Reflectance Measurements of Human Skin*

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Category: research

Abstract

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1 Introduction

As computer rendering technology advances, efforts are being made to render realistic human forms. One of the intrinsic challenges in doing so is to create skin with a convincing appearance.

One important component of surface appearance is the directional variation of reflectance, expressed as the *bidirectional reflectance distribution function* (BRDF). The dramatic difference in appearance between satin and velvet, for example, is mainly due to the very different BRDFs of the two fabrics.

BRDF measurements have traditionally been made with a *gonioreflectometer*, a specially-built instrument that positions a light source and a detector with respect to a flat sample. Human skin, however, doesn't come in flat samples, and any method used to extract such a sample will inevitably alter its appearance.

Our technique can acquire BRDF data over a large subset of the complete hemisphere from the skin of a living human subject. The method is an extension of techniques developed for measuring BRDFs of inanimate objects[8]. It works by taking a series of photographs of a convex part of the body; each image captures light reflected from many differently-oriented parts of the surface. This drastically reduces the time needed to acquire data; a typical measurement session takes less than half an hour. In addition, none of the positions of the camera, light source, or the subject need be controlled carefully. Our approach derives the positions and orientations automatically from the measurement images. This conveniently handles subject motion during the measurements. Although the apparatus is simple and the measurement rapid, the resulting data cover a large, useful subset of the BRDF hemisphere; at a minimum, the incidence plane can be measured to near-grazing angles in incidence and exitance.

Renderings using our results capture subtle differences between the skin of different subjects and illustrate that skin shows several interesting features in reflectance. We hope that this technique will lead to better understanding of the special reflectance properties of skin, verification of reflectance models, and perhaps the development of new models.

2 Related work

The BRDF is a function in five dimensions: two for the illumination direction, two for the reflection direction, and one for wavelength. In this paper, we assume that skin is *isotropic*—it has no grain, or directionality. For such a surface the BRDF has just four degrees of freedom.

One traditional method of describing a BRDF is with a predictive model, such as that of Torrance and Sparrow[10]. The best effort at such a model for skin is the simulation approach of Hanrahan and Krueger[3]. Such models must, however, be verified by the results of physical measurement; even after verification, measurements may be the only way to determine their parameters. Human skin is an especially sensitive case: to model the skin of a particular individual, very subtle effects must be distinguished, and accurate measurements are the most reliable way to do this.

In measuring a BRDF, the three or four angular dimensions of the BRDF are traditionally handled by specialized mechanisms that position a light source and a detector at various directions from a flat sample of the material to be measured [7]. Because three, four, or five dimensions must be sampled sequentially, measuring reflectance functions can be time-consuming: even with modern computer controls and precision motors, measuring a full isotropic BRDF takes at least several hours.

Such devices are difficult to use to measure human skin because a flat sample is needed, geometric alignment is critical, and because of the time needed for a complete measurement.

Dana et al.[1] used a video camera and a robot to acquire reflectances for a sample of human skin, sample 39 in the Columbia-Utrecht Reflectance and Texture Database (CuReT). This skin was apparently removed from a cadaver, allowing the preparation of a flat sample, its mounting in their positioning device and stability for the time needed to gather BRDF information.

Our technique takes a different approach: rather than trying to correct the natural curvature of the human form, we use it to present many different angles to the detector simultaneously. Using an imaging detector allows many samples to be acquired in a fraction of a second. Dana et al. used this array of simultaneous samples to measure spatial variation of the BRDF; by assuming that the BRDF is constant over the area of skin we measure, we can use them to acquire a large range of angles in each image.

Similar image-based techniques have been used before to measure BRDFs, notably by Lu et al.[5], Marschner[6], and Sato et al.[9]. The first two used samples of ideal geometry (cylinders or spheres) to simplify the task of calculating reflection geometry. Sato et al.[9] extended the technique by acquiring geometry together with reflectance properties. They used a fixed geometry of source and camera, depending on the information in a limited range of angles to estimate the parameters of a simple BRDF model.

We have extended this class of techniques further in two ways to apply it to the skin of living humans. First, we can extract valid BRDF values from the complex shapes of the human form, since we measure the geometry of the subject and calculate the reflection geometry at each pixel. Measuring the geometry separately and varying the relationship of source to camera enables us to extract the full angular dependence. In exchange for our more complete angular coverage, we sacrifice the ability to measure spatially-dependent properties.

Second, we use photogrammetry to determine the precise viewing and illumination geometry. The images we use for measurement also contain all necessary information to measure the relative positions of source, sensor, and subject. This not only simplifies the equipment needed, but it enables us to deal easily with a living subject. Instead of trying to prevent subject motion (which would degrade the accuracy of our measurements), we simply measure the position change and account for it.

The following sections describe the specifics of our system and give the results of measuring several subjects under various conditions.

3 BRDF Background

The reflectance of an opaque surface at a point can be completely characterized by the BRDF. It is called *bidirectional* because it is a function of both the illumination direction $\hat{\omega}_i$ and the reflection direction $\hat{\omega}_e$. The BRDF ρ_{bd} is the ratio of the differential radiance exiting the surface in direction $\hat{\omega}_e$ to the incident irradiance through the differential solid angle $d\omega_i$ about the direction $\hat{\omega}_i$ (at a particular wavelength λ):

$$\rho_{bd}(\hat{\omega}_i, \hat{\omega}_e) = \frac{dL(\hat{\omega}_e)}{dI(\hat{\omega}_i)}. \tag{1}$$

The BRDF is thus a function in five dimensions, but in this paper we assume that human skin is an *isotropic* material: the reflectance is independent of rotating the incident and exitant directions about the surface normal. For such a surface, the BRDF depends only on four variables.

We further assume that all light reflection is local, i.e. that the light leaving a given point on the skin surface depends only on the light reaching that point. In principle, skin is a volume scatterer: a significant amount of light

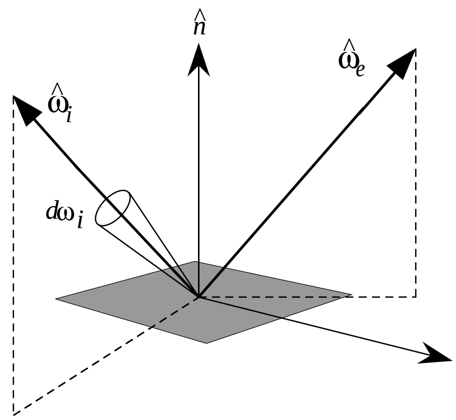

Figure 1: Geometry of Surface Reflection

enters, is scattered by various elements beneath the surface, and then re-emerges from the surface, possibly at a different point. All dielectric surfaces exhibit this to some extent, but inaccuracies in treating such surfaces as local surface reflectors are usually negligible. Similarly, we model all reflection effects with a BRDF.

4 Method

Our method, illustrated in Figure 2, is designed to measure the BRDF of a curved area of human skin. It is an extension of the work presented in a companion paper[8], which covers some of the more technical details. We assume that the reflectance of the sample area is uniform: freckles, moles, and hair should be avoided, as should obvious changes in skin color or gloss. We have chosen to measure the forehead, as it presents a suitable curvature, basically rigid shape, convenient size, and reasonably uniform reflectance, and it presents no offense to modesty. The technique can also work on other body parts, such as the nose, an arm or leg, or the back or shoulder.

The subject wears a headdress with machine-readable targets to track the position of the head automatically. Another set of targets around the light source and on a fixed structure in the environment provides an absolute reference frame.

First, we acquire measurement images from several viewpoints, being careful to include the subject's forehead and both sets of targets in the field of view. This gives us the basic radiometric information we need to measure the BRDF.

Next, we automatically find the coded targets in each image and use their positions to find the relative positions of subject, camera, and light source in each. Combined with a geometric model of the subject's forehead, we now have all the information needed to extract the BRDF.

Using the radiometric and geometric information from the first two steps, we derender the measurement images using a modified ray tracer. For each image, we align the virtual camera with the real camera and the scanned geometry with the subject's head. The geometric model of the region of interest serves to select the desired pixels and supplies the surface location and normal information for the samples. For each pixel, the value of the corresponding BRDF sample for direction $\hat{\omega}_i$ to the light source and direction $\hat{\omega}_e$ to the focal point of the camera is expressed by

$$\rho_{bd}(\hat{\omega}_i, \hat{\omega}_e) = \frac{CD^2 L_{pixel}}{\cos\theta_i}, \tag{2}$$

where C is a scaling constant that must be determined from a calibration picture, D is the distance from the surface point to the light source, L_{pixel} is the linearized radiance value of the pixel, and θ_i is the angle between the direction $\hat{\omega}_i$ and the surface normal $\hat{n}$.

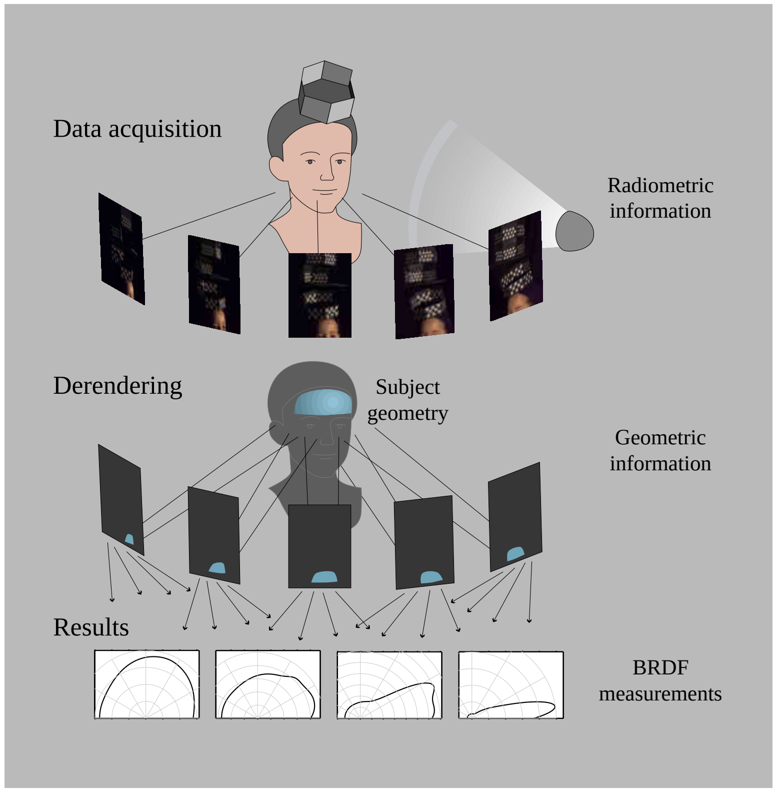

Figure 2: BRDF measurement process

The scaling factor C is derived from the independent derendering of a calibrated reflectance standard captured under the same lighting:

$$C = \frac{\rho_{bd,ref}(\hat{\omega}_i, \hat{\omega}_e)}{\cos\theta_i D^2 L_{pixel}}, \tag{3}$$

where $\rho_{bd,ref}(\hat{\omega}_i, \hat{\omega}_e)$ is the known BRDF of the calibrated standard, typically a strongly reflective diffuse sample. Averaging resulting values over different pixels provides a more accurate estimate for$C$.

The output of the derendering process is a large number of samples of the BRDF, basically in random directions. The samples can be selected and sorted for further processing, such as filtering, approximation, and visualization.

4.1 A Typical Measurement Session

First, the subject dons a carefully-designed headdress, visible in Figure 3. This headdress remains on the subject's head throughout the measurement session, and enables us to find the head's exact position in each image. It carries 48 coded targets that can be automatically located in each measurement image.

Next, we use a range scanner to scan the headdress and the subject's head. By including the headdress targets in the scan, we can determine the geometric relationship between the area of interest and the targets, which we can use later to find the pose of the head.

Then the subject moves to the measurement area, beneath a reference structure bearing another set of targets. These reference targets allow us to extract the camera pose in each image.

Then we capture several (typically about 30) images of the subject, moving the camera around a circle marked on the floor at 2 m radius. The exact position and distance of the camera is unimportant, as we can calculate its pose later. We attempt to sample the arc evenly, but minor irregularities are not a problem, because the enormous number

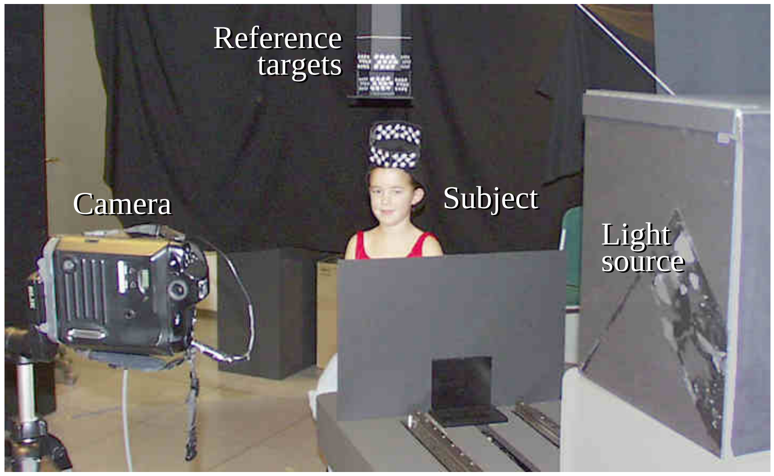

Figure 3: Measurement Setup

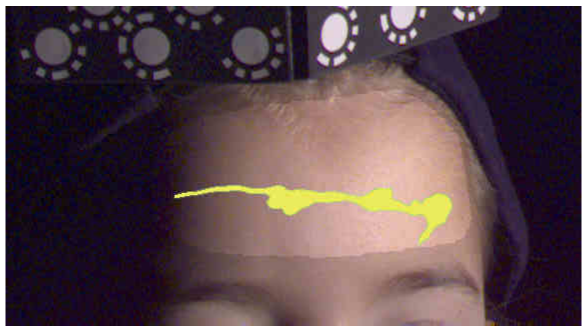

Figure 4: Incidence plane coverage of a typical measurement image

of samples gathered at each step assure a good sampling of the angular range covered. We use an electronic flash as our source, triggered by the camera's shutter. It remains stationary through the whole session.

Finally, we acquire six more images: three to determine the position of our light source, one of a calibrated reflectance sample for radiometric calibration, and two more of the calibrated sample to determine its position precisely.

Since we use a professional-grade studio flash, cycle time is rapid ($\approx$ 2 sec) and the whole session, including scanning the geometry, takes only about twenty minutes. This contrasts with traditional gonioreflectometer measurements, which can easily take large fractions of a day.

4.2 Sampling Pattern and Coverage

To clarify the sampling coverage, imagine the forehead idealized as a segment of a cylinder. Since its curvature lies along a single direction, we can arrange for the light source, camera, and surface normal always to lie in a plane. Each image will give a set of samples in the incidence plane, with a range of θ_i and θ_e. A set of these images, each acquired with the camera in a different position, samples the entire incidence plane well. We move the camera along a path from near the source (where we measure retroreflection) to opposite the source (where we measure grazing-angle reflection).

Human foreheads, of course, are not cylindrical, but most subjects have a sufficient area where curvature is primarily in one plane. We have found that the incident plane, an important subset of data in BRDF measurements, can usually be covered quite well with a typical subject, especially if he/she is careful to tilt his/her head down to bring the forehead more vertical. Figure 4 shows the pixels used for the incidence plane area in a typical measurement

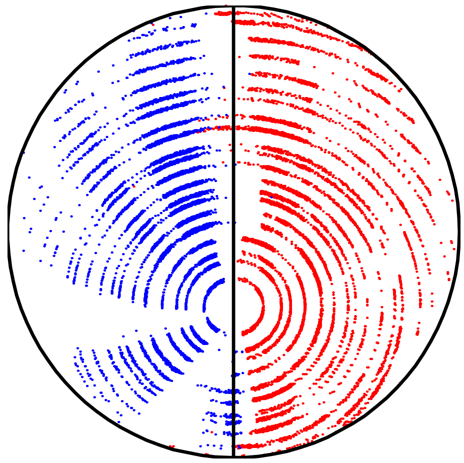

Figure 5: Typical coverage of exitant hemisphere for $\theta_i = 30^\circ$

image. The brightened area of the forehead shows the area selected for BRDF extraction; the yellow area includes all pixels in the illuminated hemisphere near the incidence plane.

The compound curvature of a real human forehead expands our coverage into a wider area of the hemisphere, as shown in Figure 5 for a typical data set. Here the data for $\theta_i = 30^\circ$ are shown in blue, with the reciprocal data ($\theta_e = 30^\circ$) in red. Though the incidence plane itself is only sparsely covered, reciprocity and symmetry allow us to interpolate values in the plane with confidence. The extreme case is to measure a completely bald subject, which should increase coverage to nearly the full bihemispherical domain of the BRDF, though raising concerns over local BRDF variations over the area of interest.

4.3 Apparatus

Our system comprises the following parts:

- A CCD camera for position and BRDF measurement (Kodak DCS 420)
- The light source: a professional-grade electronic flash powered from ordinary 110V AC current. We mounted the flash in a housing behind opal glass (82 mm disc) to depolarize it and to improve its angular uniformity.
- Photogrammetric targets attached to the subject's head, the flash, and the ceiling of the room. These were software-generated and printed on a laser printer.
- A 3D range scanner (Cyberware 3030/PS)

5 Results

5.1 One Example

We begin with the BRDF measured from a male Caucasian subject of age 43 years. Figure 6 shows a polar plot of the incidence plane for the incident angles 0°, 30°, and 60°. The BRDF is mainly Lambertian near normal incidence, but shows strong forward scattering as incident angle increases. For the line plots in this paper, we have employed a local quadratic regression procedure [2] to smooth and interpolate the data. For the renderings, we have fitted the representation of Lafortune et al.[4].

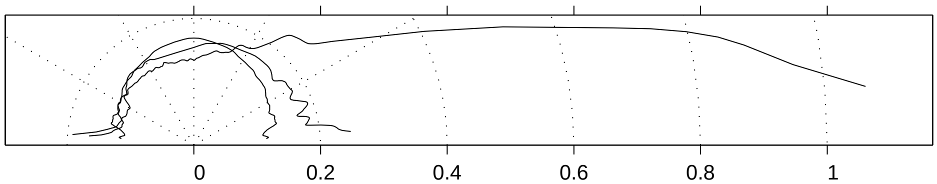

Figure 6: Polar plot of measured BRDF of human skin

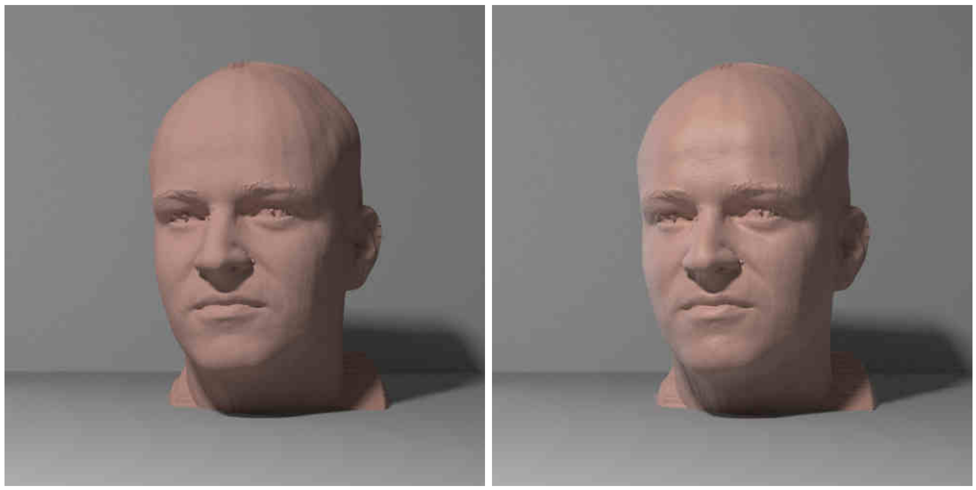

Figure 7: Sample renderings with Lambertian and measured BRDFs

Figure 7 shows an image on the right rendered using the measured BRDF. A rendering with just the Lambertian component of the BRDF is shown on the left for reference. Notice the sheen seen toward grazing angles in the right image, especially along the chin and neck. This seems to correlate with the grazing effects predicted by the simulations of Hanrahan and Krueger[3].

5.2 Natural Variation

We measured BRDFs from four different subjects[1]. The first is the example of the previous section. The second is another Caucasian male, 26 years of age and of different complexion. The third image shows the measured skin of a 9-year-old girl. Notice that our measurements are sensitive enough to capture the subtle differences in tint and shininess, and that such subtle differences in the BRDFs lead to visible differences in the renderings. The fourth subject is from South Asia (India), exhibiting not only a different skin color, but noticeably shinier skin.

5.3 Artificial Variation

We measured the forehead BRDF of the same (9-year-old) subject three times: with no preparation, after applying makeup (Cover Girl Replenishing, Soft Beige), and after removing the makeup and applying a light coating of mineral oil to simulate perspiration. Polar plots of the incidence-plane BRDF, shown in Figure 9, show significant differences only when oil is applied. We observed that the difference after applying makeup was barely visible in this case; this is confirmed by the polar plots, which show only slight differences in the BRDF.

We rendered images using the three measured BRDFs; the first and third are shown in Figure 10. As expected, the oil increases the gloss of the skin. We omit the third image, that of the skin with makeup, since it is indistinguishable from the untreated skin for the present subject.

[1] If the paper is accepted, we plan to provide measurements in machine-readable form on the proceedings CD-ROM, as space permits.

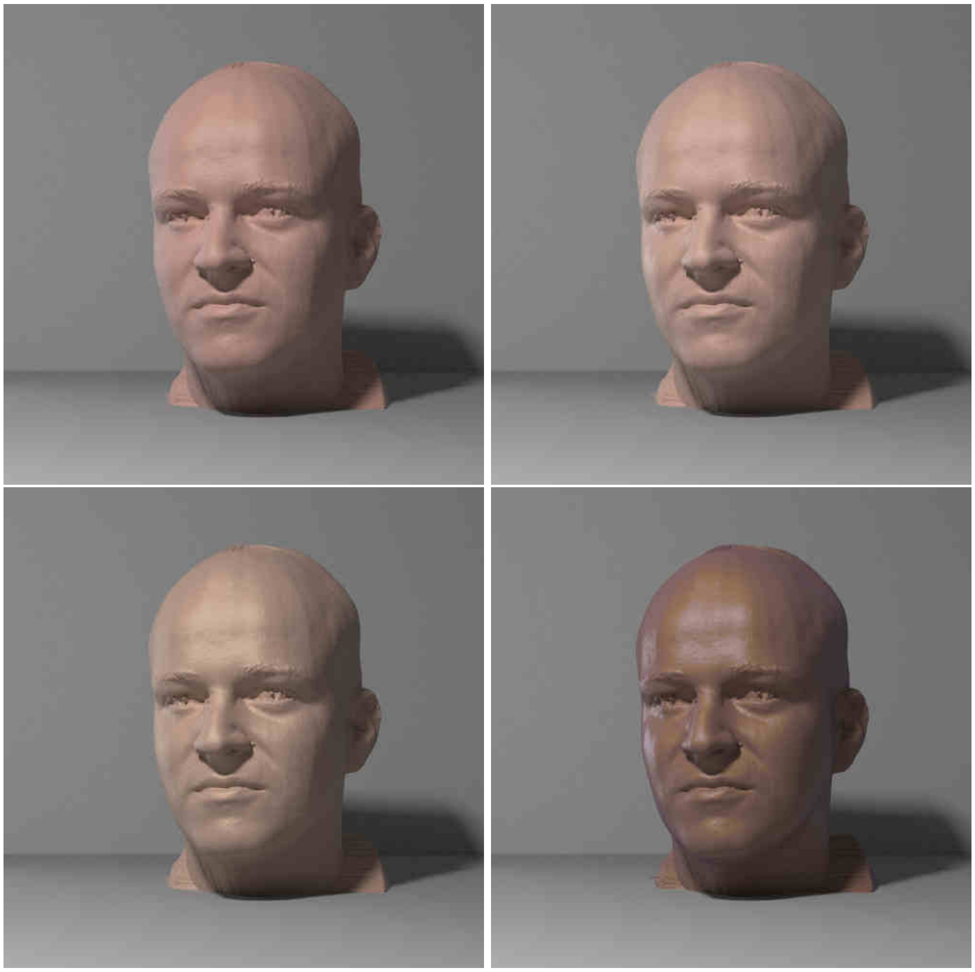

Figure 8: BRDFs measured from four different subjects

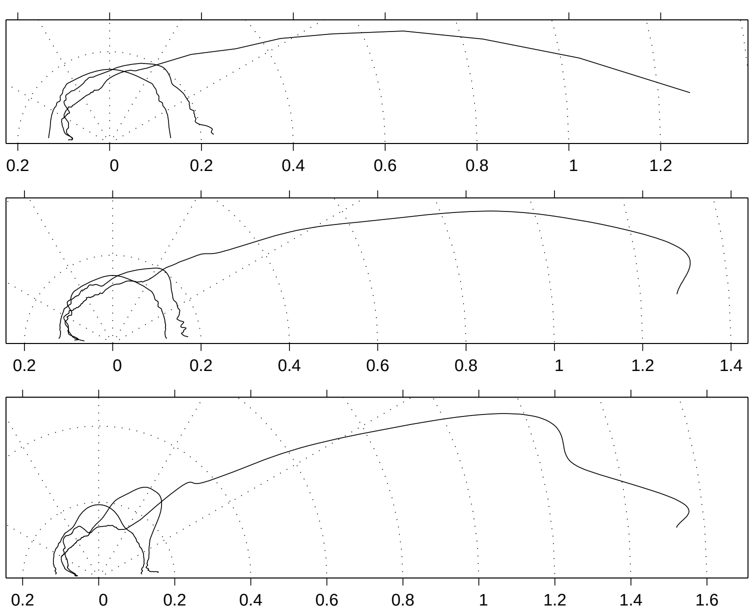

Figure 9: BRDFs of a single subject: initially, after applying makeup, and after applying mineral oil.

Figure 10: Renderings of untreated skin and skin with mineral oil

5.4 Data Quality

Our data show considerable scatter, but our technique provides abundant data in a dense sampling pattern that allows us to smooth out the scatter for better results. Figure 11 shows raw data points along with the smoothed BRDF. The two near-identical measurements (untreated and with makeup) in Section 5.3 give confidence that our measurements are quite repeatable.

There are several sources of noise in our measurements:

- Sensor noise: experience with this camera in other, similar measurements[8] makes us confident that sensor noise is a small part of the scatter we see in the measurements here.

- Errors in geometrical alignment: any error in our photogrammetric calculations will result in errors in the resultant data. The subpixel precision of our automatic target recognition helps to minimize these errors.

- Errors in normal estimation: the data from the range scanner show visible noise. We used a local planar fit to reduce this noise, but can never completely remove it. In certain situations (i.e. fine geometric detail) the smoothing may even introduce errors.

- Inadequate resolution in geometric model: our measurement images are able to resolve detail (pores, wrinkles, etc.) much finer than the resolution of the range scanner. Local detail of this sort constitutes an additional, highly localized, error in normal estimation.

- Spatial variation in the BRDF. We have carefully chosen the forehead to minimize this source of error, but some variation may remain.

6 Conclusion

This paper has described a simple technique that can measure the BRDF of living human skin using general-purpose equipment. The technique is rapid, sensitive, samples densely, and can measure to angles near grazing. The resulting data show subtle reflectance effects and subtle distinctions between similar complexions.

Our results suggest that, to render human skin convincingly under all conditions, a full directional BRDF is necessary.

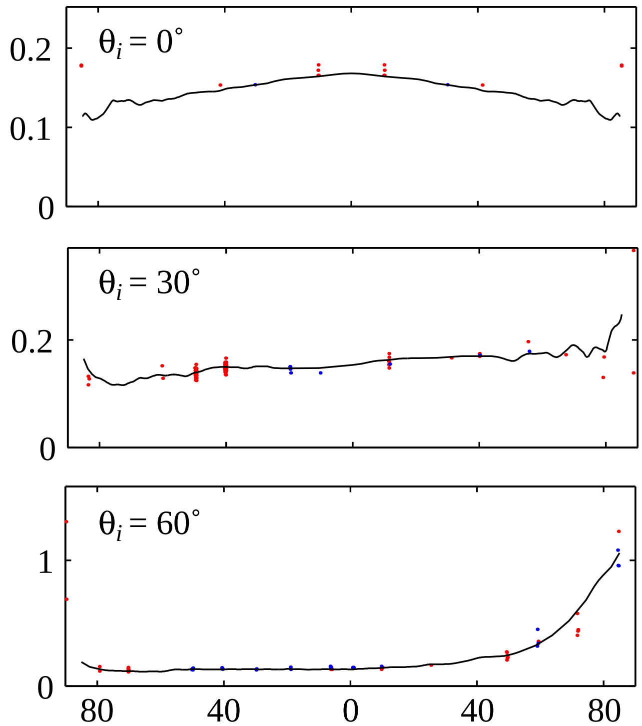

Figure 11: BRDF of typical skin, showing scatter in raw data

7 Future Work

This technique provides a tool for a large area of possible investigation, and is amenable to improvements for more generality, lower cost, and better accuracy.

We anticipate that we and others will apply it to many different areas of interest:

- Verification of predictive models
- Acquiring input data for realistic rendering of humans
- Further exploration of individual variations of complexion in a larger populace
- Characterization of differences in reflectance due to race, sun tan, and artificial tanning agents.
- Measuring global differences in skin reflectance of different body parts
- Further study of artificial modification of skin reflectance, including other forms of makeup: powder, theatrical makeup, etc.

We would like to extend our measurements to include surface areas with concavities, as are found on much of the human body, especially the face. To extract the BRDF from concave areas is a much more complex problem, as multiple scattering must be accounted for. Some progress has been made doing so in a simpler case[11], but further work is needed to be able to apply such a technique to our more complex situation.

We have measured only areas of assumed constant BRDF. A complete technique should be able to capture spatial variations of the BRDF, which are important to realistic portrayal of human figures.

Improving our estimates of surface normals could significantly reduce the scatter shown in our results. Since the camera acquires information from smaller structures than are visible in our geometric model, at best we can approximate the average surface normal over several pixels, ignoring the more local variations. It may be possible, however, to extract this smaller geometry from the measurement images by a shape-from-shading approach, especially since we can exploit our knowledge of the BRDF (reciprocity, symmetry, smoothness) to refine our estimates of surface normals and thus stabilize the process.

Finally, we may be able to dispense with the range scanner completely by acquiring complete geometric data from our measurement images. For the case of convex geometry, our measurement images contain the silhouette curves needed to extract shape from contour lines. This would provide an initial estimate of geometry which could be refined by the shape-from-shading approach suggested above.

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