Intensity Mapping for Mask Projection based Photopolymerization

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Abstract

Currently, the industrial de-facto assumption for photopolymerization systems is that the ultraviolet light of the mask-projection is uniformly distributed. This paper presents a method for measuring this intensity field or distribution of this mask-projection. By measuring the light distribution, it is shown that the emitted light is not uniformly distributed and thus the current assumption is invalid. Furthermore, a methodology for obtaining a mask to compensate for the irregularities of the projected light, that will ensure an even and controlled exposure of the photopolymer, is presented. Accordingly, it is demonstrated that this mask compensates for such irregularities, making the light projection significantly more uniformly distributed.

1 Introduction

In order to obtain precision in additive manufacturing (AM), all aspects of the manufacturing process must be under control. This paper considers a bottom-up mask-projection based photopolymerization system, in which ultraviolet (UV) light initiates a cross-linking reaction which solidifies the photopolymer [1]. Currently, the de-facto industry assumption is that the projected UV light is uniformly distributed. This paper presents a new and novel method for measuring the distribution of the projected light with a machine vision camera with a CMOS sensor and shows that the assumption of uniformity is invalid. A method for obtaining a mask that compensates for the non-uniformity is presented, and it is shown that the suggested mask makes the distribution of the projected UV light significantly more uniform.

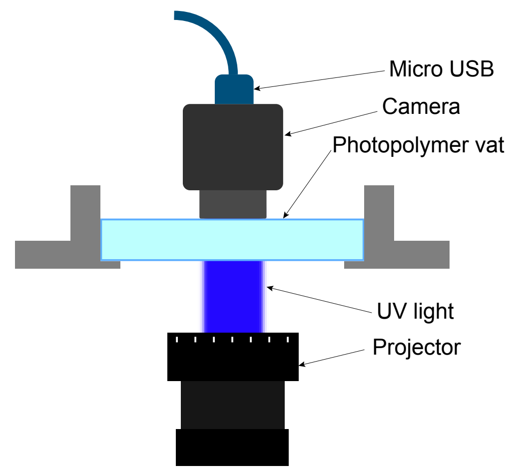

Figure 1: Representation of the image acquisition setup.

2 Method

This section will briefly describe the experimental setup. Then, the method for obtaining the intensity distribution is explained in two steps: First, how the measurements are collected. Second, how the measurements are stitched together to depict the entire area of the mask projection. The last part of the section explains how a mask for compensating for the irregularities of the projected light can be obtained.

1. Experimental setup

The vat-photopolymerization system used as a test platform was built by the Additive Manufacturing research group at the Technical University of Denmark. An area scan machine vision camera equipped with a CMOS sensor is placed on the resin vat, facing towards the projector system allowing the camera to image the light intensity field from the projector as seen in Figure 1.

However, the area of the projected light is significantly larger than the field of view of the camera. Therefore, multiple images have to be acquired from different positions to capture the entire area of projected light and subsequent stitched together. As such, this paper presents a novel method for keeping track of the position of the projected images while measuring the uniformity of the light intensity.

The photopolymerization system uses a Visitech Luxbeam Rapid System projector of LRS-WQ-HY, with a micromirror pitch of $7.54\mu m$ and depth-of-focus range of $\pm 50\mu m$ and $\pm 200\mu m$ for projection lenses with magnification factor of $1.0\times$ and $2.0\times$ respectively [5] [6]. The Blackfly S model BFS-U3-51S5M-C camera [2] was used for measuring the intensity of the projected light.

Only one channel of the Visitech Luxbeam Rapid System projector is used for projecting the UV light. Thus, the micro mirrors are constantly flickering between luminous and dark. In order to reduce this visible flickering, it is necessary to use a radiant flux of more than $0.38W$. Furthermore, an exposure time of $33333\mu s$ (one projection cycle) is used. By using a whole number of full cycles, the integral of exposed light in this time period becomes independent of when the image is taken. In order to avoid overexposing the digital camera, a UV filter is placed such that only a small ratio of the projected light reaches the camera.

2. Measurement of the projected light

The image acquisition method was executed as follows. First a numerated checkerboard was projected onto the resin vat. An image of the checkerboard was taken in order to make it possible to identify the exact position of the camera. Then, a uniform white image was projected onto the vat and a picture was taken from the same position. By moving the camera and repeating this procedure, the position and intensity of each measurement are known and the whole area of projected light can be covered. Figure 2 shows the 20 measurements needed to cover the entire area of projected light. Each checkerboard image is associated with a corresponding intensity image taken from the same position.

3. Data processing

The following protocol was implemented in order to process the raw image data to a stitched contour map. First, all the images were cropped in order to remove the area outside the field of interest and to avoid overlap between the images. In order to reduce noise from the data each image was smoothed with a Gaussian kernel of 100.

Second, a normalization was performed since the average light intensity varied across the obtained intensity images. An iterative, relative normalization method is proposed and implemented such that each image is normalized relative to the borders of its neighbors. This normalization is performed iteratively, seeded at the center image (Figure 2, Image 12). In the first iteration Image 7, 13, 17 and 11 are normalized such that their border intensities match the borders of Image 12. Note that in the following iterations some images have to be normalized with respect to two images, e.g. in the second iteration, Image 8 has to be normalized with respect to both Image 7 and 13. This is done by constructing two weight matrices, $\mathbf{W^1}$ and $\mathbf{W^2}$, that weigh how much each border should normalize a given pixel. For the images in the top right and bottom left corner the weight matrices are given by

$$W^1_{i,j} = \frac{h}{h+w}$$
$$W^2_{i,j} = \frac{w}{h+w}$$

and for the images in the top left and bottom right corner the weights are given by

$$W^1_{i,j} = \frac{h}{W+h-w}$$
$$W^2_{i,j} = \frac{W-w}{W+h-w}$$

where h, w are the height and width of a given pixel respectively, and W is the width of the image. These weight matrices ensure that a pixel is normalized by a weighted sum of both the respective borders. A Python implementation of this iterative normalization method, together with a visual example on synthetic data can be found at: `https://github.com/FrederikWarburg/`

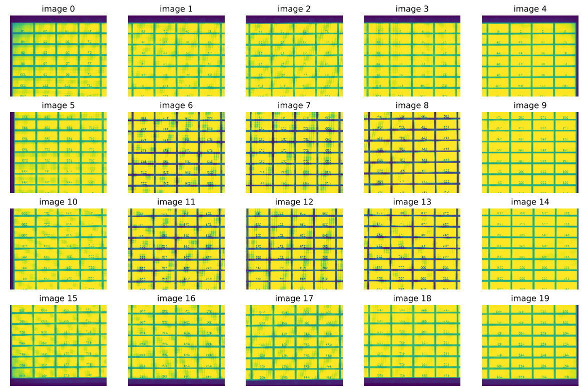

Figure 2: Images of the checkerboard covering the entire projection field.

`relative_normalization_methods#relative_normalization_methods`

4. Compensation for non-uniformity

In order to compensate for the irregularities introduced by the non-uniformly distributed intensity projection, a simple and straightforward algorithm for obtaining a correction mask is presented.

Assuming linearity between the observed intensities and the projection, the mapping between the projected image and the observed image can be expressed as

$$p_{i,j}^{obs} = k_{i,j}\, p_{i,j}^{projected} \tag{1}$$

where $p_{i,j}^{obs}$ is the observed intensity for a given pixel, $p_{i,j}^{projected}$ is the projected pixel value and $k_{i,j}$ is a constant modelling the effect.

By projecting an uniform image onto the resin vat, $k_{i,j}$ can be found as the ratio between observed and projected pixel intensities. Thus, $k_{i,j}^{-1}$ can be estimated and be used to compensate for the non-uniform projection. $k_{i,j}^{-1}$ must be normalized such that each element remains within the range $[0, 1]$. If this is not done, one risk multiplying an image with a value greater than 1 which could lead to pixel values greater than 255 which is outside the range used to represent pixel intensities. The correction image $p_{i,j}^{corrected}$, which compensates for the non-uniform mapping, can be created as

$$p_{i,j}^{corrected} = \frac{1}{\max\left(k_{i,j}^{-1}\, p_{i,j}^{projected}\right)}\, k_{i,j}^{-1}\, p_{i,j}^{projected} \tag{2}$$

Thus, applying $p_{i,j}^{corrected}$ instead of $p_{i,j}^{projected}$ will give the desired intensity and compensate for the irregularities in the projection.

3 Results

In this section, the mapping of the projected UV light is presented. The mapping shows that the projection is not uniformly distributed. Equation 2 is applied to compensate for this non-uniformity, and finally the performance of the suggested algorithm is evaluated.

1. Proof of non-uniform projection

By cropping the images and applying the iterative, relative normalization method it is possible to stitch the 20 images together without any visible stitches. Figure 3 shows an intensity map of the entire area of projected light and a contour plot of this intensity map.

From Figure 3, it becomes clear that the projected light is not uniformly distributed over the entire area of the projection. The variance (V) and Christiansen's Uniformity Coefficients (CUC) are used to measure the uniformity.

$$V = 27.68$$

where 0 indicate uniformity.

$$CUC = 97.28$$

where 100 indicate uniformity.

It is seen that both these measurements that the light distribution is not uniform. Thus, it is shown that the assumption about uniformly distributed light in photopolymer systems is invalid.

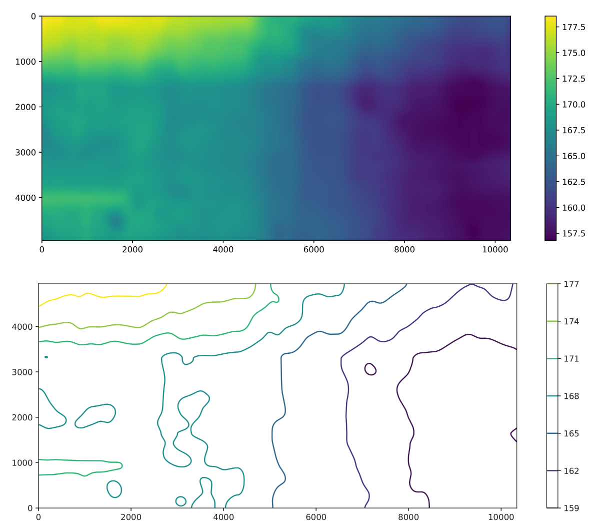

Figure 3: Intensity map of the entire area of projected light (top), and contour plot of the intensity map (bottom).

2. Compensation of non-uniform projection

Figure 3 shows that the projection is non-linear since the projection mapped an uniform, white image into a non uniform output. However, using this non uniform output enables estimation of a correction matrix $k_{i,j}$ and a correction image $p_{i,j}^{correction}$ using Equation 2. The correction of a white image is shown in Figure 4 together with a contour plot.

By projecting this correction image onto the resin vat, it is possible to compensate for the non-uniform mapping and thus obtain a significantly more uniform image. Figure 5 shows the results from applying the mask presented in Figure 4.

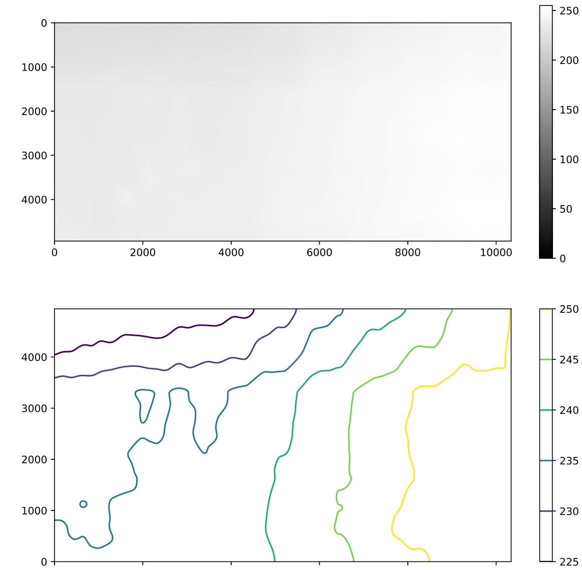

Figure 4: Normalized correction image for a white uniformly distributed image (up) and a contour plot of this normalized correction image (down).

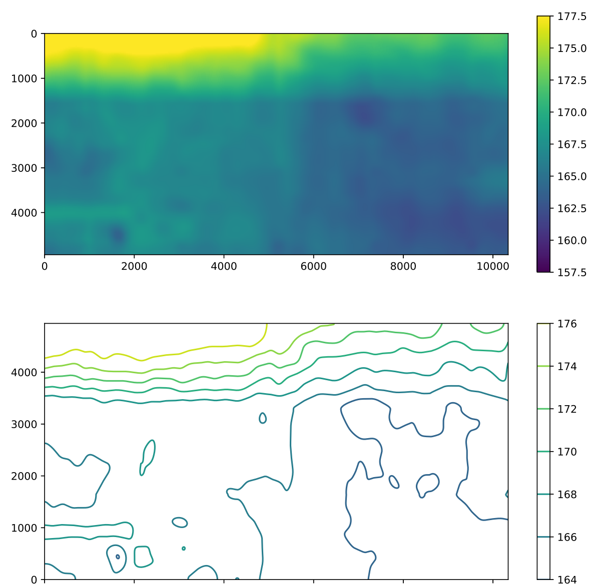

Figure 5: The results from applying the mask presented in Figure 4. Intensity map of the entire area of projected light (top), and contour plot of the intensity map (bottom).

Figure 5 shows that the strong trend from right to left observed in Figure 3 is compensated for. This makes the intensity distribution more uniform in the majority of the image, however it seen that the image is still not uniformly distributed.

In order to compensate for measurement errors several measurements were made. Figure 6 shows the uniformity measures from an experiment where four white images and one correction image were projected onto the resin vat, following by the uniformity measurements. From this figure, it is seen that the correction image scores significantly better for both the uniformity measures. Thus, the correction is compensating for the irregular mapping performed by the projector by making the observed light intensities more uniformly distributed.

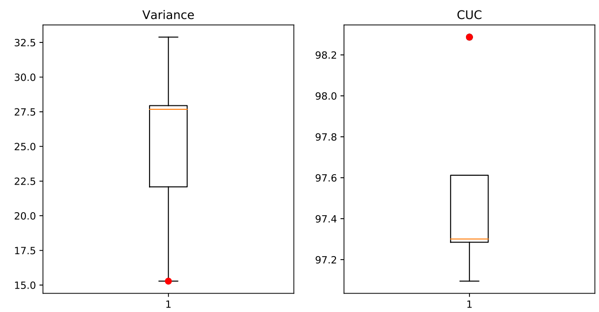

Figure 6: Boxplots showing the variance and CUC for 4 white image projections and 1 correction image. Correction image is the red dot.

4 Discussion & future work

The method described to measure the light intensity for the entire area of projection using a digital camera has shown that the projection is non-uniform and could be compensated for by using a correction matrix $k_{i,j}$. For the scope of this paper, it has only been investigated the uniformity of a pure white image. It would be of interest to repeat the experiment on images with lower pixel intensities.

In order to obtain more accurate measurements and correction matrices, a more stable camera holder should be made to ensure that the camera is moved in exactly equal steps to cover the projection on the resin vat and that the camera is held completely still when taking the set of images.

Furthermore, more sophisticated image stitching algorithms could be used to obtain the exact position of a measurement. This could be done by having a reference image im_{ref} containing many unique features, rather than a checkerboard which contains many similar (non-unique) features. Using the presented protocol, the position images could be mapped to the reference image using a homography [3]. This homography could rather easily be estimated by the feature correspondence between the position image and reference image found using e.g. SIFT features [4]. This more sophisticated image stitching method would prevent overlapping between the sets of images, and could provide an elegant way of depicting missing spots of measurements. This could provide more accurate measurements and correction masks, while reducing the time spent on data gathering.

5 Conclusion

This paper has presented a method for measuring the UV intensity distribution of the entire area of the mask-projection for a photopolymerization system. A new and novel method for measuring the projected light intensities using a digital camera is presented and it is explained how an iterative, relative normalization method can be used for stitching the measurements together to depict the intensity distribution of the entire projection area. Based on this method, it is shown that the projected light is not uniformly distributed such as previously assumed for photopolymerization systems. Furthermore, a formula for obtaining a mask that compensates for the non-uniformity is presented. It is demonstrated that applying this mask compensates for the irregularities performed by the projector, making the mapping more uniformly distributed. Thus, applying this correction image will result in more accurate projections and higher precision in AM.

References

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