Extended depth-of-field using sharpness transport across color channels

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ABSTRACT

In this paper we present an approach to extend the Depth-of-Field (DoF) for cell phone miniature camera by concurrently optimizing optical system and post-capture digital processing techniques. Our lens design seeks to increase the longitudinal chromatic aberration in a desired fashion such that, for a given object distance, at least one color plane of the RGB image contains the in-focus scene information. Typically, red is made sharp for objects at infinity, green for intermediate distances, and blue for close distances. Comparing sharpness across colors gives an estimation of the object distance and therefore allows choosing the right set of digital filters as a function of the object distance. Then, by copying the high frequencies of the sharpest color onto the other colors, we show theoretically and experimentally that it is possible to achieve a sharp image for all the colors within a larger range of DoF. We compare our technique with other approaches that also aim to increase the DoF such as Wavefront coding.

Keywords: Extended Depth-of-Field (EDoF), Digital Auto Focus (DAF), Deblurring, Computational Imaging, Longitudinal Chromatic Aberrations.

1. INTRODUCTION

We describe here a novel computational imaging method for extending the Depth-of-Field (or Depth-of-Focus) of miniature fixed-focus digital camera. This method is part of a more general framework and patented technology called "*DxO Digital Optics*" as proposed in [1] and described in e.g. [20],[21]. DxO Digital Optics is intended for application in portable consumer products such as mobile phones and uses the co-optimization of the lens design and the digital processing.

1.1 Problem concerned

With the increasing number of camera phones, the demand is rising for a photographic experience similar to the one of traditional Single-Lens Reflex (SLR) cameras in terms of latencies, low-light performance, and sharpness, as well as for new barcode and biometric scanning capabilities at close distances [2]. Despite the recent advances in the integration of miniaturized cameras in mobile devices, developing such very *human* camera systems is becoming more and more challenging.

Two of the most prevalent problems encountered when down-scaling a camera system (and thus reducing its overall dimensions) are:

- the limited space-bandwidth due to diffraction limit, also identified as the number of transported pixels [3]. Since the f-number $f_{/\#} = f/D$ (where f is the focal length and D is the entrance pupil diameter) and the diffraction spot

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diameter $\delta x \approx 2.44\lambda\, f_{/\#}$ (where λ is the centre optical wavelength of the illumination source) are independent of the lens scale, the optimal pixel size remains unchanged.

- the reduced light-gathering ability of smaller pixels (and their increasing non-idealities), resulting in cameras with lower signal-to-noise ratio (SNR) and consequently worse image quality [4].

These two problems plead for maintaining a fast system ($f_{/\#} < 2.8$) in order to limit diffraction effects and to keep a reasonable light sensitivity. Unfortunately, for fixed focus lens, designing a faster lens (*i.e.* smaller $f_{/\#}$) is usually not advantageous since DoF is reduced, minimum object distance (MOD) is increased and image quality is degraded. The MOD can be expressed as (first order approximation):

$$\boldsymbol{MOD} \sim= \frac{f^2}{2.f_{/\#}.\varepsilon} \qquad \textbf{(1)}$$

where f is the focal length of the lens and ε is the maximum acceptable blur spot for infinity and MOD. With a constant field of view, the focal length can be seen as proportional to the sensor diagonal d, and ε can be also considered as proportional to the pixel pitch p. It is then easy to see that the MOD increases with sensor resolution even keeping constant the sensor size. Consequently, the use of mechanical auto-focus appears useful for resolution equal or higher than 3Mpix for ¼" sensor in order to maintain a reasonable "in focus" object distances range, e.g. 30cm to infinity. But, even though manufacturers succeed in reducing size and cost of mechanical auto-focus, the latter are still bulky, almost doubling the size of the camera module in x and y directions.

In this paper, we present an alternative approach, in the field of computational imaging, where a fixed focus lens and digital processing are designed to achieve the same range of in focus object distances. This approach appears to be an advantageous alternative to the mechanical auto-focus in terms of size and cost.

1.2 Computational imaging approaches

In the design of high-resolution camera modules for mobile phones, the problem of finding the best trade-off between (i) imaging resolution (number of pixels), (ii) light gathering ability ($f_{/\#}$ and pixel size), and (iii) Extended Depth-of-Field (EDoF), can be overcome by combining the use of suitable amplitude or phase masks in the pupil plane of the lens with post-detection signal processing [5]. Traditional optical designs do not lend themselves well to digital restoration in the presence of defocus aberration because of both the regions of zero values in the imaging system's MTF (*cf.* inverse and Wiener filtering, etc) and the blur scale identification problem [6]. On the other hand, computational imaging methods that exploit joint optimization of optical elements and digital image post-processing enable to produce imaging systems with greatly reduced overall sensitivity to defocus-related optical aberrations.

The rest of the paper is organized as follows. The next section discusses pupil manipulations previously proposed for extending the DoF. This discussion underscores the advantages and limitations of existing EDoF solutions. In Section 3 we introduce DxO Digital Optics. We will describe how, with this technology, a new step in the field of computational imaging is accomplished by purposefully introducing during the optimization process lens flaws (*i.e.* longitudinal chromatic aberrations) that are compensated by digital image processing (*i.e.* sharpness transport across color channels) to improve system-level optical performances. In Section 4, experimental results demonstrate the capabilities of the developed technology. Finally, Section 5 concludes the paper.

2. TRADITIONAL METHODS FOR EXTENDING THE DEPTH OF FIELD

We distinguish here two general, opposite approaches to extend the DoF in placing amplitude or phase masks in the pupil plane, as identified in the following subsections 2.2 and 2.3. Both approaches can be seen as refinement of the well-known Apodization technique. We will therefore start (in 2.1) with a brief description of the idea behind Apodization.

Let us note that an additional related, but not relevant, approach involves the insertion of a microlens array between the sensor and the main lens, creating a plenoptic camera capable of capturing the 4D light-field in a single photographic exposure [7]. This property allows for an adjustable DoF along with digital refocusing without changing the $f_{/\#}$. However, this comes at the expense of a decrease in image resolution since the full resolution of the image sensor is not available in the final image that the plenoptic camera outputs.

2.1 Shaping the PSF by Apodization

Deconvolution by signal processing is one way to increase the depth of field. However, even with a diffraction limited optical system, we are quickly limited by the "shape" of the PSF. For example, the defocus will create some zeros on its Fourier transform for some frequencies and therefore cannot be inverted properly. Noticing that the PSF can be seen, as a first approximation, as a scaled version of the pupil shape (where the scale factor is related to the defocus), the idea of *Apodization* [8] occurs naturally. Apodization is typically obtained by central or annular obstruction in the aperture of the system. The pupil is then shaped in a way that its Fourier transform reaches zero for higher frequencies compared to the unaltered pupil. If the cut-off frequency (frequency where the MTF is equal to zero) is increased by a factor of 2, the minimum object distance will decrease by a factor of 2 as well. But this technique suffers two major limitations. Firstly, Apodization is essentially an amplitude modulation of the pupil function which significantly reduces the amount of transmitted light through the optical system, thus leading to lower mean SNR. Secondly, the PSF is scaled by a factor related to the defocus (or that is to the object distance) which is unknown by essence. As the PSF size is unknown, either blind deconvolution algorithms have to be used (see section 2.3) or prior information on the scene should be available.

2.2 Having a "defocus-invariant" PSF (and MTF)

The majority of the literature on EDoF techniques has described methods of jointly generating defocus pattern as invariant to object distance as possible and using one focus-independent digital filter to restore the resulting intermediate image.

In miniature camera applications for which light gathering ability is critical, phase modulation of the pupil function offers a complementary or alternative solution for the EDoF problem [5]. By adding a non-absorbing like aspheric optical elements such as cubic-phase or cosine form-phase masks[2], it is possible to code the received incoherent wavefront in such ways that

(i) the PSF of the imaging system becomes more insensitive to misfocus, and

(ii) The PSF is "shaped"[3] so that its MTF (magnitude of its Fourier transform) has no nulls in its spectrum (up to at least half Nyquist frequency), while the full-aperture area is maintained [9].

Once these two conditions are achieved it is then possible to digitally restore the image by a standard deconvolution technique whose parameters can be learned from the so-shaped PSF. The first condition theoretically implies that the PSF will spread on a larger size than the one of a traditional diffraction limited lens, on its own depth of field. The blur spot can be constant with defocus at a cost of a bigger size. Somehow, the extension of the depth of field is achieved here by a trade-off between MTF and SNR.

Beside this theoretical aspect, practical designs show some additional limitations: wavefront coding adversely affects the shape of the PSF. In general, the more insensitive the PSF size is to defocus, the less comparable its shape is to that obtained from a diffraction-limited system. For instance, the non-radially symmetric PSF produced from a cubic-phase mask (often considered as a good candidate for EDoF) tends to boost diagonal frequencies of the scene objects which make occlusion artifacts more visible in the restored image [10]. Occlusion artifacts arise from the approximation made when modeling spatially varying defocus blur as a convolution in the 2D image plane rather than in the 4D light-field. In a very similar approach to wavefront coding, the aspheric optical element is replaced by a (purportedly) non-diffractive, annular binary phase mask attached to the entrance pupil of the lens [11]. Based on this principle, a dual focusing system was demonstrated that is capable of providing sharp images over two discrete ranges of object distances simultaneously [12].The drawbacks of this technology include the inherent MTF degradation between the distinct near and far DoF ranges (which implies a SNR loss), and presumably the greater complexity involved in controlling odd aberrations for front aperture design.

Making the MTF as insensitive as possible to the defocus appears to be the major source of these drawbacks and also adds a strong constraint in the lens design. The technique introduced in this paper does not impose such constraint on the optical system. Before presenting how this constraint can be avoided, let review an interesting alternative.

[2] Note that using phase modulation of the pupil function is not the only way to obtain the two conditions. Most of the effects can be achieve using traditional lens designs at the price of adding more constraint in the lens design stage.
[3] More generally "Wavefront coding" refers to the action of shaping or "coding" the PSF in an advantageous manner.

2.3 Having PSF highly variant and discriminative to defocus

More recently, an opposite approach was taken by Levin *et al.* [6], see also[14]. It consists in making defocus pattern different and easier to discriminate as a function of depth in order to apply adaptive deconvolution. This is achieved by designing a binary transmission mask, *i.e.* a specific optical power-absorbing *apodizer*, that causes the MTF of the imaging system to have a distinct pattern of zeros at low frequencies (rather than at high frequencies to be more robust to noise) for each depth-dependent blurring scale. Although some of the image content is sacrificed, reconstruction of a sharp image is made possible by the use of an iterative least squares procedure with a sparse prior on image derivatives. Despite several optimizations, this procedure remains computationally very expensive, and resulting images inherit a "synthetic" look due to the –aggressive- digital filtering [13].

3. DXO DIGITAL OPTICS (AND SHARPNESS TRANSPORT)

DxO Digital Optics is a new computational imaging method [1] where specific lens flaws are introduced at lens design level and then leveraged by the mean of signal processing to achieve better performance systems. One application of DxO Digital Optics is the extended DoF without increasing the cost or the complexity of the optics, and with no need to increase the $f_{/\#}$, thus to increase the noise level.

3.1 General idea

The general idea for extending DoF can be summarized as follow:

- Introduce longitudinal chromatic aberrations in the lens design, causing the three color channels having different focus and depth of field
- Cumulate their depth of field by "transporting" the sharpness of the "in focus" channel to the other channels.

This technology differs from the other EDoF techniques in the following: first, the introduced longitudinal chromatic aberrations can be used to get a rough estimation of the object distance and therefore allow the use of adapted filters. Second, for each distance in the final DoF, at least one color channel is sharp. So that, unlike alternative techniques (section 2.2), the sharpness of the blurred channels is not recovered by amplifying high frequencies (and noise!) but by simply copying high frequencies of the sharpest channel to the others. This yields benefits that are discussed in sections 3.4 and 3.5.

3.2 Introducing Longitudinal Chromatic Aberrations

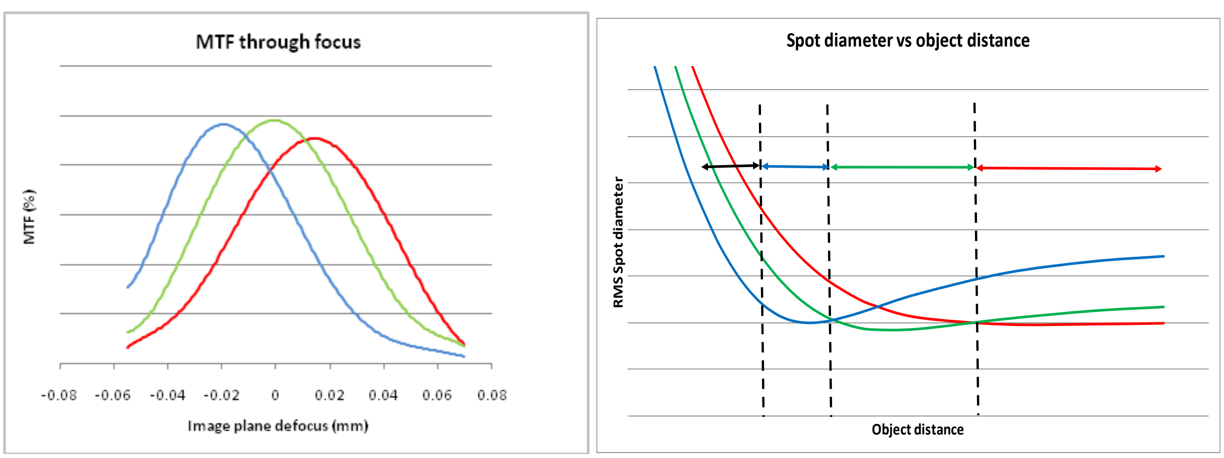
In a color imaging system which exhibits longitudinal chromatic aberrations, the Red-Green-Blue (RGB) components are brought to focus on different planes in the image space, thereby resulting in various levels of sharpness (or reciprocally blur) in the sensor plane for each color channel depending on the object distance as depicted in Figure 1. When not optically corrected (e.g. very simple lenses), the variation of focal length due to longitudinal chromatic aberrations causes near objects to appear blurred in the green and red channels, mid-range objects to appear blurred in the blue and red channels, and far objects to appear blurred in the blue and green channels. Effects of longitudinal chromatic aberration in images are identified as an unwanted concentric chromatic blur that causes color fringing artifacts, particularly noticeable along the edges of backlit objects. Note also that, when considering details in an image, the human retina is more sensitive to the green color; hence, the eye is more sensitive to defocus errors in the green color channel.

Let's point that the longitudinal chromatic aberrations occur naturally in color imaging system due to wavelength-dependent index of refraction of plastic or glass lenses. Traditional camera optical design seeks to minimize such longitudinal chromatic aberrations in order to avoid a degradation of the quality of the final color image. Traditional methods through purely optical means, includes the use of additional lenses or lens made of different materials or hybrid refractive-diffractive elements. This leads to complex and therefore over-constrained optical design [15].

At a first level, instead of using optical means, signal processing can also be used to correct longitudinal chromatic aberrations. This approach not only allows the optical design specifications of the target lens to be relaxed, thus giving the optical designer greater freedom in optimizing other lens parameters (e.g. $f_{/\#}$), but also allows the overall imaging performance of the system to be improved. Now, additionally, DxO Digital Optics uses with great benefit the inherent spread between the color channels to increase DoF.

The lens design seeks to control longitudinal chromatic aberrations in a known fashion so that on the desired range of DoF: (i) each color channel is separated as shown in Figure 2(a); and (ii) the sharpness of (at least) one of the three color channels exceeds a predetermined threshold as illustrated in Figure 2(b). The sharpness of a color channel is plotted here as the *rms* diameter of the spot diagram (the smallest, the sharpest). The color image captured through such an optical system – with at least one color channel in focus – is then processed by a sharpness transport engine.

Fig. 1. Example of chromatic blurring effects due to longitudinal chromatic aberration (LCA); the relative amount of defocus between color channels is a function of object distance; Left: Original color image captured through an optical system which exhibits high LCA; Right: RGB channels for: (Top) a far object, where the red component is the sharpest; (Middle) an object at an intermediate distance, where the green component is the sharpest; and (Bottom) a close-up object, where the blue component is the sharpest.



(a) (b)

Fig. 2. (**a**) Typical through-focus MTF plot of a lens system with strong longitudinal chromatic aberration; the relative positions of the best focus planes for the RGB color channels (*i.e.* at the peak of each through-focus plot) represent the amount of chromatic focus shift at the centre of the field of view; (**b**) Control of longitudinal chromatic aberration for EDoF; this plot shows how the *rms* diameter of the

blur spot within each (RGB) color channel changes as a function of object distance; each color channel has its own effective DoF, as depicted by the colored arrows.

3.3 Image Restoration

DxO Digital Optics engine aims to digitally compensate for the so-introduced chromatic aberrations. But, by this means, it also aims to increase the DoF. It receives the stream of *raw* mosaic-like image data (with only one color element available in each pixel location) directly from the image sensor. The image processing engine filters the pixel values *on-the-fly* and outputs *raw* image data (with enhanced DoF). The output of DxO Digital Optics engine is a RAW image that can be converted by any Image Signal Processor (ISP) into an RGB visible image.

The processing pipeline includes the steps of:

(i) estimating a depth map,

(ii) transporting the sharpness across color channel(s) according to the depth map,

(iii) and, optionally, a final image reconstruction similar to those that would be applied for a standard lens.

3.3.1. Estimating the depth map

In the first step of generating a depth map, each pixel is assigned a depth value corresponding to a specific range of object distances. This can be achieved with a single shot by simply comparing relative sharpness across color channels. (Note that the chromatic blur coding information resulting from such pairwise comparisons has previously been used in camera systems to reconstruct a dense depth (or object distance) map using a single image [16]. Also, other possible uses of chromatic blur can be found in [1] or [17]).

The relative sharpness between channels can be measured by computing, on the neighborhood of each pixel at (Bayer block) location (x_0,y_0) in the color plane I_i (i = R, G or B), the normalized sum M_i of differences between the local gradient and the average gradient, which is given by

$$M_{i=\mathrm{R,G,B}}(x_0,y_0) = \frac{\overline{\left|\nabla I_i(x,y) - \overline{\nabla I_i(x_0,y_0)}\right|}}{\overline{\nabla I_i(x_0,y_0)}} \tag{3}$$

where ∇I_i denotes the magnitude of the local gradient of I_i and $\overline{X}$ is the local average of X values in Bayer's neighborhood. Normalizing the sharpness measurements in this manner equalizes the gradient strength across the color channels.

3.3.2 Sharpness Transport across color channels

Main objective of the object distance estimation is to select the right set of filtering parameters to reconstruct the image. As sharpness depends on the object distance (see figure 2.b), thanks to its estimation, the filtering parameters will be automatically adapted to the situation. The range of object distances can be segmented into few (three, four…) coarse sub-ranges where filtering parameters can be chosen constant. Typically, we chose at least three ranges, that respectively correspond to the DoF of blue, green and red color channels, and that can refer to “scene modes” such as *macro*, *portrait* and *landscape*. (See figure 2).

The digital filters will consist in restoring sharpness to all color channels. Sharpness transport uses the fact that for all range of distances within the extended DoF, at least one channel is sharp: the correction of the blurred channel(s) is then performed by just copying high frequencies of the sharpest channel to the others. The easiest way to implement it is to add to each blurred channel a high-pass of the sharpest one: blur channel += HP(sharpest channel), with HP an adequate high-pass filter. This can be more generally written as:

$$C_{i=R,G,B}\,out = C_{i=R,G,B}\,in + a_{\mathrm{i},R}\,HP_{i,R}(C_R) + a_{\mathrm{i},G}\,HP_{i,G}(C_G) + a_{\mathrm{i},B}\,HP_{i,B}(C_B). \tag{4}$$

Where: i denotes the considered color channel, $HP_{i,j}$ denotes a high pass filters applied on color channel j and added to channel i and the $a_{i,j}$ denote weighting coefficients.

Both weighting coefficients and high pass filters coefficients ($a_{i,j}$ and $HP_{i,j}$) are predetermined from lens data or prior calibration experiments. They have to be determined for each value of the influent parameters such as: position within the image field, object distance, light spectrum, etc.

Also, the frequency response of the filter in each color channel is defined so as to bring the reduced MTF of the blurred color channel(s) to the level of the (in focus) sharp channel. To take into account scale differences across color channels due to object colors or illuminants, the coefficients have to be rescaled depending on the local dominant color.

Specific care around non linearities that occur in the capture chain (e.g. saturations) also has to be taken into account in this reconstruction. This leads to an effectively more complex digital compensation than the formula (2). But, equation (2) can still be seen as representative of the method.

Unlike standard deblurring techniques which tend to amplify noise (*cf*. noise variance being amplified by the L2 norm of the filter), sharpness transport across color channels advantageously provides a small denoising effect. This extra capability is inherent to the blending operation performed (in the mosaic domain) between pixels of different color channels. After sharpness transport, MTF will be similar in the different color channels and at the level of a traditional lens within its in-focus range. Of course the depth of field of the system will be larger (thanks to the addition of the three color channels DoF).

3.3.3 (Optional) final image reconstruction

After the sharpness transportation, all color channels share roughly the same MTF level, whichis similar to the level obtained with a traditional lens at best focus. It is then possible to apply a traditional restoration algorithm to improve the MTF further and filter noise at the same time. For example, a locally adaptive filtering that smoothes noise in the homogenous regions, while enhancing sharpness and edges in the other regions of the image could be used (*cf*. bilateral filtering).

3.4 A New Trade-off

DxO Digital Optics builds on the idea of leveraging longitudinal chromatic aberrations to offer a new range of capabilities, including EDoF. Behind that idea, there is an underlying assumption that color channels are highly correlated. This assumption holds for several reasons:

First, because it is a likely case for most natural images: luminance high frequency variations (due to objects shape, shadows, boundaries, textures) are more predominant at small scales than chrominance ones.

Second, because our eyes are more sensitive to luminance high frequencies than chrominance ones. Also the Bayer structure (2 greens, 1 red, 1 blue in a mosaic) as well as the jpeg compression (sub-sampling of chromatic components) are direct consequences of that fact: there is no need to consider chrominance high frequencies as the eyes do not see them.

In other words, the proposed sharpness transportation technique takes advantage of the spectral information redundancy inherent in images to recover information that has been lost due to chromatic blurring effects. We trade off the extension of the depth of field and the loss of chrominance high frequencies that would be lost anyway after jpeg compression. It is a kind of free lunch.

In addition, designing such a lens gives the lens designer the flexibility to relax the constraints on the amount of longitudinal chromatic aberration, which makes it even easier than designing traditional fixed focus lens. Indeed, having an extra degree of freedom permits for example to reach higher MTF performances (better image quality) and/or reduce the sensitivity of the lens and/or reduce the size of the lens. Also, a strong advantage of such a technology is to be able to use standard piece of equipment to test and assemble the manufactured lens. Compared to a lens designed with a cubic phase mask which needs to have a specific orientation relative to the image plane, this technology does not have specific requirements. Such a lens is then easily mass producible for applications such as the ones of the cameraphone business.

3.5 Comparison with other EDoF technologies

Great advantage of this approach is that the image reconstruction (signal processing) can be automatically adapted to the so-estimated object distance. This is the key point: it gives the extra advantage for the lens designers of not having to control the variations of the PSF with respect to the object distance (see section 2.1). It is not necessary anymore to shape the MTF so as to make it invariant with the object distance.

Another advantage is that we do not have the obligation to trade off the amount of extension of DoF and the loss in MTF (and therefore the noise level). As for any distance (of the final DoF), at least one of the color channels is sharp, the MTF amplification (gain) is limited. Figure 5 shows examples of MTF amplifications for a particular DxO Digital Optics module: they are at similar level than these of a standard lens.

4. RESULTS

An example of the use of DxO Digital Optics to extend DoF while reducing optical system complexity is illustrated through the fabrication of a three mega-pixel (1.75μm pixel pitch) camera module for mobile phones. This example demonstrates a camera-module with a MOD (Minimal Object Distance) of 15cm in comparison to traditional cell phone camera module designs. The lens operates at *f*/2.8 with a diagonal FOV of 68 degrees.

Figure 3 illustrates the output of the depth estimation for two color images captured through the chromatically aberrated lens system. The indoor scene in Figure 3(a) contains three test targets placed at different distances (between 0.3m and 5m from the camera). These three targets are composed of a grid of black dots printed on white paper. The diameter of the dots is adjusted for each target so that the dots of all targets have roughly the same size in the image. The outdoor scene in Figure 3(b) which was captured in an urban environment contains objects over a wide range of distances (from 0.25m to infinity). Figures 3(c) and 3(d) show the resulting depth maps computed from these indoor and outdoor images, respectively. Depth estimations fall into four categories which include the three scene modes *macro*, *portrait* and *landscape* as described above, and one additional mode *undefined*. This latter mode corresponds to pixels that cannot be related to a depth value. This typically occurs in poorly textured regions. Pixels labeled as *undefined* are represented by black pixels in the depth map. The depth maps reveal that the image processing engine can accurately recover depth along most of the image edges.

The MTF versus frequency of the fabricated camera module, after sharpness transport, for each color channel are given in Figure 4. The reconstructed MTF is almost invariant (and above 50% at half Nyquist frequency) over the distance range of 0.25m – 5m, and yield a reasonable image down to 0.15m.

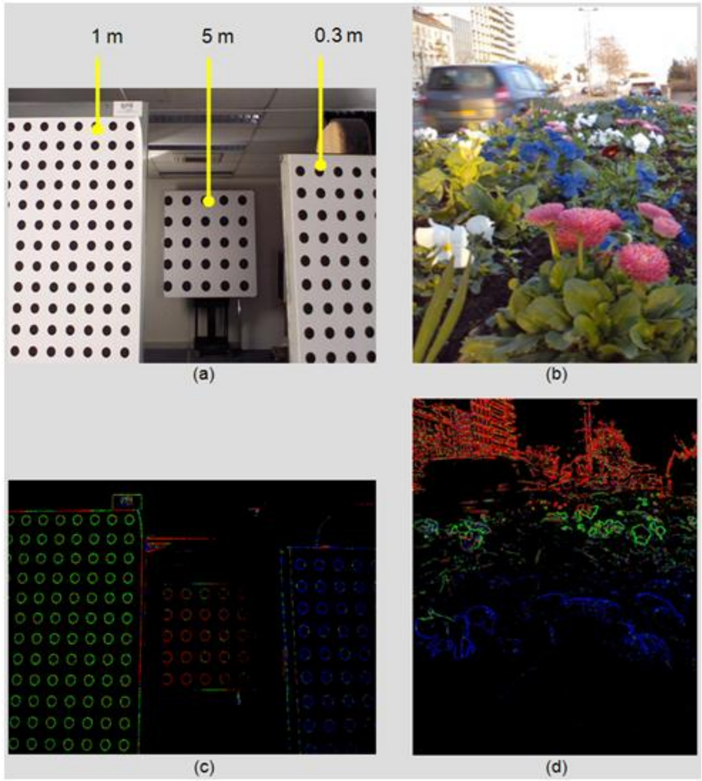
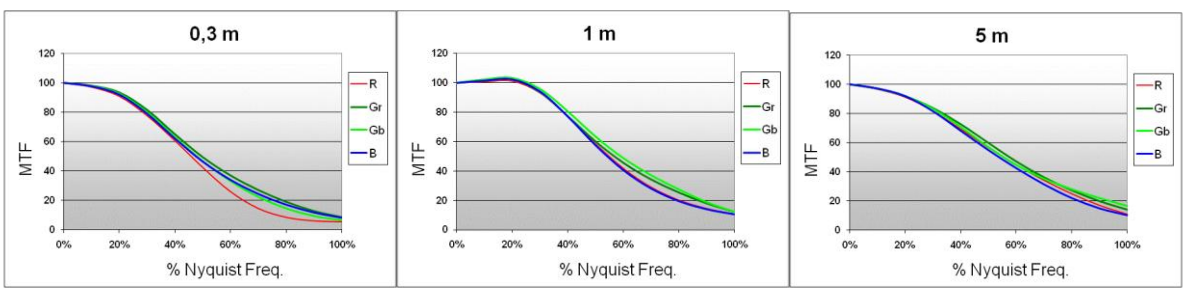


Fig. 3. Depth estimation: (**a**,**b**) Color images acquired from a chromatically aberrated camera system; (**c**,**d**) Recovered (coarse) depth maps; blue, red, and green colors highlight scene modes *macro*, *portrait*, and *landscape*, respectively.



(a) (b) (c)

Fig. 4. MTF versus frequency – after sharpness transport processing – for each color channel, at working distances of: (**a**) 0.3m; (**b**) 1m; and (**c**) 5m. Spatial frequency is normalized to the Nyquist frequency $f_N = (2\times Pixel\ Size)^{-1}$.

As discussed in section 3.5, the MTF amplifications (to achieve final MTF as shown in fig.4) are very limited and similar to those applied for a standard lens. For a traditional sharpening method, one can define the MTF amplification as the ratio between final and initial MTF. The larger the ratio, the larger is the amplification of the noise. Due to particularities of DxO Digital Optics, as the final MTF of a given color channel depends on the initial MTF of the sharpest channel the MTF amplification can then be defined, for each color channel, as the ratio between the final MTF of the color channels and the initial MTF of the sharpest channel. As the final MTF of the color channels are almost identical after processing (see fig. 4), this boils down in the ratio between final MTF and the MTF of the sharpest channel. The fig. 5 plots MTF amplification, for the 4 different objects distances (5m, 1m, 30cm and below) – we recall that the filter parameters will be different for these distances thanks to the distance estimation step.

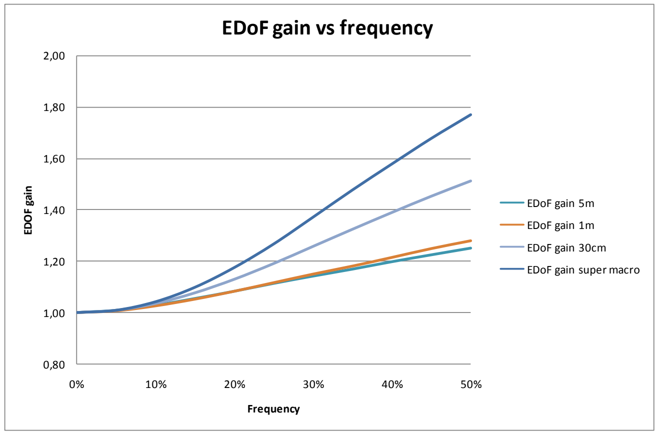
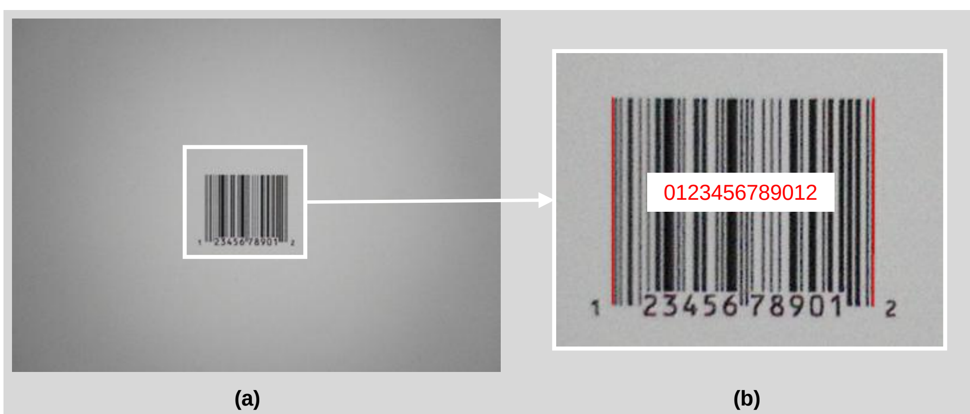


Fig 5. EDoF gain: MTF amplification as a function of the spatial frequency (50% is half Nyquist). The MTF amplification is shown here as the ratio between a perfect lens (diffraction limited only and focused each time to the indicated distance) vs the MTF of the sharpest color channel of the DxO Digital Optics lens. Above 30cm, the MTF amplification is similar to those of a standard lens at its best focus. As consequence the extension of the DoF is achieved without degrading the SNR.

For scene distant from the camera from 10cm to 20cm (see black arrow in figure 2), specific additional filters that further leverage blue channel sharpness allows to further extend the MoD. We call this reconstruction mode “super macro”. It allows considering interesting applications of close imaging such as barcode / QR code reading. Figure 6 shows an example of a barcode 0.25mm pitch shot at 15cm, and a QR code shot at 10cm with the same camera module. Both are successfully recognized by a standard barcode reader software. Figure 7 shows curves indicating the number of dpi (dot per inch) that are resolved as a function of the object distance. The right part of each curve (decrease of dpi) is directly linked to the sensor resolution limit: even with a perfect lens, the number of dpi is decreasing as the inverse of the object distance. The left part of each curve is mostly due to the out of focus. The smaller the distance, the stronger is the out of focus blur, and therefore the smaller the dpi is. With respect to a standard lens, DxO Digital Optics allows to greatly increase the maximum dpi that can be read.



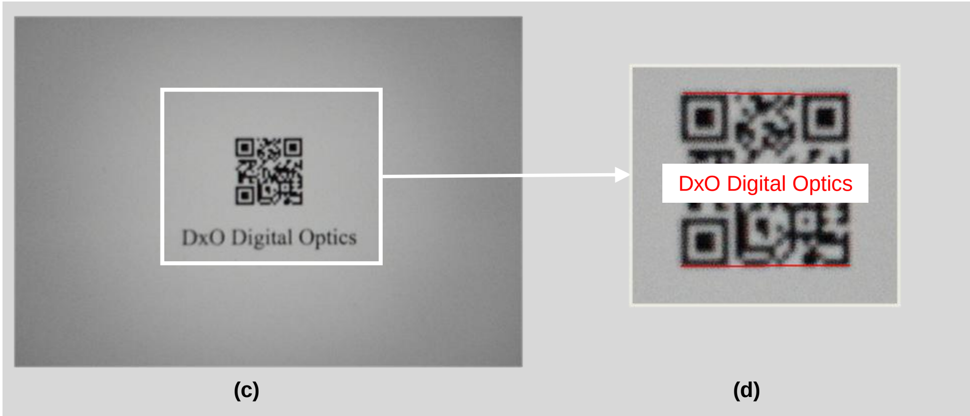


Fig. 6. Example of barcode and QR code reading capability –(**a.b**) : barcode EAN13 type, 0.25mm module size at working distance of 15cm. (**c,d**) QR code at working distance of 10cm. Image is not perfectly sharp, but resolving power is enough to read the QR code.

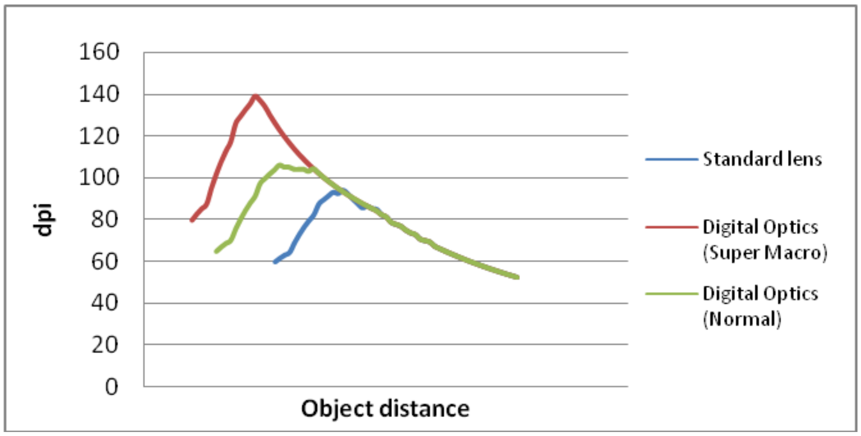


Fig. 7. Resolving resolution as a function of an object distance (3Mpix ¼”). The number of dpi – dot per inch- indicates the resolving resolution (measured on the object) as a function of the object distance. For large distance, this number is limited by the sensor resolution (and therefore decreases as the inverse of the distance). For small distance, this number is limited by the DoF limitation. The improvement of DoF, brings by DxO Digital Optics, increases the maximum dpi.

5. DISCUSSION AND CONCLUSION

We have presented an application of DxO Digital Optics. We showed how, with this technology, a new step in the field of computational imaging is accomplished by purposefully introducing during the optimization process lens flaws (*i.e.* longitudinal chromatic aberrations) which are compensated by digital image processing (*i.e.* sharpness transport across color channels) to improve system-level optical performances. This technology can be used to greatly increase depth-of-field and optical performances while reducing the size, weight and cost of imaging systems. DxO Digital Optics can also be seen as an alternative to traditional mechanical auto-focus.

We have compared this approach to other computational imaging techniques for extending DoF. We know that all techniques need to have a trade-off between the extension of the DoF and some loss for other camera characteristics. Whereas most of the existing techniques trade DoF extension and average lens’ MTF levels - and therefore camera SNR - our approach trades DoF extension and chrominance high-frequencies. Noticing that such trade-off is already done by most traditional cameras (due to sensor Bayer structure and due to jpeg compression), our approach generates a gain in the DoF without any loss at system level with respect to a traditional camera within its own depth of field. At last, our approach appears to be “orthogonal” to the others, and therefore we believe that it can be combined with wave-front coding, so as to cumulate their respective benefits.

For any digital camera system, the amount of useful information contained in the output jpg image is much smaller than the amount of raw information provided by sensor. Digital processing is supposed to make appropriate trade-offs to produce an image as faithful as possible to the original scene, or at least to what human eye can see from that scene (we mentioned the example of jpg compression trade-off). Providing a change in the camera system, a large amount of captured information could be used for other purposes. Our approach consists in choosing to capture depth information rather than chrominance high frequencies and use it to increase the depth of field without damaging perceptible image quality.

More generally, optical and sensor designs are constantly subjected to downscaling and cost cutting, which naturally makes their performances decrease. On the contrary, digital processing follows Moore's law, and therefore becomes more powerful each day. Consequently, it seems natural to transfer the complexity of the other camera components to the digital processing. Avoiding the need of a mechanical auto-focus by the "digital" extension of the DoF of a fixed focus lens is an example of such transfer. We have no doubt that lot of future improvements will come from the co-optimization of digital processing capabilities and camera components at system level, following the principle of human vision and its eye/brain system.

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