Integrating lens design with digital camera simulation

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ABSTRACT

We describe a method for integrating information from lens design into image system simulation tools. By coordinating these tools, image system designers can visualize the consequences of altering lens parameters. We describe the critical computational issues we addressed in converting lens design calculations into a format that could be used to model image information as it flows through the imaging pipeline from capture to display. The lens design software calculates information about relative illumination, geometrical distortion, and the wavelength and field height dependent optical point spread functions (PSF). These data are read by the image systems simulation tool, and they are used to transform the multispectral input radiance into a multispectral irradiance image at the sensor. Because the optical characteristics of lenses frequently vary significantly across the image field, the process is not shift-invariant. Hence, the method is computationally intense and includes a number of parameters and methods designed to reduce artifacts that can arise in shift-variant filtering. The predicted sensor irradiance image includes the effects of geometric distortion, relative illumination, vignetting, pupil aberrations, as well as the blurring effects of monochromatic and chromatic aberrations, and diffraction.

Keywords: Lens design software, digital camera simulation, shift-variant imaging, optical system modeling

1. INTRODUCTION

Image system designers need to understand how the wide range of imaging pipeline parameters influences image quality and visual appearance. Because the goal is to understand the perceptual consequence of many different factors, designers can benefit from image systems simulation software like ***ISET*** [1] (Image Systems Evaluation Toolkit), which includes rigorous models of the scene, optics, sensor, and processing stages. By combining models of the entire pipeline into a single simulation environment, the user can study the visual consequences of altering different imaging properties, including: (1) a radiometric description of the scene, (2) optical transformation of the scene to irradiance signals at the sensor, (3) sensor capture, and (4) digital image processing for display.

Modeling image formation, that is how optical elements convert scene radiance into sensor irradiance, is particularly challenging. Good image formation algorithms should produce radiometrically consistent results that model the effects of monochromatic and chromatic aberrations, pupil aberrations, vignetting, and diffraction. Locally these factors behave linearly, but the effects of interest vary significantly across the image field so that the complete image formation model is not shift-invariant (i.e., the process is shift-variant). Hence simulation of the image formation is computationally intensive; the characteristics of the lens must be characterized for each wavelength at many spatial positions, and the appropriate operator must be used at different image locations. Several special purpose models to implement this calculation have been proposed and discussed in the literature[2,3,4,5], but none of these models or programs account for all of the optical effects produced in real optical systems for whole multispectral images.

Developing and verifying the software needed to compute the physical optics data for the image formation algorithms would be a formidable task. Fortunately, there are proven commercial lens design software programs, like Code V®[6] and Zemax®[7], which are capable of providing all of the required optical data for virtually any camera lens. These programs utilize a combination of geometric ray tracing, Fourier transforms, diffraction integrals, and related algorithms

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to model and quantify accurately the phenomena produced by aberrations and diffraction in imaging optical systems. This software is developed for lens designers, who are principally concerned with optimization of image quality related lens parameters, such as monochromatic and chromatic aberrations, modulation transfer function (MTF), point spread function (PSF) size, field distortion, and relative illumination. Image system designers, on the other hand, are concerned with the impact of these factors on final overall image quality and visual appearance. Consequently, their goal is to visualize the consequence of modifying lens parameters on image quality. The effect of lens parameters on image quality depends on other system components, such as the sensor and image processing algorithms.

We describe an approach to integrating lens design and imaging simulation. The approach uses commercial lens design software to calculate key optical parameters from the lens design; these parameters include the optical point spread function (PSF) as a function of field height and wavelength, field distortions and relative illumination. These data are imported into the image systems software that applies an image formation algorithm (linear shift-variant) as part of the complete imaging pipeline. By integrating these two tools, the effect of changing lens designs can be evaluated within the full imaging pipeline. We demonstrate the computational methods and illustrate the results for several different lenses.

Anticipated uses of the model include the evaluation of lens designs, visualization of camera performance, generation of image data for virtual camera simulators, and classroom instruction of imaging systems principles. Non-ideal systems like cell phone cameras and atypical applications like multispectral or thermal imaging could also benefit from the inter-operability of optical design and digital camera simulation programs.

2. METHODOLOGY

The camera lens optical system model is based upon a generalized imaging system model and coordinate system where a 2-dimensional object spectral radiance [W/(m^2·sr·nm)] distribution is mapped to a 2-dimensional spectral image irradiance [W/(m^2·nm)] distribution as illustrated in Figure 1. The significant properties of the imaging system can be derived from a real physical optical system. The object scene is assumed to be plane and Lambertian and the optical system is assumed to be rotationally symmetric.

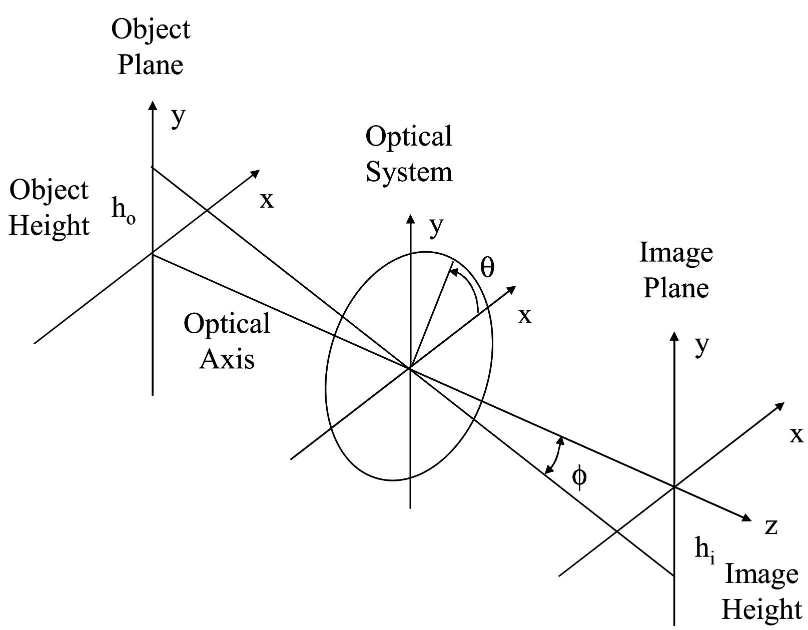

Figure 1. Imaging System

2.1 Imaging Systems theory

The image formation process in an optical system with incoherent illumination can be described by a convolution operation[8].

$$I_{image}(x,y,\lambda) = PSF(x,y,\lambda) \otimes I_{ideal}(x,y,\lambda) \tag{1}$$

where :

$$I_{ideal}(x,y,\lambda) \cong \frac{\pi T(\lambda) L_{scene}(\frac{x}{m},\frac{y}{m},\lambda) R(x,y,\lambda)}{4(f/\#_{eff})^2} \tag{2}$$

PSF is the point spread function of the optical system

$\otimes$ is the convolution operator

I_{ideal} is the ideal, unaberrated, geometric image irradiance distribution

m is the magnification of the optical system

T is the transmittance of the optics

L_{scene} is the Lambertian object scene radiance distribution

R is the relative illumination factor

$f/\#_{eff}$ = effective f - number = 0.5/NA

The point spread function, *PSF*, is the image of a point object formed by the optical system. The *PSF* includes all of the optical aberrations and diffraction occurring in the optical system. I_{ideal} is the image irradiance distribution that would be produced by an ideal optical system with no aberrations or diffraction. *R* is the relative illumination factor that typically has a value of 1 for the on-axis image point. For an ideal thin lens, *R* would be equal to the cosine-fourth factor. The relative illumination factor also includes the effects of vignetting, pupil aberrations, and angle of incidence.

Alternatively, from a spatial frequency perspective, image formation can be viewed as a linear filtering process.

$$FT\{I_{image}(x,y,\lambda)\} = FT\{PSF(x,y,\lambda)\} \cdot FT\{I_{ideal}(x,y,\lambda)\} \tag{3}$$

$$FT\{I_{image}(x,y,\lambda)\} = OTF(f_x, f_y, \lambda) \cdot FT\{I_{ideal}(x,y,\lambda)\} \tag{4}$$

$$I_{image}(x,y,\lambda) = FT^{-1}\{OTF \cdot FT\{I_{ideal}(x,y,\lambda)\}\} \tag{5}$$

where :

FT is the Fourier Transform Operator

The optical transfer function, *OTF*, is the Fourier transform of the *PSF*. From equations (4) and (5) we see that the OTF filters the spatial frequency components of the image.

Equation (1) is valid if the optical system is isoplanatic over the entire image region. An optical system is isoplanatic[9] if the translation of the object point in object plane translates, but otherwise leaves unchanged, the irradiance distribution of the PSF. Such a system is also said to be shift-invariant. However, most practical optical systems, like camera lenses, are not isoplanatic; the PSF changes appreciably as the object point shifts.

Even though they are not isoplanatic, optical systems with incoherent illumination satisfy the properties of homogeneity and superposition in irradiance and are a linear system. To model this shift-variant linearity, the image plane can be divided into smaller sections over which there is negligible change in the PSF. Each locally isoplanatic section will have its own particular PSF and OTF associated with it. So image formation can be achieved by convolving each section with its associated PSF, and the individual section can be summed to obtain the final image irradiance distribution. Equivalently, the final image irradiance distribution can be obtained by filtering the spatial frequency components of each isoplanatic section with its associated OTF, followed by inverse Fourier transforming the filtered section transforms and summing the results to obtain the final image irradiance distribution. Enabling the PSF to vary in the image formation process produces a linear shift-variant camera lens model.

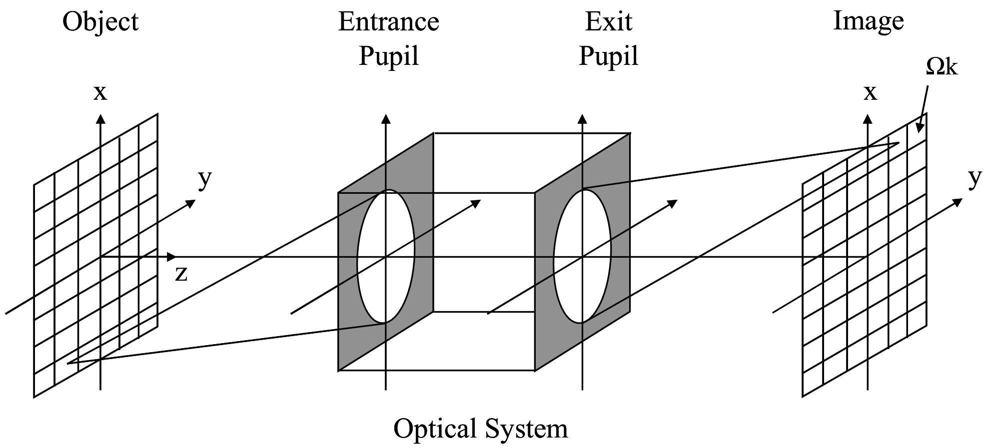

Figure 2. Linear Shift-variant Imaging System with image plane segmented into isoplanatic regions, Ω1, Ω2,Ö , Ωn

Let $\Omega k,\ k = 1, 2, ..., n$, be isoplanatic sections in the image plane, then :

$$I_{image}(x, y, \lambda) = \sum_k PSF_{\Omega k}(x, y, \lambda) \otimes I_{ideal\Omega k}(x, y, \lambda) \tag{7}$$

or

$$I_{image}(x, y, \lambda) = FT^{-1}\left\{\sum_k OTF_{\Omega k} \cdot FT\{I_{ideal\Omega k}(x, y, \lambda)\}\right\} \tag{8}$$

To insure the radiometry is preserved, the OTFs are normalized.

$$OTF(f_x, f_y, \lambda) = \frac{FT\{PSF\}}{FT\{PSF\}\big|_{f_x=0,\, f_y=0}} \tag{9}$$

2.2 Computational method

The computational method and algorithms we implemented are based on the equations developed in the previous section, and the image, section, and computational spaces shown in Figure 3.

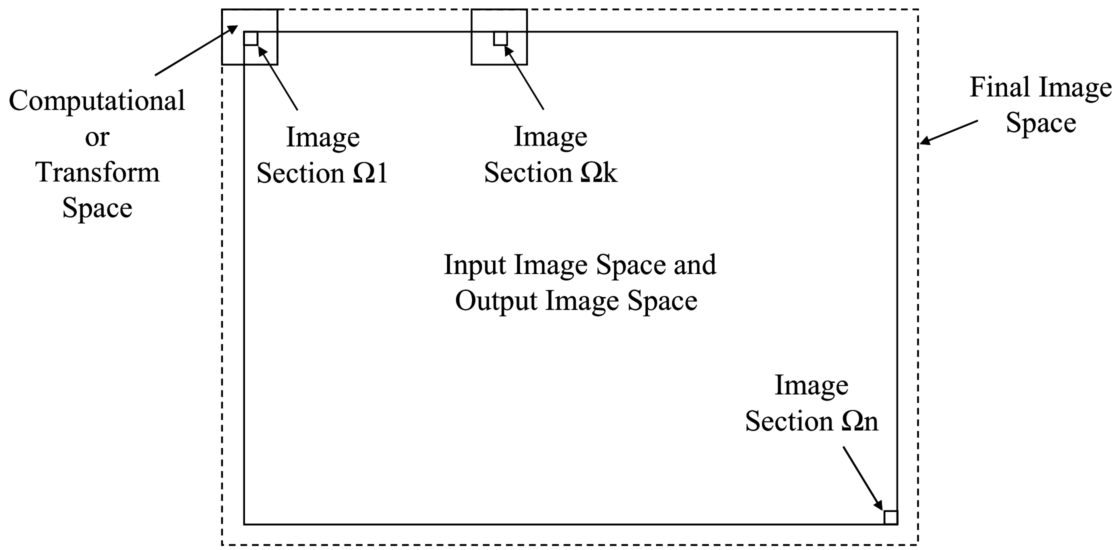

Figure 3. Computational and Image Spaces

The procedure is outlined below:

1. Generate the first-order optical system parameter data. Generate the distorted image height matrix, relative illumination matrix, and PSF matrix for a set of image heights spanning the image sensor dimensions, and for selected wavelengths within the desired spectral range.
2. Apply distortion shifts and relative illumination factors to the ideal input image for each selected wavelength. For each selected wavelength: Fourier transform image sections. Select, interpolate, and rotate PSFs, then apply Fourier transform to produce OTFs. Normalize the OTFs. Multiply each image section by the appropriate normalized OTF. Inverse Fourier transform the result to obtain the filtered image. Sum the resulting image sections to form the final image.

Note that the image formation process is performed image section by image section and the results are eventually assembled to produce the final image. The image section size can be reduced to a single pixel or can even be changed to a higher resolution prior to filtering and down converted to render the final image, but speed and efficiency are sacrificed. The computational space must be large enough to accommodate the PSF, OTF, image section spatial frequencies, and any spreading and shifting of the filtered image section.

Developing and implementing the shift-variant imaging algorithm used in the camera lens model was not as straightforward as initially anticipated. Several key techniques and process steps needed to achieve computational efficiency and minimize image artifacts were developed and tested before arriving at the current version. These are briefly discussed in the sections that follow.

2.2.1 Generating the optical system data

Automating the optical system data generation from the lens design program, for a given lens with a specific object scene distance, is critical to enabling efficiency and ease of use. The real chief ray height, relative illumination, and PSF are needed at several points across the image field for selected wavelengths within the scene spectral range. If the optical system is rotationally symmetric, then the data set only needs to span half the diagonal image field typically along one of the coordinate axes (x or y). Only a sampled set of these parameters is required since rotation and interpolation is employed to determine the data needed for in-between points in the image field when needed. In addition, a file containing the first-order optical system parameters (e.g., effective focal length, field of view, magnification, reference wavelength, etc.,) used for other computations in the model is generated.

Most lens design programs have built-in programming language capabilities that can be used to automate batch processing and generation of data from the various design and analysis features contained in these programs. General purpose macros or scripts were written in both the Code V® Macro-Plus and Zemax® ZPL programming languages to automate production of the required data in ascii text (.txt) files or binary data (.dat) files. These files are used and processed by the image systems software to implement the shift-variant imaging algorithms.

2.2.2 Applying distortion and relative illumination factors to the ideal image

To achieve accurate radiometry, the imaging model must account for illumination effects in the optical system and image formation process, especially for off-axis image points. Determining the impact of these effects can be difficult especially when vignetting, pupil aberrations, and large off-axis angles of incidence are present[10]. Fortunately, the relative illumination factors computed by lens design programs can be used to account accurately for illumination effects on the image irradiance distribution.

Distortion is an aberration that affects both image geometry and the energy distribution in the image. This occurs because distortion shrinks or stretches the image locally and non-uniformly across the image plane. So the image of a particular object point will be blurred, by diffraction and other aberrations, and shifted by distortion. However, the size of the distortion shifts can be many times larger than the dimensions of the PSF and, therefore, significantly impacts the computational efficiency because the computational space must be increased accordingly. It was also found that convolving or filtering the image sections when the distortion shift was included in the PSF produced spiderweb like artifacts and other illumination related errors in the image irradiance.

Much more accurate results were obtained by separating the application of the distortion shifts and filtering to the ideal image. These two calculations are separable because the distortion aberration shifts the PSF but does not significantly affect the shape of the PSF. Furthermore, we also found that distorting the ideal image and applying the relative illumination factors pixel by pixel, followed by OTF filtering of the resulting image section by image section, produces an image irradiance distribution that is radiometrically accurate, free of gross artifacts, and much quicker to compute. Note also that lateral chromatic aberrations will be accounted for as this procedure is carried out for each selected wavelength in the spectral range of the object scene.

Since the distortion is applied before the filtering operation, the PSFs must not include the position shift associated with distortion. Instead, the real image height position corresponds to the center grid point of the PSF data for each wavelength. Generating the PSF data in this format from a lens design program is straightforward.

Performing the calculations involving distortion and relative illumination require interpolation of both parameters. To accomplish this, the distortion and relative illumination data generated by the lens design program are least-squares fit to a polynomial and the coefficients are used for interpolation. Polynomials from 4^{th} order up to 8^{th} order were found to be sufficient. Linear algebra techniques[11] are able to perform the least-squares fitting very quickly and efficiently.

2.2.3 Filtering and forming the final image

Blurring by the PSF or, equivalently filtering by the OTF, of the distorted and relative illumination adjusted ideal image is performed sequentially, one isoplanatic section, Ωk, at a time, for each selected wavelength. Prior to this, the PSF data must be resized and resampled to match the size and pixel dimensions of the computational or transform space. For each selected wavelength, the computational space is stepped through the image space section by section, the appropriate PSF is interpolated, rotated, and Fourier transformed to produce the OTF. Normalization of the OTF by the zero-frequency or DC component, as shown in equation (9), is performed to insure that extra energy is not added to the image in the filtering process. The image section is zero-padded to match the computational space size and then Fourier transformed into its spatial frequency components. Filtering is accomplished by multiplying the normalized OTF and the transformed image section. The filtered image sections are inverse Fourier transformed and the resulting image sections are summed to form the final image for the selected wavelength. The complete spectral image can now be formed from an appropriately weighted sum of the final images. Again since these filtering operations are performed for each selected wavelength, the effects of chromatic aberrations are incorporated.

In the process of developing and testing our algorithms, we found that interpolating the PSF instead of the OTF produced more stable and accurate results. The PSF contains pixel values that are proportional to the PSF irradiance values, which makes interpolation more amenable to simpler techniques. The OTF contains both real and imaginary components, and basic interpolation techniques can be problematic.

There is also a difference in the PSF output from Code V® and Zemax®. The PSF calculation in Code V® includes the effects of projection onto a flat image plane for off-axis image points. The FFT PSF[5] calculation in Zemax® does not, and predicts a better than actual performance at non-zero image heights. Zemax® does have the Huygens PSF option which does account for the projection effect but is not accessible through the ZPL programming language at this point in time.

3. DATA

Edmund Industrial Optics provided us with the prescriptions of their line of Finite Conjugate Micro Video Imaging Lenses[12] and approved our use of them for the purpose of studying and developing our computer models. One advantage of modeling these lenses is that we can purchase them and compare actual test results with our simulations.

Much of the data presented in this section were generated by Code V®, Zemax®, and LightTools®[13] for a 1/3 inch sensor format using the R54-852 Finite Conjugate Micro Video Imaging Lens[12] prescription supplied by Edmund Industrial Optics.

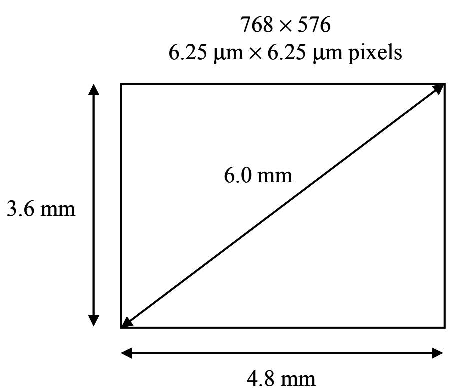

Figure 4. 1/3 inch Sensor Format

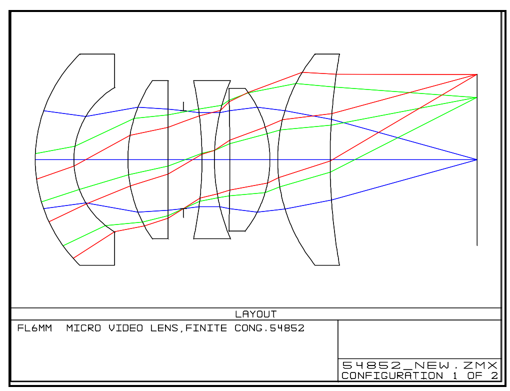

Figure 5. R54-852 Lens Layout

The lens has a focal length of 6.0 mm and is operating at NA = 0.264 and magnification = –0.024, with a 250 mm object distance. The full angular field of view is 52.4 degrees. The lens also has some vignetting at the larger off-axis image points. Distortion is roughly −10% (negative distortion is barrel type distortion), the longitudinal chromatic aberration (axial color) is fairly well corrected, and the lateral chromatic aberration (lateral color) is < 15 µm. The lens is not diffraction limited. Figure 5 shows the layout of the lens.

Figures 6 and 7 shows the least squares polynomial fit of the distorted image height and relative illumination for the 587.6 nm wavelength. The resulting coefficients are used for the interpolation of these parameters for that wavelength. Negative or barrel distortion produces a relative illumination profile that can be very different from a cosine-fourth law roll-off in irradiance level. Figure 8 shows the comparison and close agreement of the simulation results produced by the model and LightTools®.

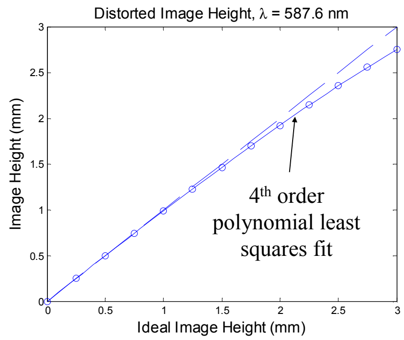

Figure 6. Least squares fit of distortion data

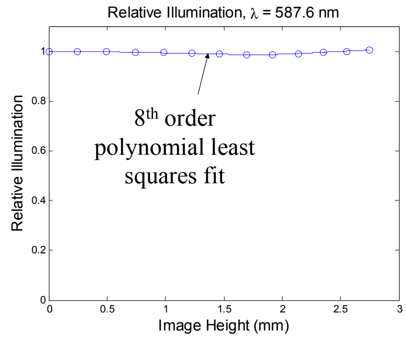

Figure 7. Least squares fit of relative illumination data

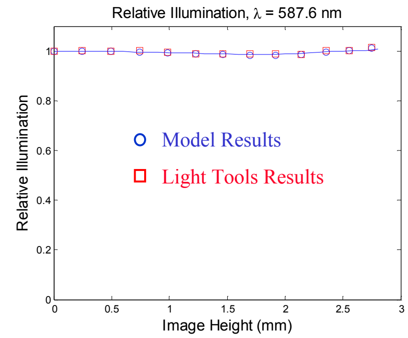

Figure 8. LightTools simulation comparison

The set of PSFs as a function of image height generated by Code V® for the 587.6 nm wavelength are displayed in 32 µm x 32 µm frames in figure 9. The images have been individually scaled to show the detailed structure in each PSF.

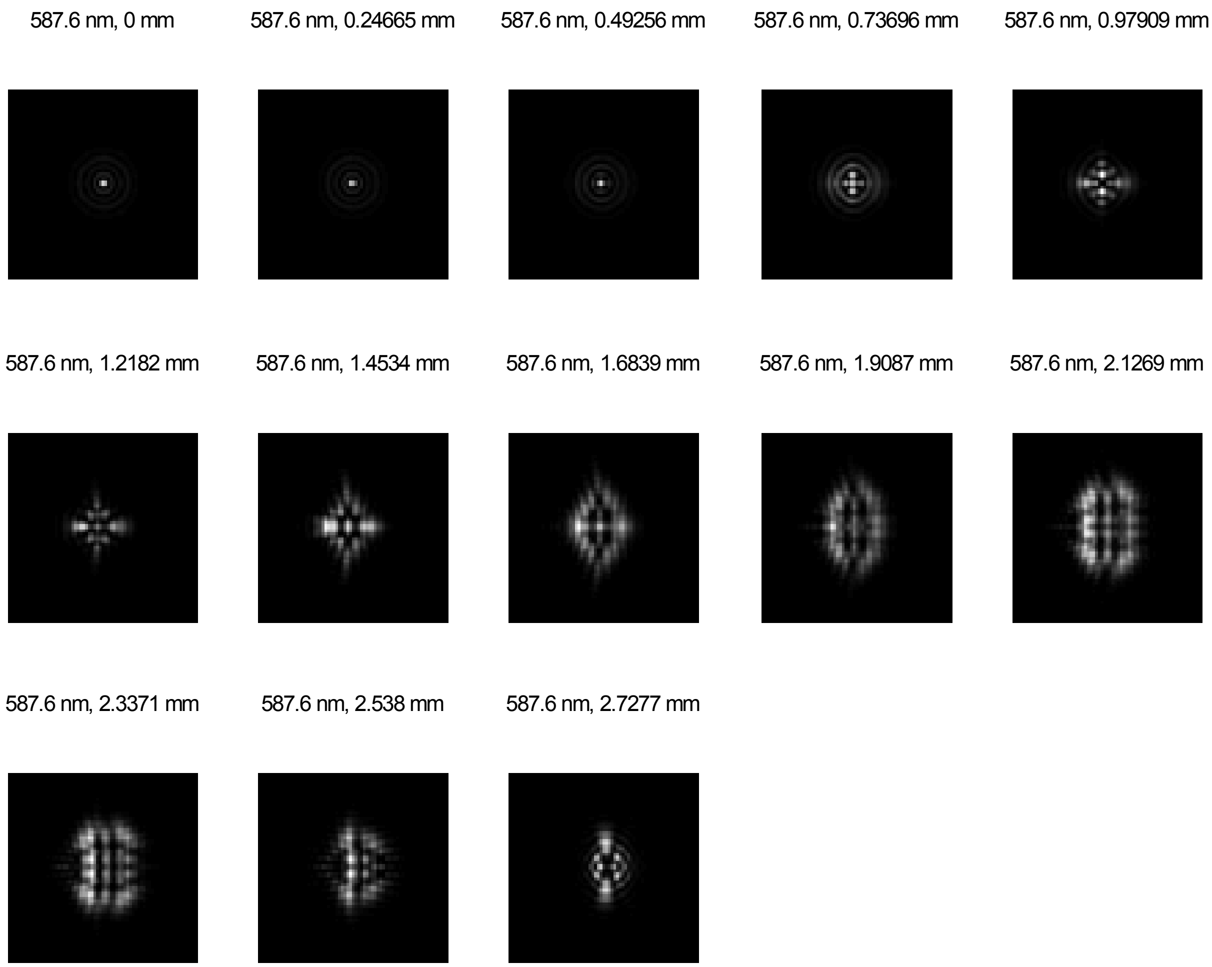

Figure 9. Set of PSFs for 587.6 nm

4. RESULTS

Figures 10 and 11 show 1/3 inch format, 768 x 576 ideal and shift-variant filtered checkerboard images and cross-sectional normalized irradiance profiles for the 587.6 nm wavelength. A 64x64 computational space and 16 pixel image sections were used. The complete calculation was performed in 63.6 seconds using MATLAB®[14] on a Pentium M 1.5 GHz PC. The distortion is clearly evident in the filtered image and the effects of blurring can be seen in its normalized irradiance profile. The negative or barrel type distortion compresses the image to a greater degree with increasing radial distance. This produces a much more uniform off-axis irradiance profile as compared with a cosine-fourth illumination profile.

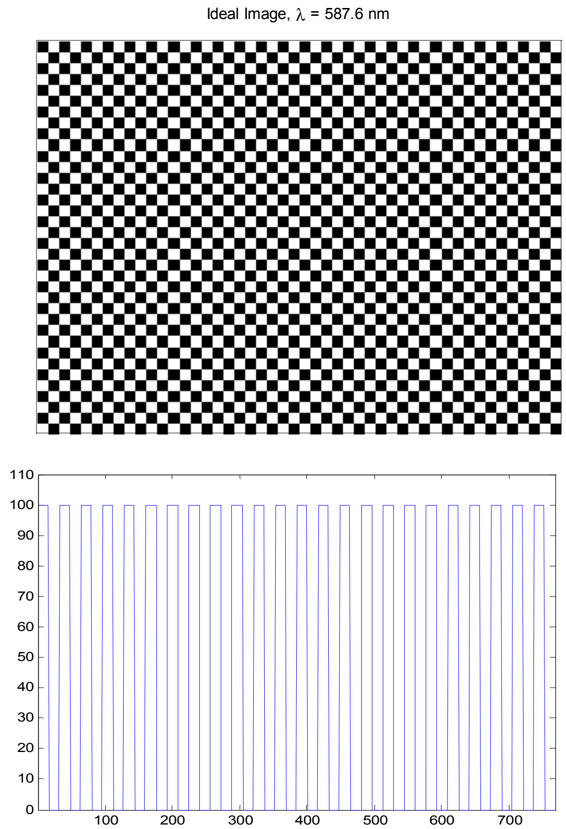

Figure 10. Ideal Image for 587.6 nm

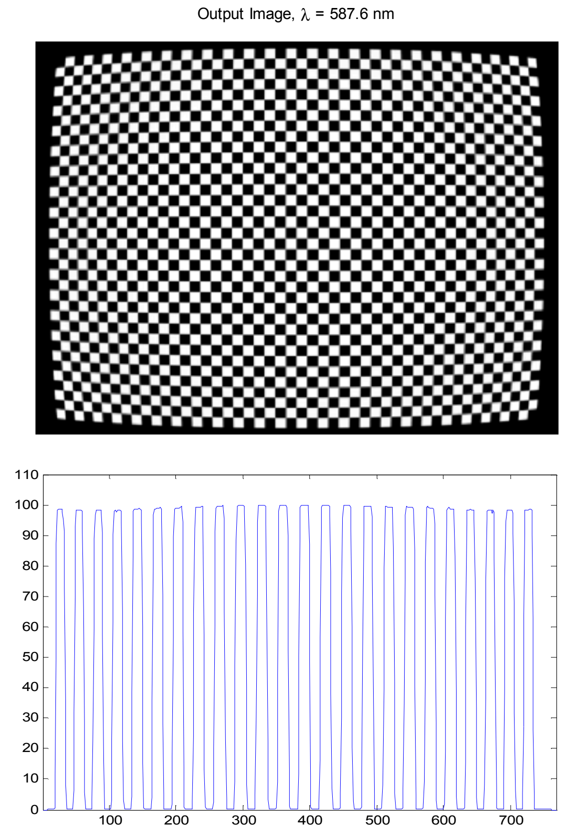

Figure 11. Final Image for 587.6 nm

The shift-variant imaging algorithms have been incorporated into ***ISET*** digital camera simulation program and full spectrum images were produced with a few different lens types. The results for two lenses, the Edmund lens and a fish eye lens, are presented below. These calculations were performed using a multispectral radiance image as input. The radiance image was specified at 31 wavelength samples, and the input spatial resolution was 253x380 spatial samples. The point spread was applied to 16x16 pixel blocks. The complete calculation was performed in about 10 minutes on a Pentium M, 1.8 GHz PC.

The fisheye lens, shown in Figure 12, has a focal length of 25.25 mm and is operating at f/4. This lens covers a full field of view of 140 degrees for the image shown in Figure 13(c). This lens has very high levels of distortion up to –56.6% at the edge of the field of view. The longitudinal chromatic aberration (axial color) is 44 µm, and the lateral chromatic aberration (lateral color) is < 142 µm. The lens is not diffraction limited.

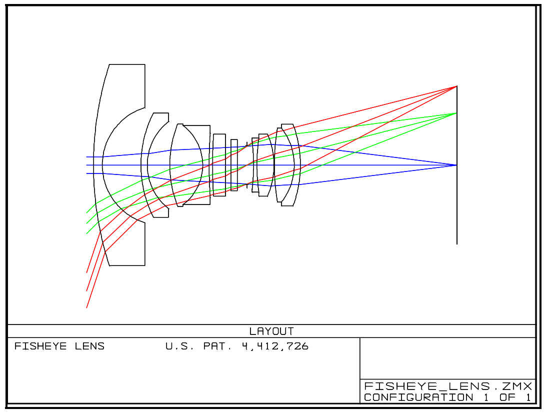

Figure 12. Fisheye Lens Layout

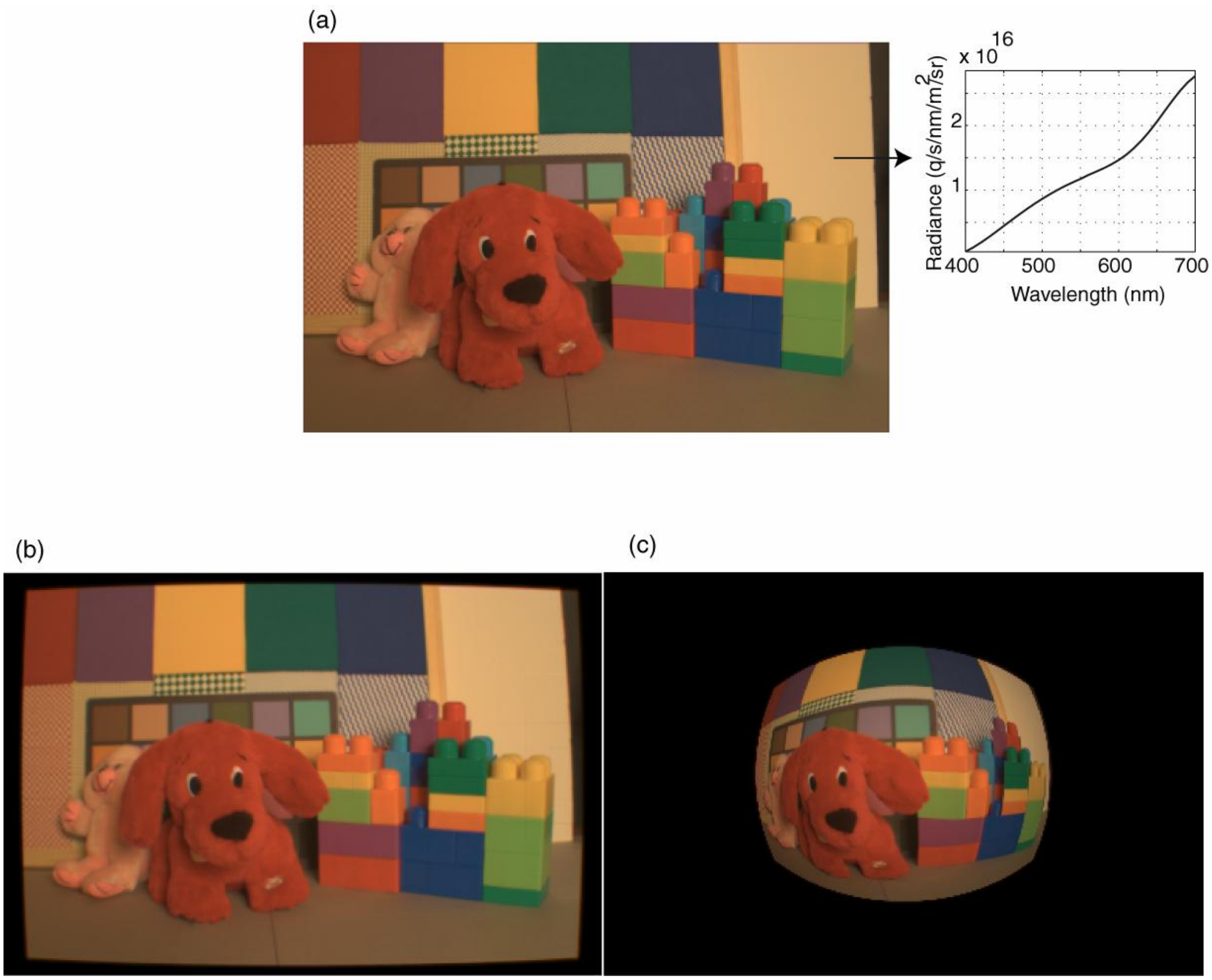

Figure 13. Illustration of multispectral calculations combined with optical simulation. (a) The multispectral input image is shown at the top. The spectral radiance of in a small region of the image is shown at the right. The rendered images, for the Edmund lens (b) and a fish eye lens (c) are shown below. The geometric distortion, relative illumination, and multiple point spread functions used to compute these images were derived from the lens prescriptions using Code V®.

5. CONCLUSIONS

We describe a method of incorporating lens design information into the computational imaging pipeline of image system simulation software. The critical optical system data are derived in an automated process from commercial lens design software. These data are complete in the sense that they can be used to generate radiometrically consistent results that fully account for the effects of monochromatic and chromatic aberrations, pupil aberrations, vignetting, and diffraction to provide a physically accurate representation of the image. The procedure is general in that sense that it can be used to simulate the digital image quality for a wide range and variety of lens types.

The integration of these methods should be helpful in two ways. First, the combination of lens design and image simulation software should help lens designers and system designers assess and verify lens and digital camera performance. The relationships between image quality and appearance, and lens specifications can now be visualized and more fully quantified. Better decision making regarding design trade-offs will be fostered. Even applications that use lenses that are not well corrected can be evaluated. As long as ray tracing and PSF data can be generated for their optical systems, accurate image simulation and visualization can be performed for multispectral imaging and thermal imaging systems. Second, the simulation technology is helpful for classroom and laboratory instruction in optics and photography. Concepts can now be communicated and illustrated in a more compelling manner.

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