Design and optimization of a Wavefront Coded® miniature camera

Hans B. Wach, Ramkumar Narayanswamy, Kenneth Kubala, Edward R. Dowski Jr.; CDM Optics, Inc; Boulder, CO/USA

Abstract

The increasing demand for higher image quality, over a larger imaging volume, at a lower cost, requiring less power in smaller packages requires a new imaging system design approach. One approach that is delivering next-generation imaging systems involves Wavefront Coding™. Wavefront Coded® imaging, a novel computational imaging technology, is being used to increase imaging volume while maintaining low F/#: something not possible with traditional optical design. Wavefront Coded® imaging systems are designed and optimized over a very complex trade-space including optics, mechanics, manufacturing, signal processing, and image quality. We present an overview of the trade space as well as the design methodology and the custom software used in the design of a miniature camera system which maintains good image quality from infinity to very close conjugates without having to stop down or refocus the system.

Background

Digital imaging systems are being designed into numerous devices of our modern world from cars, to toys, and phones to pills. As applications continue to grow the specifications are becoming increasingly difficult to meet using traditional imaging technologies. The requirements for these new systems fall into four main categories: mechanical, optical, fabrication and usability. Low power and cost are frequently included as additional requirements.

Mechanically, these systems are required to be very small in all three dimensions and, possibly, avoid moving parts for cost, power and usability reasons. The systems must also be robust to assembly tolerances, mechanical shock and environmental conditions including large temperature ranges.

Typical requirements that constrain the optical sub-system are the need for high image quality and adequate low light level performance. In addition to having an aggressive form factor (z-height in particular) the system designer is often limited to the use of moldable plastic for cost reasons. The sensor's light capturing ability, including color filter array, IR block filter, microlenses and chief ray acceptance angle are other consideration for the system designer.

The small size of these systems and the complexity of the optical designs often require high precision fabrication. Cost and yield issues impose overall system requirements which further challenge the system designer.

Usability is another requirement that the system must be designed for. The system must produce good quality images over a range of lighting conditions, object distances and environmental/temperature ranges.

While the individual sets of requirements are challenging to meet on their own, meeting the entire ensemble of requirements is extremely difficult as many of the requirements are contradictory to one another. For example, for usability purposes it is often required that the system have a large imaging volume. This requirement would lead a traditional designer to design a system with a high F/#. A design with a high F/# however would violate the goal of having good low light level performance. The system designer's challenge is to find a solution that best balances all of these complex tradeoffs.

We begin by introducing a technology called Wavefront Coding™ which decouples many of the traditional degrees of freedom, creating a trade space that is much easier to work with. The next section outlines the optimization methodology and describes a proprietary system design tool that aids the designer in the design and optimization of these specialized systems. We conclude this paper with a discussion on the advantages of this computational imaging technology and the potential it offers for future designs.

The Wavefront Coding™ Solution

Since 1995 CDM Optics has pioneered the jointly optimized design of optics, mechanics, detection and signal processing for modern imaging systems. We call this methodology Wavefront Coding™ [1]. In the following sections we introduce Wavefront Coding™, describe the implications or cost of this technology and finally show this technology affects the design trade-space

What is Wavefront Coding™?

Wavefront Coding™ technology provides a means of overcoming a number of the challenges of high volume, miniature camera design. By designing the optical system to produce specialized wavefronts, the imaging system can preserve more information over a larger error space compared to a traditional design. While the intermediate Wavefront Coded® image directly formed on the sensor contains more information than a traditional optic, the information may not be in a form that is optimized for a human observer or a particular machine vision algorithm. That is, the intermediate image is blurred compared to a diffraction-limited system, but blurred in a controlled way. Post processing the intermediate image can transform this information into a more useable or traditional form. High resolution imagery viewed by a human, for example, often requires post processing to form sharp and clear images. However, there are numerous examples where post processing is not necessary. One example is low resolution video. Another example is task-based imaging applications, such as biometrics, where a classification algorithm can be modified to operate directly on the intermediate image.

In short, Wavefront Coded® imaging can deliver systems that perform over a greater error space than a traditional system. This extended error space is delivered by keeping the MTF (modulation transfer function), or equivalently the PSF (point spread function), invariant to generalized focus-like errors. These errors can come from optical aberrations, mechanical/fabrication errors, thermal focus shifts and from shifting the object outside of the traditional imaging volume.

The Wavefront Coded® MTF is usually below the MTF of the corresponding diffraction-limited traditional system operating at the best-focus position. However, as the aberrations increase, the traditional system rapidly loses modulation, while the Wavefront Coded® system maintains its modulation. Signal processing can be used to boost the MTF of the Wavefront Coded® system to match the MTF of the corresponding traditional system at best-focus position. Example MTFs from a traditional system and from a Wavefront Coded® system are shown in Figure 1.

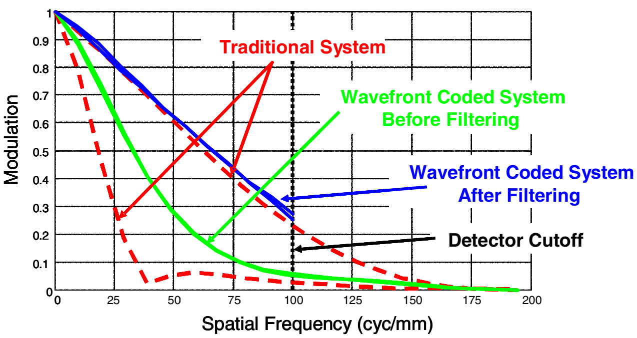

Figure 1: *Simulated MTFs from the Wavefront Coded® and traditional systems for two object conjugates are shown. The dashed lines show the traditional system MTF, while the solid lines show the Wavefront Coded® MTF before and after processing. The detector's cutoff frequency is also shown.*

The Cost of Wavefront Coding™

While Wavefront Coding™ provides the system designer a methodology for increased error space coverage it comes with a cost. As mentioned above, the optical MTF of the Wavefront Coded® system can be lower than the diffraction-limited traditional system in a small region of the error space. This lower MTF in the presence of noise can translate to a lower SNR (signal to noise ratio) at the best focus plane. At planes away from best focus the Wavefront Coded system can have a higher SNR when compared to the traditional system.

Wavefront Coded® systems typically also carry a computation cost associated with reconstructing the intermediate image. In applications which require it, reconstruction is used to boost the optical Wavefront Coded® MTFs to the target MTF.

The primary factor determining these costs is the size of the error space the Wavefront Coded® system should operate over. Growing the error space can lead to a larger SNR trade-off and higher computation cost. Our experience indicates that users prefer the increased error space coverage even if it could mean slightly lower SNR at best focus and the need for post processing. In practice the SNR loss and the cost of reconstruction are difficult to quantify due to sophisticated non-linear noise reduction and image reconstruction techniques which can be realized on today's powerful and inexpensive electronic hardware.

Understanding the Trade-space

The system designer must consider numerous tradeoffs to position the imaging system such that it meets all its requirements. The SNR and computational costs are additional tradeoffs that the Wavefront Coding™ system designer must consider. However, these new tradeoffs enable the designer to decouple some of the other constraints.

Typically the cost and yield of an imaging system is directly related to the level of precision required during fabrication. These contradictory constraints are decoupled through the use of Wavefront Coding™ by decreasing the required system tolerances. The system designer can keep costs down and yields up by modifying the optics, introducing additional post processing and jointly optimizing the entire system.

Another example of decoupled constraints afforded by Wavefront Coding™ is the traditional tradeoff between the light capturing ability of a lens and depth of field. Lenses with low F/# ideally have higher modulation at the detector cut-off frequency and better low light level performance compared to a corresponding higher F/# lens. In order to increase the depth of field of the system a traditional system designer must sacrifice the benefits of the lower F/# lens. However, a Wavefront Coded® designer is allowed the benefit of increased imaging volume while retaining low light performance.

All of the tradeoffs in Wavefront Coding™ are essentially trading physical optics for electronics. While the cost of electronics is expected to decrease exponentially with time, there is no such cost decrease expected from optics. The tradeoff between optics and electronics in jointly optimized systems should then continually tilt towards use of more electronics and less optics as a means to further improve quality and lower system costs.

Optimization of a Wavefront Coded® System

As mentioned above, Wavefront Coding™ is an innovative technology which allows the designer to jointly optimize all aspects of an imaging system, including optics, mechanics, detection and signal processing. Currently there are no commercially available design tools that allow the simultaneous optimization of these degrees of freedom. CDM Optics has developed a sophisticated software design and simulation tool which we describe below.

Optimization Procedure

The Wavefront Coding™ methodology of jointly optimizing each component of an imaging system requires the means of specifying and modeling the components of the optical system, simulating sampled images with accurate detector models [2], performing signal processing on the sampled images, forming figures of merit based on the goals of the particular system, and optimization of the system variables in order to minimize the metrics and reach a final system [3]. Figure 2 describes the block diagram of the software tools that realize this methodology.

Notice that the Wavefront Coding™ methodology optimizes the complete system model, not just the optical subsystem as is typical in traditional optical design. During the optimization process both the optics and signal processing degrees of freedom are controlled by an optimizer with figures of merit that have knowledge of the entire imaging system.

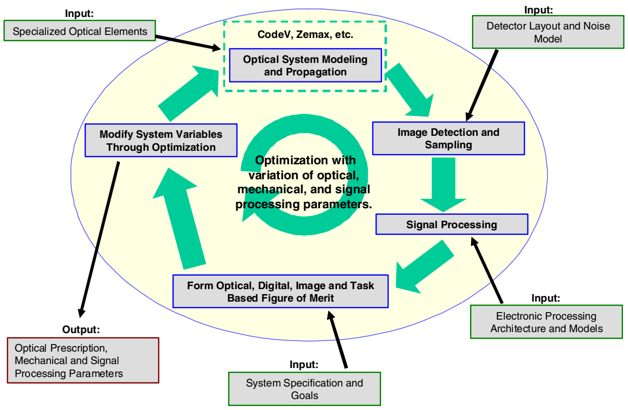

Figure 2: *Block diagram of methodology for optimized design of Wavefront Coded® imaging systems. Design components include the optics, sensor, signal processing and metrics. Inputs to the design components are specialized optical elements, detector layout and noise models, electronic processing architectures, as well as optical/digital system design goals. The output can be an optical prescription as well as mechanical and signal processing parameters.*

Design Tools

CDM Optics has generated an integrated design package called *WFCDesign*™ to provide joint optimization of Wavefront Coded® imaging systems. This tool allows both physical and algorithmic goals to be jointly realized with a high degree of efficiency and accuracy [4]. *WFCDesign*™ interfaces to numerous commercial analysis, design, signal processing, and simulation packages, enabling joint optimization using industry-standard tools.

WFCDesign™ is a block-based architecture that represents designs as connected collections of configurable blocks. Block types may include optical, signal processing, analysis, display, optimization, input/output, or user-defined. A design consists of connected instances of blocks organized to reflect the information flow of the system. Each block instance in a chain is configurable though property values which can be modified individually. During optimization, the design is executed iteratively by the optimizer (which may be a part of the chain itself or provided by an external entity).

The block-based architecture provides flexibility, extensibility, power and speed. Flexibility is provided through user-configured block property values and through the ability to add, remove, re-order and connect blocks in the chain. Extensibility is achieved through the ability of users to develop and incorporate new blocks into the tool as well as a mechanism to interface with other applications such as optical CAD programs, optimizers, etc. Another powerful feature of the architecture is the ability of blocks to query the property and data values of other blocks at runtime. This allows a block instance to change its behavior at runtime based upon the state of other block instances. This also allows an optimizer block access to any of the properties of blocks in the chain at runtime. Execution speed is achieved through efficient implementation of blocks and core architecture. Further speed increases are possible through distribution of parallel data paths to separate processors.

The graphical user interface (GUI) to *WFCDesign*™ provides an easy to use interface for designing, modeling and optimizing computational imaging systems. Some of the key features of the GUI are the Design Editor, Display windows, and Properties View toolbar as shown in Figure 3.

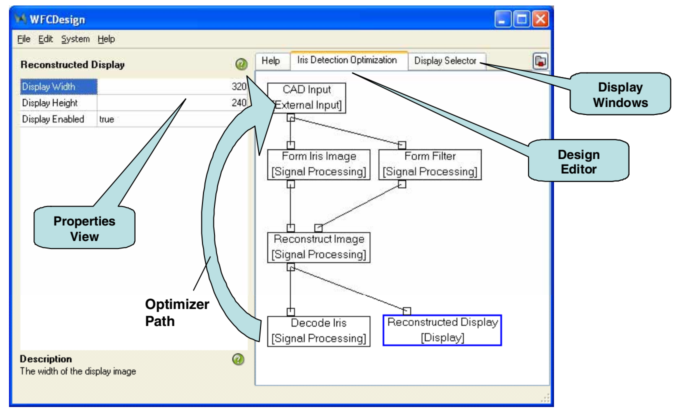

Figure 3: *The graphical user interface (GUI) for WFCDesign™. The Design Editor window shows a block diagram for the design of an iris detection system. The design includes connections to a CAD system, signal processing blocks pertinent to reconstructing iris images for automatic recognition, and finally an iris decoding block which provides a figure of merit to the optimization. The Display windows (not shown) display reconstructed data in this case, and the Properties View toolbar lists the available properties for a selected block instance (in this case the display).*

Conclusions

As we continue to develop Wavefront Coding™ technology we are continually exploring new ways of adapting our design tools to efficiently search the highly constrained trade-space. New metrics are being developed to bridge the gap between subjective evaluation and quantitative analysis. These changes have resulted in producing better solutions in a shorter amount of time.

By embracing the innovative Wavefront Coded® design methodology a digital imaging system designer is given new degrees of freedom which decouple many of the traditional constraints resulting in systems with better performance and/or lower cost. The use of good design methodologies and tools is a necessity for navigating the ever expanding trade-space. We have presented a design methodology and a tool to aid in the design of better, more cost effective digital imaging systems.

References

[1] W. T. Cathey and E. Dowski, "A new paradigm for imaging systems," Applied Optics, Vol 41, p 6080, October 2002.

[2] H. B. Wach, E. R. Dowski, Jr., "Noise modeling for design and simulation of computational imaging systems," Proceedings of SPIE, Vol. 5438, 2004, pp. 159-170.

[3] K. Kubala, E. Dowski and W. T. Cathey, "Reducing complexity in computational imaging systems," Optics Express, Vol. 11, No. 18, 2102 (2003).

[4] G. Johnson, A. Macon, G. Rauker, "Computational imaging design tools and methods," Proc. SPIE Vol. 5524, p. 284-294 (2004).

Author Biography

Hans Wach received his B.S. degree in 1996 and a Ph.D. in 2000 both in Electrical and Computer Engineering from the University of Colorado. He has 8 years of experience in Wavefront Coding™ technology and is currently the systems engineering manager at CDM Optics.

Ramkumar Narayanswamy has a Ph.D. from the University of Colorado and has worked in the field of imaging for over 15 years. He is currently responsible for Program and Product management at CDM Optics.

Kenneth Kubala received his Ph.D. degree in Electrical Engineering from the University of Colorado in 2001. His research for his Ph.D. thesis was in variable addressability imaging systems which create an information efficient transformation that is matched to what the human visual system can perceive. Currently he is working at CDM Optics as the director of engineering on the design and optimization of computational imaging systems.

Edward R. Dowski, Jr. received his BS in Electrical Engineering from the University of Rhode Island, Kingston, and his Ph.D. in Optics and Signal Processing from the University of Colorado, Boulder. After co-inventing Wavefront Coding™ technology in 1995 he helped found CDM Optics. Dr. Dowski now serves as President of the company.