Interactive Appearance Manipulation of Fiber-based Materials

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Abstract: Achieving a visually appealing experience for the user interaction with photo-realistic digitized micro-fiber materials is a challenging task. While state-of-the-art high-quality fabric modeling techniques rely on complex micro-geometry representations that are computationally expensive and not well-suited for interactive rendering, previous interactive reflectance models reach a speed-up at the cost of discarding many of the effects of light exchange that significantly contribute to the appearance of fabric materials. In this paper, we present a novel, example-based technique for the interactive manipulation of micro-fiber materials based on bidirectional texture functions (BTFs) that allow considering fine details in the surface reflectance behavior. BTFs of the respective material sample are acquired for varying fiber orientations and combined to a single texture representation that encodes material appearance depending on the view and light conditions as well as the orientations of the fibers. This model can be efficiently evaluated depending on the user input which, as demonstrated by our results, allows a realistic simulation of the interaction with micro-fiber materials in real-time.

1 INTRODUCTION

Due to their wide-spread application for e.g. cloth, towels or furniture, textiles are among the most important materials we encounter in our daily life. With the ongoing trend towards the creation of realistic content for industrial applications in entertainment or advertisement, there is also an industrial demand for accurately capturing the characteristics of textiles as well as modeling the changes in appearance that are induced by user-manipulations.

When considering textiles, their structural and optical complexity can be seen in the huge number of individual variants ranging from micro-fiber materials to fluffy carpets. It is not only the reflectance behavior of the individual fibers but also the surface structures at different scales that determine the appearance of textiles. While larger structures such as the involved yarns influence the appearance characteristics of fluffy carpets, there is no such yarn level present for micro-fiber materials and, instead, the orientations of the small fibers on the surface have a major influence on the reflectance behavior. Unfortunately, accurately modeling textile materials is challenging as complex, mesoscopic effects of light exchange such as the self-masking, self-occlusions, scattering within the fibers and parallax effects induced by the fibers occur at the surface. State-of-the-art approaches typically rely on representing the micro-scale geometry of fabrics in terms of high-resolution volumes, fiber curves or procedural, fiber-based models which carry the burden of high computational demands.

An even more challenging scenario includes the additional interactive manipulation of digital material representations. As we all know, moving fingers over micro-fiber materials induces a change in the structure of the underlying material, i.e. the small fibers are redirected according to the orientation of the movement while certain constraints such as a possibly dominating fiber structure due to the manufacturing process are met. The re-orientation of the fibers, in turn, leads to a change in appearance when being touched. In this paper, we aim at reproducing this painting-like interaction for digitized materials.

Unfortunately, the computational effort of the above-mentioned high-quality fabric modeling techniques renders them impractical for an interactive manipulation in real-time. To overcome this problem, we present a novel, example-based technique for the interactive manipulation of micro-fiber materials. Our approach is based on the observations that already a small number of equilibrium states of fiber orientations are sufficient to describe the complex appearance of a fiber-based material and that painting-like interactions with the material change these states. This, in turn, changes the appearance in the corre-

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sponding area. Furthermore, we argue that direction-depending reflectance characteristics as given by oriented fibers can be rendered photo-realistically using bidirectional texture functions (BTFs) (Dana et al., 1997) that capture mesoscopic effects in their data-driven representation. Therefore, we represent the appearance of the individual states of the material using BTFs but other representations such as spatially varying bidirectional reflectance distribution functions (SVBRDFs) or anisotropic microflake models (Jakob et al., 2010) might be used as well. Our example-based technique allows for the interactive manipulation of micro-fiber materials by combining the individual BTFs into a single representation that can be evaluated in real-time and allows a realistic simulation of the interaction with micro-fiber materials. In terms of realism, our approach clearly outperforms previous approaches for the interactive manipulation of micro-fiber surfaces (Velinov and Hullin, 2016) that rely on SVBRDFs and cannot reproduce fine details of light exchange induced by the fibers.

2 MICRO-FIBER MATERIALS

With our approach, we focus on micro-fiber materials such as velvet, plush, flannel, towels, suede and alcantara. Some examples are shown in Figure 1. These materials are characterized by loose micro-scale fibers of different lengths that are not aligned with the underlying macroscopic surface geometry. Depending on the manufacturing process, these fibers might have certain dominant orientations. These orientations can be influenced by external forces such as tactile user interaction. Pressing and moving e.g. with a finger over such materials gives the impression of a painting-like interaction as the fiber orientations are changed. After leaving a certain region with the finger, the fibers in this region re-orient to an equilibrium state that is responsible for the appearance, i.e. the reflectance behavior of the material in the corresponding area. Depending on the equilibrium state, the fibers also might occlude each other, cast shadows and produce interreflections. This leads to variations in material appearance depending on the orientations of the fibers and the respective view-light conditions.

Figure 2a) shows a material with a predominant fiber orientation in its initial state. In this example, the dominant fiber orientation is not upright but rather along a certain direction over the surface. User interaction in terms of sweeping the fingers over the material into or against the dominant fiber direction induces different equilibrium states of the fibers that influence the appearance as can be seen in Figure 2b).

Figure 1: Exemplary samples for micro-fiber materials.

Figure 2: Illustration of the appearance changes due to different fiber orientations: (a) initial state where the fibers are mainly oriented upright, (b) state where the fibers are brushed along and against the dominant fiber orientation defined by the material structure, and (c) state where the fibers are brushed perpendicular to the dominant fiber orientation and along the opposite direction.

If the manipulation is carried out perpendicular to the dominant fiber direction, the appearance does not change if the direction is inverted (see Figure 2c)). For some materials, additional states have to be taken into account, e.g. if pressure is applied.

The key observation demonstrated by this example is the fact that for a large number of micro-fiber materials it is sufficient to consider only a finite number of states. Depending on the material characteristics, this number might vary but is expected to be rather small. For example, if the material has no dominant fiber orientation, the consideration of the initial state where the fibers stand upright and the state where the fibers are brushed along an arbitrary direction is sufficient. Capturing the states relevant for a certain material hence allows the interactive synthesis of the digitized counterpart of the material.

3 RELATED WORK

Our approach represents a connection between the photo-realistic modeling and rendering of fabrics and the interactive material synthesis. In the following, we discuss the most related work in these domains.

Appearance Representation for Textile Materials. Due to the wide-spread use of fabric materials in graphics applications in visual prototyping, advertisement or entertainment, the realistic appearance modeling of fabrics has gained attention and intensively investigated in the literature. We only briefly discuss the most recent developments and refer to respective surveys (Yuen and Wünsche, 2011; Schröder et al., 2012) for more detailed discussions. While early investigations focused on BRDF-based microfacet models (Ashikmin et al., 2000), recent state-of the-art techniques rely on the modeling of the micro-scale geometry of fabrics using volumetric scattering models (Schröder et al., 2011; Jakob et al., 2010; Zhao et al., 2011) and fiber-based models (Irawan and Marschner, 2012; Sadeghi et al., 2013; Khungurn et al., 2015; Schröder et al., 2015; Zhao et al., 2016). The latter approaches can be used in combination with BRDF models, models based on bidirectional fiber scattering distribution functions (BFSDFs) or models based on bidirectional curve scattering distribution functions (BCSDFs) for modeling the reflectance behavior of the individual fibers.

The reason for the success of such micro-scale models lies in the detailed consideration of individual characteristics such as fiber orientations and reflectance behavior of the individual fibers which allows to accurately represent the light exchange on fabric surfaces. However, such high-quality fabric models have high computational demands as well as high memory requirements and, hence, cannot be used for real-time rendering but only for static scenes. In contrast, the interactive simulation of fabrics requires more light-weight reflectance models as e.g. the adjustment of millions of fibers and the recalculation of the light exchange are too costly even for current graphics hardware. With the goal of speeding up the times required for the rendering of fabrics, bidirectional texture functions have been synthesized based on known micro-geometry in (Schröder et al., 2013). Since their introduction (Dana et al., 1997), BTFs have become a popular data-driven reflectance model for the photo-realistic depiction of a huge variety of materials with a surface reflectance behavior ranging from diffuse to glossy to even local subsurface scattering characteristics. A BTF represents the reflectance behavior at the spatial position $\mathbf{x}$ on the object surface depending on the direction ω_l of the incoming light and the view direction ω_v and is therefore defined as a six-dimensional function $\rho_{BTF}(\mathbf{x}, \omega_l, \omega_v)$. For detailed surveys on BTFs, we refer to (Haindl and Filip, 2013; Schwartz et al., 2014; Weinmann et al., 2016). BTFs are parameterized on a flat approximation of the true surface. This allows capturing mesoscopic effects of light exchange such as self-occlusions, self-shadowing or interreflections that occur in surface scratches of fiber-based materials as well as local subsurface scattering in the data-driven reflectance representation. While it is well-known that BTFs can be efficiently compressed (Müller, 2009) and used for interactive object visualization (e.g. (Schwartz et al., 2013a)), the editing of BTFs is difficult. The latter is the the reason for the development of other approaches that use simpler reflectance models based on SVBRDFs. Most closely related to the goal of our work is the fitting of an anisotropic SVBRDF model based on a single-layer microflake model that can be edited interactively by manipulating its parameters (Velinov and Hullin, 2016). While this technique aims at a small memory consumption and high rendering speed, this has been achieved at the cost of not accurately modeling the aforementioned mesoscopic effects, that contribute to the appearance of micro-fiber materials. While such fine effects of light exchange are captured in the image-based BTF, including such effects in an SVBRDF-based representation would require the explicit modeling of fine surface details in the geometry.

In contrast, our approach is directly based on BTFs that are acquired using state-of-the-art acquisition devices and do not require the fitting of a micro-fiber model. In order to allow an interaction with the respective material, several BTFs acquired for different states of possible fiber orientations are combined into a single model and, during the interactive synthesis, texture lookups are used to achieve a visually pleasing impression of the material appearance. As we use BTFs, we have a higher memory footprint but still achieve interactive rendering performance while considering the aforementioned effects. Therefore, our results yield a better visual experience of the material characteristics. To the best of our knowledge, our approach is the first interactive framework for manipulating fiber-based materials using BTFs.

Interactions with Texture. Interactions with texture has become a well-studied topic. The most recent approaches include the interactive, data-driven high-fidelity painting system *RealBrush* (Lu et al., 2013) and the interactive, example-based texture painting approach presented in (Lukáč et al., 2015). The latter approach allows to transfer textures with dominant orientation features onto user-specified, global direction fields while preserving local texture structures. While in this work only directional features of 2D textures are exploited to generate new textures that follow a user-specified direction field, our technique allows to interactively modify the direction field and at the same time synthesize novel textures from a set of pre-defined textures that represent different equilibrium states. This way, it allows for the manipulation of complex surface reflectance characteristics.

Time-varying or Interactive Material Synthesis. Many applications consider time-varying material appearance. Seminal work focused on modeling changes in appearance for burning, drying, corrosion and decaying processes and proposed the first densely measured database of time and spatially-varying appearance of flat samples (Gu et al., 2006). Similar effects were considered in (Sun et al., 2006) with the drying of different paints or wet surfaces such as cement, plaster and fabrics, and the accumulation of dusts on surfaces and the melting of materials such as chocolate. In both works, flat materials were considered and analytical BRDFs were fit to acquired measurements performed under varying view-light conditions and at multiple time instances. Furthermore, time-varying BTFs have been proposed that also consider mesoscopic effects (Langenbucher et al., 2010).

Interactive material design has been studied by considering manipulations on both small-scale geometry and materials (Wu et al., 2011). However, scattering effects that are important for accurate appearance reproduction at small-scale structures as well as anisotropic material characteristics are not considered. More recently, variations in material appearance induced by interactive user manipulation have been modeled based on an anisotropic SVBRDF model (Velinov and Hullin, 2016).

4 METHODOLOGY

In this section, we first provide an overview of the proposed technique and subsequently discuss the respective key components in more detail.

The main components of our techniques are illustrated in Figure 3. In a pre-processing stage, we acquire micro-fiber materials in different states such as different fiber orientations (see Section 2) using a state-of-the-art reflectance acquisition device. This results in the computation of one BTF for each equilibrium state of the fibers. The resulting BTFs are then combined into a single texture array that holds the information regarding the appearance of a respective material under different view-light configurations and different orientations of the fibers. In the final online stage, an interactive appearance simulation takes the per-material texture array to specify an initial configuration of view and light conditions as well as the fiber directions and allows the user to virtually brush the material with his/her fingers and change the view and light conditions, while the appearance changes accordingly.

4.1 Reflectance Representation and Acquisition

As the reproduction of fine details in the reflectance behavior induced by the individual fibers is of utmost importance for a visually appealing impression of the material, we focus on the use of BTFs for modeling the reflectance behavior of micro-fiber materials. In particular, we measure an individual material sample several times for different fiber states τ with a standard acquisition device (Schwartz et al., 2013b). A material sample with a certain fiber state τ is placed onto a turntable and observed by eleven cameras that are mounted on an arc with increments of 7.5° and have a resolution of $2{,}048 \times 2{,}048$ pixels. After an initial structured light based acquisition of the approximate surface, the 198 LED light sources mounted on the upper hemisphere are used to sequentially illuminate the material sample from different light source positions while the material sample is captured by the cameras under different turntable rotations. After the acquisition, we project the captured HDR images onto the surface which is followed by a resampling of the data into local coordinate systems at each surface point and a final Decorrelated Full-Matrix-Factorization (DFMF) compression. During the compression, an SVD is computed for each color channel after a conversion into the YUV color space, which results in Eigen-ABRDFs and Eigen-Textures. From these, the most informative ones are kept to achieve the compression. Finally, this results in an individual BTF for each of the fiber states. In order to obtain a single reflectance representation that also encodes the changes in reflectance behavior induced by the fiber characteristics in addition to the view and light directions, these BTFs $\rho_{BTF_\tau}(\mathbf{x}, \omega_l, \omega_v)$ are merged into a single BTF $\rho_{BTF}(\mathbf{x}, \omega_l, \omega_v, \tau)$ that additionally includes the dependency on the fiber state τ.

4.2 Interactive Simulation

The data-driven representation resulting from the previous step models material appearance depending on

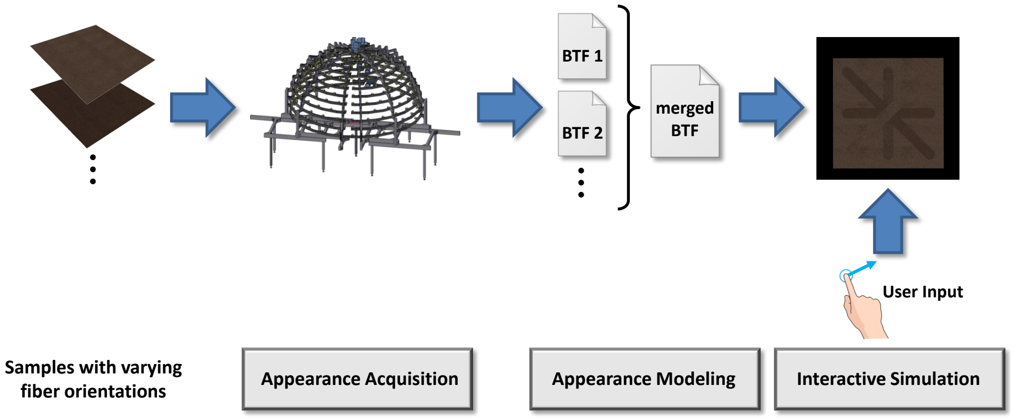

Figure 3: Overview of the main components of the proposed technique: In an initial step, micro-fiber materials with different fiber orientations are acquired with a reflectance acquisition device which results in one BTF per fiber orientation of the material. The individual BTFs are combined into a single texture array that contains the reflectance characteristics of the material under varying view and light conditions as well as varying fiber orientations. Based on this representation and an input by the user, an interactive simulation of the reflectance behavior for manipulated fiber orientations is achieved.

the spatial position on the micro-fiber surface, the view direction, the light direction and the state τ of the fibers. Before we describe how an efficient rendering can be performed despite the rather high dimensionality of the measure data, we first discuss the realization of user interactions with micro-fiber materials.

User Interaction. To achieve an appealing experience for the painting-like interaction of the user with the material, we aim at an as-intuitive-as-possible interface that allows the user to brush over the digitized micro-fiber material. In more detail, the material is shown to the user who can change the viewing and lighting conditions and is allowed to directly paint on the object via the mouse. The latter is implemented by projecting the mouse position into the uv-parametrization of the object and using the resulting coordinates to draw in a direction texture. This texture has three color channels that hold the direction of the stroke (d_x, d_y) in uv-space in the red and green color channels, and a brush-strength s in the blue-channel, where $s = 1$ means that the material is completely brushed and $s = 0$ means that the corresponding equilibrium state remains unchanged. To take into account that a hard transition between brushed and unbrushed fibers at the edges of a stroke is unrealistic for the simulated materials, we interpolate s between 0 and 1 at the edges of the stroke. By interpolating the corresponding BTFs of the borders of the brush-stroke according to s, we approximate the reflectance behavior at these parts. Please note, that a more accurate interpolation might be achieved based on more sophisticated techniques (Bonneel et al., 2011), however, simple linear interpolation allows for faster rendering. While drawing, we brush all fibers below the virtual ”‘finger”’ in the direction of the movement of the finger independent of their position relative to the brush center, but according to the resulting equilibrium state. This state is chosen depending on the angle between the movement direction of the finger in texture space and the dominant fiber direction stored with each material. At each frame, only the parts of the direction texture which were changed during the frame are updated in the video memory.

Rendering. Based on the aforementioned direction texture generated by the user interactions, the reflectance model from Section 4.1 has to be efficiently evaluated on the GPU. For this purpose, the measured BTFs, consisting of the Eigen-Textures and Eigen-ABRDFs for the three color-channels, and the direction texture containing the user generated direction field and brush-strength information are passed to the fragment shader. The shader samples the direction-texture to determine which state of the material has to be applied for the current fragment, and how the corresponding BTF has to be rotated in order to align its orientation according to the user-defined direction texture. Note, that the BTFs are oriented in such a way that the positive u-axis of the corresponding 2D texture is aligned with its dominant fiber direction. If the brush strength is $s = 0$, the shader only evaluates the BTF representing the material in its initial state. For $s = 1$, the BTF for the state τ corresponding to the direction of the brush stroke is evaluated. If $0 < s < 1$, which occurs on the edges of a brush stroke, the BTFs acquired for the initial state and the state with the adequate fiber orientations are evaluated and the results are interpolated. The material state which needs to be sampled is determined from the angle α between the vector $(1,0)$ in uv-space and the direction $\mathbf{d} = (d_x, d_y)$ of the brush stroke. Since only a few fiber orientations for a few angles were measured, we select the one which is closest to the angle α of the brush stroke. The directions ω_l and ω_v used to sample the BTF are defined w.r.t. the local coordinate system at $\mathbf{x}$. For sampling the material brushed into a certain direction $\mathbf{d}$ at a texel $\mathbf{x}$, we rotate the tangent $\mathbf{t}$ defining the local coordinate system by $-\alpha = -\text{atan}(\frac{d_y}{d_x})$ around the normal $\mathbf{n}$, and the texture-coordinate by α around the center of the texture. The rotated coordinate system and texture-coordinate are then used to sample the BTF of the brushed material.

5 RESULTS

We evaluate our technique with respect to its capability to accurately reproduce the characteristic material appearance during user interaction and its rendering performance.

5.1 Visual Quality

To evaluate the proposed method regarding the achieved visual quality, we measured BTFs of a fiber based material sample in two different states: One state where all fibers of the material are arranged upwards, and a second state where all fibers were brushed into one direction. As the used material does not have a predominant direction, it is sufficient to capture only one direction of the fibers, as the appearance is invariant to the direction of interaction. Figure 4 shows original images of the material sample, lit from different directions, were the fibers in the middle were brushed from right to left. It is clearly visible that the individual parts have a different reflectance behavior when the light direction changes. Figure 5 shows how the material rendered using our method behaves when the light or view direction is changed. Mesoscopic effects of light exchange such as interreflections, self-shadowing and self-occlusions are preserved in the synthesized material as well as parallax effects. As the used BTFs are not tileable, there are discontinuities in the textures. Figure 6 shows a comparison to a previous technique (Velinov and Hullin, 2016). Furthermore, Figure 7 shows a rendering of the material applied to a curved object using an environment map.

5.2 Rendering Performance

All of our renderings were performed on a machine with a NVidia Geforce 980 GTX with 4GB of VRAM. The most costly part of our shader is the evaluation of the BTFs, as this comes with a high amount of texture lookups per fragment, especially when both BTFs have to be evaluated on the edges of a brush-stroke. The visual quality of BTFs greatly depends on the number of BTF components used for rendering. In our evaluations, we obtained the insight that using 50 Eigen-Textures and Eigen-ABRDFs for the brightness-channel and eight Eigen-Textures and Eigen-ABRDFs for the color channels is sufficient for a good visual quality, while allowing for high framerates. For rendering without user manipulations, we achieved framerates of 125 frames per second in average with the BTF settings mentioned above for the scene in the bottom row of Figure 5. During user interaction, where parts of the direction texture are changed and uploaded to the GPU, which is a rather slow operation, the framerate drops down to 80 FPS. The used BTFs have a resolution of 900×400 pixels, and about 50 MB of video memory each for the used settings.

6 CONCLUSION

In this paper, we proposed a data-driven method to interactively manipulate fiber-based materials. As demonstrated in our experiments, our technique is capable of reproducing several effects such as self-occlusions, self-shadowing or the scattering between the fibers during the interactive simulation and, hence, clearly outperforms the previous state-of-the-art (Velinov and Hullin, 2016) that cannot reproduce such effects reliably in terms of realism. To overcome the limited size of the measured BTFs, one could apply the concept of video-textures (Schödl et al., 2000) to hide the tiling-artifacts. This could be achieved by searching for patches inside the BTF for the current material state that are similar to the one currently under the brush, instead of moving over the border of the BTF texture. Our framework relies on the availability of BTFs measured for different material states. For certain materials and scenarios, such as brushing fiber-based materials, where only a few states have to be considered, this simple approach is is highly efficient. To include further interactions such as compacting the fibers, additional states of the considered material have to be measured. This means that the total acquisition effort might become impractical if many states have to be considered. However, as at


Top Right Bottom Left Up

Figure 4: The material sample used for our experiments under different lighting conditions where parts of the sample were brushed into the direction indicated by the red arrow using a finger. Note that the fibers in the unbrushed parts are not arranged straight upwards, which is why there is a larger change in brightness also in these parts.

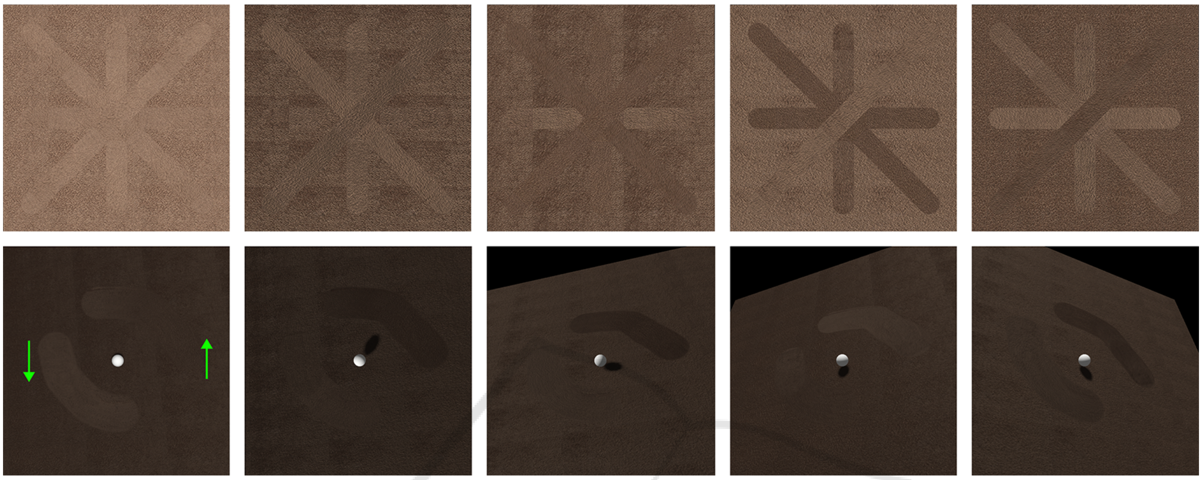

Figure 5: Renderings of the captured material using our technique: When brushing the fibers into different directions (top row), the characteristic differences in appearance induced by the fiber orientations are clearly visible as the light direction changes. Furthermore, renderings of two finger-strokes obtained using our technique are shown (bottom row). The arrows in the bottom-left image indicate the directions in which the virtual finger was moved. The white sphere is included to better visualize the light direction. The fibers in the brushed areas behave differently depending on their orientation and the view-light conditions. This figure is best viewed in color and by using the zoom function.

Figure 6: Comparison between the real material (upper left), our measured BTF (upper right) and renderings of the manipulated material obtained using a state-of-the-art technique (Velinov and Hullin, 2016) (bottom left) and our technique (bottom right). Please note that the lighting conditions are different in the photo and the renderings.

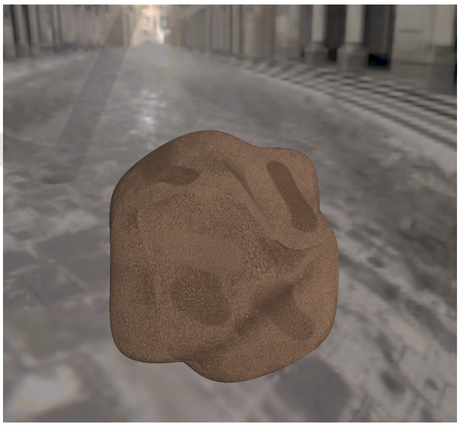

Figure 7: Rendering of the material with several brush-strokes under environment-lighting. The environment is approximated by eight directional lights.

most two BTFs have to be evaluated for a single fragment, the efficiency of the rendering pipeline remains unchanged but the memory consumption increases. Furthermore, a more general editing of the materials such as changing its colors is not possible. Such a material editing might be implemented by fitting

SVBRDFs to the BTF data, storing the residual of the Y channel in a BTF and adding the residual again during the rendering process.

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