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Designing freeform luminaire optics for additive manufacturing: lessons learned

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ABSTRACT

Automated tools for the design of freeform illumination optics have enabled a new class of high-quality, high-efficiency luminaires for general lighting. Additive manufacturing takes this concept to the next level – allowing for completely custom luminaires to be designed and manufactured for very specific use cases. This paper looks at the optical designs created and manufactured for a Department of Energy project exploring the use of additive manufacturing for the lighting market. The subtle nuances of designing freeform optics for additive manufacturing as well as results of optical testing of material and surface quality will be discussed. Finally, comparisons will be provided between the simulated, as-designed optical performance and that of the measured parts.

Keywords: Freeform optics, Illumination system, Additive manufacturing, LED lighting, 3D printing

1. INTRODUCTION

3D printing technology has existed for many years[1], but the technology has not widely been adapted for optical applications due to low optical clarity of the printable polymers. As part of the U.S. Department of Energy's research into the applicability of additive manufacturing for custom luminaires, we have been able to design, print, and test several optical lenses to determine the viability of the technology for optical applications. In this paper, we will discuss the application space for which the luminaires were designed, the designs created for this project, any testing results of the as-printed optics performed to date, and review design concepts for additive manufacturing that were not realized as part of this project.

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Building Technologies Office Award Number DE-EE0009695. The EERE sponsored this program in order to advance the availability of a software tool that can provide even the least experienced designers functionality that allows them to design an energy-efficient lighting plans that utilize custom luminaires that are all printed via additive manufacturing techniques.

2. THE PROJECT APPLICATION SPACE

For the DOE project, the team selected a mixed-use warehouse space that exists at one of Eaton's facilities. The location consists of a mixture of open space, standalone manufacturing machines, hand-assembly benches, and storage racks. The location is lighted by a number and variety of off-the-shelf (OTS) light-emitting-diode (LED) luminaires. The space was chosen for a variety of reasons, including:

- Accessibility and availability of the space for a lighting retrofit
- The number and types of different lighting requirements
- The relatively low-quality illumination achieved with the current OTS luminaires

The layout of the application space and the existing luminaires can be seen in the renderings of Figure 1. The existing luminaires are arranged in a rectangular grid with irregular row and column spacing. Luminaires are 140 inches off the floor. As is typical with many mixed-use spaces such as this one, the lighting was designed to evenly illuminate the floor of the space, and any functions added later to the space cause gaps in coverage or create regions of less-than-ideal lighting.

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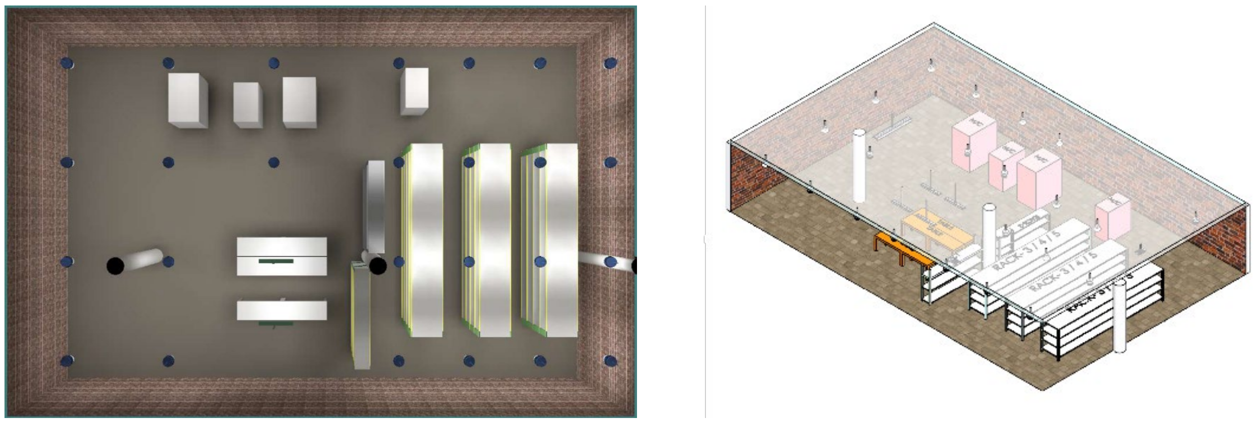

Figure 1: Top-down and isometric renderings of the application space

The goal of this project was to design new LED luminaires that:

- Used the existing luminaire locations without modification
- Maximized wall-efficiency (total optical power / total electrical power) onto the application space surfaces
- Improved the lighting quality in the application space
- Showcased the use of 3D printing and automated freeform optical design algorithms

In order to maximize the lighting quality and application efficacy, the team developed lighting quality targets for three principal areas in the application space: the open areas, the task lighting, and the rack lighting.

Open Area Lighting Requirements

The horizontal surfaces comprising the open area of the application space were required to have a maximum illuminance of 15 foot-candle (fc) and a minimum illuminance uniformity (average/minimum) of 10.0. The rough dimensions of the area to be illuminated were 547 inches by 854 inches. The maximum illuminance and the area of 3,244 square feet give an estimated maximum luminous flux of 48,660 lumens.

Task Area Lighting Requirements

The task area lighting requirements assume that the horizontal tabletops being illuminated are 30 inches above the floor. The illuminance requirements in this region are higher than in other areas due to the nature of the work being performed. The maximum illuminance was specified to be 50 fc with a minimum illuminance uniformity (average/minimum) of 2.0. The goal was to illuminate a 30 inch by 144 inch region with a non-uniform illuminance distribution given by the graphic in Figure 2. The maximum total luminous flux, calculated by summing the maximum illuminance multiplied by the area of each of the sub regions in the specification is 7,220 lumens.

144-in (12-ft)

72-in (6-ft) | 72-in (6-ft)

30-in

40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
40	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	40
40	45	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	45	40
40	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	40
40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40

	Illuminance	Percent coverage
Max	50 fc	17%
min	40 fc	45%
average	44 fc	38%
Max:min	1.25	
avg:min	**1.09**	

Figure 2: Distribution of maximum illuminance required for the task area

Rack Area Lighting Requirements

The rack area consists of several vertical surfaces. Generally, the same luminaires used for illuminating these vertical surfaces also needed to illuminate the floor space between racks. The lighting requirements for the horizontal floor was the same as the open area. For the vertical surfaces, an illuminance distribution with a gradient from floor to the top of the rack was defined. The maximum illuminance at the top of the racks was specified to be 20 fc and the illuminance uniformity (average/minimum) on the vertical surfaces was specified to be greater than or equal to 5. Figure 3 shows the required maximum illuminance as a function of rack height.

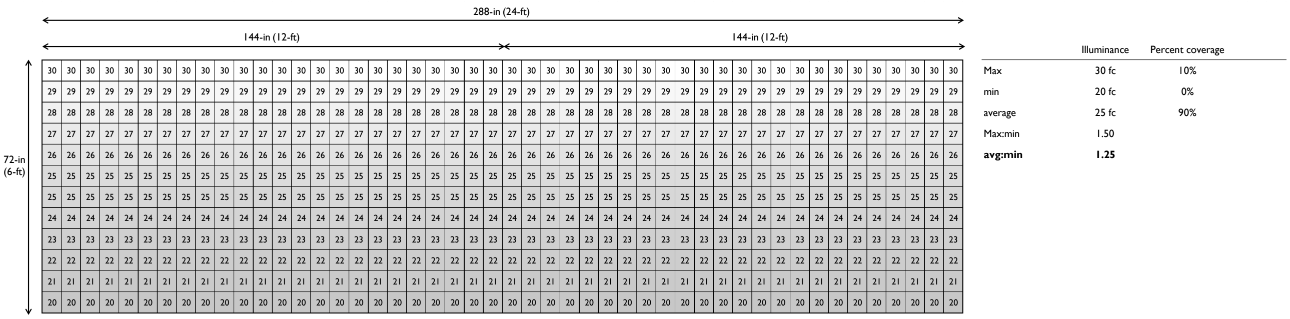

Figure 3: Maximum illuminance distribution for the rack lighting

Given the maximum illuminance distribution and the area being illuminated, the estimated total luminous flux for the rack luminaires was 1,308 lumens per vertical surface.

3. FIRST GENERATION OPTICAL DESIGNS

Two different LEDs were considered for the first generation of optical designs. One LED, from OSRAM, was an OSCONIQ P 3737 LED whose part number was GW PUSTA1.PM[2]. It produces approximately 500 lumens of luminous flux with a minimum color rendering index (CRI) of 70. The second LED was another 3737 from Nichia. Its part number was NV4WB35AR[3]. It produces about 760 lumens of luminous flux with a minimum CRI of 90. The test luminaires were manufactured with the OSRAM LED.

Various optical polymers used with additive manufacturing were measured for this project. In general, the refractive index was found to be near 1.47[4][5], with no attempt made at characterizing the dispersive properties of the plastic. For the designs, no bulk absorption was considered, but like the refractive index, the measured bulk absorption was measured to be similar to acrylic (PMMA), but slightly more absorptive.

Each of the optical designs for this generation and the next were performed in the LightTools illumination design and analysis software package[6]. This the optical designs for this generation consist of freeform lens elements designed using LightTools' freeform design feature[7], which takes as input the desired illuminance distribution and the spatial and angular distribution of the LED and automatically calculates the freeform lens surface that creates the illuminance pattern.

Open Area Optical Design

While the ultimate goal of the DOE project is to further the availability of fully custom luminaires using additive manufacturing, the team decided to create the smallest number of optical designs that could be used to illuminate the space and meet the lighting requirements. Since the application space uses a non-uniform spacing between adjacent luminaires, we decided to have the open area optical design target the maximum spacing between fixtures. By doing this, any two fixtures with closer spacing will have a bright region of overlapping illuminance, as opposed to a dark region. As such, the freeform design feature in LightTools was told to uniformly illuminate a 163 inch by 163 inch square region from a distance of 140 inches.

The resulting design and simulated illuminance distributions are shown in Figure 4. This is a fairly standard Type 5 square optic that is found in many exterior luminaires. This design is able to place more than 80% of the light leaving the LED into the target region.

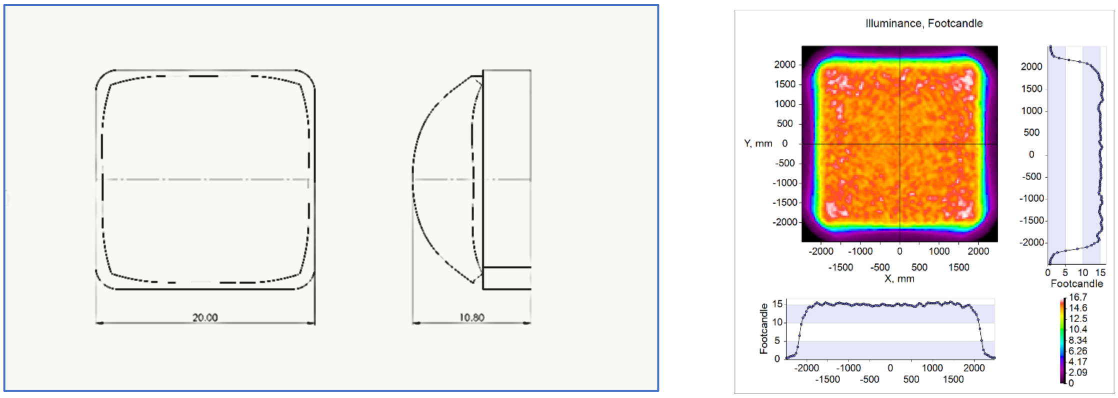

Figure 4: First generation open area optical design and simulated illuminance distribution

Task Area Optical Design

The task area lighting is a bit more challenging to design due to the non-uniform spatial illuminance target. However, the automated freeform design algorithm was able to meet the targets with more than 90% of the LED output being focused on the target region. Figure 5 shows resulting optical design and simulated illuminance distribution for this lens. The shape of the lens is similar to the open area optic with a raised central pillow that creates the non-uniformity in the illuminance.

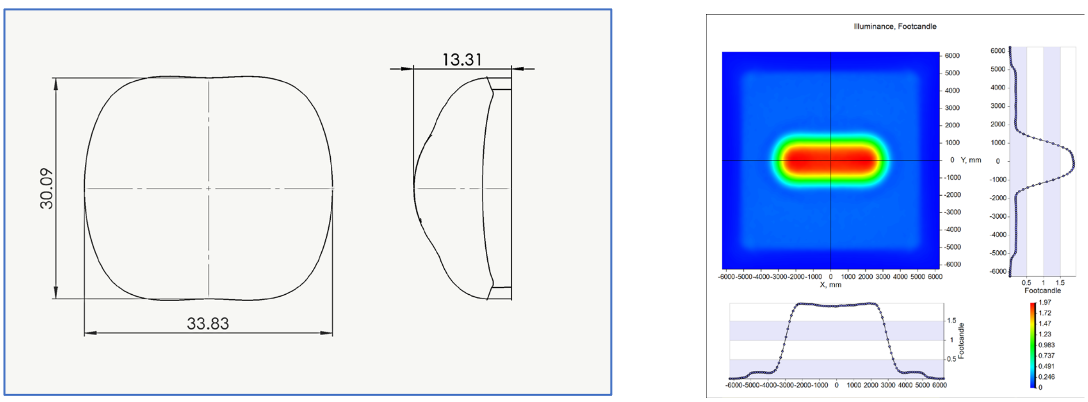

Figure 5: First generation task area optical design and simulated illuminance distribution

Rack Area Optical Design

The optical design for the racks was the most challenging, as the location of the luminaires forces the lens to need very tight illuminance control on the obliquely illuminated vertical faces of the racks. The luminaires are placed directly above the racks, so it is only possible to illuminate the vertical faces of adjacent racks and some of the floor. Figure 6 shows the geometry of the racks and the resulting illuminance distribution relative to the position of one luminaire. The XYZ coordinate axes represent the luminaire location, the dark red cuboid is the rack over which the luminaire is placed, and the vertical faces on which the illuminance distribution is shown are the vertical faces of adjacent racks. Two luminaires, with opposite orientations, are required to create a full rack distribution.

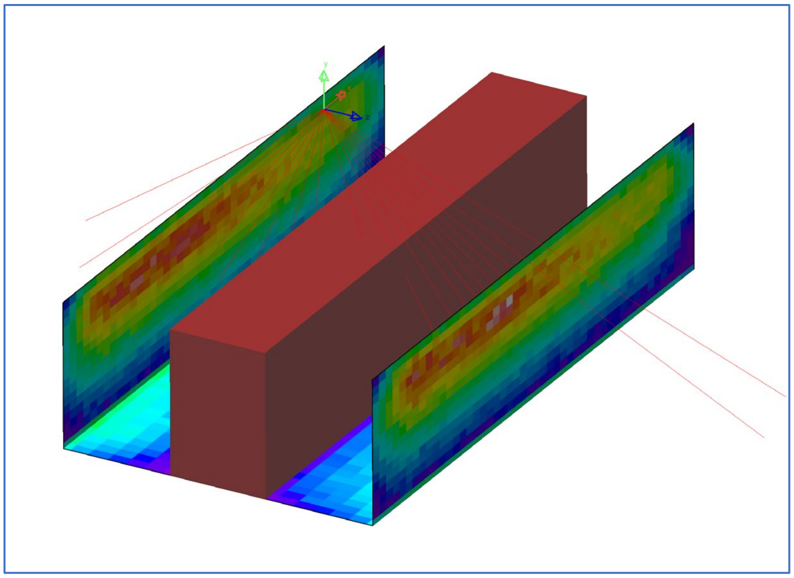

Figure 6: Layout of the rack illumination elements and the resulting illuminance distribution on the floor and vertical faces of adjacent racks

Two types of targets were explored for the freeform design feature of LightTools. In the simplest case, a conformal receiver was defined that covered the vertical faces and the floor. A non-uniform illuminance target was then used with the conformal receiver so that a gradient could be created on the vertical faces, a reduce illuminance could be uniformly placed on the floor, and a null region could be created where the rack over which the luminaire is placed exists. The second type of target, which yielded the best results, involved projecting the vertical faces onto the floor from the center of the luminaire and modifying the relative target distribution by using a grayscale image. Figure 7 shows various attempts at defining a grayscale target to illuminate the projected faces. The two trapezoidal regions at the top and bottom are the projection of the vertical faces onto the floor, the two rectangular regions near the middle are the aisles, and the black regions are that which should not be illuminated.

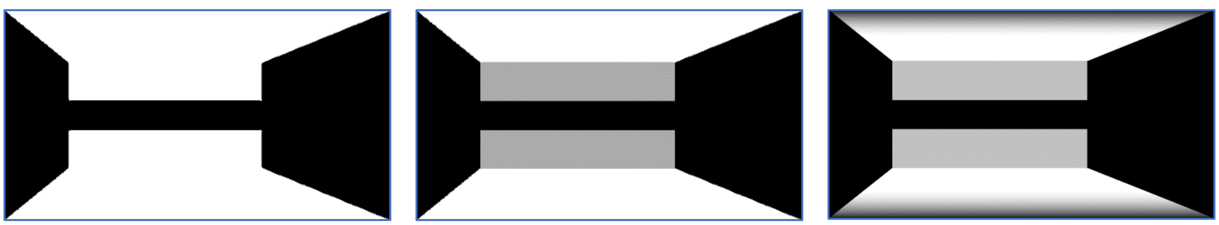

Figure 7: Three attempts to define a grayscale target distribution for the vertical and horizontal faces of the system projected onto the floor

Figure 8 shows the resulting lens. This optic is less efficient that the other designs, only placing 68% of the LED light onto the target surfaces; however, a significant portion of the uncontrolled light stays within the application space, principally spilling out of the row and onto the floor beyond the rack ends. This uncontrolled light that stays within the application space is not considered lost in the application efficacy calculation.

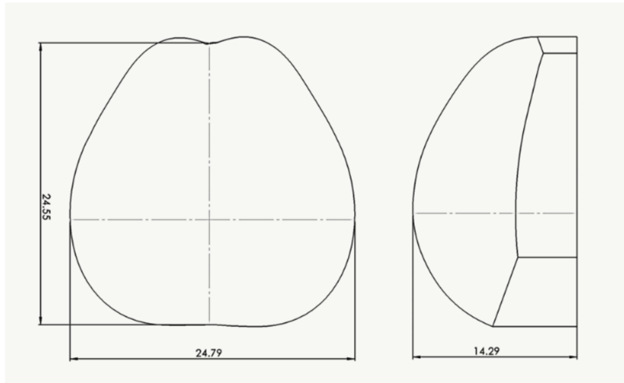

Figure 8: Shape and dimensions of the first-generation rack optic

Testing Results on Printed Parts

Each of the first-generation optical designs were printed using additive manufacturing techniques, as previously described. Luminaires were measured on a goniophotometer by Eaton and comparisons were made between the as-printed intensity vs. the as-simulated intensity. Figure 9 shows the measured and simulated intensity on two orthogonal lateral slices. As you can see, the general shapes of the distributions are similar, but there is not perfect correlation. We concluded that the lenses were manufactured correctly, but there was not enough control of the placement of the optic relative to the LEDs. For this generation of designs, individual lenses were printed and glued onto the printed circuit board (PCB) by-hand.

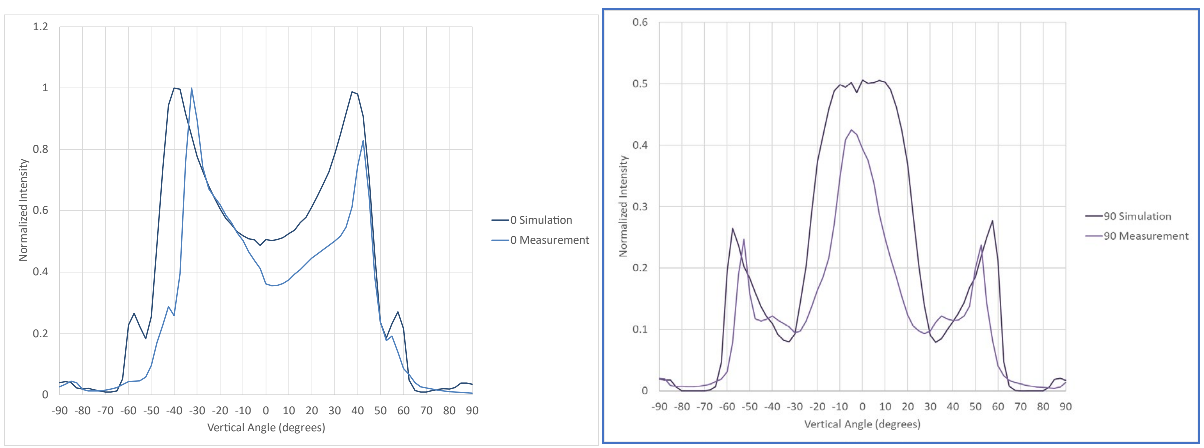

Figure 9: Comparison of the measured intensity and the simulated intensity for the first generation task area design

4. SECOND GENERATION OPTICAL DESIGNS

With the first generation of optical design complete and manufactured, we embarked on a second round of optical and mechanical designs to incorporate the lessons learned, namely:

- Use an LED with a greater lm/W efficiency, in order to get closer to the DOE goal of 180 lm/W for the entire system, including power conversion losses by the LED drivers
- Improve the placement of the lenses with respect to the LEDs
- Reduce manual assembly tasks

To achieve these goals, several changes were made that required new optical designs. First, a new LED was chosen that had a higher lm/W efficiency. We chose the OSRAM OSCONIQ S 5050 LED, whose part number is GW Q9LR31.EM[8]. This LED produces about 500 lm at 120 mA with a CRI of 80. Secondly, the PCB layout was fixed before the optical designs were complete to space the LEDs in a 3 x 4 array with 50 mm pitch between LEDs. By fixing the LED pitch, the thermal and mechanical structures could be designed in parallel with the optical designs. Finally, the resulting optical designs were to be incorporated into a single plastic part that would be snapped into the mechanical housing. By printing all 12 lenses into one plastic part, the need for manually gluing individual lenses to the PCB was removed and alignment of the lenses relative to the LEDs was greatly improved.

The polymer and its properties were unchanged between the first- and second-generation designs. In general, the size of each lens increased due to the increased size of the emitting area of the LED.

Open Area Optical Design

As with the first-generation design, the design of the open area lens is fairly traditional. The application efficacy of the second-generation design is greater than 75%. Figure 10 shows the 12-up lens plate and the simulated illuminance on the floor.

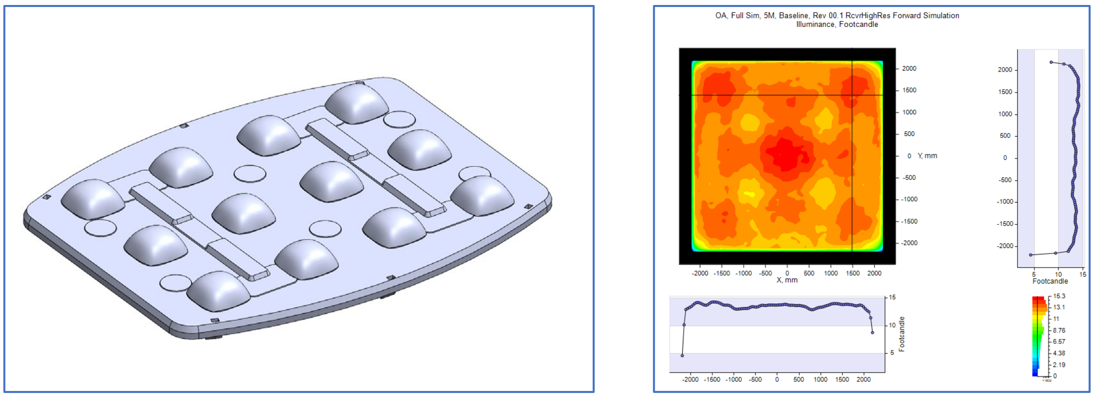

Figure 10: Second generation design and performance of the open area lens

Task Area Optical Design

The resulting lens design for the second-generation task area is significantly deeper than the previous design due, in part, to the larger LED. While the simulated efficacy of the design is greater than 75%, bulk absorption within the plastic cannot be ignored in these thick parts, so the actual number will likely be significantly less. This optical design requires two luminaires per table, one mirrored with respect to the other, in order to create the desired illuminance distribution. Figure 11 shows the size and shape of the individual optical design and the simulated performance of two mirrored luminaires on the table surface.

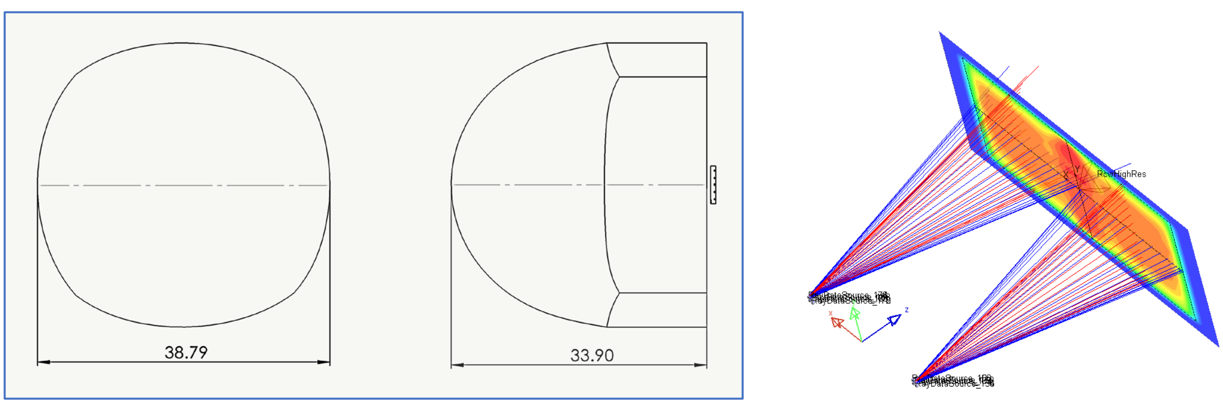

Figure 11: Dimensions and simulated illuminance of the second generation task area lens

Figure 12 shows a rendering of the 12-up lens design on the mechanical housing.

Figure 12: Rendering of the second-generation task area luminaire and its 3D-printed metal housing and heatsink

Rack Area Optical Design

This lens design marked a departure from the previous ones in that the freeform design feature of LightTools was not used. Instead, a collimating optic that utilizes total internal reflection (TIR) was used to keep the optical efficiency above 75%. Figure 13 shows the dimensions of one row of lenses. With a 50 mm LED pitch, the lenses overlap to create one piece. It’s worth noting that a 12-up lens comprising four of these rows cannot be manufactured using conventional injection molding techniques, as the undercut between lenses would result in the part being die-locked.

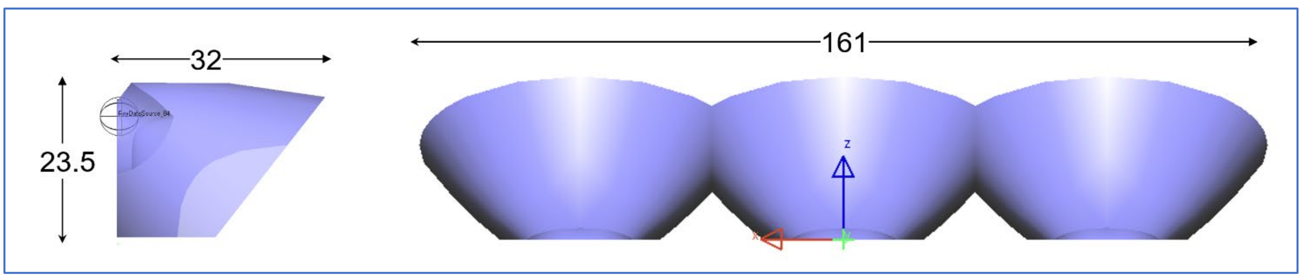

Figure 13: One row of lenses in the second-generation rack optic layout

This design requires two luminaires per rack. One half of the lenses and LEDs illuminate one vertical face and the others illuminate the opposite face of the adjacent rack. Figure 14 shows the simulated illuminance distribution on the vertical face of one rack due to the contribution of two luminaires.

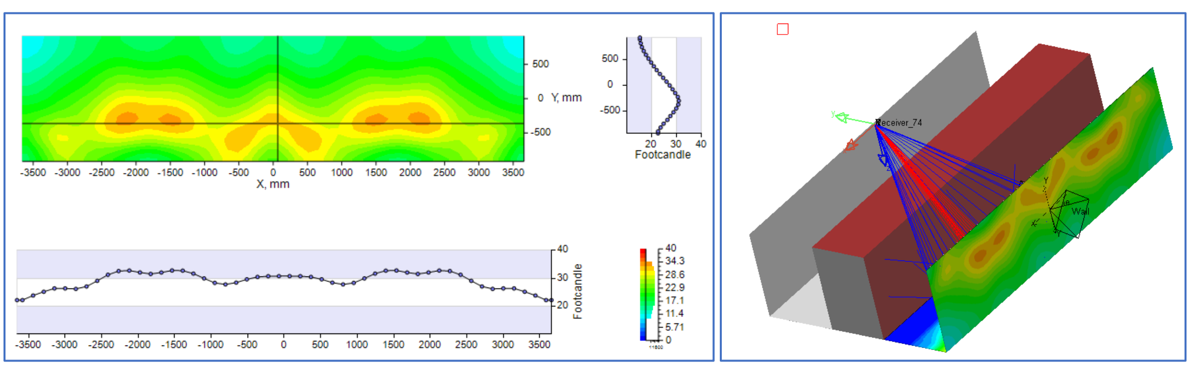

Figure 14: Simulated illuminance of the second-generation rack area lens on one vertical face of the rack

Figure 15 shows a rendering of the rack lens and its heatsink.

Figure 15: Rendering of the 12-up second-generation rack lens and its heatsink

Testing Results on Printed Parts

As of the time of writing, each of the types of luminaires has been printed and assembled. Intensity measurements have been made of each luminaire, but no comparison has been made to the simulated performance. It is worth mentioning that severe out-gassing has been observed from either the lenses or another component of the system, which has degraded the performance of the LEDs. Explorations into the root-cause of the outgassing are ongoing.

5. LESSONS LEARNED AND UNEXPLORED CONCEPTS

As these designs represent our first foray into optical design for 3D-printing, we learned a lot about some of the limitations and capabilities of this manufacturing technology. For instance, when printing optical surfaces, a secondary post-processing step was required, as the step-size of the printing was not small enough to make a smooth surface. The post-processing applied smoothed the surfaces by removing material from the part. More work is needed to understand the impact of post-processing on surface figure.

It is also valuable to note is the limitation on an unsupported step. When 3D printing a part, the maximum angle that can be made without support is about 45-degrees. For the optical designs we created as part of this project, this was not a limitation.

Finally, two concepts that we considered during these designs, but did not implement due to time constraints, were that of a tilted PCB or a reflector incorporated into the heatsink. Since almost every aspect of these luminaires is 3D-printed, including the heatsink and PCB, alternative geometries of can be considered. These optical designs employed refractive elements only, but reflector shapes can be printed into the heatsink as an additional optical element. It is unknown what reflectivity can be achieved.

Also, with 3D printing, non-planar heatsink geometries can be can also be incorporated into the optical design. Since the PCB traces are being printed directly onto the heatsink, individual LEDs can be placed on their own tilted surfaces. This departure from plane geometry would be beneficial for the rack area designs, as the oblique illumination of the vertical rack faces is difficult to achieve without loss in efficiency. If the LEDs were allowed to tilt by 30-degrees from the plane of the heatsink, as shown in Figure XX, efficiencies greater than 88% can be achieved along with a greater degree of control for the illuminance distribution.

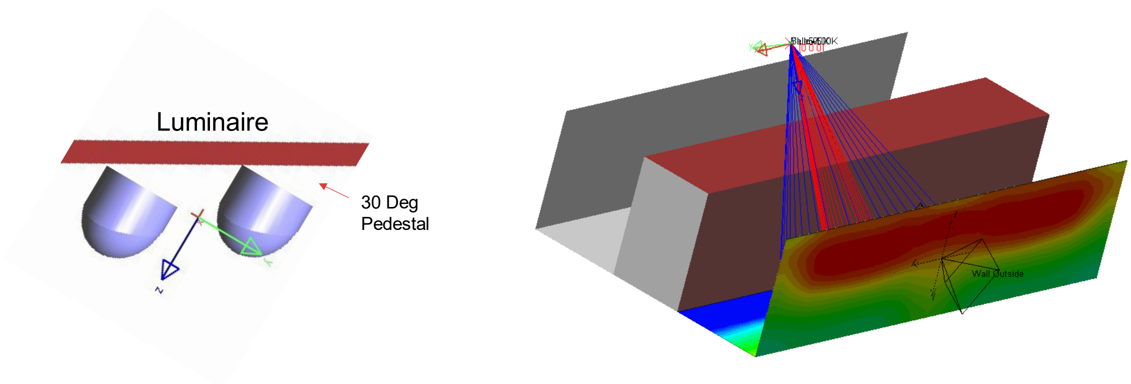

Figure 16: A design for a rack optic that utilizes a 30-degree tilt in of the LEDs and the resultant illuminance distribution

6. CONCLUSIONS

As part of a DOE-funded project investigating the viability of additive manufacturing for the rapid development and manufacture of custom luminaires, we created six different optical designs over two generations to efficiently illuminate a mixed-use application space. The lenses were all manufactured using additive manufacturing techniques out of a polymer whose optical properties closely resembles that of acrylic (PMMA). While more testing needs to be completed in order to fully understand the impact of the manufacturing process, namely the post-processing steps designed to create a smooth surface, some degree of correlation was achieved between the performance of the as-printed part versus the as-simulated design.

Over the course of this project, one key takeaway was evident: additive manufacturing has the potential to enable a larger design space than previously possible, especially when 3D printing is utilized on all components of the system, not just the optics. We were able to realize design forms that would be difficult or impossible to manufacture with conventional injection-molding techniques. We were also able to show concept designs that clearly exhibited the tradeoffs between optical and mechanical complexity.

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