Freeform Optics

A couple weeks ago in Photon Snacks I discussed the four research areas of the Wyant College of Optical Sciences. In that article I also discussed how the faculty members overlap with those four groups, overlap between the core undergraduate courses, and some suggestions on how to potentially find employment in a research group. If you want to read more, go here. In this week's Photon Snacks, I am going to focus on a particular research are in the Optical Engineering group: Freeform Optics. I have dabbled in this area including conducting research, presenting results, working on conferences, and teaching about it (OPTI 485/585 – Illumination Engineering).

What is freeform optics? From the literature,[1] freeform optics is defined as:

- Any non-rotationally symmetric surface or
- A symmetric surface that is rotated about any axis that is not its axis of symmetry.

Thus, it is essentially an optic that lacks symmetry with respect to the optical axis. Some of the best examples of such are the headlights and taillamps on cars, which are often faceted reflectors for bulbs or asymmetric arrays for LED sources. The first mention of freeform in the optics literature that I could find was 2002 in a JOSA A paper by Harald Ries and Julius Muschaweck,[2] in which the abstract says:

> Freeform optical surfaces embedded in three-dimensional space, without any symmetry, are tailored so as to solve the archetypal problem of illumination design: redistribute the radiation of a given small light source onto a given reference surface, thus achieving a desired irradiance distribution on that surface. The shape of the optical surface is found by solving a set of partial nonlinear differential equations. For most cases, a few topologically distinct solutions exist, given suitable boundary conditions.[3]

The definition as provided in Ref. [1] agrees with this assessment from Ries and Muschaweck; however, often there are variations in what people consider to be a freeform optic. One such is that the surface can be rotationally symmetric with respect to the optical axis, but the shape of the optic is no-standard, i.e., it is not a conic like a sphere, parabola, ellipse, etc. In the end with this more liberal interpretation of freeform one would say that the optic shape is non-traditional, or to put it simply, it is "funky."

In the next section I provide more insight about why we need to look at freeform optics and their utility. Following that I provide insight into the design techniques of such optics. I end with some conclusions and the column byline which encourages you to go to the always available Photon Snacks survey on what you want to see in this column. I will be acting upon this survey in the coming weeks of Photon Snacks.

Why Freeform Optics?

Increasingly we are asked to design challenging optical systems, especially as they move to off-axis systems to make more effective use of space limitations, emission from real sources, reduction of aberrations or increase in imaging system performance, and/or tailored illumination at targets. My field is nonimaging optics, rather than imaging optics, so I will use an example from the illumination field to drive the arguments that follow. Consider a parabolic mirror with a point source at its focus. As shown in Fig. 1, this setup gives collimated light coming from the reflector, which is shown in the intensity distribution (lm/sr or W/sr, i.e., the angular distribution arising from this optic) as a bright spot in one angular direction (0 degrees in both transverse directions – i.e., along the optical axis of the parabola). This geometry is fictitious due to a number of realistic considerations:

- The source will not be a point source – it will have some size, which is described as an extended source,
- The source cannot be placed accurately with respect to the focus of the parabola – there are source tolerances in the position and orientation with respect to the geometrical arrangement,
- Each source and reflector will have some manufacturing variation– there are tolerances in the manufacture of the optical system, and
- The source and reflector will have optical characteristic variation – such as source emission variation/tolerances in its spectral radiance distribution and the reflector can have spectral coating variation/tolerances.

Simply, the sources and the reflectors cannot be made perfectly individually or in their system integration. Thus, one will be get variation in the resulting target illumination. Figure 2 shows the resulting intensity distribution taking into account the extended nature of the source and a slight position error for the placement of the source with respect to the focus of the parabola. Such can be benign (e.g., small optical power reduction) to dramatic (e.g., observable color or spectrum over the illumination target). In the end, we can use freeform optics to make a more tolerant optical system that can alleviate concerns due to fabrication errors, while make the said system more efficient.

Thus, freeform optics provide more tools for an illumination designer to be able to model and build for the following real-world considerations:

- Tolerances: handle variation in the source and reflector optical parameters, geometry parameters, and setup between these two components and
- Extended source: real sources have a real size that varies over their spatial extent and over their angular emission characteristics, and

Thus, illumination designers can include the desired lighting demands (e.g., bright spotlight to illuminate the target with a range of light falloff away from the target being a sharp cutoff outside the target to slow transition falloff. There are reasons for either that arise from perception demands, which means it is observer and application dependent. A good example of such is the illumination provided in stores for the new, hot items that are at full price – they are illuminated well with most light on such products (i.e., sharp cutoff – the light is on the goods that they want to sell) to poorer lighting on sale items (i.e., slow falloff in lighting).

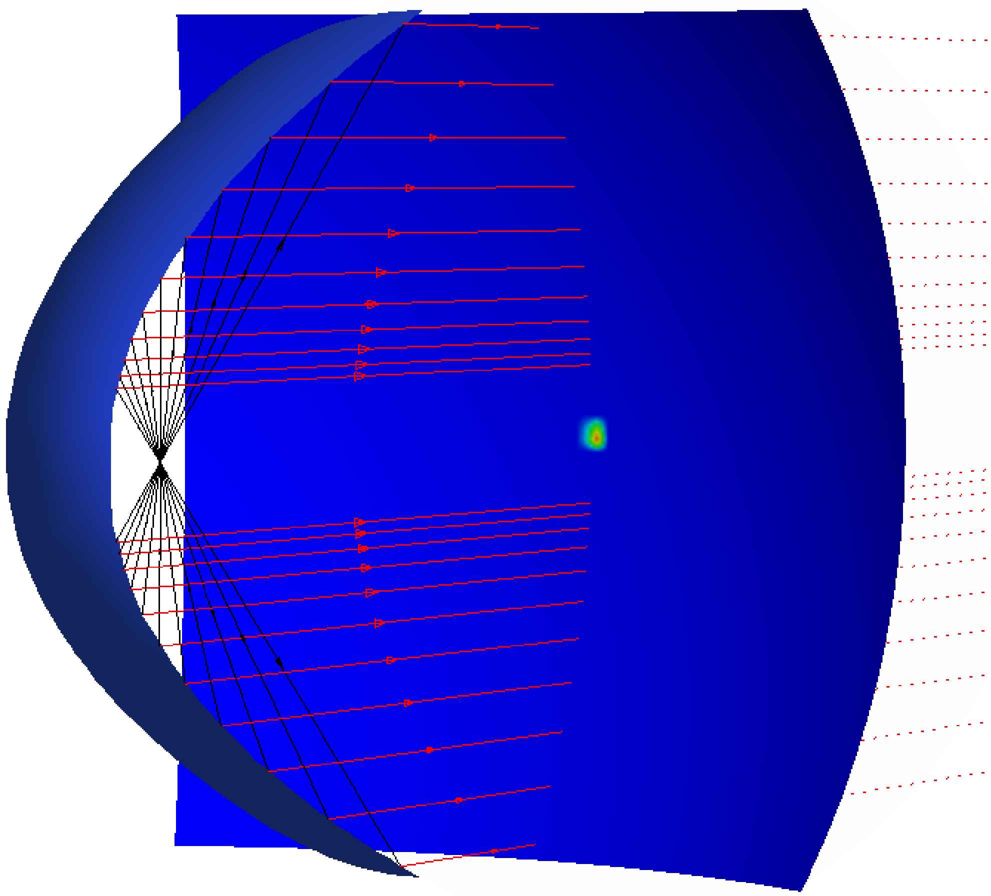

Figure 1. Intensity distribution (lm/sr or W/sr) for a point source located at the focus of a parabolic reflector. You only get radiation (rays) parallel to the optical axis, which means the angle of the rays is 0 degrees in both transverse directions (*x* and *y*). Plotting the intensity means that there is only reflected radiation at this point. The intensity distribution is plotted on the blue surface to the right – i.e., this shows that only one angle is illuminated.

How Freeform Optics?

Over the past 20 years many design methods for freeform optics have been reported, including:

- Oliker/composite ellipse method: think of a faceted reflector where patches on the surface are made with distinct elliptical surfaces. You place the source at a common focus for all of the ellipses comprising the reflector surface. The challenge in the design is to ensure that the edges of the patches come together to form smooth seams (i.e., first derivates of surface slope are as close as possible along with needs on the zeroth and second derivates).[4] Note that this method is extended to the refractive optics too.

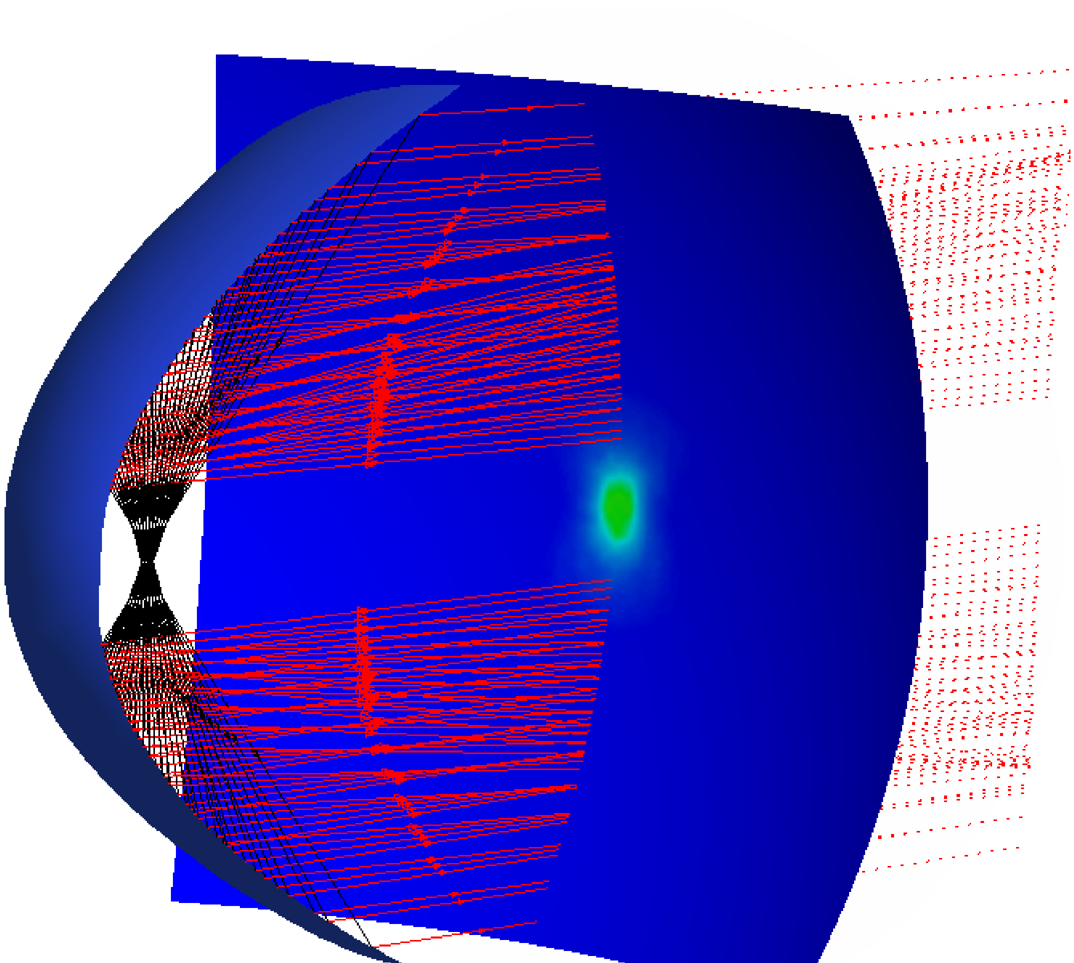

Figure 2. Intensity distribution (lm/sr or W/sr) for an extended source located near the focus of a parabolic reflector. You get radiation (rays) over an angular span around the parallel direction to the optical axis, which means the angular distribution of radiation has been spread (smeared) over a range. Plotting the intensity means that there is reflected radiation over this extended solid angle. The intensity distribution is plotted on the blue surface to the right – i.e., this shows that now we have a broader distribution with the peak intensity reduced.

- Monge-Ampère/ray targeting method: at control points on the optic surface you perturb the surface slope so that the outgoing ray goes to the desired location at a target (near field) or the desired direction (far field). Thus, for an input wave front from a source, one specifies the outgoing wave front. The challenge once again is to make sure the optic is smooth (i.e., same specification on derivates).[5, 6]
- Simultaneous Optical Surfaces: an advanced method that maps up to *N* wave fronts at the input of an optical surface to *N* wave fronts at the output along with control of the wave fronts between the *N* that you have specified (i.e., the weighting of the wave fronts in the outgoing radiation can be specified). It does this by first specifying the spine of the optic along with the ribs that radiate from the spine. The spine-rib combination provides the shape of the resulting optics.[7]

The first thing you learn is that these methods are at first restricted to the design with point sources (or small sources centered at the location of a point source). A number of extensions have been developed to handle the real life characteristics of sources, including the fact that it is not a point source but an extended source, but the methods do not include the tolerances of the design. Tolerancing is done separately. You will learn in optical design courses and in your career, we typically spend 90% of the time on the design and 10% of the time on tolerancing; however, the ratio of time should be switched. Thus, increasingly optical designers are including tolerancing in the formal design process. The mantra is becoming, why spend all the time designing if the system cannot be built to function effectively, so rather than making the two design steps independent, do them concurrently.

The second thing you learn is that all of the methods either talk about taking input wave fronts and mapping them to output wave fronts or taking input rays and mapping them to output rays. At first blush these two processes seem distinct, but they are actually one and the same. How does one work with a wave front? They use the perpendiculars to these wave fronts, which are the rays that define the shape of the wave fronts. Thus, most if not all of the freeform design methods are based on ray targeting or mapping. Additionally, extended sources do not easily work with a single or limited number of wave fronts. There are wave fronts coming out of each point of the source with resulting wave fronts going to each point of the target distribution. So, we may need more than N wave fronts as described previously, which is the main reason we are restricted to small or point source designs.

The result is that you may want to throw up your hands and just find another thing on which to work. As can be seen in the references, there is a wealth of design work in this areal but the mathematics is demanding for explaining the seemingly simple ray targeting. In the end the surfaces are numerical constructs based on NURBS (non-uniform rational B-splines, which CAD software uses). So, why do we develop these demanding mathematical constructs, when we can just work in the numerical space of tracing rays? In optical design and analysis software you can change the local slope of the surface based on where you want the ray to go at the target. You can also include the toleranced rays, which are rays that are offset from the nominal source to include source variation and also optic variation by perturbing the shape of the optical design. Thus, you trace all of these rays in a series of iterations to converge onto a solution that meets the desired illumination demands while it takes into account the expected tolerances.

Figure 3 shows an example wall-wash system for illuminating interior building walls. Wall washes are placed in the ceiling about one meter from a wall to provide as uniform illumination of the wall with minimal light on the floor (and even ceiling). It is an off-axis design made further complicated by the wide range of angles and distances to the wall locations. In radiometry (OPTI 306) you learn that there is a dependence on the cosine of the angle of illumination and an inverse d^2 dependence for the illuminance (lm/m^2) , where d is the distance from the source to a location on the wall.

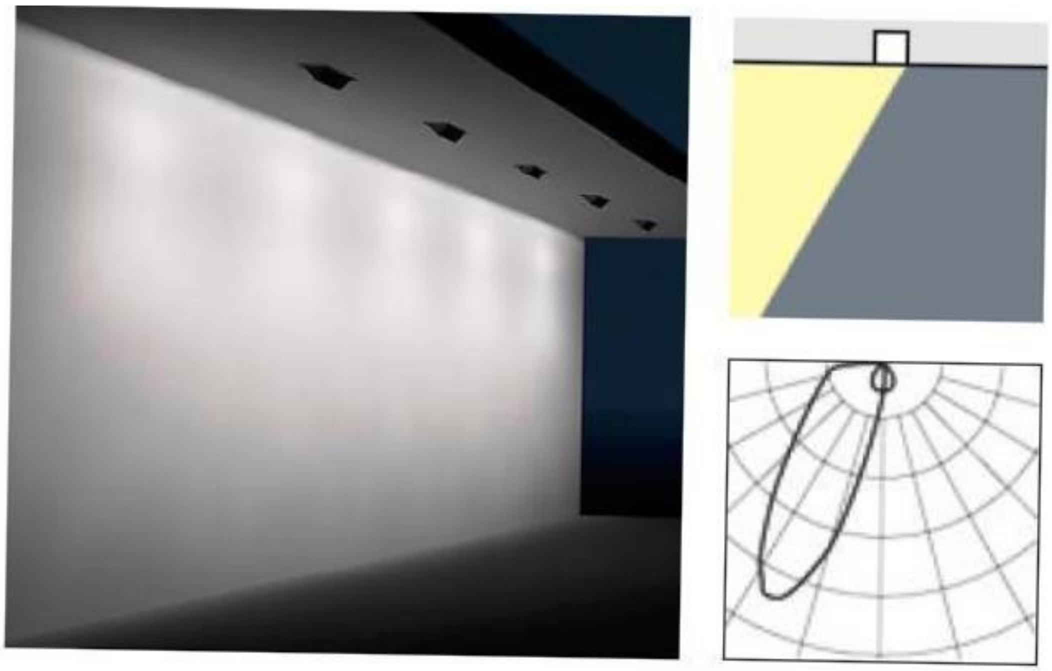

Figure 3. Example of a wall-wash illumination system. Note that the wall lighting is not uniform![8]

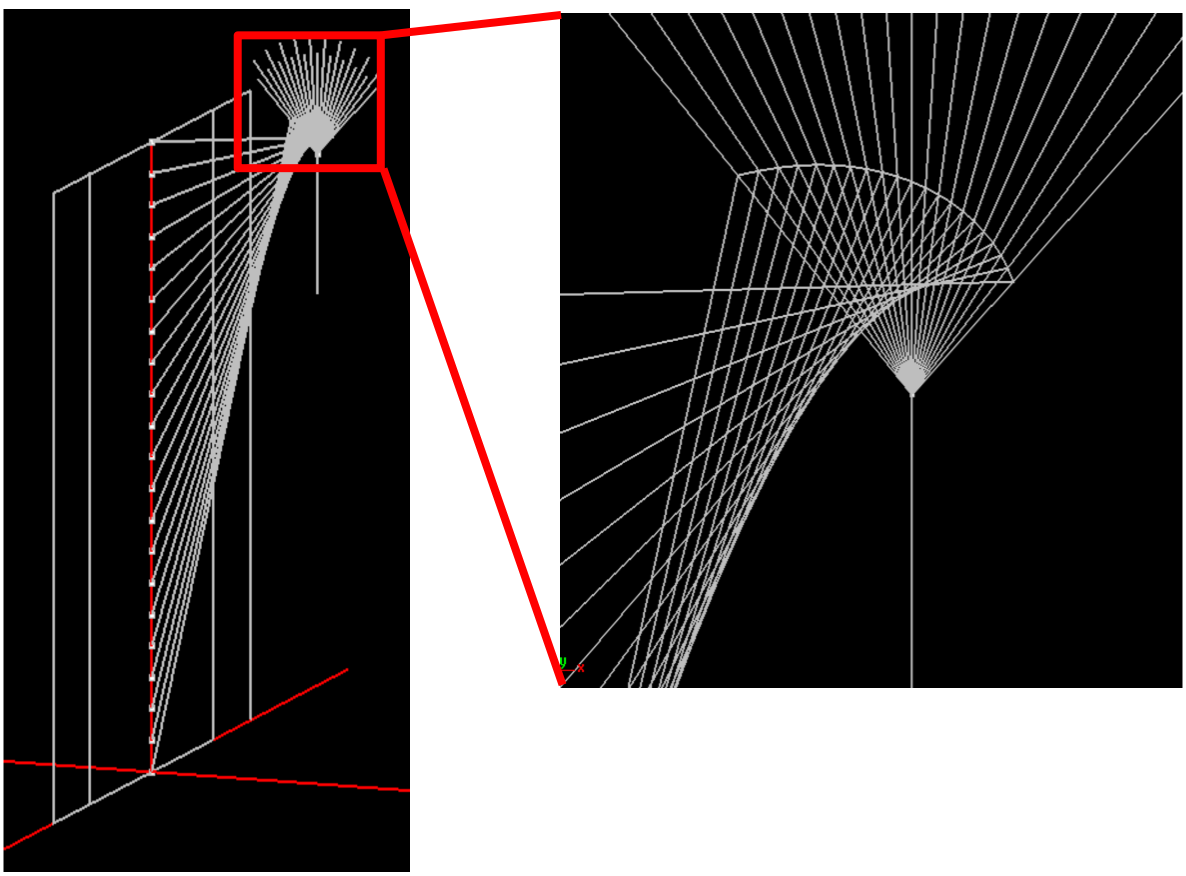

Figure 4. The tracing of the cross section of the optics that defines the base optic spine. The ribs are perpendicular to the spine (and come out of page for the curved cross section shown in the right-hand inset.

The first step is to design a base optic that uniformly illuminates on axis each point on the wall. Figure 4 shows this in steps of every 5 degrees or so. This step defines the spine of the optic, and ribs which are perpendicular to the spine are made that will be perturbed in the next step. Figure 5a shows the irradiance distribution on the wall for the point source case, and Figure 5b shows the case when a realistic LED model replace this source. Note that the design is decent, but further modeling shows that it is intolerance to misplacement of the LEDs.

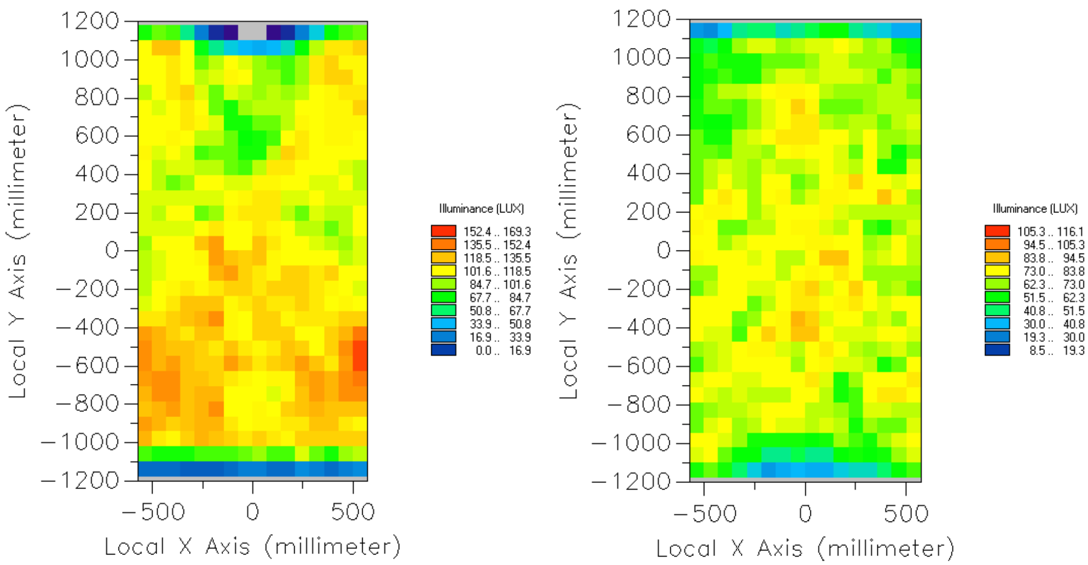

Figure 5. Illuminance in a 1-meter+ width on the wall from the ceiling to the floor for (a) point source and (b) real LED model. See Ref. [2] for the details.

The next step is do the iterative perturbation of the optic so that it better handles the illumination demands while being tolerant to ±1 mm of LED displacement in its position. Note that this is a rather large tolerance. Ref. [2] discusses the details of the ray-targeting algorithm. The resulting shape of the optic is shown in Fig. 6 and the illumination on the wall with four units with different tolerances is shown in Fig. 7. Note that Fig. 7 gives the illuminance (lm/m^2) logarithmically since the human eyes responds as such. The distribution on the wall accommodates this amount of variation, but there is still work to be done since there is still some level of non-uniformity and toward the ceiling and floor has some weak illumination.

Conclusions

As presented freeform optics are the current rage in the field of optical design – both for imaging (lenses, telescopes, etc.) and nonimaging (illumination, lighting, etc.) systems. They provide a multitude of additional controls to address aberrations in imaging systems or improve efficiency (étendue conservation!) in nonimaging systems. Design tools in software such as

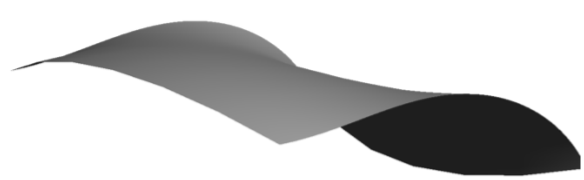

Figure 6. Shape of the resulting wall-wash freeform optic. It has mirror (left-right) symmetry.

LightTools, CODE V, Zemax, FRED, and so forth are being provided, and optics manufacturers are developing better capabilities to manufacture these challenging optics. Fabrication methods include additive methods (i.e., 3D printing), injection molding, and even grinding and polishing. Expect this sector of optical design research to flourish over the next few decades. If you are interested in conducting research in this area at OpSci consider reaching out to Prof. Ron Liang, Prof. Daewook Kim, and others. I include myself in the others, and one area I am looking to do more work is lighting of precious works of art using off-axis wall-wash illumination.

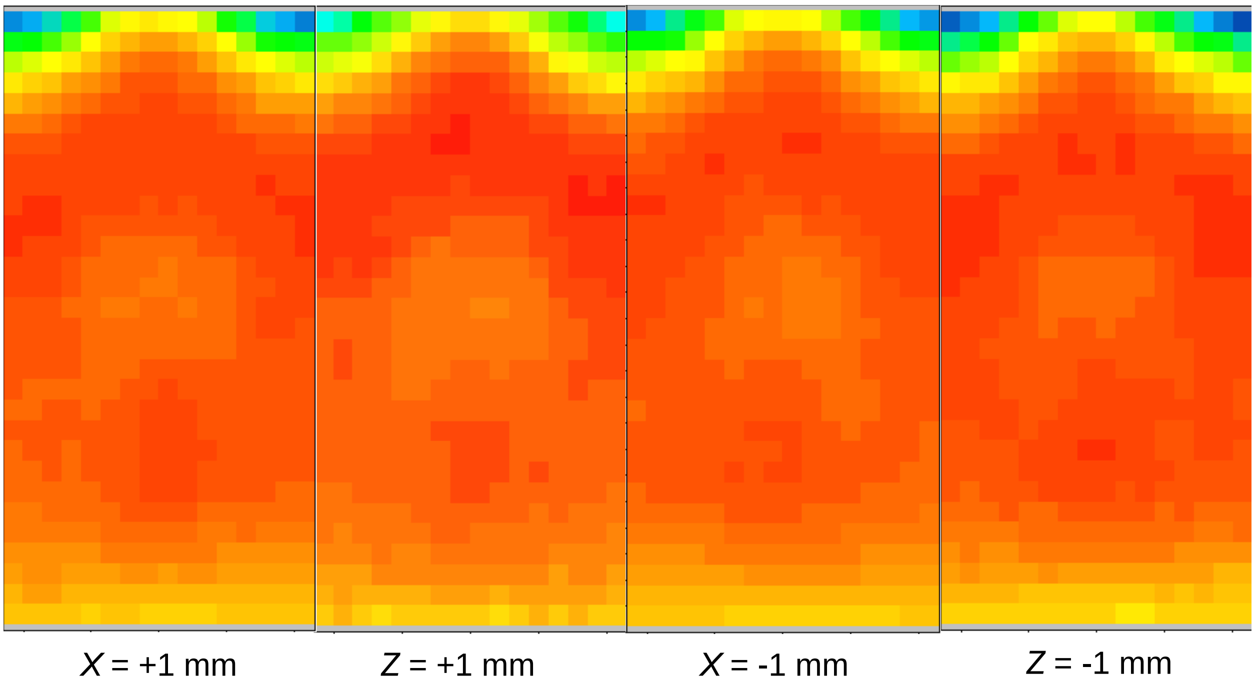

Figure 7. Illuminance on the wall for four units. The text at the bottom of each section denotes the tolerance error for the location of the source for the given section. Note that the illuminance is plotted logarithmically since the eye responds as such. See Ref. [2] for the details.

Photon Snacks is a column for Light Bytes edited by John Koshel, Associate Dean for Undergraduate Affairs in the Wyant College of Optical Sciences. You can find the previously written articles at https://wp.optics.arizona.edu/jkoshel/photon-snacks/. Additionally, make suggestions for articles (or even write one!) by emailing jkoshel@optics.arizona.edu or by visiting the survey anytime at https://forms.gle/ibC9LhPemeniJwhv9.

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