

Fast interpolation-based quality evaluation for digital-optical system optimization

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Abstract: We describe a computationally-efficient approach to approximate the end-to-end MSE merit function for evaluating and optimizing digital-optical imaging systems based on interpolation. We use commercial lens design software to verify the approach.

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OCIS codes: (110.1758) Computational Imaging, (000.4430) Numerical Approximation and Analysis, (070.0070) Fourier Optics and Signal Processing.

1. Introduction

Following the trend pioneered by [1] of designing electro-optical image system by exploring cooperative interaction between optical, detector, and digital processing subsystems, new methods for jointly optimizing both the optical and the digital subsystems have been proposed recently [2]. Therein, the performance of such *digital-optical* systems are evaluated from an end-to-end perspective using the mean square error (MSE) image quality metric. As shown in [2], the MSE for a particular field location is given by

$$\text{MSE}(u) = \frac{1}{4\omega_N^2} \int_{|\omega_1| < \omega_N} \int_{|\omega_2| < \omega_N} S_e(\omega_1, \omega_2) d\omega_1 d\omega_2, \quad S_e(\omega_1, \omega_2) = \frac{S_{uu}(\omega_1, \omega_2) S_{nn}(\omega_1, \omega_2)}{|H(\omega_1, \omega_2)|^2 S_{uu}(\omega_1, \omega_2) + S_{nn}(\omega_1, \omega_2)}, \quad (1)$$

where S_{uu} is the power spectral density (PSD) of the image source, S_{nn} the noise power spectral density, $H(\omega_1, \omega_2)$ is the system optical transfer function (OTF) as a function of spatial frequency coordinates $\omega_{1,2}$, and ω_N is the Nyquist frequency of the digital detector. The OTF for a particular field angle is given by

$$H(\omega_1, \omega_2) = \mathcal{F}[|\mathcal{F}(P(r, \phi))|^2], \quad (2)$$

where \mathcal{F} is the Fourier transform operator and $P(r, \phi) = A(r, \phi) \exp(iW(r, \phi))$ is the pupil function with transmission function A and wave front error function W , which measures the optical path difference (OPD) [3]. Using MSE as the merit function in the optimization step of a digital-optical imaging system design has lead to novel system designs and functionalities such as those described in [4] and [5].

Computing the MSE function of Eq. 1 requires rectangular discretization of the OPD and OTF domains in order to take advantage of the the Fast Fourier Transform (FFT). As is common to most commercial lens design software (Zemax, Code-V, OSLO), the straightforward approach for computing a two-dimensional OTF surface using FFTs is based on first computing the OPD values within the pupil on a rectangular grid of size $B \times B$ (typically $B = 64, 128, 256$). This was the discretization approach employed in [2, 4]. The next step in calculating MSE applies FFT operations to a zero-padded two-dimensional array on a $2B \times 2B$ grid. Finally, the MSE performance metric is calculated by performing a rectangular-rule integration of the error function S_e within the sampling band of the system which is of size $2B \cdot u \times 2B \cdot u$, where $u \frac{\omega_N}{\omega_D}$ is the ratio of the sampling frequency divided by the diffraction-limited spatial frequency $\omega_D \approx \frac{1}{\lambda F\#}$.

Calculating the MSE in this fashion presents two challenges. First, when the imaging system is significantly under-sampling ($u < 0.2$), as is the case for many consumer imaging applications, then the accuracy of the MSE calculation suffers from insufficient sampling within the sampling band. In such cases, zero-crossings in the MTF may not be evaluated when computing the error function S_e leading to poor system designs showing erroneously high-quality MSE performance. The straightforward approach for addressing this problem involves increasing the sampling rate B of the OPD function to compensate. Unfortunately, this approach requires large numbers of ray traces to compute the wavefront error function significantly slowing down the calculation of MSE. Optimizing digital-optical systems becomes extremely slow due to the shear number of ray-traces required to evaluate system quality. Solving the second problem has been attempted in [6] by computing the OTF from a finite Taylor-series expansion of the pupil function,

but the speed-ups described in this approach assume minimal optical aberrations. Severely aberrated systems, such as those encountered in extended depth-of-field systems, will not benefit from such an approach. We first addressed this problem in [7], but did not test the the approach using commercial lens design software.

In this paper, we introduce a novel fast approach for calculating end-to-end MSE based on non-rectangular grid topologies and computationally efficient interpolation that is simple to integrate with commercial lens design software tools. We verify the acceleration achieved by the proposed approach using real ray-tracing calculations performed by Zemax. An overview of the proposed new computational pipeline is shown in Fig. 1.

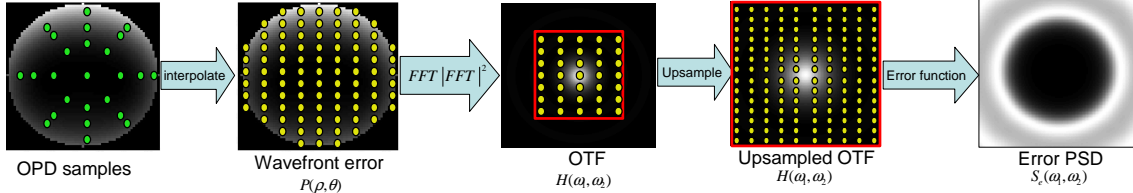


Fig. 1. Proposed pipeline for fast calculation of the MSE measure for optimization of digital-optical imaging systems using interpolation-based approximations.

2. New MSE pipeline with non-rectangular sampling grids

Our proposed approach relies on simple interpolation applied at two stages of the pipeline to both improve efficiency and accuracy of the MSE calculation. First, we address the speed problem by changing the sampling grid topology when performing ray traces followed by fast interpolation onto the $B \times B$ grid. Specifically, we employ a polar grid of L rings and K arms when performing ray tracing (green dots in Fig. 1 as is commonly used when evaluating OPD-RMS during traditional optical system design [8, 9]). The polar grid sampling strategy has been shown appropriate for efficiently sampling the OPD on the pupil, since the OPD is typically represented by a few lower order Seidel aberrations [8]. We then compute samples on the regular $B \times B$ grid by linearly interpolating the ray-traced OPD prior to the FFT operation. Second, we address the accuracy problem by resampling the OTF function onto a higher resolution grid using interpolation of the complex OTF function. By interpolating the OTF function prior to calculating the error function S_e , we avoid the approximation errors associated with insufficient OTF samples. Adding the interpolation at this point in the pipeline has the added benefit of additional reduction in computational complexity. In our implementation, we utilize linear interpolation for resampling both the wavefront error function and the OTF function, although higher order interpolation schemes would most likely show improved performance. Interpolation accelerates the process by being only a linear order of complexity with respect to the number of samples. This represents significantly fewer operations than either ray tracing or FFT operations.

3. Experiments

In order to test the accuracy of our proposed MSE calculation approximation, we evaluate the MSE of a 5.75 mm focal length, 40 degree field-of-view, F 3.0 extended depth-of-field (EDoF) triplet imaging system. The EDoF property is achieved by employing the spherical coding design principle [5] which intentionally adds significant spherical aberration to the optical system. In this case, the five waves of spherical aberration lowers the MTF as shown in the left side of Fig. 2 (computed by Zemax). The MTF is shown when the back focal distance is 3.34 mm.

In order to evaluate the accuracy of the proposed approximation scheme, we evaluate the on-axis end-to-end system RMSE (square root of MSE) as a function of back focal distance. We implemented our MSE approximation pipeline using a *user-defined operand* within the Zemax lens design tool. This allows us to calculate the actual compute times required to compute the RMSE including the ray-tracing computation times. We first compute the RMSE as a function of back focal distance using the straightforward approach based on $B \times B = 128 \times 128$ rectangular sampling grid as a baseline for comparison (denoted Type 0). This baseline RMSE is shown as the black dotted curve in the right side of Fig. 2. Then we evaluate the RMSE using four different versions of the proposed approximation technique; namely, 8 ring and 8 arm ray sampling interpolated to 64×64 OPD grid followed by a $2 \times$ upsampling of the OTF (Type I), 8 ring and 8 arm ray sampling interpolated to 128×128 rectangular grid with no OTF interpolation (Type II), 16 ring and 16 arm ray sampling grid interpolated to 64×64 rectangular OPD grid followed by $2 \times$ OTF interpolation (Type III), and 16 ring and 16 arm ray sampling interpolated to a 128×128 rectangular OPD grid with no OTF interpolation

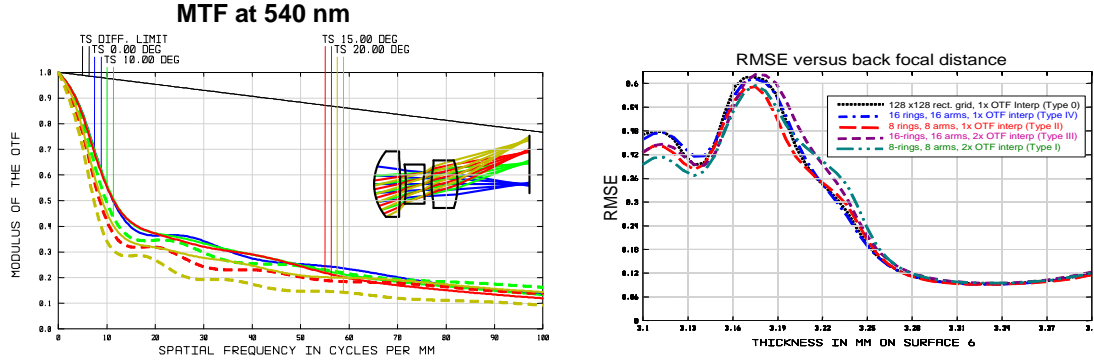


Fig. 2. The left graph shows the MTF at BFL=3.34 mm for the spherical-coded triplet imaging system. The right graph compares the computed RMSE as a function of back focal distance using the straightforward baseline approach (dotted black) and four versions of the proposed approximation scheme.

(Type IV). The calculated RMSE for these four other approaches are shown in the right side of Fig. 2. We note that all four approximation schemes produce RMSE values closely tracking that of the baseline RMSE. Even the 8 arm, 8 ring approximation with OTF upsampling, which shows the poorest approximation, would suffice for optimization demonstrating the accuracy of the proposed approach.

We then measured the computation time in milliseconds on a 3.2 GHz Xeon processor machine of the five different MSE calculation schemes. Specifically, we measured the amount of time required for the combination of ray tracing and interpolation (if applicable) so as to evaluate the speed-up of the proposed scheme. The resulting average computation times are shown in Table 1. We observe that the proposed approach accelerates the RMSE calculation by an average of $20\times$ with minimal degradation in RMSE quality.

Type 0	Type I	Type II	Type III	Type IV
201	5	10	11	14

Table 1. Table comparing the time in milliseconds required to compute the RMSE

4. Conclusions

We have introduced a new architecture computing the end-to-end MSE merit function used in optimization of digital-optical imaging systems. We verified that new approach accelerates the MSE calculation by a factor of about $20\times$ while preserving MSE accuracy. The proposed acceleration makes the task of designing digital-optical systems computational tractable.

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