Estimating the surface normal of artwork using a DLP projector

KOICHI TAKASE [1] AND ROY S. BERNS [2]

[1] TOPPAN Printing co., ltd.
[2] Munsell Color Science Laboratory, Rochester Institute of Technology

Summary: The surface normals of a flat surface and a work of art were measured by a DLP projector and a traditional collimated tungsten source. The DLP projector resulted in reduced performance, a result of spatial non-uniformity caused by its low resolution. By defocusing the DLP projector, equivalent performance was achieved.

Introduction

Realistic image rendering requires knowledge of a work of art's BRDF, surface normal, and topography. Illuminating the object from a number of angles using a conventional light source and collimating optics enables the estimation of BRDF and surface normal. Often, topography is determined using either a laser scanner or structured light (Batlle et al. 1998, Curless 1999). Thus, two different imaging systems are required for complete characterization. Alternatively, it is possible to use a computer-controlled projector and sequentially display uniform and structured light, thereby reducing the system complexity and cost. However, there are resolution tradeoffs because of the inherent low resolution of projectors. Furthermore, the design differences between LCD, LCOS, and DLP projectors result in differing performance. The most appropriate technology for this approach is a DLP projector, demonstrated by Narasimhan et al. (2008). Experiments were performed to evaluate the accuracy of estimating the surface normal using a DLP projector compared with traditional lighting.

Measurement and Evaluation

Three illumination conditions were used, described in Table 1. A voltage-regulated Oriel 60000 QTH tungsten source with collimating optics was used as the traditional source. The DLP projector was an Optoma EzPro 755, with a resolution of 1024x768 pixels. The camera was a Canon EOS 5D with a resolution of 4368x2912 pixels. The light sources and camera angles were fixed at 40°. Targets were rotated in a single plane using the MCSL three-axis goniometer (2008). The experimental configuration is shown in Figure 1.

Table 1. Illumination conditions.

#	Device	Focus
1	Tungsten light source	-
2	DLP projector	In focus
3	DLP projector	Out of focus

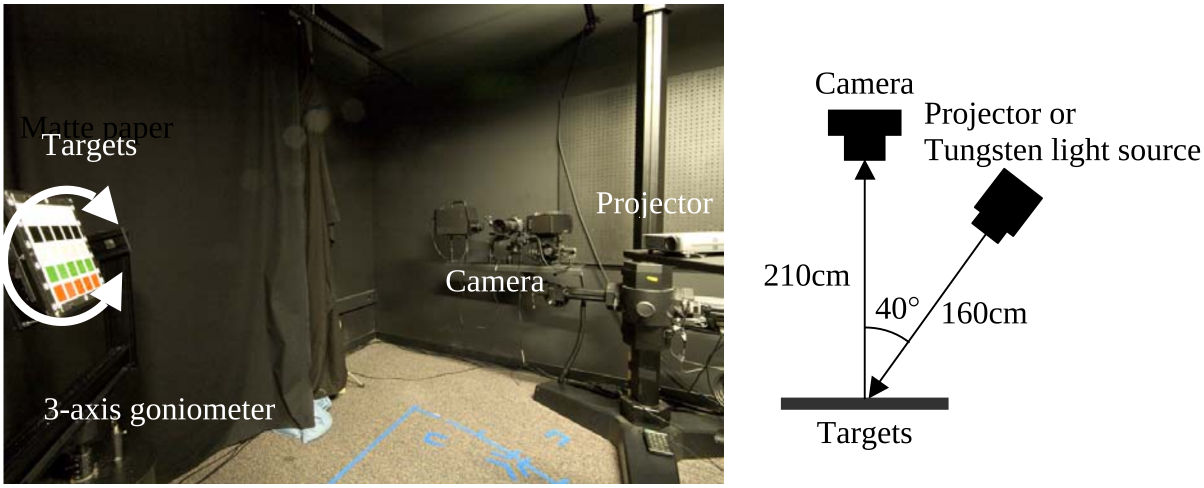


Fig 1. Experimental setup.

Two samples were used in the experiments: a Gray 5.5 Color-aid matte paper affixed to a firm support and a small, unvarnished oil painting. Images were captured at 12 different rotations and the surface normal at each pixel was estimated using photometric stereo methods. See (Reinhard et al. 1998) for a review.

Using photometric stereo methods, the surface normal **n** at each position was estimated as follows:

$$\mathbf{n} = \frac{pseudoinverse(\mathbf{S})\mathbf{l}}{\rho}, \quad (1)$$

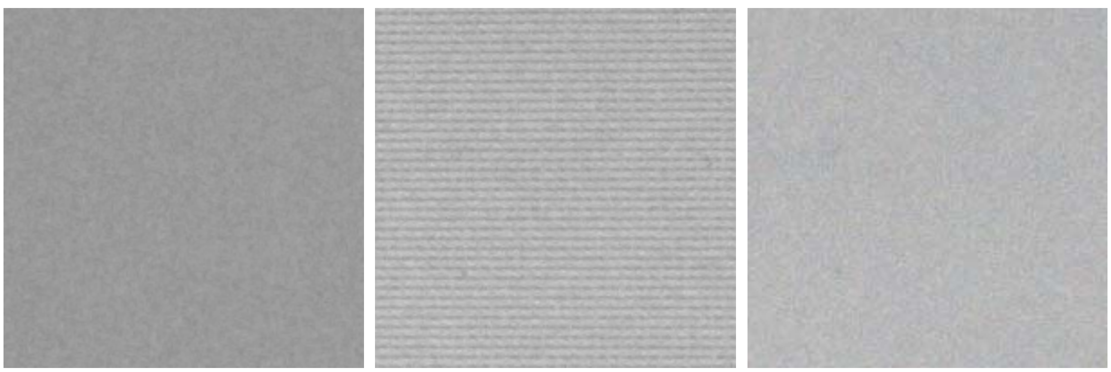
$$\rho = |\mathbf{S}^{-1}\mathbf{l}|, \quad (2)$$

where the function *pseudoinverse* calculates a pseudoinverse matrix of an input, **S** is an n-by-3 matrix, which is composed of *n* illumination direction vectors, **l** is an n-by-1 vector of digital counts for each illumination direction, and ρ is albedo.

In photometoric stereo methods, the light source irradiance is assumed to be uniform. Therefore flat fielding was performed using images of an Avian fluorilon diffuser. The rotated target images were manually aligned, and the surface normals were estimated. A portion of the raw captured images for the matte gray for each condition is shown in Figure 2. Irradiance non-uniformity caused by the low resolution of the focused projector is clearly evident. Because of the non-uniformity, the estimation accuracy in condition #2 was lower than in conditions #1 and #3, as shown in Figure 3. The boxes and the error bars represent mean and standard deviation of the estimation error for each condition, respectively. Although flat fielding could reduce the non-uniformity and remove the radiance reduction caused by camera dust, the flat fielding could not remove the non-uniformity perfectly, which is shown in Figure 4. The estimation accuracy under conditions #1 and #3 was the same because the illumination by the out-of-focus projector was more similar to that from the traditional light source. Example renderings using the estimated surface normals followed by histogram equalization to accentuate differences are shown in Figure 5. The paper was illuminated from 40° by a collimated light source. The bump in the rendered image of condition # 2 could be seen despite the flat surface.

The influence of the number of captured images for the estimation was also evaluated, shown in Figure 6. The accuracy was improved by increasing the number of images since it can reduce the influence of irradiance non-uniformity for condition # 2 and camera noise for each condition.

The surface normals of a work of art were also estimated in each condition. For the artwork, HDR images were captured using multiple exposure times (Debevec and Malik 1997) because a wide dynamic range was necessary to capture the range of reflectance levels found over the surface of the object with a minimum of noise. The images rendered using the estimated surface normals are shown in Figure 7. The bump could be found on the flat portion of the painting in the rendered image of condition # 2, which was caused by the low resolution of the projector. A portion of the canvas bump disappeared or blurred in all conditions. This error was caused by image resampling for image rotation, alignment error, shadows and interreflections. The resampling and alignment problems can be solved by moving the light source instead of the objects.



Tungsten light source DLP projector, in-focus DLP projector, out-of-focus

Fig 2. A portion of raw captured images for the color-aid matte paper.

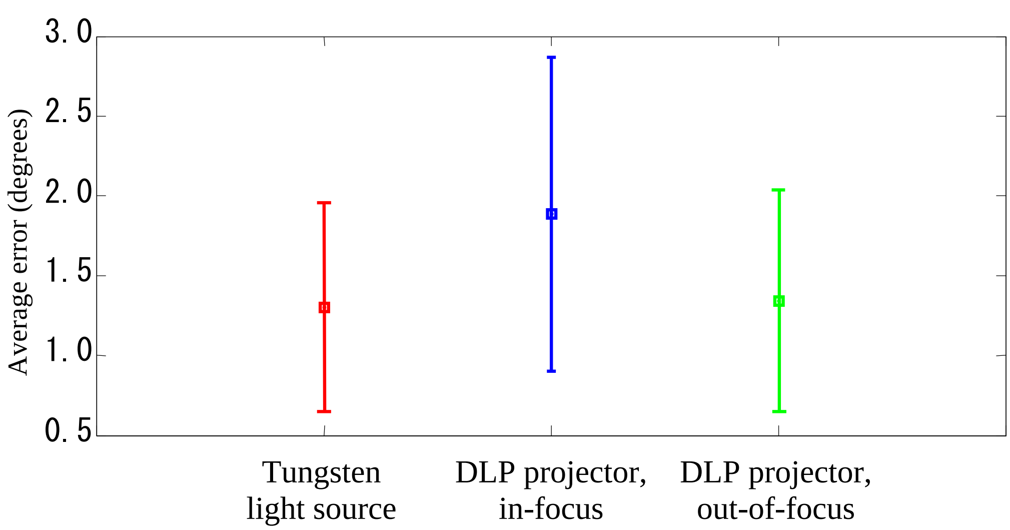


Fig 3. Average error and one standard deviation of surface normal estimation of the color-aid matte paper based on 12 rotation angles.

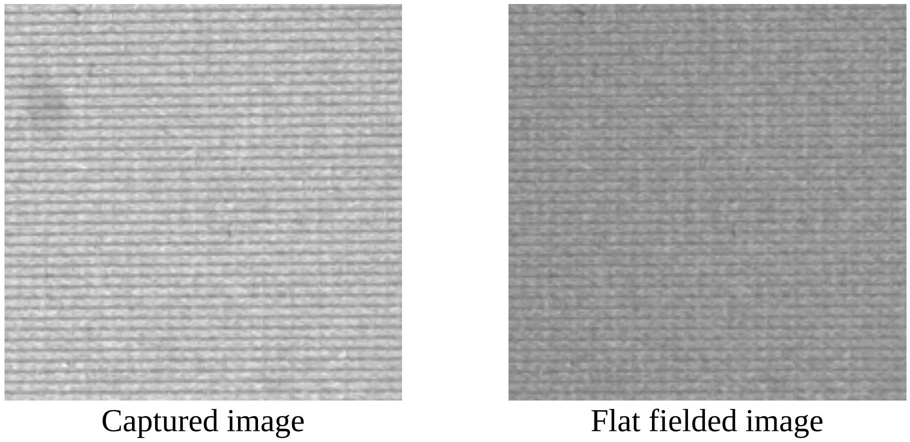


Fig 4. Effect of flat fielding for a DLP projector.

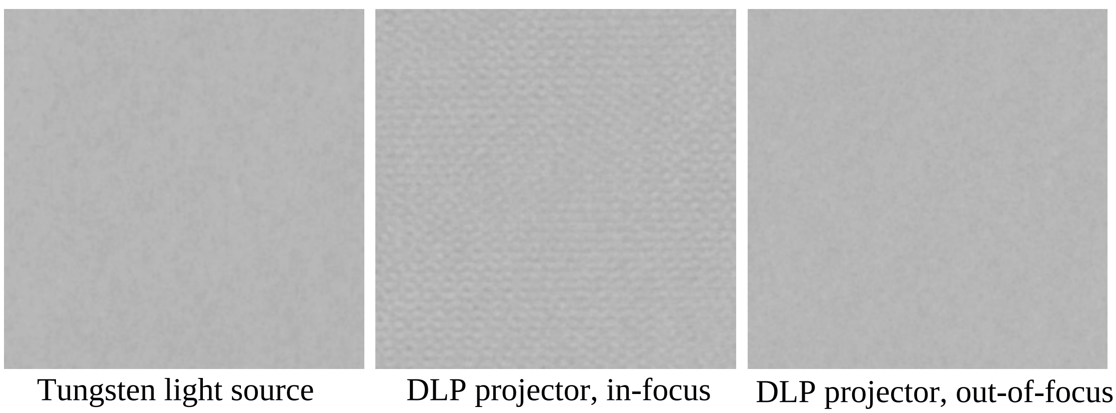


Fig 5. A portion of rendered images using the estimated surface normals followed by histogram equalization.

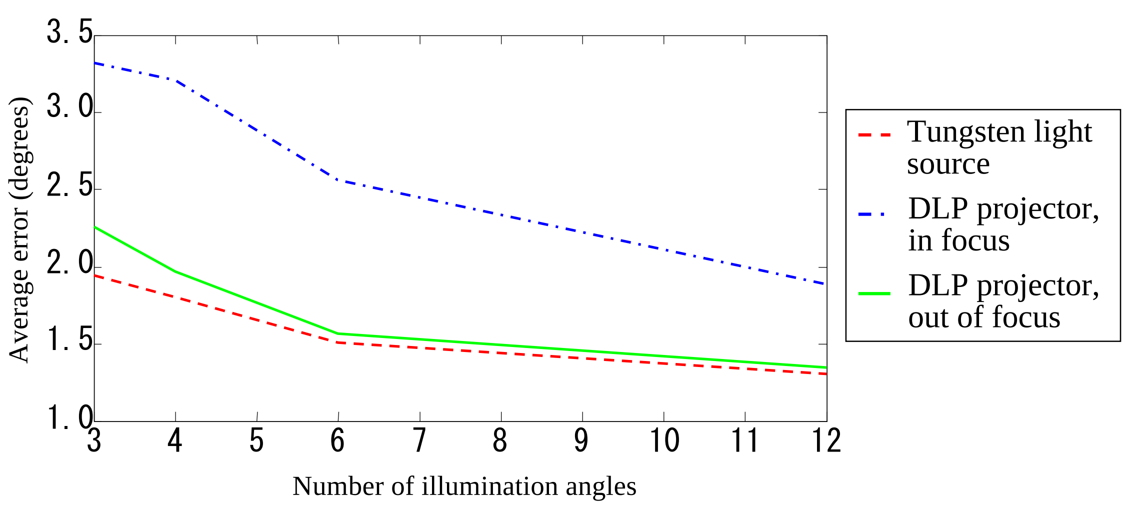


Fig 6. Estimation error as a function of the number of angles.

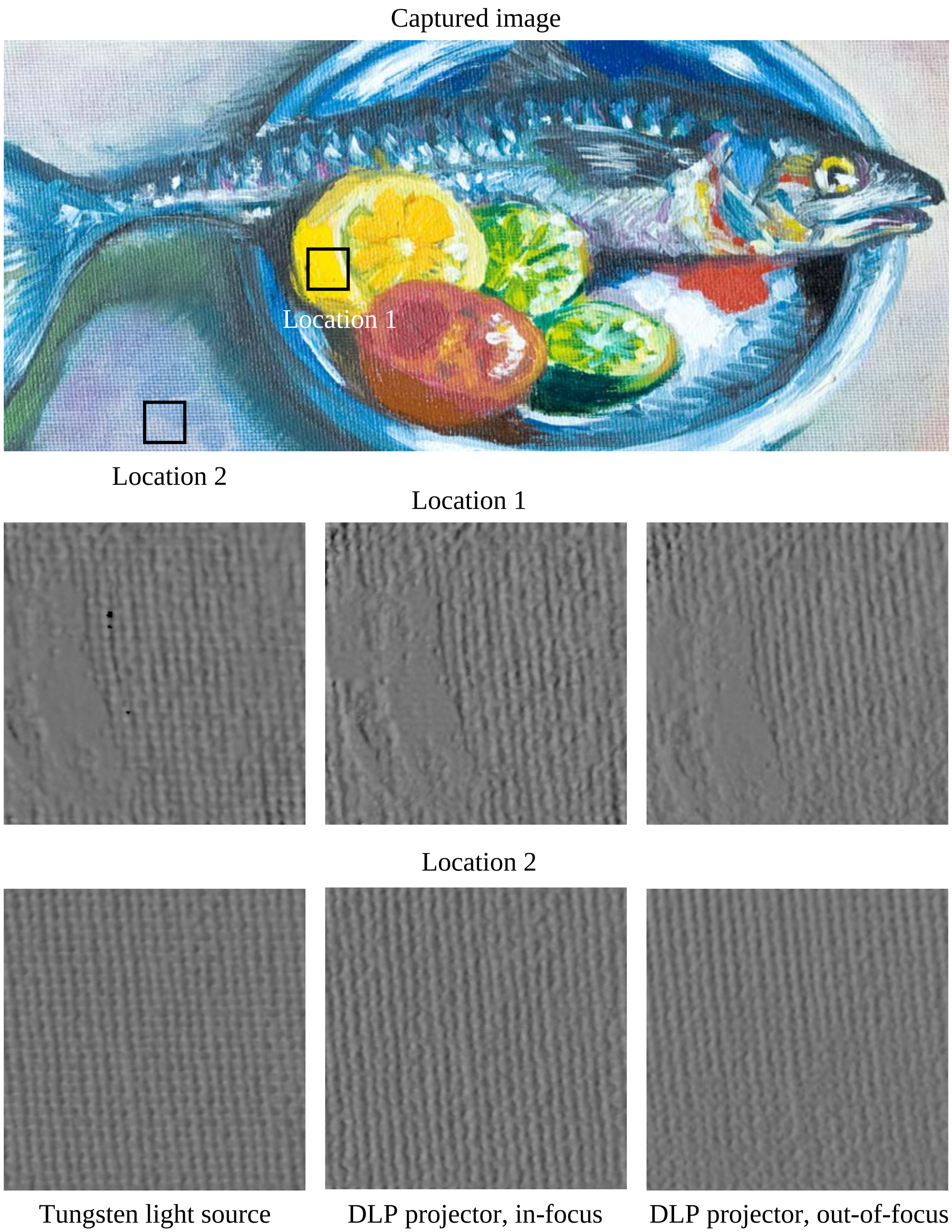


Fig 7. Captured image and image rendered using the estimated surface normals of an unvarnished oil painting on canvas board.

Conclusions

In this research, the accuracy of estimating surface normal using a DLP projector was evaluated. The surface normals of a flat surface and a work of art were measured under three illumination conditions and estimated with a photometric stereo method. It was found that the DLP projector can be used for the measurement of surface normals when it is out of focus. The accuracy of artwork estimation in each illumination condition was low, which was caused by shadows and interreflections. The interreflections can be eliminated with the projector using Nayar et al.'s method (2006). By estimating surface normals without the shadow part in the interreflection-free images, the accuracy can be improved, the subject of our future work.

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Contact information
Koichi Takase
E-mail: kztpci@cis.rit.edu
Phone: 585-475-4443

Roy S. Berns
E-mail: berns@cis.rit.edu
Phone: 585-475-2230
Munsell Color Science Laboratory, Chester F. Carlson Center for Imaging Science,
Rochester Institute of Technology, 54 Lomb Memorial Drive, Rochester, NY 14623