SIGNAL PROCESSING CONCEPTS HELP TEACH OPTICAL ENGINEERING

Cameron H. G. Wright

Dept. of Elec. and Comp. Engineering
University of Wyoming, WY
c.h.g.wright@ieee.org

Thad B. Welch

Dept. of Elec. and Comp. Engineering
Boise State University, ID
t.b.welch@ieee.org

Michael G. Morrow

Dept. of Elec. and Comp. Engineering
University of Wisconsin-Madison, WI
morrow@ieee.org

ABSTRACT

The challenge of teaching practical optical engineering in a single course can be overcome by taking advantage of existing student knowledge of signal processing concepts. Such an approach greatly facilitates student mastery of new topics. This paper describes how professors can use this technique to efficiently teach optical engineering.

Index Terms— signal processing, optical imaging, digital imaging, optical engineering, engineering education

1. INTRODUCTION

An efficient method of teaching practical optical engineering fundamentals in one course is described. For students who have a background in signal processing (SP), we leverage existing knowledge of topics such as Fourier analysis, filtering, and sampling (both spatial and temporal) to allow them to learn the new concepts more quickly and intuitively. We make extensive use of MATLAB plots and simulations, and provide engineering graduate students, in only a single course, the necessary working knowledge of optical engineering to support their research efforts. Specifically, we found many students were using digital cameras and other imaging systems to obtain critical research data, yet they had no background in optical engineering. As a result, they lacked an ability to design an appropriate imaging setup, and had little appreciation for limitations that must be taken into account when interpreting image data. Without any background in optical engineering, common errors or misconceptions could cause the students' research data to be compromised.

Our approach is consistent with established theories of andragogy (i.e., teaching adults) [1]. Specifically, we applied the andragological learning theory of constructionism, which derives from Piaget's well-regarded epistemological theory of constructivism [2–4]. A salient aspect of constructionism that applies to our approach was summarized by Ausubel [5]:

> "If I had to reduce all educational psychology to just one principle, I would say this: The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him/her accordingly" (p. iv).

In other words, our students more easily learn new concepts if we leverage their existing knowledge, or what is sometimes called their "existing cognitive framework." This comes as no surprise to an experienced professor, but it is reassuring to see that the method is consistent with established principles of educational psychology.

The authors have been taking advantage of existing cognitive frameworks, active learning methods, and experiential exercises using both MATLAB and C to teach various DSP topics to students for many years [6–13]. A similar approach can help teach students, who have some prior SP knowledge, the new topic of optical engineering. Note: a more preliminary description of this method was included in [14, 15].

2. TEACHING METHOD

Rather than taking the typical approach of first teaching theoretical optics, and then following that (usually in a second course) with application-oriented optical engineering, we taught practical optical engineering in a single course by emphasizing concepts that bridge SP and optical engineering, such as Fourier optics [16] and the basics of spatial sampling. For example, we used the known concept of an impulse response and defined it, in optical engineering terms, as the point spread function (PSF). The students knew that the Fourier transform (FT) of the impulse response yields the system transfer function (from which the frequency and phase response are obtained), and so we easily established that the FT of the PSF is the optical transfer function (OTF). This allowed exploration of the magnitude of the OTF, which is the modulation transfer function (MTF); the MTF is used extensively for both analysis and design aspects of modern optical engineering. The MTF provides the "frequency response" of the optical system. While a FT associated with lenses and lens systems is continuous, the FT for sampled sensor arrays (such as those used in essentially all digital cameras) is discrete [16–19]. However, both are typically calculated using the discrete FFT using a tool such as MATLAB.

The Fourier transform pair of the PSF and MTF provides an example of how MATLAB is used in this way, as shown in Fig. 1. The top half of Fig. 1 shows a diffraction-limited Airy disk resulting from a circularly symmetric lens and aperture arrangement (assuming zero aberrations and far-field condi-

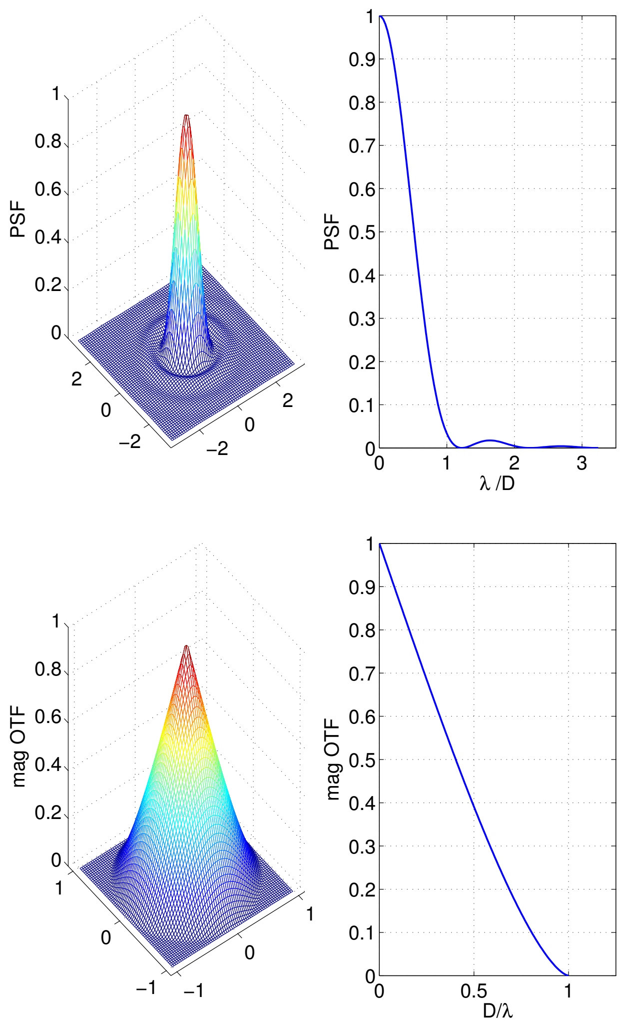

Fig. 1: The PSF (top) and MTF (bottom) from a diffraction-limited optical system with a circular aperture. The limiting aperture has diameter D, and the light has wavelength λ.

tions). The bottom half of Fig. 1 shows the associated MTF. From analyses such as this, using little more than linear systems theory used previously for SP but now applied to optics, the students quickly began to understand about the optical "cutoff frequency" predicted by the MTF. Since no spatial frequency higher than D/λ can be imaged by this optical system, no valid conclusions should be drawn from any image data beyond this physical limit. Furthermore, the contrast of an image generally decreases as the spatial frequency increases, since contrast is directly related to the MTF value at a given spatial frequency.

While the above example assumed no aberrations, real-world lens systems are not perfect. Aberrations can be a complicated and confusing subject for students, yet they can be presented and modeled as simple phase deviations in the wavefronts of the incident light. By using MATLAB scripts

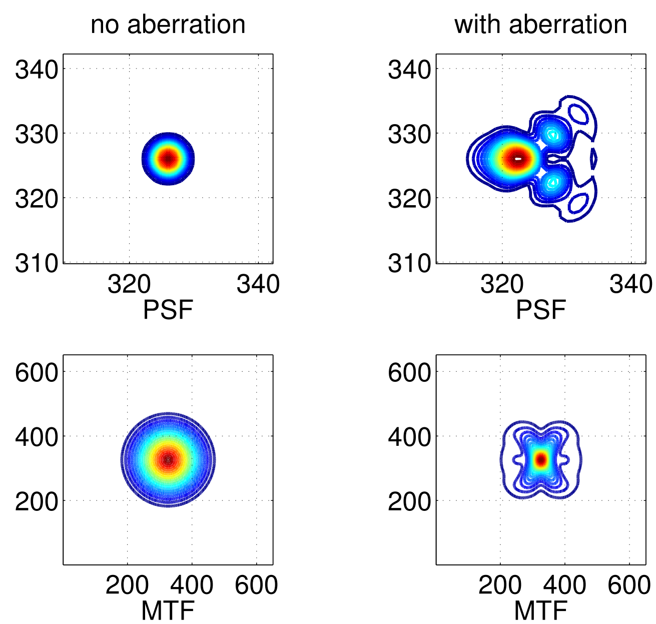

Fig. 2: Contour plots of the PSF and MTF without (on the left) and with (on the right) aberrations. The simulated aberrations are a combination of coma in x and astigmatism in y. To show more detail, the PSF plots (top row) are "zoomed in" compared to the MTF plots (bottom row). Unlike Fig. 1, the units for the coordinate axes are arbitrary.

that apply Zernike polynomials to the aperture function phase term, we can easily simulate any aberration. Such a simulation is shown in Fig. 2. Contour plots of the PSF and MTF are created with MATLAB, both without aberrations and with two forms of 3rd-order monochromatic aberrations (coma and astigmatism) combined. In Fig. 2, the effect of both coma in x and astigmatism in y is simulated such that each type of aberration contributes a wavefront deviation of 2/10 of a wavelength. Combinations of multiple aberrations such as shown here can be very challenging to visualize, yet they can be easily investigated using MATLAB and common SP-type techniques using appropriate Zernike polynomials with the phase term of the generalized aperture function.

Specifically, the aperture function that combines the two types of aberrations that are shown in Fig. 2 is:

$$A_0(x_a, y_a)e^{j2\pi\left(z_c\left[\sqrt{8}\left(3r^3-2r\right)\cos\theta\right]+z_a\left[\sqrt{6}\,r^2\sin(2\theta)\right]\right)} \quad (1)$$

where x_a and y_a represent Cartesian coordinates at the aperture plane of the optical system, z_c is a constant that represents the "amount" of coma, z_a is a constant that represents the "amount" of astigmatism, $r = \sqrt{x_a^2 + y_a^2}$, and $\theta = \arctan(y_a/x_a)$. Both z_c and z_a are expressed as fractions of a wavelength. The aperture function with zero aberrations would be A_0 without the phase term. Zernike polynomials that are used to model 3rd-order monochromatic aberrations

Table 1: Orthonormal Zernike polynomials used to model the five types of monochromatic aberrations.

Name	Direction	Zernike polymomial
distortion	$x-$tilt	$2r\cos\theta$
distortion	$y-$tilt	$2r\sin\theta$
field curvature	NA	$\sqrt{3}\left(2r^2-1\right)$
astigmatism	x	$\sqrt{6}\,r^2\cos\left(2\theta\right)$
astigmatism	y	$\sqrt{6}\,r^2\sin\left(2\theta\right)$
coma	x	$\sqrt{8}\left(3r^3-2r\right)\cos\theta$
coma	y	$\sqrt{8}\left(3r^3-2r\right)\sin\theta$
spherical	NA	$\sqrt{5}\left(6r^4-6r^2+1\right)$

are listed in Table 1; 5th-order and 7th-order aberrations can be modeled with similar Zernike polynomials.

Students can simulate various types and combinations of aberration by adjusting the phase term of the aperture function A_0. The magnitude squared of the FT of the aperture function is the PSF, and the magnitude of the FT of the PSF is the MTF. . . and once again we leverage existing knowledge of SP theory to allow insightful optical engineering calculations. Once the lens system is understood, the camera's sensor array can be similarly investigated, using the students' existing knowledge of SP theory.

If MTFs of each part of a camera system can be estimated, students can combine them to investigate the overall camera limitations. For example, an imaging system can includes optics, a CMOS detector array, and various electronics. The images will be displayed on a monitor screen. Each of these four subsystems has its own independent MTF. Given some reasonable assumptions, the overall system MTF will be the product of all four individual MTFs, shown as E. See Fig. 3. Compared to the optical cutoff frequency due only to the optics, the system "cutoff frequency" is much lower. While the lens system may be able to image certain fine lines and sharp edges in a given scene, much of this high frequency detail will never be recorded by the camera or show up on the monitor screen, due to the effects of the other MTFs. A realization of camera limitations such as these often surprise our students.

We also cover an MTF treatment of the non-LSI spatial sampling effects of the camera sensor arrays, using familiar SP techniques. This allows us to address the usual concerns such as aliasing, with variations related to color cameras. An example of this is the color-specific sparse sampling arrays that result from using a Bayer mosaic color filter array (CFA), as shown in Fig. 4. Obtaining a three-color, full-resolution image from the sparse arrays requires interpolation and image enhancement steps as used in proprietary demosaicing algorithms; this also has spatial frequency effects on the image. These concepts are easily presented in known SP terms.

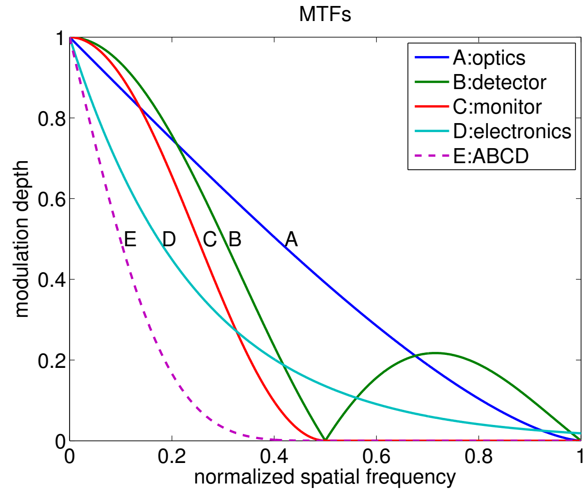

Fig. 3: The independent MTFs for subsystems A through D are multiplied to obtain the overall system MTF shown as E. The spatial frequency axis is normalized with regard to the optical cutoff frequency D/λ.

We use Fourier optics, MTF methods, and sampling theory to leverage the students' prior knowledge of SP theory. The course also covers related concepts such as the effect of apertures, sensors, pixel size, depth of field, field of view, reflection, refraction, etc. Overall, the students obtain a practical working knowledge of optical engineering (from a single course) that provides the knowledge needed to support their research efforts.

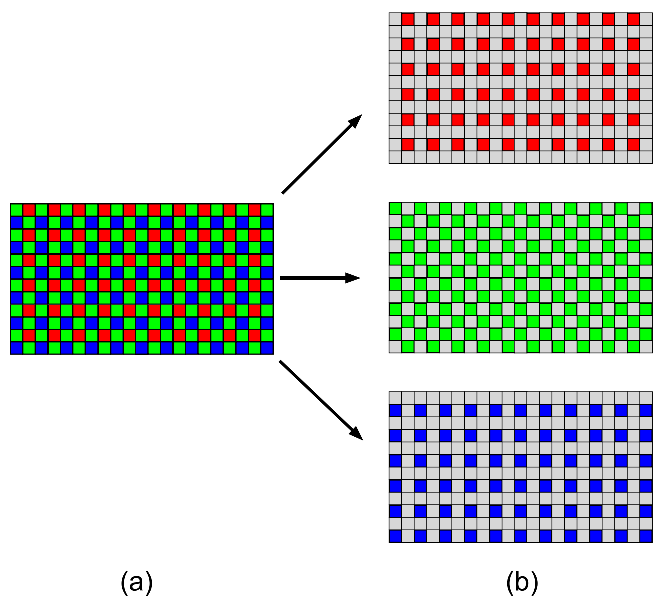

Fig. 4: A Bayer mosaic color filter array (a) results in three sparse sampling arrays (b) to provide color information for a digital camera.

3. PROBLEMS AVOIDED

Many problems are avoided when students are given a practical knowledge of optical engineering. Before taking our course, students would often make non-quantitative and overly-optimistic estimates of various imaging limitations (e.g., those due to diffraction, spatial sampling, motion blur, aberrations, polarization, spatial integration of the pixel area, optical low pass filters, color filter arrays, and lossy compression effects of JPEG). Some students seemed unaware that these limitations even existed before taking the course.

For example, one student needed to use a camera to detect surface damage to a device that would show up only as very small cracks or deformations. By analyzing the spatial frequency characteristics of the predicted overall MTF, it was found that the digital camera imaging system originally specified would not have been able to detect such tiny damage features. Basic optical engineering led the student to specify and assemble an imaging system which was able to reliably show the detail required.

Another student planned to use a single-sensor color camera to take images that included periodic patterns on the objects of interest, using broadband "white" light illumination. Through an understanding gained in the course regarding the different spatial sampling frequency of green versus blue and red due to the CFA, the student was able to choose a lens and object distance that avoided aliasing the patterns.

As a final example, a student project included designing an improved version of the SportVU system used for professional (NBA) basketball games. The current system uses 6 cameras spaced around the basketball court to capture image data on all 10 players and the ball during the game. The student needed to quantify aspects for multiple cameras such as field of view, depth of field, crop factor, motion blur, contrast limits, and operation in the presence of multiple spurious reflections. The concepts presented in this single course, leveraged with the student's existing understanding of SP principles, allowed him to move forward with his research.

4. STUDENT FEEDBACK AND RESULTS

So far, the graduate-level course we created using this method has been taught twice (Spring 2013, Spring 2014) to University of Wyoming students majoring in electrical, computer, mechanical, civil, and chemical engineering. While the electrical and computer engineering students had the strongest background in SP, the other graduate students had sufficient preparation in linear systems theory, Fourier transforms, and other foundational topics of SP, so the method was successful with all the students. Survey items were given to the students semester's end as a way to assess if our ideas about the efficacy of a constructionism approach using a single course in optical engineering would be realized.

For the survey, a 5-point Likert psychometric scale was used: 1–strongly disagree, 2–disagree, 3–neutral, 4–agree, and 5–strongly agree. Twelve students responded; the mean results are shown in square brackets below for the survey items pertinent to this paper.

- I had very little or no background in optics or optical engineering prior to enrolling in this course. [4.5]
- This course took good advantage of my prior knowledge of topics such as linear systems theory and Fourier transforms. [3.9]
- I am now confident in my ability to quantitatively evaluate a digital camera system or similar type of imaging system. [4.2]

As seen above, the students believed that the course described herein was effective in providing to them the necessary understanding of optical engineering. It was efficient in that it was accomplished with only a single course. The traditional approach to teaching material such as this is to use at least two courses. Additional feedback from several of the students who took the course revealed that they were able to quickly and effectively use their new knowledge of optical engineering for their own research areas. They were also able to confidently include both the associated theory and the specific optical engineering analysis of their individual test setups in their dissertations.

5. CONCLUSIONS

For students learning a new topic area, a particularly efficient and effective method takes best advantage of the students' prior knowledge. By making links to their existing cognitive frameworks, our students were far less intimidated by the new subject material, and more quickly mastered an acceptable level of expertise, compared to a "starting from scratch" approach to a new topic area. This method of relating new optical engineering concepts to known SP concepts helped "bridge the gap," and proved very effective for these students.

An experienced professor will not be surprised by this conclusion, yet the confirmation of the technique as described herein is welcome reinforcement of the approach. A faculty member who wishes to take best advantage of this method will need to thoughtfully identify and use the most appropriate parts of the students' existing knowledge base, and structure the course from that perspective.

While there are some excellent books that cover various subsets of this course in great detail, no existing book was found that spanned the entire imaging system from end-to-end at an appropriate level of detail and rigor for *technical users*, not *designers*, of digital cameras. To fill this need, a new textbook was written to support the course. After incorporating many helpful suggestions from our students and colleagues, a final version of the book is nearly complete and will be published soon.

6. REFERENCES

[1] H. Gardner, *The Development and Education of the Mind: The Selected Works of Howard Gardner*. World Library of Educationalists, New York: Routledge, 2006.

[2] J. Piaget, *The Psychology of Intelligence*. New York: Routledge, 1950.

[3] I. Harel and S. Papert, *Constructionism*. New York: Ablex Publishing, 1991.

[4] M. Cakir, "Constructivist approaches to learning in science and their implications for science pedagogy: A literature review," *International Journal of Environmental & Science Education*, vol. 3, no. 4, pp. 193–206, 2008.

[5] D. P. Ausubel, J. D. Novak, and H. Hanesian, *Educational Psychology: A Cognitive View*. Geneva, IL (USA): Holt McDougal, 2nd ed., 1978.

[6] C. H. G. Wright and T. B. Welch, "Teaching real-world DSP using MATLAB," *ASEE Comput. Educ. J.*, pp. 1–5, January–March 1999.

[7] T. B. Welch, M. G. Morrow, and C. H. G. Wright, "Teaching practical hands-on DSP with MATLAB and the C31 DSK," in *Proceedings of the 2000 ASEE Annual Conference*, June 2000. Paper 1320-03.

[8] T. B. Welch, C. H. G. Wright, and M. G. Morrow, "Poles and zeroes and MATLAB, oh my!," *ASEE Comput. Educ. J.*, pp. 70–72, April–June 2000.

[9] C. H. G. Wright, T. B. Welch, D. M. Etter, and M. G. Morrow, "Teaching DSP: Bridging the gap from theory to real-time hardware," *ASEE Comput. Educ. J.*, pp. 14–26, July–September 2003.

[10] C. H. G. Wright, M. G. Morrow, M. C. Allie, and T. B. Welch, "Enhancing engineering education and outreach using real-time DSP," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. III, Apr. 2008.

[11] T. B. Welch, C. H. G. Wright, and M. G. Morrow, "The DSP of money," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, pp. 2309–2312, Apr. 2009.

[12] T. B. Welch, C. H. G. Wright, and M. G. Morrow, *Real-Time Digital Signal Processing: From MATLAB to C with C6x DSPs*. Boca Raton, FL (USA): CRC Press, 2nd ed., 2012.

[13] M. G. Morrow, C. H. G. Wright, and T. B. Welch, "Real-time DSP for adaptive filters: A teaching opportunity," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, May 2013.

[14] C. H. G. Wright, T. B. Welch, and M. G. Morrow, "Using student knowledge of linear systems theory to facilitate the learning of optical engineering," in *Proceedings of the 2015 ASEE Annual Conference*, pp. 26.1683.1–26.1683.11, June 2015. DOI: 10.18260/p.25019.

[15] C. H. G. Wright, T. B. Welch, and M. G. Morrow, "Leveraging student knowledge of DSP for optical engineering," in *Proceedings of the 2015 IEEE Signal Processing and Signal Processing Education Workshop*, pp. 148–153, Aug. 2015.

[16] J. W. Goodman, *Introduction to Fourier Optics*. New York: McGraw-Hill, 2nd ed., 1996.

[17] G. D. Boreman, *Modulation Transfer Function in Optical and Electro-Optical Systems*, vol. TT52 of *Tutorial Texts in Optical Engineering*. Bellingham, WA (USA): SPIE Press, 2001.

[18] G. C. Holst and T. S. Lomheim, *CMOS/CCD Sensors and Camera Systems*. Bellingham, WA (USA): SPIE Press, 2nd ed., 2011.

[19] R. H. Vollmerhausen, D. A. Reago, Jr., and R. G. Driggers, *Analysis and Evaluation of Sampled Imaging Systems*. Bellingham, WA (USA): SPIE Press, 2010.