A Mitsuba-based Study on Trade-offs Between Projection and Reflection Based Systems in Structured-Light 3D Imaging

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Abstract: We present a first study on the trade-offs between projection and reflection based 3D imaging systems under diffusive and specular reflection mixtures. Experiments are conducted in our projection/reflection simulator framework using the Mitsuba2 renderer.

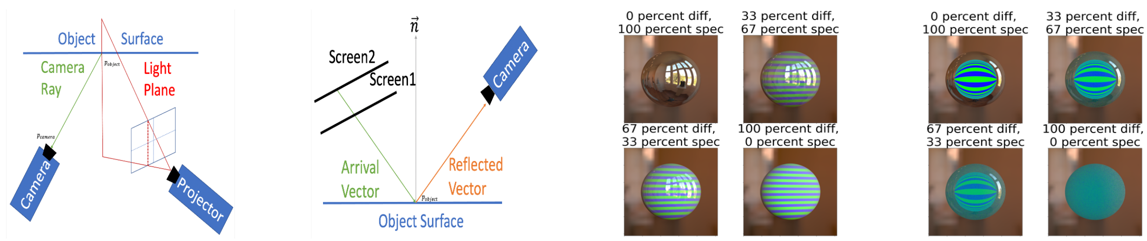
1. Introduction

Three-dimensional (3D) surface metrology techniques have been widely used in many areas, including cultural heritage, medical diagnosis, entertainment, etc [2] [4]. Projection based methods, such as active triangulation [4], are the established methods in surface metrology to reconstruct the 3D surface of smooth diffuse objects. Reflection based methods, such as deflectometry [1], are the established methods in surface metrology to reconstruct the 3D surface of specular, mirror-like objects. Both techniques however, face major challenges from uncooperative materials. Specular reflection raises difficulties for projection based methods as environment lighting interferes with the projected pattern. Reflection based measurement are hindered by diffusive scattering since they introduce blurring to the reflected pattern. Most materials do not fall exactly into the idealized category of either purely specular or diffuse, but instead exhibit a mixture of the two properties. The question then arises that given an object whose material is a particular combination of specular and diffusive reflection, is projection or reflection based techniques more suitable for 3D surface measurement for this object?

In this work, we investigate the trade-off between projection or reflection based systems in 3D surface measurement under different combinations of diffusive and specular reflection. We build a python-based simulation framework using the Mistuba2 renderer [3]. Our framework allows users to a) construct and simulate projection/reflection based setups with the desired camera and projector/screen parameters as well as patterns, b) configure the proportion of diffuse vs specular reflection of the inspected object.

2. Mitsuba-based Projection/Reflection Simulator

In our framework, the scattering property of the inspected object is modeled as a combination of diffuse and specular reflection, where an adjustable weight parameter $w \in [0,1]$ specifying the proportion of diffuse reflection ($w = 0$: pure specular, $w = 1$: pure diffuse). Fig. 1c 1d illustrate the appearance of a sphere with different material settings when illuminated with a projector(Fig. 1c) or screen(Fig. 1d).



(a) Projection System Setup (b) Deflectometry Setup (c) Projector Illumination (d) Screen Illumination

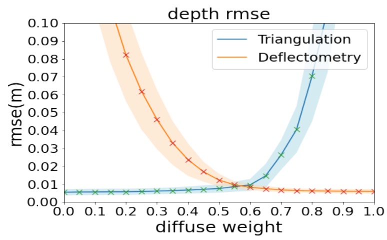
Fig. 1: Experiment setups and simulated images

In our simulation setup, the object is placed within the camera's field of view. The projector/screen as well as an additional environment map serve as the light sources of the scene. We use the "projector" plug-in in Mitsuba2 to set the projector's extrinsics, field of view, and the projected pattern stored in an image. We model the screen as a rectangular emitter, with the displayed pattern stored in an image. For the rendering procedure, we use a Monte-Carlo path tracer integrator. We seed the renderer to ensure deterministic Monte-Carlo sampling. We artificially add 5% Poisson noise to the rendered images post render.

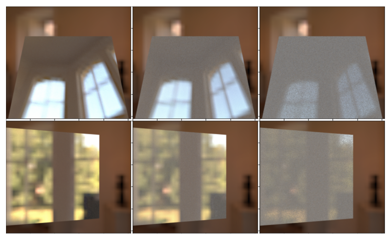
In both methods, we use a sequence of 9 binary greycode patterns. For the projector based triangulation, the surface location is calculated using triangulation between the camera ray and projector light plane, which is decoded from the patterns. In the deflectometry method, we use a shifted screen approach to tackle the normal-depth-ambiguity problem, where the arrival ray is determined by its two intersection points with the screen at two locations (Fig. 1a). For each screen location, we use greycode patterns in two directions to find the ray intersection points between the arrival ray and the screen. Using the two ray screen intersections we get the arrival ray. We then find the least square intersection between the camera ray and the arrival ray to compute the surface location (Fig. 1b).

3. Experiments

To test our results, we generated 100 plane shapes with random size, orientation, and position, and we run both triangulation and deflectometry depth reconstruction. We use Mitsuba2's position integrator to produce ground truth depth maps for each setup. For each shape and material profile, we calculate the root mean-square error(RMSE) of the calculated depth vs. the ground truth depth. We then plot the mean and sigma of the RMSE value of the 100 random shapes obtained at each material configuration for the two methods. The objects inspected are within a bounding box of size 1.5m.



(a) Depth RMSE error vs. material properties



(b) Sample planes with 0.1, 0.5, 0.9 diffuse weight (left to right)

Fig. 2: Experiment Results

As the material property deviates from the optimal setting for each method, both the average and sigma of the RMSE increases. We can see that the error does not increase much when the desired scattering property is more than 50 %. This is related the robustness to noise when using a binary pattern. However, for both methods, when the desired scattering property weight falls under 0.5, the rate of degradation in reconstruction quality gets increasingly higher. This shows that as factors of noise for both methods start to dominate the imaging, we get more imprecise and erratic reconstructions. We can also see the deflectomery method performs better than active triangulation when the diffuse weight in under 0.55 (more than 45% specular reflection), while the active triangulation method is superior when there is more than 55% diffuse scattering.

4. Discussion and Outlook

In this work, we introduced our framework for simulating projection and reflection systems for 3D imaging, and demonstrated our framework by performing a first study on the trade-offs between projection and reflection imaging systems under different material mixtures of diffuse scattering and specular reflection. Looking forward, we would also like to use this framework to investigate 3D surface metrology in more complex materials, such as transparent materials (glass), and materials with sub-surface scattering (skin, wax).

References

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