Microscale Optical Capture System for Digital Fabric Recreation

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Abstract: Synthetic images are ubiquitous in the world, being extensively used in advertising, industrial design and prototyping. However, automatic digital reproduction of fabrics is still an open problem in industrial contexts, due to the inherent complexity of cloth appearance. We present a system to capture images of fabrics at micron resolution, lit from a set of collimated beams of LED luminaires distributed along the hemisphere. The system ensures plane wavefront with a 1:1 magnification while minimizing self-occlusions. It also allows for specular and diffuse light components separation through polarization, has a very accurate focusing system and a shallow depth of field for depth extraction. We demonstrate the system is suitable for later extraction of geometric and optical properties of the cloth at the fiber level, which is the main requisite for high fidelity photo-realistic cloth rendering.

1 INTRODUCTION

Cloth rendering is a very active research area in computer graphics, and is becoming of increasing interest of many other fields. This is because digitally reproducing the appearance of fabrics has many applications not only in the entertainment industry but also in the context of textile design and manufacturing. However, the appearance of cloth is the result of complex light scattering interactions that occur within the micro-structures present at the fiber level in textiles (Aliaga el al. 2017). Thus, micro scale optical capturing systems are needed for accurately extracting the geometric and optical properties of the fabric that allow to reproduce the appearance under any lighting condition, allowing rendering solutions that reach the scale of fibers, (hundreds of micrometers), to gain accuracy and predictive power (Zhao et al. 2011).

Most existing devices are targeted to capture generic surface-like (without volumetric structure) materials at a millimeter scale, usually focused in extracting the surface normals and its reflectance, the latest in the form of a Bidirectional Reflectance Distribution Function (BRDF) that can be spatially varying (SV-BRDF). For this, digital cameras are used to capture images with basically two approaches. One of them uses multiple viewing and lighting directions covering the hemisphere centered in the normal of the material surface in order to recover the Bidirectional Reflectance Distribution Functions (BTF). The other one relies on a single fixed view and multiple light sources. All these systems commonly work with small magnification relations (Schwartz et al. 2014), since they are interested in recovering the SV-BRDF or the BTF because they need a number of different viewing directions. This implies many issues related to depth of field at grazing angles, particularly critical when trying to reach very fine resolutions. Thus, these kind of solutions are very useful for mid-distance (a meter) material appearance modeling, but do not provide small enough pixel size to take the real details, and therefore are not well suited when the goal is to extract geometric and optical properties for later use in a realistic rendering context, for instance in the case of realistic fabrics.

Very few works present a microscale optical capturing system. A recent example is the work of Nam and colleagues (Nam et al. 2016). They implement cameras with macro lens, leading to very short optical working distances that allow reducing the dimensions of the system up to a few tens of millimeters. Their system uses multiple LEDs and a fixed viewing direction, working with up to 5:1 magnification. All components are built in a 40 mm

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radius dome and captured sizes are of the order of 2 millimeters.

However, systems with such small dimensions are not always suitable for predictive rendering in the context of textile industry. The reason is that cloth can be seen as a structure tiled along the material, and such minimum tileable structure can often be much larger than 1-2 mm for a great percentage of fabric types. Thus, the capturing system needs a compromise between magnification and sample size. This is not simple to accomplish due to the thickness that some fibers can present, some below 5 microns, and the self-occlusions of the system at such short working distances.

Relevant optical parameters for microscale capturing systems are the divergence of the incident lights and the acceptance angles for the captured light. For industry purposes, exposure times become also critical. All of them are related to the dimension of the sample and the distances from the light sources and the camera to the sample. As distances become shorter and/or samples become larger, divergences and acceptance angles increase. The impact of these optical factors on the accuracy of the measured reflectance can be relevant, impairing final results of the rendering processes.

Having in mind these considerations, we present in this paper a novel microscale optical capturing system with low divergence (1º) of the incident light and low acceptance angle (<8º) of the captured light. It has 75 collimated high power white LEDs as light sources at a distance of 650 mm from the sample. The image is captured by a digital camera using 50 mm focal objective with a 25 mm length extension tube. This provides a working distance of 100 mm and at the same time maintains x0.5 magnifications for microscale captures, with an image size of 4x4 microns per pixel.

Because of the dimensions of the structure, the optical system also makes possible a simple polarization analysis by separating diffuse and specular light components, and depth analysis using focal stacks thanks to its very shallow depth of field. The design of the system makes it robust to vibrations and takes into account all the mentioned optical factors in order to assure a suitable system specialized for capturing fibrous materials like fabrics. It improves previous approaches for such goals, and it is optimal for capturing high quality data that can be used to achieve realistic rendering fabrics.

2 MESUREMENT SYSTEM

The microscale optical capturing system consists of four main different parts: mechanical structure, lighting system, image capture system and holder.

2.1 Mechanical Structure

The whole system (Figure 1) is a 1.2 m diameter hemisphere-shaped structure, built with black anodized aluminum profiles. There are nine aluminum arms, formed by nine sections, which support the "theoretical" 81 light modules pointed towards the target fabric. Due to the occlusion of the camera, it will eventually be 75 light.

This design removes most secondary reflections, which could interfere with a measurement, adding wrong illumination to the fabric to be sampled.

Figure 1: Optical capture system.

This structure is completely isolated from the fabric holder and the camera support, in order to avoid any mechanical vibrations during the capture.

2.2 Lighting System

Each of the light modules consist of several pieces: a high power white LED, a collimating lens, a linear polarizer, and a 3D printed case (see Figure 2). These cases are attached to the structure at regular intervals and can be suitably aligned towards the target.

The lighting modules have been designed to produce a low divergence incident beam. The 20 mm effective diameter, 16 mm focal lenses, combined with the 3x3 mm LEDs, result in an exit beam divergence of 5º (blue in Figure 2):

$$D = \frac{Source\ radius}{focal\ length} = \frac{\frac{3mm}{2}}{16mm} = 0.09\ rad \cong 5° \qquad (1)$$

However, as the size of the captured target image is 10x7.5 mm, at a distance of 650 mm from the source, the divergence of the incident beam is 1.3º horizontal and 1º vertical (green in Figure 2):

$$D' = \frac{Sample + lens\ diameter}{2\ x\ distance} = \frac{10 + 25mm}{1300mm} = 0.03\ rad \cong 1.5° \quad (2)$$

In the end, the effective divergence on the target will be lower, as this is only the divergence of the limiting rays. In Figure 2, yellow lines corresponds to a perfect collimated beam from a point light source.

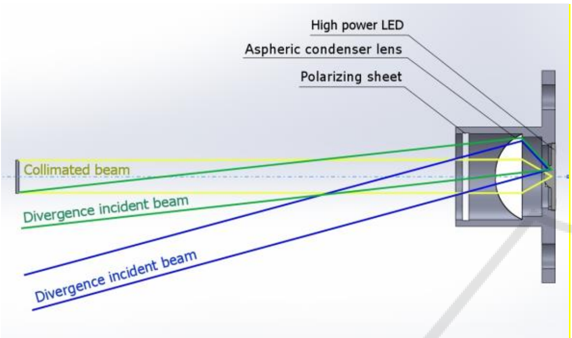

Figure 2: Lighting modules and beam divergence.

The linear polarizer can be manually rotated to adjust the polarization to that of the polarization analyzer placed on the camera, allowing to separate light components in later post-processing. Additionally, the LEDs are uniformly distributed at 18º intervals, making possible the illumination of the target with many incoming light directions over the hemisphere.

2.3 Image Capture System

Given the thickness of the individual fibers forming the cloth, most of the times in the order of microns, we have designed the capture system with a resolution of 4x4 microns per pixel. At the same time, the system should be able to capture images of around 10x10 mm in size, in order to determine the fabric structure of the yarn level, which is usually in such range of sizes.

We use a Mightex SME-B050 monochrome camera, with a 2560x1920 resolution and a 2.2x2.2 um pixel size. A 50 mm focal lens with a 25 mm extension space provide 0.5 magnification at a distance of 100 mm. The space works as an extension tube and is key to achieve a large working distance without losing magnification. Such large distance is required to avoid the systems to cast shadows on the

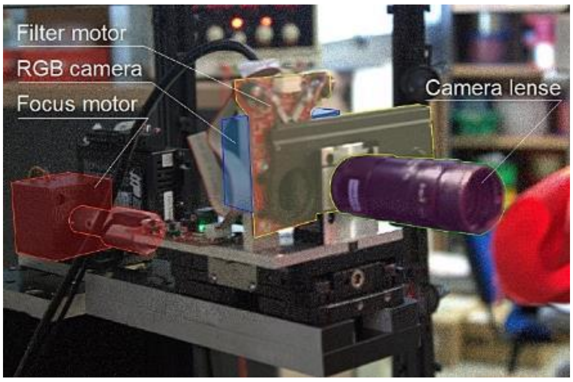

Figure 3: Image capture system.

fabric sample, that is, reducing light occlusions to the minimum possible.

A multi-position motorized filter slider with three RGB filters has been placed at the space between camera and lens. With these filters, we can perform color analysis without the loss of resolution due the placement of the pixels in the mosaic of a color sensor (Bayer pattern).

In addition, a polarization analyzer consisting of two crossed linear polarizes can be placed in front of the lens, with the aim of separating specular and diffuse light component, taking advantage of the depolarizing nature of light paths after a number of bounces or interactions with the medium.

Finally, the whole capture system is mounted over a motorized linear travel stage, providing automatic camera focus. This also allows to perform depth analysis of the fabric samples by using focal stacks and depth from defocus techniques.

2.4 Fabric Holder

The fabric holder (Figure 4) can be displaced using an XY translation mount to capture different fabric sections. It can also be rotated to capture both sides of the sample. The holder has also been design to meet the requirement of minimal light occlusions that could shadow the target.

3 CALIBRATION AND QUALITY TESTS

This section describes the series of tests performed to ensure the correct performance of our measurement system.

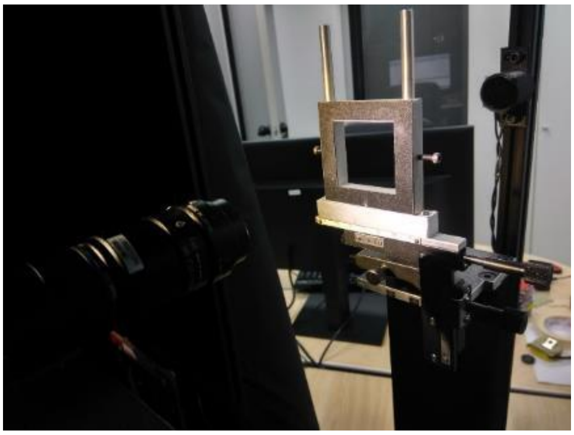

Figure 4: Fabric holder.

3.1 USAF Resolution Test

The optical resolution of the complete optical system has been measured, using the standard 1951 USAF resolution test (Figure 5 a), to be 7-5, which is equivalent to 203 line-pair/mm. Therefore the resolution of the system is limited only by the camera pixel size (454 pixels / mm), and not by the lens and extension used.

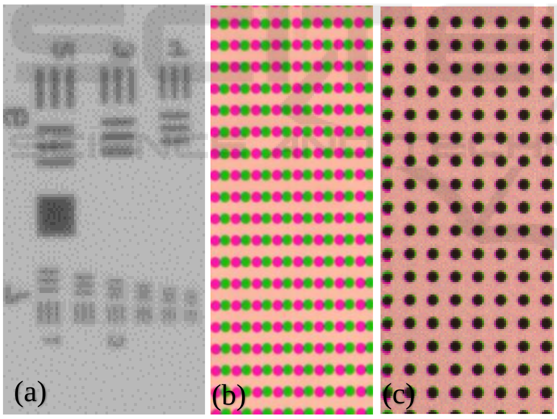

Figure 5: Captures of 1951 USAF test (a) and spacing grid displaced (b), and corrected (c).

3.2 Fixed Frequency Grid Distortion Targets

A 125 µm uniform spacing grid has been used to evaluate image distortion and chromatic aberration and displacement. This test shows that the distortion is under the resolution level of the system in the whole image.

We observe, however, chromatic aberration and image displacement when using different RGB filters. Both are repetitive and can be easily corrected (Figure 5 b,c). The chromatic aberration is corrected by changing the working distance of the camera for each filter with the motorized linear stage. The displacement is fixed during image processing.

These corrections remain constant, so they only had to be determined once, during a calibration process.

3.3 LED Uniformity Analysis

The lighting system uses XP-L2 Cree white LEDs. We have tested their uniformity, both in power and color, using a *Laser 2000 Smini* spectrometer, with a 225 to 1000 nm spectral range. The average color temperature of the LED batch was 5639 K with a standard deviation of 367K (Figure 6). The luminous flux was 245 lm on average with a standard deviation of 43 lm.

These variations have been calibrated and the results used during the image processing stage to correct non-uniformities.

6102	6650	5108	5544	5831	4964	5103	5513	5233
5731	5936	5769	5515	5613	5251	5382	5114	5871
5564	5894	5357	5406	5120	5270	5545	5442	5853
5682	6064	5636	5147		5287	6361	5817	5487
5480	5909	5047				5676	5569	5824
5217	6242	5316	5263		5109	6091	5312	5551
5653	6207	5431	5854		5608	5870	5697	6211
6010	6171	6178	5708	5981	6198	5838	5540	5403
5317	6087	5588	5745	6090	5668	5801	5352	5710

Figure 6: LED color temperature calibration.

4 CAPTURED IMAGES

We show below some of the images captured with our systems. Figure 7 shows images obtained directly from the camera for a given illumination angle. Already showing how some specific types of fibers (e.g. fly out fibers) emerge under particular lighting conditions.

For geometric extraction purposes, diffuse lighting becomes very useful instead of direct collimated light. Taking advantages of the additive nature light, Figure 8 show the composite images obtained combining the frames taken under each of the 76 possible incoming light directions.

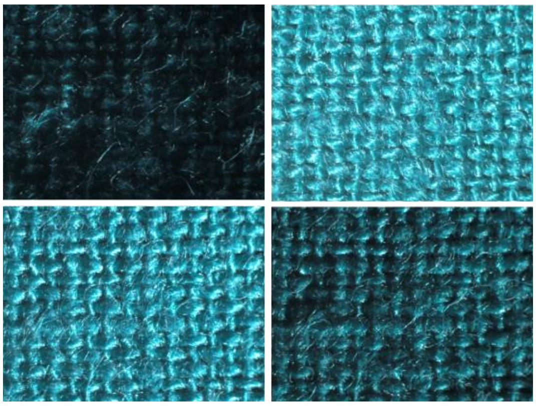

Figure 7: Images of a sample under four different incoming light direction.

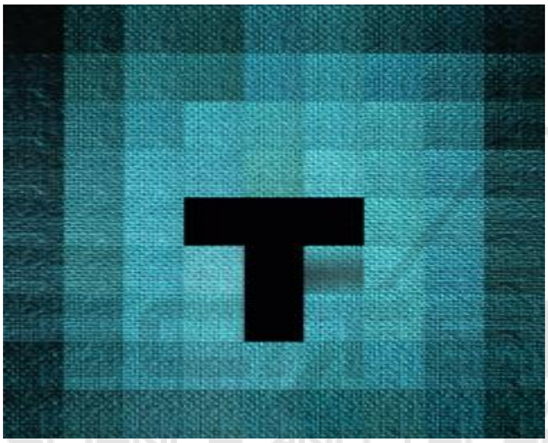

Figure 8: Composite images of the 75 different angle captures. The black images of the center are due to the occluded LEDs.

5 RENDERING RESULTS

The data obtained with the presented optical capture system are well suited to extract the geometric and optical properties of the fabric at the fiber level. These properties are then used as input for a photo-realistic rendering engine based volumetric path tracing, and the preliminary tests show compelling results (Figure 9). Essentially, the engine simulates the light transport at the scale of fibers, also modeling the anisotropic light scattering patterns at micron scale. Such properties are properly extracted with the presented device, which provides enough resolution, small enough pixel size and good level of light collimation to meet our requirements.

Figure 9: Synthetic recreation of a garment using our rendering engine and the geometric and optical parameters extracted by the presented optical capture system.

6 CONCLUSIONS

We have designed and built a microscale optical capture system. It meets the resolution and size requirements for a realistic cloth rendering, while keeping the incident beam divergence around 1º.

The design of the system makes it robust to vibrations, and a proper calibration of the system corrects all deviations due to LED non-uniformities, and lens and filters chromatic aberrations and displacements.

The system makes possible a polarization analysis of light for specular and diffuse reflection discrimination, also allowing to perform a depth analysis using focal stacks of the fabric thanks to a precise control over the working distance of the camera. The captured images demonstrate the system reaches the required quality for fabric digital reproduction purposes, as the preliminary renderings using this technology show.

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