernike polynomials [2] for each red, green and blue color individually. Then we calculate restoration filters, which are referred to as "DeConvolution Filters" (DCF). It could be calculated by a standard Winer filter:

***Figure 1**: **left**: image acquired by the lens-less (pin-hole) camera; **right**: same image after applying restoration*

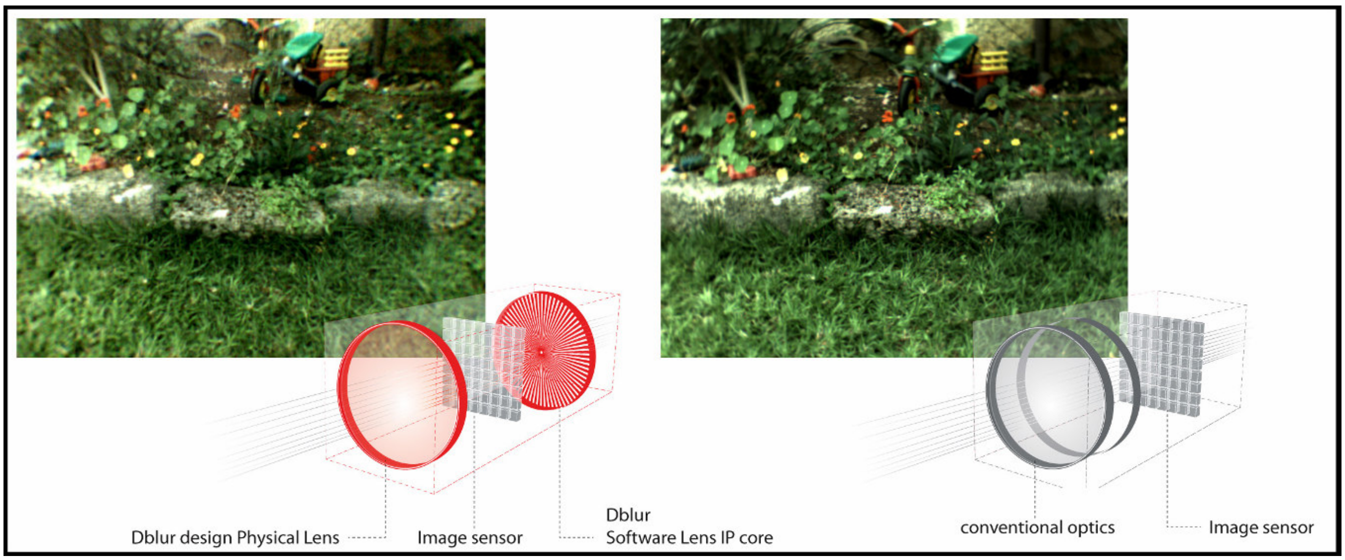

***Figure 2.** The left VGA image was acquired with a Dblur camera with one physical and a Software Lens™; the image on the right was acquired with a standard camera with two physical lenses*

$$d=\frac{h^*}{h^*h+\alpha}\quad, \tag{1}$$

where h is a Fourier transform of PSF; d is a Fourier transform of DCF; and α is a small constant value that should satisfy stability conditions. After the DCF calculation, a final system PSF function is calculated. Then we can estimate a final system resolution, MTF, and other system rates. Our method is aimed at minimizing final system PSF. Generally restoration process is characterized as a high pass (HP) filter which increase noise. However Dblur's Software Lens™ is designed to minimize this effect to generate optimized trade-off between noise gain and restoration effect.

No-Moving Parts Autofocus: Enhanced Depth of Field Solution (EDoF)

Standard optical systems are designed to minimize PSF for one specific object distance: i.e. the focus distance. As a result, only objects acquired from this specific distance are sharpened whereas objects acquired from other distances are blurred in the resulting image. Different mechanical systems have been developed in classic photography to control the camera's focus distance. They consist of moving parts and are known as autofocus (AF) mechanisms. However with reduced mobile camera size involving moving parts becomes expensive and unreliable. Several papers have been published to design optical systems with stable PSF across object distance [3, 4]. These use digital image processing to enhance final image quality. However, they do not take into consideration digital processing during the optics design. Moreover, some of these articles are based on the use of external asymmetric optical filters, which require precise calibration of the optical camera with digital processing.

To verify our methodology, we have developed a 2.0 Mp EDoF camera prototype. In this camera, all objects are in focus regardless of the distance between the object and the camera, featuring final MTF for various object distances that surpass standard camera specifications (all in focus 10cm – infinity).

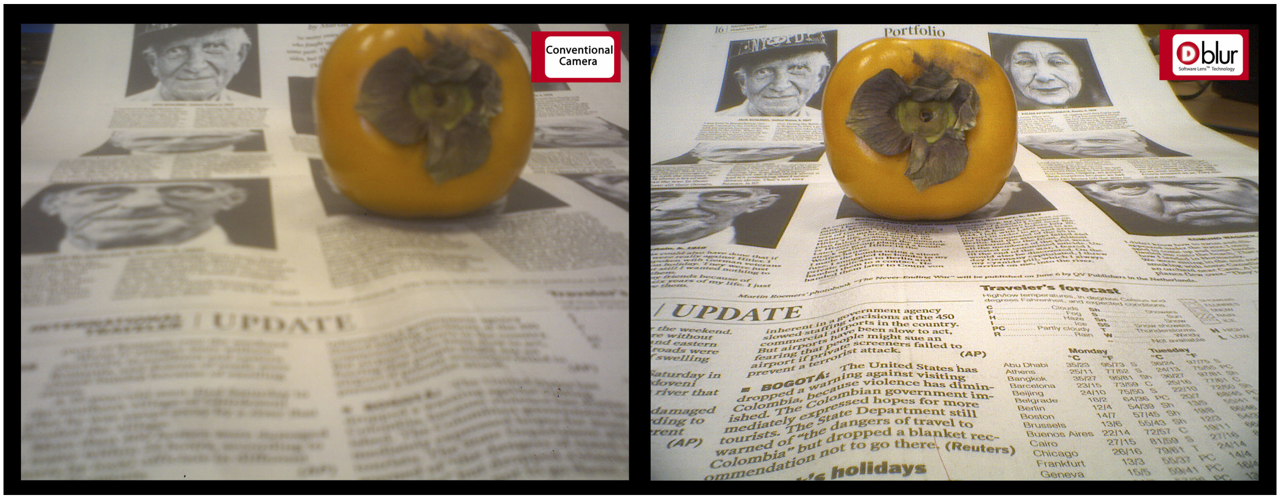

Figure 3. *Left image acquired by a market standard conventional mobile camera. Right image acquired by a Dblur EDoF camera. Objects distance 8cm to 70cm.*

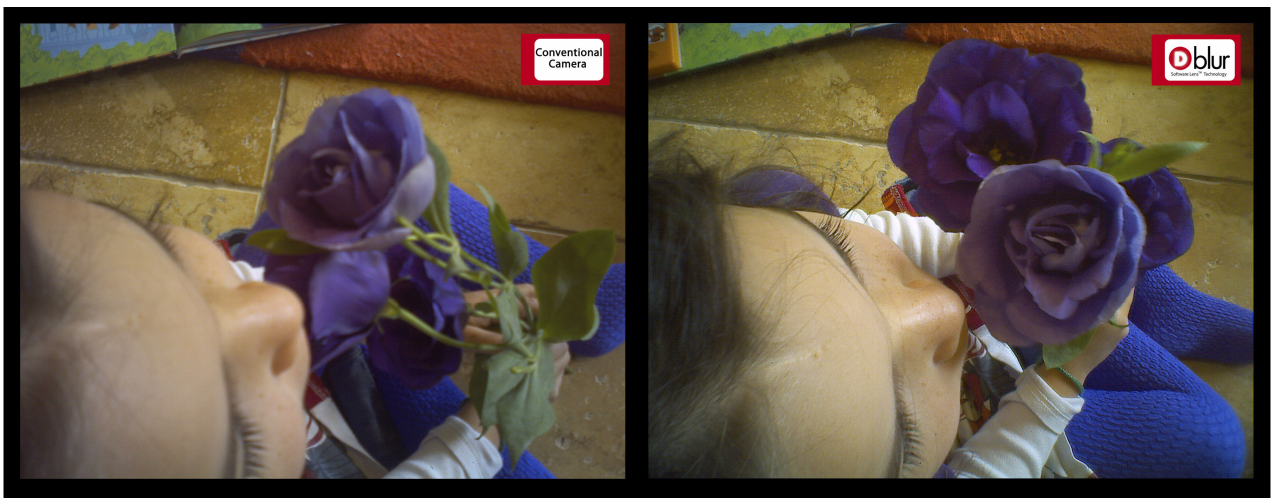

Figure 4. *Left image acquired by a market standard conventional mobile camera. Right image acquired by a Dblur EDoF camera. Objects distance 10cm to 100cm.*

No moving parts are included in this camera. The camera's optical specifications, such as F# and total track, are aligned with the market. The camera is made of three plastic lenses that were manufactured using standard manufacturing process. Moreover a Standard 2.0Mp CMOS sensor with a pixel pitch of 2.8 µm has been used. Figures 3 and 4 present the images acquired with Dblur's and benchmark cameras.

It can see that all objects are in focus. The object distances of the first images vary from 8 cm to 70 cm, while object distances of second image vary from 10 cm to 1 m. With our camera, the achieved resolution is stable for all object distances. Moreover, we cannot define a focus length for this camera. We can see that image that was acquired by Dblur camera module is slightly noisy than image that has acquired by benchmark camera.

Conclusion

This paper describes a new methodology for optical design that takes advantage of the capabilities of digital processing for improving optical parameters during the lens design process.

We design the Software Lens^{TM} in conjunction with the optical design. The paper presented experimental results for EDoF optical design with our methodology. Other optical solutions could be designed by our methodology, for example, optical system with short total track, low F#, low chief ray angle, simplified optical zoom and finally, optical systems with a resolution higher than the lens diffraction limit.

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Authors Biography

Alex Alon received his BS in physics from Tel Aviv University (1993) and his MS in physics from Weizmann Institute in Rehovot. Since then he has been a color scientist in Scitex Herzlia IL (1998), co-founded Dblur Technologies and worked in Dblur Technologies Herzlia IL(2000). His work has focused on image restoration algorithms and Software Lens technology.

Irina Alon received her BS in physics and mathematics from the Hebrew University in Jerusalem (1998). Since then she has co-founded Dblur Technologies and worked in Dblur Technologies Herzlia IL. Her work has focused on image restoration algorithms and Software Lens technology.

Anatoly Litvinov joined Dblur in 2004 and is responsible for Dblur’s image processing algorithm. Prior to this Anatoly served in Israel’s Air Force as an Electrical Engineer. From 1997 to 2000 he acted as a senior designer in IBM’s Cheap Design group. Anatoly holds a B.Sc (1998, Technion – Israel Institute of Technology) and M.Sc (2005, Technion), in Electrical Engineering. His M.S.c Thesis was focusing at image mosaics and radiometric problems.

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