

A versatile material reflectance measurement system for use in production

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Abstract

In this paper we present our developed bidirectional reflectance distribution capturing pipeline. It includes a constructed gonioreflectometer for reflectance measurements, as well as extensive software for operation, data visualization and parameter fitting of analytic models. Our focus is on the flexible user interface, aimed at material appearance creation for computer graphics, and targeted both for production and research employment.

Key challenges have been in providing a user friendly and effective software for functioning in a production environment, abstracting the details of the calculations involved in the reflectance capturing and fitting. We show how a combination of well-tuned tools can make complex processes such as reflectance calibration, measurement and fitting highly automated in a fast and easy work-flow, from material scanning to model parameters optimized for use in rendering. At the same time, the developed software provides a modifiable interface for detailed control. The importance of having good reflectance visualizations is also demonstrated, where the software plotting tools are able to show vital details of a reflectance distribution, giving valuable insight in to a materials properties and a models accuracy of fit to measured data, on both a local and global level.

1. Introduction

Visual realism and predictive rendering results are the central challenges in many computer graphics applications. These aspects are especially important in applications such as product visualization and rendering for commercials, where the synthesized images cannot in any way deviate from the corresponding real world objects. The key factors in the creation of high fidelity renderings are accurate modeling of the scene light transport and scattering events. This has led to research and development of advanced material models, so called bi-directional reflectance distribution functions (BRDF). A BRDF is a 4D function describing the reflectance and spectral characteristics of a material at a point on a surface with only a small number of parameters, typically three to five.

BRDFs are traditionally modeled by hand by an artist who adjust the parameters such that the model mimics the properties of the desired real world material. This is, however, a time consuming and difficult task, and the result is also often not fully reliable. A major difficulty for the artist during

BRDF modeling is to understand which visual effects of the material are introduced by the BRDF and which effects that are caused by the virtual light setup used during modeling.

This has led to the introduction of methods for measuring real world materials [WLL*08] and using this information for parameter fitting of BRDF models have been proposed. Using measured material data enables highly accurate numerical modeling of real world BRDFs in a fast and convenient way. This, however, comes with the drawback that the measuring and parameter fitting procedures are very complex, and requires deep understanding of material modeling, color science, and numerical optimization techniques. It is therefore highly important to develop tools that make such systems viable for use by artists in fast paced production environments.

In this paper, we present an overview of our pipeline for measuring, processing and fitting of BRDF parameters to real world material properties. Our pipeline consists of a custom built high accuracy camera based gonioreflectometer, and a software pipeline for data processing and BRDF

parameter fitting. Our software framework has been specifically developed to support artistic requirements of non-technical experts and includes a set of carefully selected techniques for visualization of the data at each stage in the process, and interaction tools which gives the user full control over the parameter fitting process.

2. Background

Having a good estimation of a materials reflectance properties plays an important role in many different areas, such as in the paper, textile and color industry; and to a large extent in computer graphics where the rendering equation used for creating synthetic images is governed by the bidirectional reflectance distribution function [Kaj86]. The BRDF specifies for each light direction incident at a surface point on a material, how it is distributed over the hemisphere above the point when reflected. It is usually formulated in spherical coordinates with four dimensions for the incoming and outgoing polar and azimuthal angles, $\rho(\varphi_i, \theta_i, \varphi_o, \theta_o) = \rho(\vec{\omega}_i, \vec{\omega}_o)$.

A number of models for describing BRDFs have been proposed – both empirical (such as the Blinn-Phong [Bli77] and Ward [War92] models) and physically based (*e.g.* the Cook-Torrance model [CT81]). For many material modeling purposes such models can describe the reflectance well. However, given a real-world material which should be reproduced in rendering it is not straightforward to set the parameters of a BRDF model by hand cause of the high dimensionality; although the modeling may be perceived as accurate from a certain viewing direction and under certain lighting conditions, it can behave differently in other circumstances. Having parameters that are fitted to a reflectance measurement of the material instead, ensures that the model is used globally optimized to the sought material.

Constructions built for reflectance measurements are named gonireflectometers and classically utilizes a four degrees of freedom setup, where a light source and a detector can be placed at any angle in the hemisphere above a material sample point. This usually provides a high precision and well-controlled measurement environment where one measurement is done for each light source/detector positioning. Examples of such high precision and multi-spectral measurement devices are *e.g.* the Spectral Tri-function Automated Reference Reflectometer (STARR), developed at National Institute of Standards and Technology (NIST) [PB96], or the examples from the Physikalisch-Technische Bundesanstalt [Erb80, HGH06]. While these represent expensive high standard equipment, a simpler gonireflectometer with commercially available components and a straight-forward design was presented by [WSB*98].

With image-based techniques it is possible to use information from different pixels on the sensor for simultaneous capturing of a set of reflectance samples, resulting in a significant increase in speed of a BRDF scanning. However, with measurements on pixel level it is difficult to match the

high precision of classic single detector gonireflectometers. If the data should be used for optimizing an analytic model, this is not a significant problem, since small inaccuracies have little effect on the final outcome.

Different methods have been presented for performing multiple angle readings. One is by having a curved mirror reflecting different angles onto different parts of the image plane. In [War92], Ward captures the reflectance for all excitant reflectance angles in the same image using a hemispherical mirror and a fish-eye lens, yielding fast measurements. The concept with an ellipsoidal mirror, but in a different setup, was also brought to a small hand-held device in [DR97, MDL*98], aimed at use in the industry together with a graphical user interface (GUI) for operation. An alternate approach is to have a parabolic mirror focus on a measurement point on a material sample, with light incident on the mirror, so that it shows an image of the reflectance for a set of angles [DW04].

Instead of having mirrors to enable multiple reflectance readings, a material geometry other than planar can be used to create an angular image. In [MWL*99, MWLT00] spherical samples were used together with a light source to cover a large part of the outgoing reflectance angles in one image. The technique was also extended to include general concave objects by having their geometry known, *e.g.* by scanning. A similar approach for fast measurements was taken in [MPBM03], and extended in [NDM05] to incorporate anisotropic materials by performing measurements on a set of material strips on a rotating cylinder, where the strip orientations represent different azimuthal light angles.

3. System overview

The reflectance measurement setup is shown in Figure 1, and is related to the one described in [WSB*98], with four stepper motors controlling the four axes of incident and excitant light directions, but it utilizes a CCD camera as reflectance detector. The 4-axis construction offers greater flexibility and improved quality compared to image-based multi-angular capturing approaches, with the possibility to average a measurement over a region. Furthermore, the setup supports continuous movement of the rig while the camera is reading, where capturing can be done at over 20 positions per second.

The built device utilizes 0.002° resolution stepper motor rotary tables, a 14-bit 1388x1038 pixels CCD sensor firewire camera, and a halogen light source with equalizer for a temporally consistent output. With a rig construction like ours, where the camera and the light source are kept on arms rotating above the material sample, the angles close to retro-reflection are occluded. In our case the camera is placed closer to the material than the light source, which result in an occluded region of about $\pm 5^\circ$. Except for these angles, all directions in the hemisphere can be captured at high angular precision and accuracy.

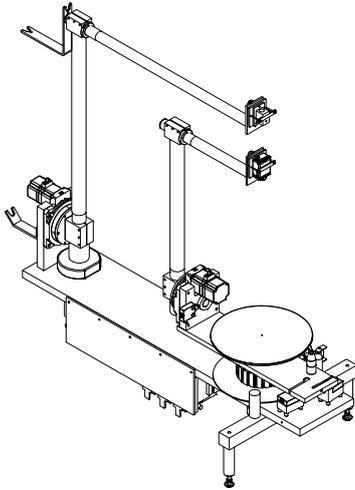
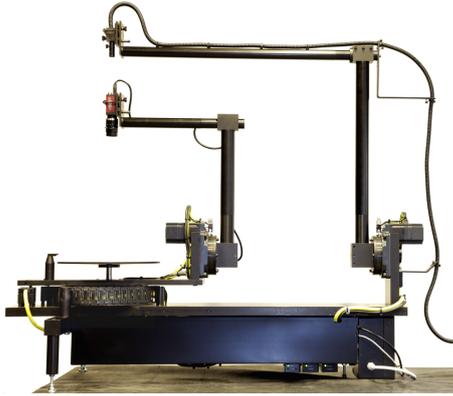


Figure 1: The capturing device with stepper motors controlling rotation of the arms. Instead of having the light arm rotating for different incident azimuthal angles, the material plate can be rotated.

A reflectance scanning is performed by having the camera doing continuous sweeps over the material, capturing the reflectance at predefined positions as the average over a user specified pixel radius. Denoting the incoming light direction (φ_i, θ_i) and the outgoing direction (φ_o, θ_o) , where φ and θ are the azimuthal and polar angles respectively, this means that the camera sweeps are accomplished by having φ_i , θ_i and φ_o fixed while θ_o is continuously changed.

To be able to cover the dynamic range of reflectance, multiple exposures are needed [DM97]. Having the camera moving continuously over the material sample, it would be inefficient to stop at every saturated sample position and capture with shorter exposure times. Instead, the camera completes a sweep over the material ignoring over-exposed samples. Subsequently, the camera is swept over these sample positions using a shorter exposure time. The procedure is repeated until there are no saturated samples left to scan.

To enable simultaneous threaded calculations of reflectance, the captured images in a material scan are directly stored in a queue which is processed in a second thread, so that the reflectance evaluation processing does not become a bottleneck. The processed samples are then stored as unstructured data in four dimensional space, where each sample is assigned an incoming and outgoing light direction. The unstructured storing is to have an extendable approach for data storage, *e.g.* enabling adaptive sampling schemes. When used in visualizations the data is extrapolated onto a 4D uniform grid for simple and fast look-up.

4. Visualization and interaction

In providing a versatile system for physically based material reflectance modeling, we have developed comprehensive tools for measuring, viewing and fitting model parameters to BRDF data. With the software we try to address a number of general requirements we put on our system, which can be summarized as follows:

1. Users should be able to perform calibration of the system, *e.g.* for correct color output.
2. Performing a material scan should be on a selected level of abstraction; that is, selected from predefined settings or in a more manual approach.
3. Visualization of BRDF data should be able to show detailed reflectance properties in an informative manner, and make viewing of the high dimensionality intuitive.
4. Optimization of analytic BRDF model parameters to the measured data should be possible, and automated to the extent it is possible. It should be easy to change the fitting conditions for finding alternative parameter solutions.
5. Interaction with the software should be intuitive, and suitable usage both in production and more advanced areas.

4.1. User interface

To be able to use complex measurement equipment such as the gonioreflectometer in a production environment, a well-deployed user interface is of great importance. We propose an interface aimed at providing a fast and highly automated work-flow, from the measurement of material reflectance to exported BRDF model fitted to the gathered data. The software, for which the interface is demonstrated in Figure 2, enables automated and direct procedures for easy integration in a production pipeline at the same time as supporting a large number of user inputs, and an “advanced mode” for research oriented usage.

The process of measuring and fitting a material is depicted in Figure 3. A general calibration file stores the state of the GUI, while the camera calibration and color profile are created through a calibration procedure in a wizard. The output of a measurement is binary unstructured reflectance data, onto which a color profile can be applied and a fitting

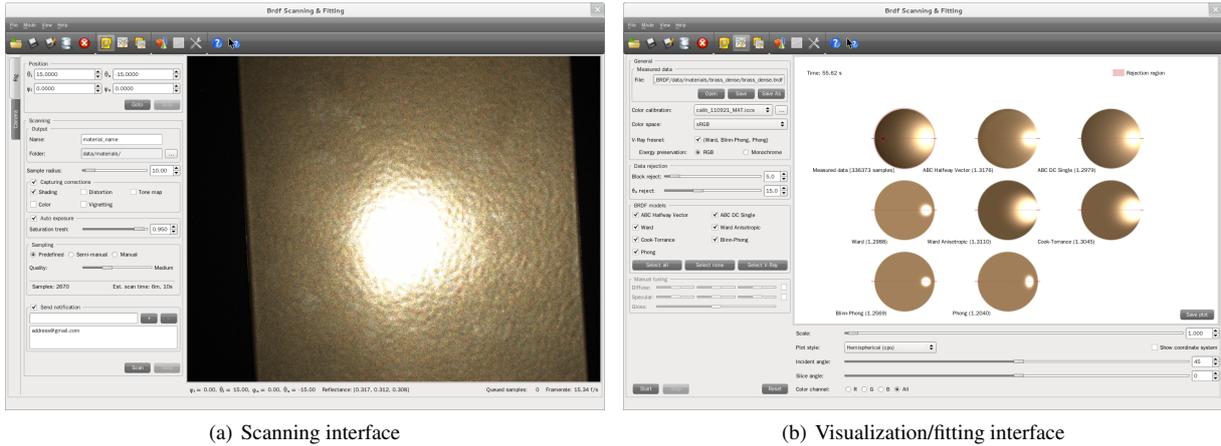


Figure 2: Overview of the interface, which is divided into a scanning and a visualization/fitting interface.

started. The final outcome is optimized BRDF model parameters output to useful file formats for use in rendering.

Since the terminology used in relation to reflectance capturing and fitting not always is self-explanatory for those not familiar with the details of BRDFs, through-out the interface informative help is provided on all constituent tools by means of offering mouse triggered help on widgets.

4.2. Visualization modes

Having four dimensional data, careful thought is needed for visualizations, to show the details of a BRDF. The plotting and rendering tools available in the interface illustrates a measured materials reflectance in an informative manner from different abstraction levels, for insight into the material properties, and for comparison to parametric models in the fitting procedure. There are four different ways of visualizing the reflectance as function of incoming/outgoing angles, shown in Figure 4:

- **Polar plot, Figure 4(a):** For a specified incident light direction, the plot shows the reflectance along a selected ϕ_0 , or slice angle, plotted in the direction of the reflection. It illustrates a slice of the reflectance distribution in

the hemisphere above the measured point, where the plotted data shows the magnitude as the distance to the origin of the plot. The direct correspondence to the reflectance distribution makes the visualization informative and easy to interpret. The restriction to one slice angle, however, makes it difficult to get an overview of the global BRDF shape, but for a local – in depth – comparison of measured data and fitted reflectance model small differences are easy to distinguish using the polar plot.

- **Cartesian plot, Figure 4(b):** The visualization is similar to the polar plot, but here the slice of the hemisphere has been transformed to a cartesian coordinate system so that the vertical distance represents the reflectance for the different angles. While the polar plot gives an intuitive view of the reflectance distribution, the cartesian version shows an abstracted representation that is easy to read and use for comparison with BRDF models.
- **Hemispherical plot, Figure 4(c):** The reflectance is drawn as colors for the entire hemisphere, viewed from above, for the specified incident light direction. In this way a large amount of data can be visualized simultaneously, for an easy overview of the reflectance distribution over all excitant directions. While the rendering shows a global image of the reflectance, it is difficult to see small local differences when comparing to a fitted BRDF model.
- **Geometric plot, Figure 4(d):** Here, the hemispherical plot is rendered with GPU acceleration and interaction can take place, turning the plot for different views. Furthermore, there is an option which adds a geometric scaling according to the reflectance, creating a 3D representation of the distribution. This “extrusion” can be modified to get more or less effect, in visualization purposes, and can be seen as the 3D equivalent of the polar plot. Having the distribution rendered as a geometry provides very intuitive information on the material reflectance on a global

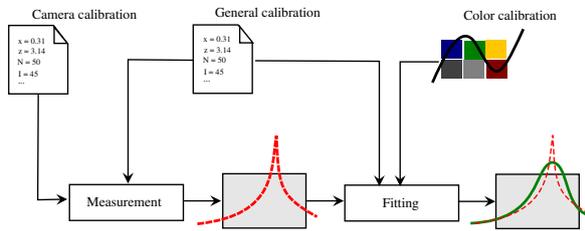


Figure 3: Material measurement and fitting pipeline.

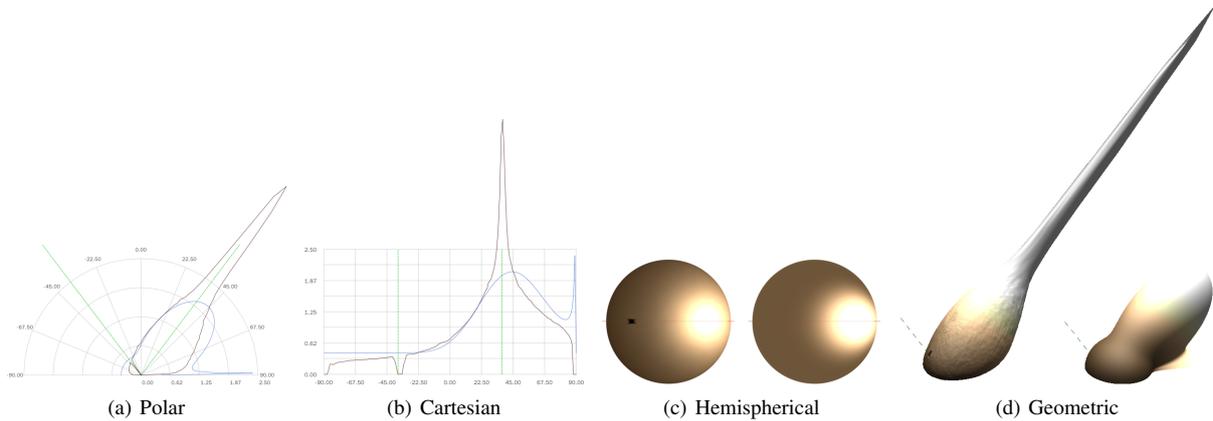


Figure 4: Examples of the different visualization modes. Plotted together with the measured data is a fitted Ward BRDF.

level, and comparing to a fitted BRDF model differences are easy to spot.

To summarize, the different rendering options are complementing each other. They all play important parts in an informative system for visualization of a measured materials reflectance properties and comparing it to a parameter fitting, on both a local and global level.

4.3. Parameter optimization

The fitting of an analytic model to the measured data is done in a non-linear least square manner using the Levenberg-Marquardt method, in a C/C++ implementation [Lou04]. During the optimization the visualizations are updated with the new parameters, and error measurements formulated as the root mean square difference are displayed, for visual feedback of the fitting progress and comparison by means of mathematical similarity.

For a fitting process, default start parameters, possibly scaled by the maximum input reflectance value, yields good results with most materials. However, since the parameter space, especially at high dimensions, can have a number of local minima, changing the parameters starting positions can give a different final outcome. To enable tuning of the parameters for a fitting, the interface provides interactive tools. The tuning is performed with sliders for diffuse and specular parts of the RGB-channels for a BRDF model, and with a slider for the general gloss, or width of the specular peak. With this classification of the tuning tools, the process becomes intuitive for an artist familiar with simple material properties.

Since the construction of the measurement stage makes samples around the retro-reflection direction occluded, there will be a set of faulty reflectance measurements. To avoid having this data affecting the fitting, the interface provides an option where the user can input an angle specifying the

radius of a circular area around the retro-reflection direction where data will be ignored. Furthermore, a user specified amount of positions near gracing angles can also be specified for rejection; since polar angles near $\theta = 90^\circ$ are sensitive to calibration, and measured from a smaller material projection area on the sensor, this is useful for removing unreliable data.

One difficulty when fitting to highly specular materials is the high contrast between diffuse and specular values in the BRDF, which can make the parameter optimization overemphasize the large specular peak, resulting in lost accuracy of the diffuse parts. To overcome this problem the fitting interface provides an option for fitting to the logarithmic BRDF, decreasing the diffuse/specular contrast. To have a

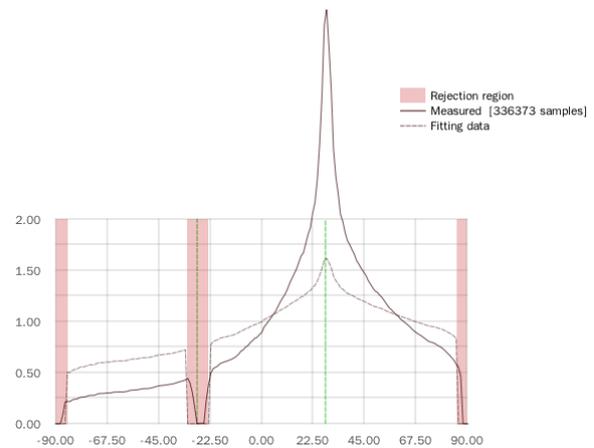


Figure 5: Visualization of logarithmic fitting conditions, plotted together with the original data. Note that the data is completely ignored in the rejection regions, represented by red.

stable logarithmic BRDF, avoiding the problems of near zero values, it is formulated according to Equation 1, where σ is a user parameter for controlling the contrast reduction. The impact of the contrast reduced BRDF for fitting can be seen in the screenshot in Figure 5, where $\sigma = 0.1$.

$$\rho_{\log} = \log_{10}\left(1 + \frac{\rho}{\sigma}\right), \quad \sigma > 0 \quad (1)$$

4.4. Calibration

Of great importance for the quality of a measurement process outcome is having a good calibration. Most calibrations can be performed when setting up the capturing system, but some need consideration during usage. For example can a color calibration be needed, e.g. when changing the light source lamp. The software offers standard color profiling – provided by the Argyll Color Management System (ACMS) [Gil08] – in an easy to use wizard interface (Figure 6), targeted for non-research production. Since the measurement rig enables light incident from all directions in the hemisphere, it would be an ideal stage for capturing a color chart and evaluating its diffuse color. However, the capturing distance puts restrictions to the size of the color chart, and a more general approach is therefore taken. The camera arm is rotated by 90° , so that the chart can be captured at any distance. This produces a color transformation that is calibrated in color, but not in scale cause of the capturing lighting conditions. The correct scaling is found by evaluating the diffuse color of an arbitrary reference patch in the measurement setup, with light incident from a set of directions representing the hemisphere. Applying the color profile, it is used to find the correct scaling.

The created color profile can be applied directly in the measurements, but a more general approach is to use it externally on to the data when performing a fitting, enabling changing of profile.

5. Discussion

Four material measurements are visualized in Figure 7, both plotted for red, green and blue color channels in cartesian coordinates, drawn as colors for the excitant hemisphere from above, and rendered in 3D. A Ward BRDF model has been fitted to the materials; it is plotted together with the measured data in the cartesian plot, and drawn next to the higher dimensional visualizations. The fittings have been performed with the default settings, and the calibration used was created in the calibration wizard. The measurements shows very dense data, for visualization; in practical situations measurements can be significantly sparser without sacrificing fitting quality.

The figure also shows the importance of having good reflectance visualizations in the fitting process. With information only from the cartesian plot, the optimization of the

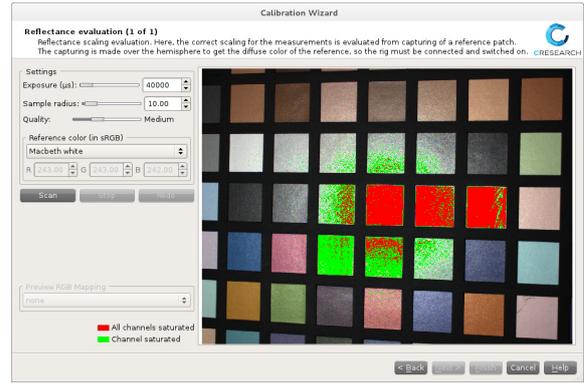


Figure 6: Screenshot from the calibration wizard. The example shows the interface for evaluation of the reflectance scaling.

Ward model to the silver lacquer material seem to be ill-fitting. However, the geometric rendering more clearly illustrates a distribution with a narrow specular peak and a more spread specular base, where the fitted BRDF has conformed to the base, resulting in a globally more optimized result. In the hemispherical color rendering this global optimization can also be seen, where the high specular peak is cropped to white. In conclusion – the visualizations of the distribution where the entire hemisphere of excitant reflectance is shown, can give valuable information of the material appearance behavior and the parameter optimization result that is difficult to see in a classic 2D plot.

Having a construction with a 4-axis capturing stage and a high performing camera, we can make measurements of high quality, with high precision information on reflectance directions and a complete image of information for each measurement position. Using this information to calculate the reflectance averaged over a small user specified pixel region we yield data with large noise reductions as compared to image-based approaches where large areas of the reflectance hemisphere are captured simultaneously. The improved data comes at the cost of longer measurement times, but with the system construction and software, enabling continuous movement while capturing, and the possibility to extend measurements to use more of the captured image data, the time can be significantly reduced as compared to 4-axis gonioreflectometers that need to halt at every measurement position.

The measurement time depends to a large extent on the material; a highly specular material is slower to scan compared to a diffuse since the specular peak have to be traversed several times with shortened exposure time. The time also depends on the stepper motor controller settings, i.e. max speed and acceleration. How fast the rig can be set to move is governed by the frame rate of the camera and the exposure time used. The utilized camera can capture at 16 frames per

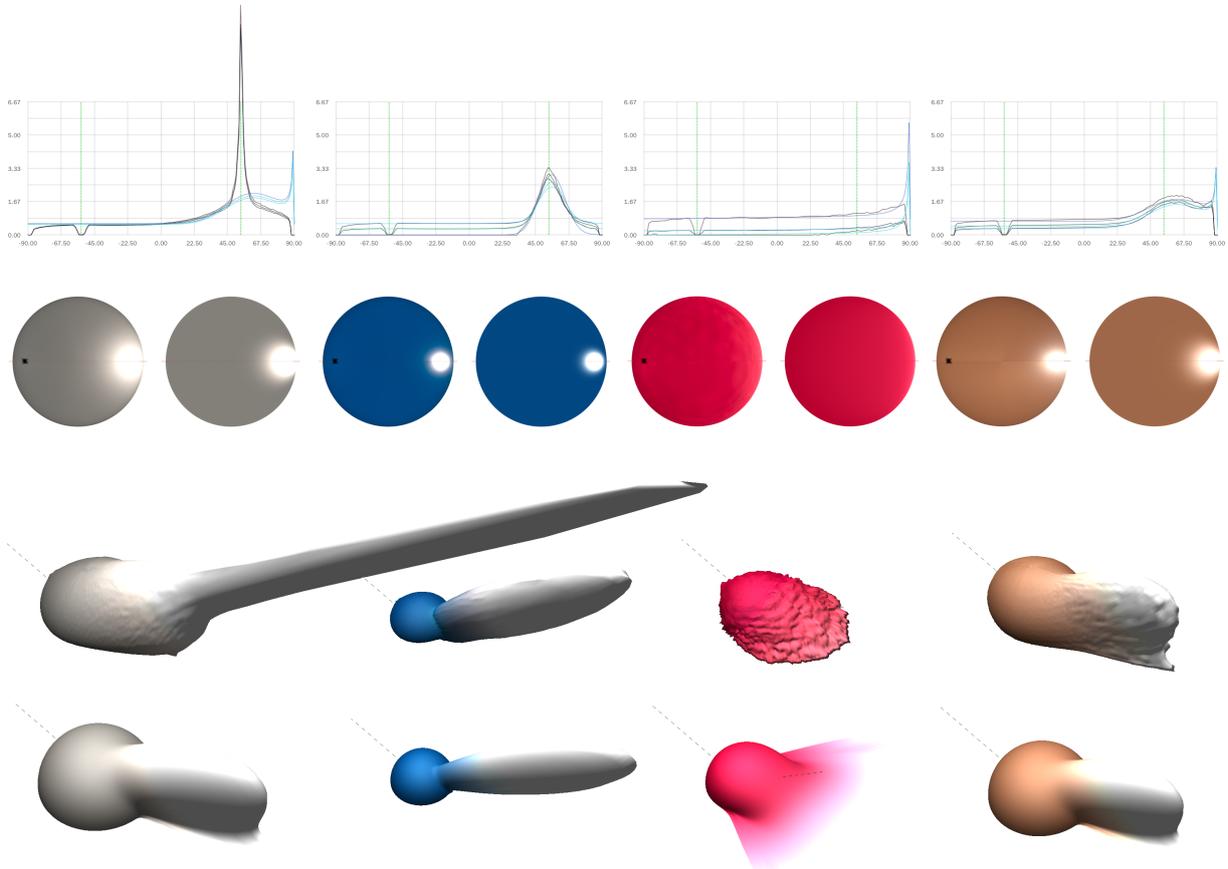


Figure 7: Different material measurements, together with a fitted Ward BRDF. From left to right: silver lacquer, blue lacquer, red textile, wood.

second at highest resolution. However, if only some part of the sensor need to be used, the frame rate can be increased. In the examples in Figure 7, the measurements were sampled uniformly spaced at every 1° in both ϕ_o and θ_o , and the stepper motors ran at a max speed of $20^\circ/s$. For one incident light direction, scanning took approximately between 40 and 50 minutes. For a good optimization, a set of incident direction need to be used, but the excitant directions could be sampled significantly sparser, and therefore the total scanning – for use in fitting – does not need to take more than 10–15 minutes for isotropic materials.

The parameter optimization time depends on parameters such as number of measured samples, shape of BRDF, number of parameters in the BRDF model, model function, CPU used etc. In most cases it is finished in a matter of seconds, or possibly minutes with a dense measurement sampling scheme.

We have only used our measurement system assuming isotropic materials, thus needing only one dimension – the polar angle – in the incident light, and with fitting to

isotropic BRDF models. However, the system is fully capable of measuring anisotropic materials, adding the dimension of the incident azimuthal light angle.

6. Further work

The developed system is centered around the different interaction and visualization possibilities, for achieving a system for easy use in many application areas. To further confirm that the requirements are fulfilled, an evaluation should optimally be performed. The capturing pipeline should be tested by a number of people with different backgrounds in the area, to evaluate the measurement, visualization and fitting interfaces with respect to parameters such as usability, efficiency and quality of outcome.

The capturing device is at the moment used in its simplest form for BRDF measurements, with a single reflectance measurement for each position of the scanning rig. Further work is intended with the setup though, and since emphasis has been on extendibility a strong research platform is provided for such work.

In the current system only a fraction of the pixels in an image are used, and many extensions of the setup could be done using more of the information. With this data multiple samples can be retrieved simultaneously, either for capturing different light directions on a homogenous material, or for calculating values for a spatially varying BRDF. Another useful extension would be to estimate a non-planar geometry and use for scanning.

The current measurements are done at the spectral locations achieved with the RGB-filters of the camera. Generalizing this for larger coverage of the spectral domain could be done with for example a filter setup.

The measurements we have done are all sampled uniformly by specifying a range and a sampling density for each dimension of the BRDF $(\varphi_i, \theta_i, \varphi_o, \theta_o)$. Having a setup like ours, however, it would be interesting to investigate the possibilities of having an adaptive sampling scheme. Since the fastest changes in a materials reflectance happens close to the specular peak, around the perfect reflection direction, an adaptive scheme would measure this area more thoroughly, and differently depending on the material. Alternatively, a fixed sampling scheme where the specularity is sampled more densely than the diffuse parts, would yield measurements more effective than uniform sampling.

7. Conclusion

In this paper we have demonstrated our flexible material reflectance measurement system, centered around the interaction and visualization possibilities. We have shown how the developed software enables an abstraction of the calculations and understanding needed in measurement of reflectance and optimization of BRDF models to measured data. The user interface of the software provides a scanning and fitting environment which could be used at a highly automated level in a simple physical material modeling work-flow. We have also pointed to the importance of having different and comprehensive visualization tools, both for insight in to the reflectance properties of the material and for confirming the accuracy of an optimization process.

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