

Wavefront Coding: A modern method of achieving high performance and/or low cost imaging systems

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ABSTRACT

This paper gives a brief introduction into the background, application, and design of Wavefront Coding imaging systems. Wavefront Coding is a general technique of using generalized aspheric optics and digital signal processing to greatly increase the performance and/or reduce the cost of imaging systems. The type of aspheric optics employed results in optical imaging characteristics that are very insensitive to misfocus related aberrations. A sharp and clear image is not directly produced from the optics, however, digital signal processing applied to the sampled image produces a sharp and clear final image that is also insensitive to misfocus related aberrations. This paper gives an overview of Wavefront Coding and example images related to the two applications of machine vision/label reading and biometric imaging. Design techniques of Wavefront Coding are unique from that of traditional imaging system design since both the optics and digital processing characteristics of the system are *jointly* optimized for optimum system performance.

Keywords: wavefront coding, extended depth of field, optical/digital imaging, optical design

1. INTRODUCTION

Wavefront Coding is a general technique used to greatly increase imaging performance while also reducing the size, weight, and cost of imaging systems. Wavefront Coding combines non-rotationally symmetric aspheric optical elements and digital signal processing in a fundamental manner to vastly extend the depth of field of imaging systems¹. With Wavefront Coding the depth of field or depth of focus of an imaging system can be increased by a factor of ten or more compared to traditional imaging systems, for a given aperture size or F/#. Wavefront Coding optical elements are phase surfaces and as such do not absorb light or increase exposure or illumination requirements. Such extended depth of field performance is impossible with traditional imaging techniques without dramatic loss of optical power, such as required with stopped down apertures. Increased depth of field / depth of focus also enables imaging systems to be physically less expensive, smaller, or lighter by controlling misfocus related aberrations that are traditionally controlled by adding lens elements or increasing lens complexity. Misfocus related aberrations that can be controlled with Wavefront Coding include chromatic aberration², Petzval curvature, astigmatism, spherical aberration^{3,4}, and temperature related misfocus.

Section 2 below provides an introduction to Wavefront Coding through block diagrams, point spread functions (PSFs), modulation transfer functions (MTFs), and ray diagrams. Section 3 presents examples of Wavefront Coding imaging for machine vision and biometrics applications. A description of our jointly optimized design techniques for Wavefront Coded imaging systems is found in section 4.

2. BACKGROUND ON WAVEFRONT CODING

A block diagram of a typical Wavefront Coding imaging system is shown in Fig. 1. A special purpose optical aspheric element is placed at or near the aperture stop of the imaging system. This optical element modifies the imaging system in such a way that the resulting PSF and optical transfer function (OTF) are insensitive to a range of misfocus or misfocus-

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related aberrations. The PSF and OTF are not, however, the same as that obtained with a good quality in-focus imaging system. Making the imaging system insensitive to misfocus aberrations results in images with a specialized, well defined blur. This blur is removed with digital signal processing.

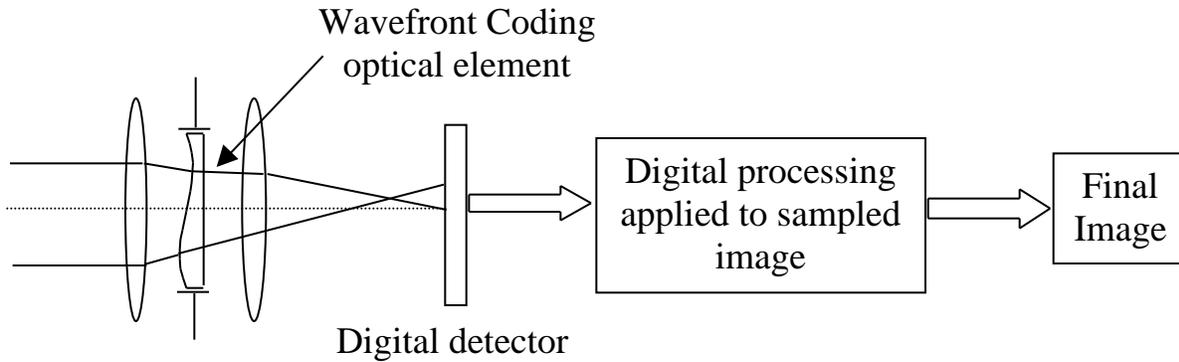


Fig. 1: Block diagram of Wavefront Coding imaging systems. The optical section is a traditional optical system modified with a generalized aspheric Wavefront Coding optical element placed near the aperture stop. The addition of this optical element in the imaging system results in images with a specialized well defined blur or point spread function that is insensitive to misfocus. Digital processing applied to the sampled image produces a sharp and clear image that is very insensitive to misfocus effects.

Experimental PSFs from a traditional imaging system and a Wavefront Coded imaging systems are shown in Fig. 2. Figures 2a and 2b show PSFs from a traditional imaging system when (a) in focus and (b) with a large amount of defocus. The PSFs of a Wavefront Coded imaging system (before signal processing) in comparison are shown in Figs 2c and 2d. These PSFs are from a rectangularly separable Wavefront Coded system. Notice that the circular PSFs from the traditional imaging system in 2a and 2b change drastically with misfocus. The PSFs from the Wavefront Coded imaging system show almost no noticeable change with misfocus. Digital processing to remove the misfocus blur applied to a misfocused traditional imaging system requires the processing to be *dependent* on the amount of misfocus present in different areas of the image. In many situations the amount of misfocus is *unknown* and difficult to calculate. In addition, the MTF of the misfocused traditional imaging system can often contain zeros or nulls that further increase the difficulty of the digital processing. In contrast, the constant nature of PSFs with misfocus from the Wavefront Coded system is what is needed to eliminate the dependencies of digital processing on misfocus. Digital processing applied to the CCD or CMOS detected image is independent of misfocus and the actual scene being imaged. In addition, the MTF of Wavefront Coded imaging systems, both in and out of focus, contain no zeros or nulls allowing high quality final images.

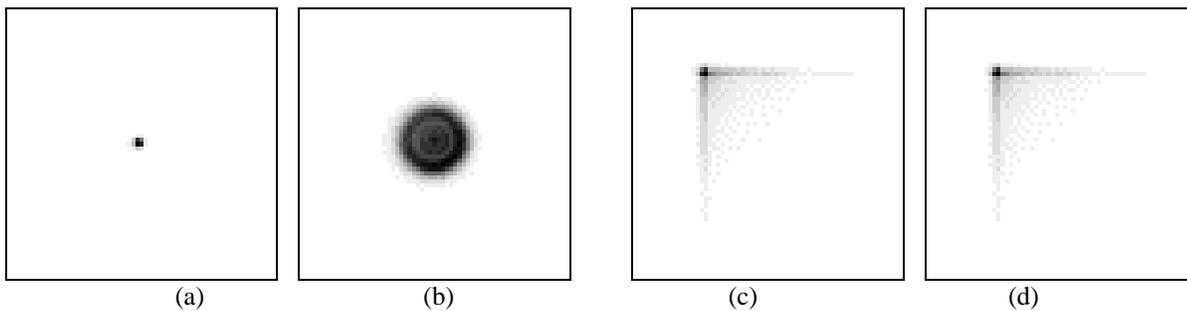


Fig. 2: Measured PSFs with traditional (a,b) and Wavefront Coded (c,d) imaging systems. The in-focus PSF of the traditional imaging system (a) and out of focus PSF (b) differ greatly and result in a loss of contrast. In comparison, the corresponding in-focus (c) and out of focus (b) PSFs of the Wavefront Coding imaging systems are nearly identical to each other. This results in the Wavefront Coding imaging system is very insensitive to a range of misfocus. Therefore, digital processing applied to Wavefront Coding images to restore the spatial character of the PSF is independent of misfocus.

Experimental MTFs are shown in Fig. 3. Best focus and badly misfocused MTFs are shown for a traditional imaging system, and a Wavefront Coded imaging system before and after digital processing. The traditional imaging system was a Rodenstock Rodagon $f=80\text{mm}$ lens, operating at a magnification of 0.2, modified with a 9mm square aperture placed at the original aperture location. A CCD detector with 8.7 micron square pixels was used to record the images and results in a maximum spatial frequency or aliasing foldover spatial frequency of 57 lp/mm. The MTF of the traditional imaging system is seen to drastically change with misfocus. A zero or null at approximately 25 lp/mm is also introduced in the traditional system MTF with the particular amount of misfocus shown. A general-purpose CDM Optics CPM 127-60 Wavefront Coding mask placed at the square aperture of the lens forms the MTFs before filtering. These MTFs have reduced power levels compared to the best focus traditional system MTF, but the Wavefront Coding MTFs are very insensitive to misfocus. The MTF curves of the Wavefront Coded system at the best focus and badly misfocus case are nearly identical to each other. The highest MTF curves shown in Fig 3. are the Wavefront Coded MTFs after digital filtering. The actual shape of the filtered MTFs is application dependent.

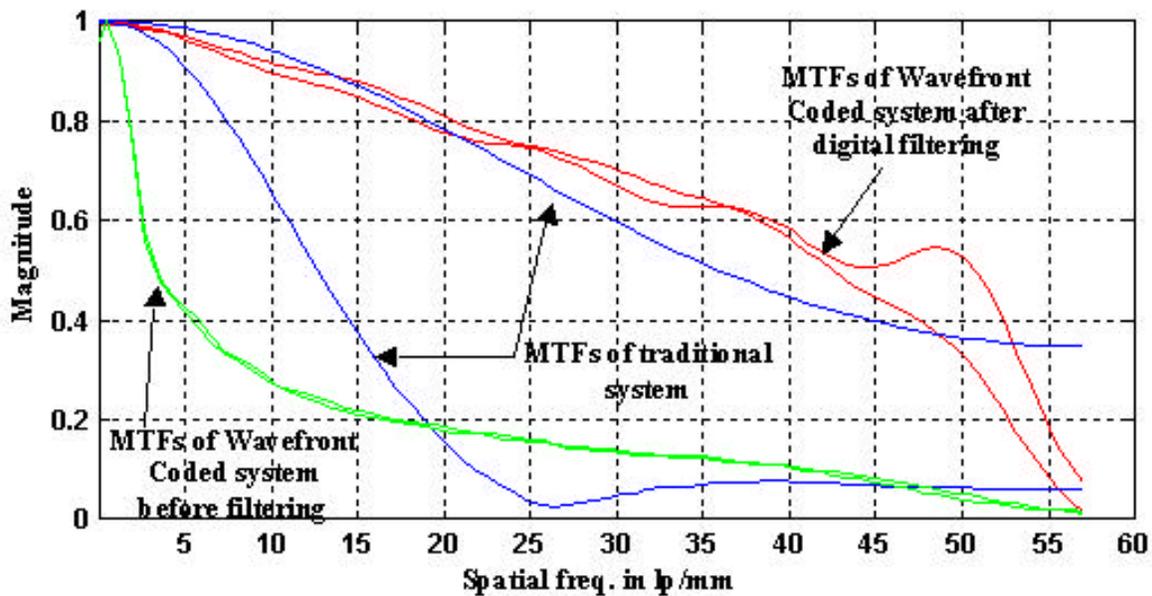


Fig. 3: Measured MTFs of traditional imaging system, Wavefront Coded imaging system before filtering, and a Wavefront Coded imaging system after filtering. Each set of MTFs contains two curves representing best focus and an out of focus image plane position. The imaging system consisted of a Rodenstock Rodagon $f=80\text{mm}$ lens operating at a magnification of 0.2 and modified with a general-purpose CDM Optics CPM 127-60 extended depth of field phase mask. The MTFs from the traditional imaging system change drastically with misfocus. The MTFs of the Wavefront Coded system are very insensitive to misfocus. After filtering the Wavefront Coded best focus and out of focus MTFs are equivalent to the best focus MTF of the traditional imaging system.

A ray-based explanation of Wavefront Coding is shown in Fig. 4. Fig. 4a shows rays from an ideal traditional lens focusing parallel light. These rays are converging to the focal point at the optical axis. The best focus image plane is at 50mm. The vertical axis represents ray height. Fig. 4b shows the rays from the imaging system after it has been modified with a simple cubic phase surface. Light rays from the modified lens no longer travel towards a point of best focus, but travel so that the distribution of the rays is very insensitive to the position of the image plane. That is, a vertical slice of the ray density near the focal region in Fig. 4b is very insensitive to the position of the image plane compared to large changes of the ray density of Fig. 4a. Notice the change in the vertical scale between these two figures. The image of a point of light will not be a point image with the modified or Wavefront Coded system but will be a specialized blur (as shown in Fig. 2). Digital signal processing on the image is required to remove this blur.

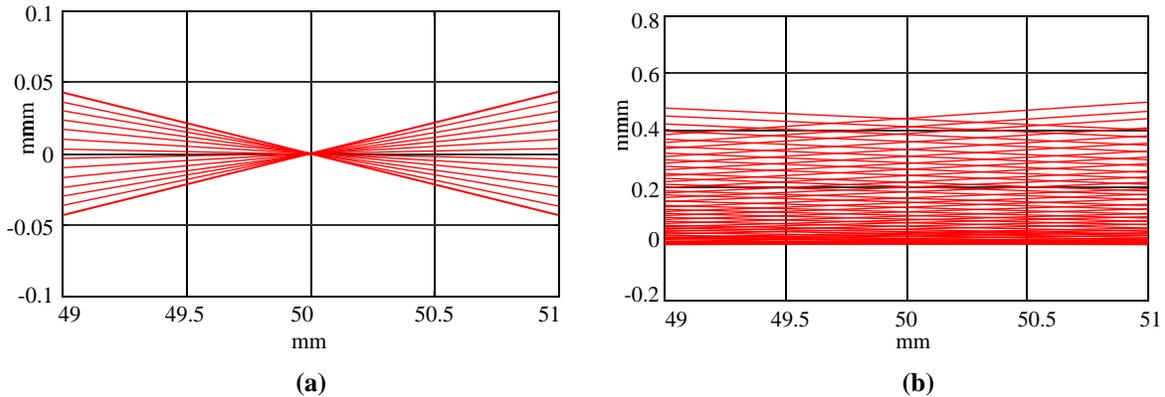


Fig. 4: Ray-based explanation of Wavefront Coding. An ideal traditional lens ($f=50\text{mm}$) focusing parallel light produces a ray density similar to (a) near the best focus image plane at 50mm (vertical axis represents ray height). After modifying the traditional imaging system with a simple cubic phase surface the ray density near the image plane of (b) results. The ray density of the traditional system is maximally sensitive to movement of the image plane or misfocus. The ray density of the Wavefront Coded system, in contrast, is seen to be very insensitive to the location of the image plane. The ray density of the Wavefront Coded imaging system also shows that a sharp image is formed nowhere behind the lens. Digital processing is required to produce a sharp image.

3. EXAMPLE APPLICATIONS

Wavefront Coding for extending the depth of field can add value to imaging applications where traditional methodologies (i.e. stopping down the aperture) are generally unacceptable. Constraints on illumination levels, exposure times, or spatial resolution often limit the application of previous optical methods. By using Wavefront Coding, applications such as machine vision or inspection, biometric analysis, and medical or microscopic imaging can enjoy fewer misfocus-related problems, without sacrificing exposure times or requiring vast quantities of illumination. In a confined environment such as medical devices and microscopes operate in, illumination is of great concern both in terms of delivery and safe power levels. In applications of machine vision or quality control inspection, exposure times must keep pace with the production line. In biometric analysis (often used for identification and security) reliable image quality must be maintained to a high degree. Wavefront Coding can supply all these applications with a viable solution to misfocus related problems, without increasing the overall cost of the system.

Below we provide examples of Wavefront Coding applied to i) machine vision, and ii) biometrics. These two examples have been chosen since they can be seen as representing two extremes, respectively: imaging machine-generated information (i.e. labels, optical character recognition, barcodes, etc.) and the imaging of highly uncontrolled objects such as greasy fingerprints or retinal scans.

Fig. 5 gives six images comparing the performance of a traditional imaging system (a-c) to a system using Wavefront Coding (d-f), for a generic binary input image. The horizontal, vertical, and diagonal lines simply represent various constructs as may be seen in labels, barcodes, or machined parts. The center images for both systems (b, e) show the in-focus or best-focus image. The images to the left of center (a, d) give images for an object that is 35mm from the best-focus position, having been moved away from the camera. The images to the right of center (c, f) show results for the object at 35mm from the best-focus position, this time having been moved toward the camera. The Wavefront Coded images (d-f) clearly show an increase in depth of field over the traditional system, providing an overall nominal depth of field of greater than $\pm 35\text{mm}$. Note that for both systems the aperture size, illumination, focal length, and object are identical, and the imaging system used is the same as described in Fig 3 except that the CDM Optics CPM 127-20 phase mask was used.

Fig. 6 gives six images comparing the performance of a traditional imaging system (a-c) to a system using Wavefront Coding (d-f) for a biometrics application. Here the image of a fingerprint may be used in a biometric identification scheme for

security. Again, the center images for both systems (b, e) show the best-focus image. The images to the left of center (a, d) give images for the finger which has been translated 40mm from the best-focus position (away from the camera) and the images to the right of center (c, f) show results for the finger translated 40mm from best-focus position (toward the camera). Again, the Wavefront Coded images (d-f) clearly show an increase in performance over the traditional system, providing a depth of field increase of 4 to 5 X over the traditional system. While with Fig 5a or 5c one may argue that the traditional imaging system still provides some resemblance to the object (albeit quite poor), in the biometric case the traditional imaging system barely produces recognizable images.

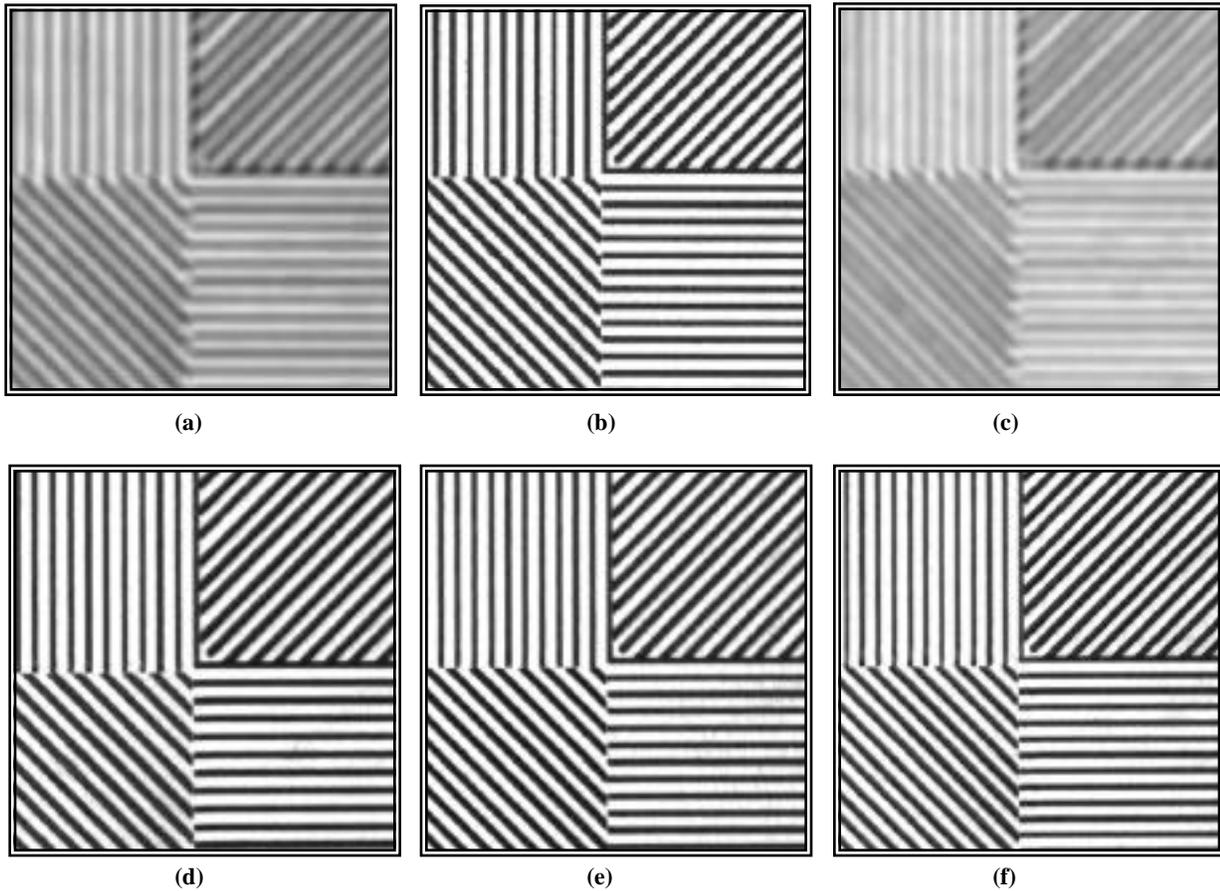


Fig. 5: Example images from machine vision/label reading application for a generic binary input. The horizontal, vertical, and diagonal lines simply represent various constructs as may be seen in labels, barcodes, or machined parts. Images from a traditional imaging system are given in a, b, and c. Images from a Wavefront Coded system are given in d, e, and f. Best focus images are b and e. Movement of the target 35mm away from best focus, away from the lens in images a and towards the lens in c, results in badly defocused images. Movement of the target in with the Wavefront Coded system, d and f, results in little noticeable change in the images. The imaging system used was the same as with Fig. 3 except the CDM Optics CPM 127-20 Wavefront Coding phase mask was used.

These two example applications show examples of an increased depth of field over a traditional imaging system. However since the Wavefront Coding technology described herein produces optical systems which are largely insensitive to misfocus errors, other applications unconcerned about depth of field may benefit as well. Plastic optical assemblies can be made insensitive to misfocus-related temperature issues and optical tolerancing (for both manufacturing and assembly) may be relaxed. In addition, the higher dynamic range provided (by the wider Wavefront Coded PSF) can help reduce blooming/smearing and saturation problems in CCD or CMOS sensors. This is beneficial for applications that typically suffer from specular reflections such as medical scopes and machine inspection systems which view assemblies containing metallic parts.

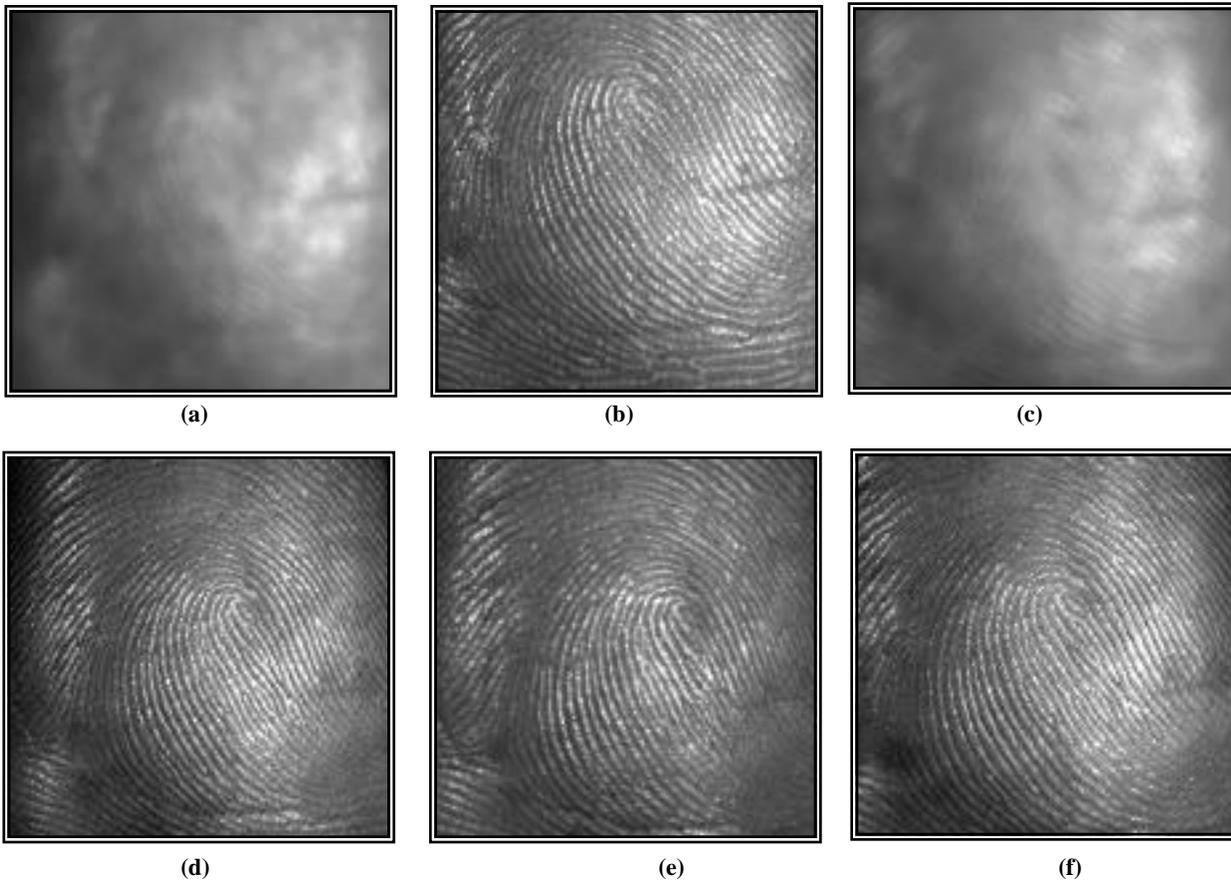


Fig. 6: Example images of biometric imaging of a fingerprint. Images with a traditional imaging are shown in a, b, and c. Images with a Wavefront Coded imaging system are shown in d, e, and f. The best focus images are given in b and e. Movement of the finger 40mm from best focus result in the images a and d (away from the lens) and c and f (towards the lens). The out of focus traditional images have very little spatial resolution. The Wavefront Coding images, both in and out of focus, are all sharp and clear.

4. DESIGN OF WAVEFRONT CODING SYSTEMS

Wavefront Coded imaging systems consist of non-traditional optical designs and digital signal processing of the resulting images. The signal processing used is dependent on the specific optical system. The Wavefront Coded optics are dependent on the type and amount of signal processing to be used. Since the optics and signal processing are closely coupled, it is natural to expect best performance from systems where the optical and digital components of the system are jointly optimized during design. Such a design is not directly possible with current commercial optical design tools. CDM Optics has developed custom software design tools that work in conjunction with commercial ray tracing software to provide optimized optical/digital Wavefront Coded system designs. The optical components are designed to minimize the changes or sensitivity of the optics to misfocus effects as well enable efficient signal processing. The digital components are designed to minimize algorithm complexity, processing time, and effects of digital processing on image noise.

The base routine for Wavefront Coding design is a commercial ray-trace program that traces rays through typical spherical and aspherical surfaces as well as general Wavefront Coding surface forms. The commercial ray-trace program is used as the main user interface and to calculate exit pupils and optimize a given set of optical and digital merit functions or operands. A block diagram of CDM Optics' general Wavefront Coding design process is shown in Fig. 7. The output of this design consists of 1) traditional optical surfaces, materials, thickness, and spacings, 2) parameters of wavefront coding surfaces, and 3) digital filter coefficients.

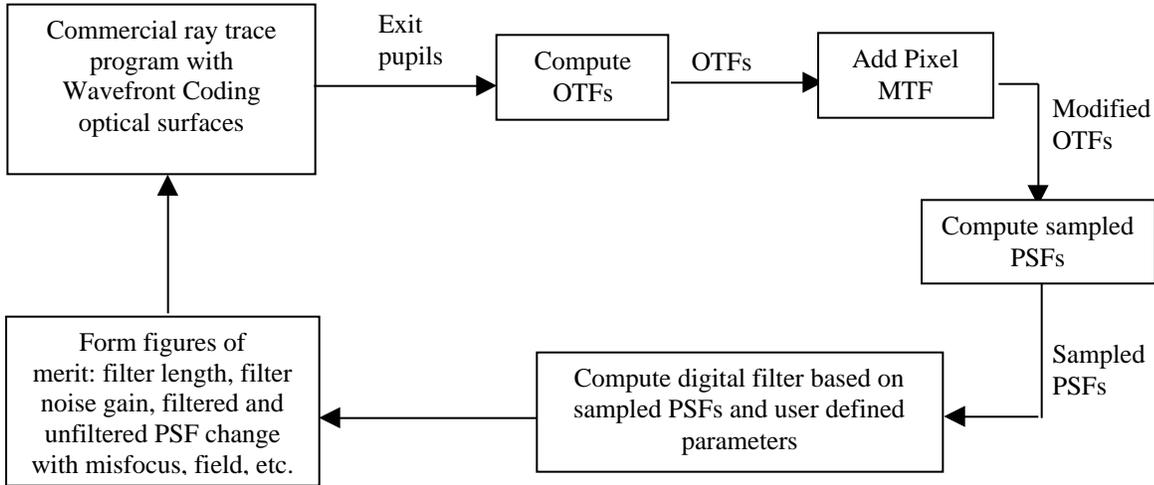


Fig. 7: Block diagram of CDM Optics design process for Wavefront Coded imaging systems. A commercial ray trace program is used as the main user interface, to calculate exit pupil OPDs, and to optimize a given set of operands. Special surface forms are used to model Wavefront Coded optical surfaces. CDM Optics' software forms OTFs and PSFs related to pixel sampled signals, digital filters, and digital processing figures of merit or operands. Digital processing figures of merit include digital filter noise gain (RMS value of digital filter), unfiltered and filtered PSF change with misfocus, change with field, etc.

The general optical/digital design loop as shown in Fig. 7 can be described as follows:

1. Start with given optical surfaces, thickness, and operating conditions (wavelengths, field of view, temperature range, sample object images, etc.).
2. Generate exit pupil optical path differences (OPDs) via traditional ray tracing.
3. Calculate OTFs
4. Include pixel OTF related to detector geometry
5. Calculate sampled OTFs and PSFs
6. Calculate digital filter coefficients for chosen processing algorithm based on sampled PSF set.
7. Form figures of merit (or Wavefront Coding operands) that are based on minimizing:
 - changes of the sampled PSF and MTF through focus, with field angle, with color, due to temperature changes, due to aliasing, etc.
 - digital processing parameters such as amount of processing, form of the processing, processing related image noise, digital filter noise gain etc.
8. Combine Wavefront Coding operands with traditional optical operands (Seidel Wavefront aberrations, RMS Wavefront errors, etc.) into optimization routines and modify optical surfaces.
9. Return to step 2.

Theoretically calculated Wavefront Coding surface forms are used as starting points for the optical optimization. One general family of rectangularly separable surface forms is given in normalized coordinates as:

$$S(x) = | \text{sign}(x) |x|$$

where $\text{sign}(x)=+1$ for $x>0$, and $\text{sign}(x)=-1$ for $x\leq 0$

The exponential parameter controls the height of the MTF over a range of misfocus, and the parameter controls the sensitivity to misfocus. In general, increasing the parameter decreases the sensitivity to misfocus while decreasing the height of the MTF and increasing the length of the resulting PSF. Fig. 8 gives a two dimensional representation of this general family of rectangularly separable Wavefront Coding surface forms.

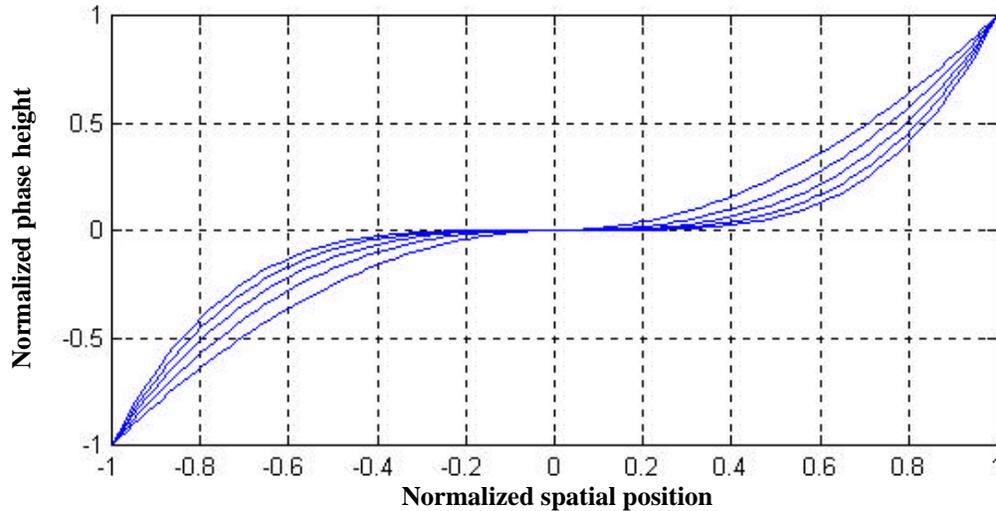


Fig. 8: Rectangularly separable Wavefront Coding surface forms shown in one dimension. The general form for this surface type is given by $\text{sign}(x) * |x|^\alpha$. Curves above show the shape of this surface for α between 2 and 4. Increasing alpha flattens the center of the curve while increasing the slope of the curve near the edges.

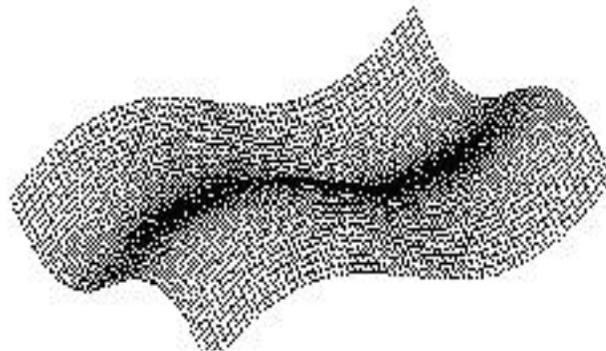


Fig. 9: Mesh view of a rectangularly separable Wavefront Coding surface. Surface form is $s(x,y)=\text{sign}(x)*|x|^{2.5} + \text{sign}(y)*|y|^{2.5}$

5. CONCLUSION

Wavefront Coded imaging systems can have significant performance advantages over traditional imaging systems. The most obvious advantage is greatly increased in depth of field / depth of focus when a traditional optical system is modified with a Wavefront Coding optical element and signal processing. Incorporating Wavefront Coding optics and signal processing into the design phase, however, will allow many other aspects of the imaging system to be enhanced. Some enhancements enabled by Wavefront Coding are:

- An inexpensive plastic lens incorporating wavefront coding into the design can produce image quality equivalent to optics of much greater complexity and expense, since the digital processing step can remove not only defocus, but

minimize the effects of chromatic aberration, Petzval curvature, astigmatism, spherical aberration, and temperature related misfocus.

- The MTF of a Wavefront Coded system can *exceed* the MTF of even a “perfect” (diffraction-limited) optical system. Although the practical limit of this effect is set by the system signal-to-noise ratio, improvements factors of 50 – 100% in the higher spatial frequencies are usually possible.
- Imaging systems with Wavefront Coding can be highly customized for special applications for much less cost than a custom-designed lens system. For some applications, Wavefront Coding might be the only way to meet all of the requirements.

6. REFERENCES

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