BRDF/BTF Measurement Device

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Abstract

Capturing surface appearance is important for a large number of applications. Appearance of real world surfaces is difficult to model as it varies with the direction of illumination as well as the direction from which it is viewed. Consequently, measurements of the BRDF (bidirectional reflectance distribution function) have been important. In addition, many applications require measuring how the entire surface reflects light, i.e. spatially varying BRDF measurements are important as well. For compactness we refer to a spatially varying BRDF as a BTF (bidirectional texture function). Measurements of BRDF and/or BTF typically require significant resources in time and equipment. In this work, a device for BRDF/BTF measurement is presented that is compact, economical and convenient. The device uses the approach of curved mirrors to remove the need for hemispherical positioning of the camera and illumination source. Instead, simple planar translations of optical components are used to vary the illumination direction and to scan the surface. Furthermore, the measurement process is fast because the device enables simultaneous measurements of multiple viewing directions.

1 Introduction

In computer vision and graphics, the interaction of surfaces with light is of fundamental interest in order to predict and simulate appearance. Real world surfaces are seldom homogeneous but instead exhibit some type of texture which may be a color or albedo variation as in a checkerboard, a paisley print or zebra stripes. Very often in real-world scenes, texture is also due to a surface height variation, e.g. pebbles, gravel, foliage and any rough surface. Appearance of textured surfaces depends on scale. At coarse scale, when the surface is viewed from a distance, local surface variations are subpixel and therefore the surface is of uniform reflectance. Here, appearance is characterized by a spatially uniform BRDF. At closer views, local surface variations give rise to local intensity variations and we observe image texture. Image texture changes with illumination and viewing direction and we call this the bidirectional texture function (BTF). That is, a spatially varying BRDF is termed the BTF. Modeling the BRDF and BTF of real world surfaces is a challenging research issue. Existing models are overly simplified and cannot fully capture the complexities and variations of real world appearance. Yet predicting appearance is a fundamental component of computer vision. For example, in stereo and motion algorithms obtaining point correspondences is a basic algorithmic building block, and predicting appearance change can enable accurate point correspondence in varied imaging conditions. Furthermore, since objects are composed of surfaces, object recognition is assisted by accurate predictions of surface appearance and changes in appearance with object pose.

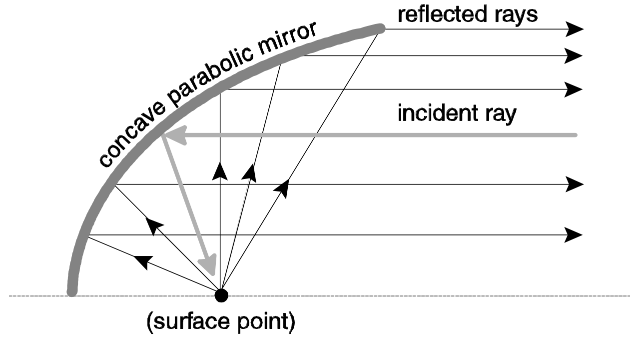

Figure 1: The focusing property of a concave parabolic mirror is exploited to simultaneously measure reflected rays from a large range of angles over the hemisphere. The same mirror is used to direct the incident illumination ray to the sample at the desired angle.

Endeavors in predicting and modeling appearance are hampered in part by the difficulty in measuring reflectance and texture. To measure surfaces in a systematic and precise manner, significant resources in time and equipment are necessary. Measurements of BRDF require sensing light reflected from an image point as a function of illumination and viewing direction. Because these directions may vary over a hemisphere, measurement setups can be quite complex to enable precise angular variations of both viewing and illumination directions. Furthermore, to measure spatially varying BRDF (i.e. BTF) added equipment complexity is necessary for sensing a surface region instead of a surface point. Prior efforts in reflectance and texture measurements include the CUReT database [6] which contains

BTF and BRDF measurements from over 60 different samples, each observed with over 200 different combinations of viewing and illumination directions. This work has been the basis of numerous recent studies in the area of surface representations [3][5][4][8][9][13][14]. These efforts represent a step towards the goal of surface representation for vision and graphics, but significant work remains. Existing models of surfaces make restrictive assumptions (e.g. local Lambertian reflectance) and are consequently limited to a small subset of real surfaces. Other models need an entire database of images to learn a particular surface behavior and are therefore only applicable to surfaces that have been carefully measured in a laboratory setting. It is desirable to develop modeling methods that use theory to reduce the number of required observed images. Furthermore, no existing models sufficiently deal with the additional issues of scale invariance or multiple light sources.

The measurements of the CUReT database were the first of its kind and proved quite useful in texture research. However, the measurement methods were time consuming, semi-automated and required mountable planar patches of the surface of interest. In many applications, such isolated patches are difficult or impossible to obtain. For example, human skin analysis requires a more convenient measurement system. In this work, we present a novel measurement device that changes the problem of moving the viewing and illumination direction in the hemisphere of possible directions to the simpler problem of translating small optical components in a plane. Figure 1 illustrates the basic idea. A concave parabolic mirror focuses light to a single point. Therefore, this mirror can be used for convenient orientation of the illumination direction. An incident ray reflecting off the mirror will reach the surface at an angle determined by the point of intersection with the mirror. The light reflected from the surface point at a large range of angles is also reflected by the mirror and can be imaged by a camera. Section 2 describes the device design in more detail, Section 3 describes the prototype construction, Section 4 gives experimental results and Section 5 describes the various applications for the device and the resulting measurements.

2 Device Design

The proposed device uses optical components such as a beam-splitter, concave parabolic mirror, CCD camera, translation stages and is illustrated in Figure 2. The beam-splitter allows simultaneous control of the illumination and viewing direction. A concave parabolic mirror section is positioned so that its focus is coincident with the surface point to be measured. The illumination source is a collimated beam of light parallel to the global plane of the surface and passing through a movable aperture. The aperture ensures that only a spot of the concave mirror is illuminated and therefore one illumination direction is measured for each aperture position. In this approach, the problem of changing illumination direction over a hemisphere is transformed to the easier problem of translating an aperture in a plane. The light reflected at each angle is reflected from the mirror to a parallel direction and diverted by the beam-splitter to the camera. The camera is equipped with an orthographic lens that images the parallel light directly incident on the lens. In this manner, a single image corresponds to reflectance measurements from all angles in a partial hemisphere. To obtain a measurement of a surface patch for spatially varying BRDF, the concave mirror is translated along the x-y plane. This arrangement also has the advantage that all light from the measurement point will reflect away from the sample and thus will not reilluminate the surface point changing the intended illumination pattern. Note that the range of viewing and illumination angles can be increased by increasing the length of the parabolic mirror section as shown in Figure 3. This figure illustrates that the range of viewing polar angle is $\theta_v \in [0, \pi/2]$ when the azimuthal angle $\phi_v = 0$. But for $\phi_v = \pi$, the viewing angle range is determined by the length of the parabolic section. That is, $\theta_v \in [0, \theta_m]$ where simple geometric arguments can be used to show that

$$\theta_m = \frac{\pi}{2} - \arctan \sqrt{\frac{\delta + f}{a\delta^2}} \quad (1)$$

for the parabolic section in Figure 3 defined by the equation $p = aq^2$ with focal length f. The range of measured reflectance angles is increased by increasing θ_m, or equivalently by increasing δ.

To account for imaging shapes that are not globally planar the basic design must be augmented. Specifically the x-y stage supporting the concave mirror is replaced with an x-y-z stage to enable scanning along the surface shape. Global surface shape can be estimated via stereo cameras or laser range-finding and may be assisted with fiducial markers.

Note that the iris aperture size determines the cone angle of the measured light and this relationship varies over the mirror surface. The finite size of the aperture lead to a ray-bundle as opposed to a single ray and depending on the position this ray bundle strikes the parabolic mirror, the cone of the incident illumination will vary. In addition, the resolution of the image of reflected light will vary over the surface of the mirror and the discussion on resolution in [11][1] is relevant for this device as well.

2.1 Related Work

The use of convex parabolic mirrors for imaging was introduced in [11][1] for use in an omnidirectional camera. Omnidirectional imaging is an analogous problem to measuring BTF except that instead of detecting intensity from all angles emerging from a single point, the omnidirectional sensor detects intensity from all angles in the world converging to a single point in order to provide a 360 degree view of a hemispherical scene. Key to the design of the omnidirectional camera is the convex parabolic camera (used in conjunction with an orthographic lens), to ensure that each image point corresponds to a single scene point. The concave parabolic camera is used in the BRDF/BTF measurement device to ensure that each image point corresponds to an emittance direction from a surface point. The problem

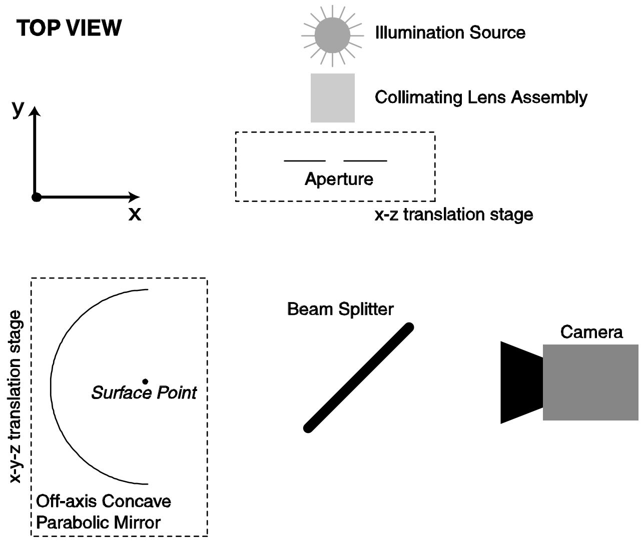

Figure 2: BRDF/BTF Measurement Device. The surface point is imaged by a CCD video camera observing an off-axis concave parabolic mirror to achieve simultaneous observation of a large range of viewing directions. Illumination direction is controlled by an aperture, i.e. translations of the aperture in the x-z plane cause variations in the illumination angle incident on the surface point. The device achieves illumination/viewing direction variations using a simple translations of the illumination aperture instead of complex gonioreflectometer equipment. Measurements of bidirectional texture are accomplished by translating the mirror in the x-y plane.

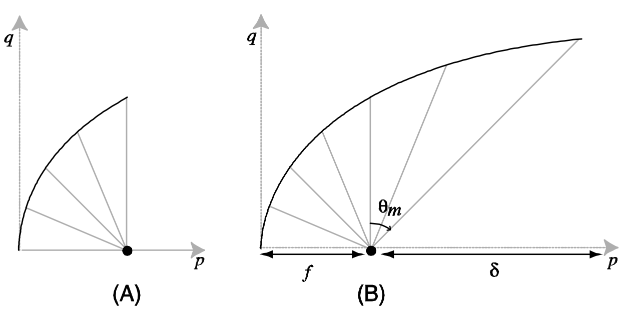

Figure 3: (A) Diagram of a typical concave parabolic mirror. (B) Diagram of an extended concave parabolic mirror.

of BRDF/BTF measurement differs from the problem of omnidirectional sensing because of illumination directional control issues. Also, the issue of surface scanning must be addressed for BTF measurement.

Measurements of BRDF/BTF are not simple, and most existing technology falls short of the ideal features for such a device. For practicality, the device should be fast and convenient. The apparatus should have as few parts as possible to minimize cost and maximize reliability. The number of moving parts should be minimal and moving parts should take simple paths. (The brute force method of moving a camera and a light source in all possible 3D directions results in a complex mechanical device). The apparatus should be simple enough that it can be made portable because in-field measurements are important for many of the applications discussed in Section 5. Some existing devices provide convenient, simultaneous measurements of multiple viewing directions but do not enable convenient precise control over illumination. In addition the device must be structured so that the sample is not re-illuminated when reflecting from device components. Measurements of BRDF at a surface point is not the only item of interest. Instead devices must have the capability of measuring BRDF over an extended sample to capture spatially varying BRDF.

The approach of using curved mirrors was used by [15] who introduced a method of measuring BRDF using a half-silvered spherical mirror and a fish-eye lens that enables simultaneously measurement of light from all viewing directions without changing camera position. This device is not ideal for BRDF/BTF measurements for a few reasons. First, there is no means of automatically changing the illumination direction over the hemisphere. Second, it is designed for measuring reflectance from a single point and extended samples could cause reflection of light to the mirror and back onto the surface, changing the illumination pattern. Finally, the distortions introduced by the fish-eye lens are not accounted for.

Another BRDF measurement device described in [7][12] uses a hemi-elliptical mirror in a hand-held device designed for industrial coating evaluation. Our device differs most significantly from this device in its method of illumination angle control. Specifically, in [7][12] the illumination direction is changed using an additional gimbal mirror which is cumbersome to control automatically. Indeed the commercial version of this device only enables illumination angle variation in a plane instead of a partial hemisphere. Angular variations of a gimbal mirror are more difficult than translational motion of an aperture. Also, when scanning a surface area for BTF measurements, the design in [7][12] requires translation of both mirrors and sensors. In our design, translating a single mirror is sufficient for scanning a small surface region.

Another device employing concave mirrors for BRDF measurement is described in [2]. This device uses two mirrors to achieve a similar functionality to the device described here. The device is consequently more complex and more difficult to prototype. Also, scanning a surface requires traversal of two mirrors instead of one. The design has two focal points and the distance between the two focal points limits the size of the object to be measured.

Some BRDF measuring methodologies such as [10] use a curved object so that multiple samples of the BRDF are obtained by imaging the entire object, e.g. a sphere. The methods assume that the BRDF of the object's surface is spatially uniform. This assumption is too limiting for many applications (e.g. measuring the spatially varying BRDF of the skin on a human face).

In summary, the main features of our device that were not collectively present in existing devices are as follows:

The device instantaneously records reflectance from multiple viewing directions over the hemisphere and conveniently controls the illumination direction over the hemisphere. No angular movements of parts is required, only translations of an aperture and a mirror. The device enables BTF measurements of an extended planar surface or a curved extended surface. A single concave parabolic mirror is used with a dual purpose of illuminating the surface point and reflecting light from the surface onto the detector. Because of the parabolic mirror, the surface can be scanned by only moving the mirror when the camera's field of view is sufficiently large. To increase the range of angles the extent of the parabolic mirror can be increased. Because of the mirror geometry, there is no re-illumination of sample.

3 Prototype Implementation

The equipment for the prototype device includes a video camera (DFW-V500 Sony digital color video camera, Chori America Inc.) with lens (55mm telecentric, Edmund Scientific), an off-axis parabolic mirror (Janos Technology A8037-175), beam splitter (K54-823 Edmund Scientific) , fiber optic illuminator (Dolan Jenner Fiber Optic Illuminator Model PL-900 Edmund Scientific) and an iris diaphragm with 0.8 mm minimum aperture and 25.4 mm maximum aperture (K53-915 Edmund Scientific). Figure 4 shows an image of the current system prototype. Figure 5 shows a closer view of the parabolic mirror and one of the test samples. The mirror specifications are illustrated in Figure 6. The light source is DC-regulated and equipped with a quartz halogen bulb. Light collimation is implemented with a convex lens series so that the incident illumination is near parallel. Note that several variations of the illumination source can be made within the context of the original design. For instance, spectral filters on the illumination source would enable BRDF measurements as a function of spectral wavelength. In addition, polarizers may be used at both the source and detector for measurements as a function of polarization angle. Subsequent prototypes will include automatic scanning by placing the aperture on an x-z stage and the mirror on an x-y-z stage. Also, scanning a non-planar sample will require an additional system component to estimate the depth of the object. While this prototype is mounted on an optical board for convenience of testing and modification, portable implementations are foreseeable extensions.

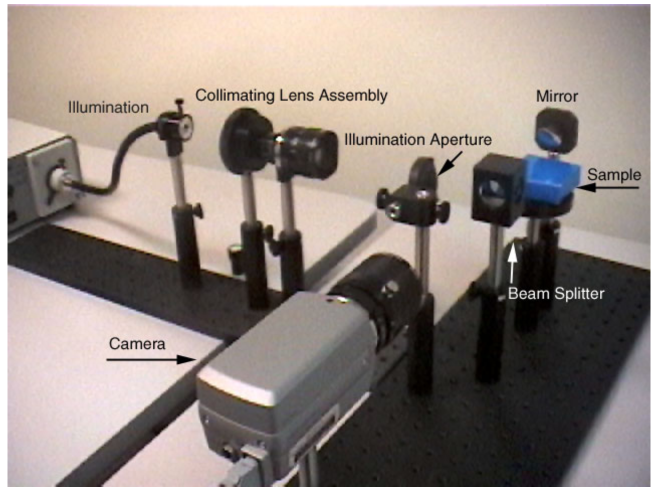

Figure 4: Device prototype including camera, illumination source, collimating lens assembly, illumination aperture, beam splitter and off-axis concave parabolic mirror. A blue specular sample to be measured is shown.

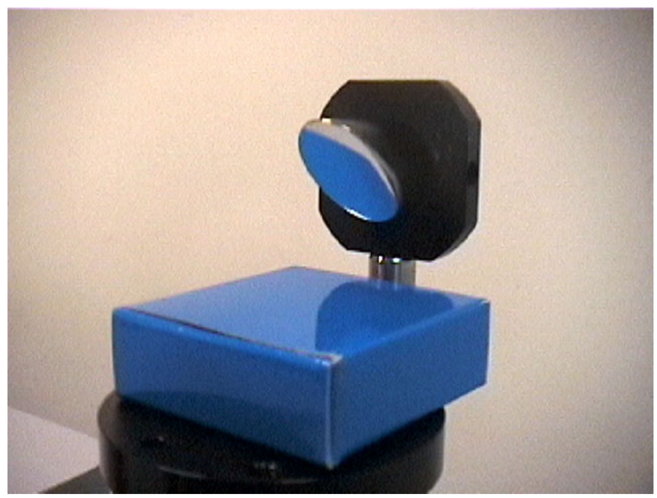

Figure 5: Off-axis concave parabolic mirror used in prototype with a sample (glossy blue cardboard) at focus.

4 Experimental Results

Images acquired from the camera component of the device are reflectance measurements from a range of viewing directions. That is, each pixel images a particular point of the mirror and so each pixel records the reflectance for a particular viewing direction. The position of the illumination aperture described in Section 2 controls the illumination direction. An aggregate reflectance measurement can be obtained by removing the aperture and thereby illuminating the sample from the full range of angles for the mirror. Illustrative examples of these aggregate reflectance measurements are shown in Figure 7. The first image (from left to right) in this figure shows the reflectance measurements for a blue glossy cardboard sample (depicted in Figure 5). Notice there are portions of this image that are near white which indicates specular reflections from the source and portions of this image that are blue where diffuse reflectance components dominate. Consider Figure 6 which illustrates the mirror specifications. In the top part of the mirror the angle between the viewing direction and the surface normal is between 0 and 22.8 degrees. For this part

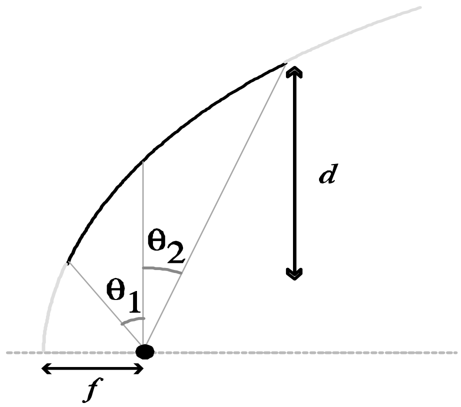

Figure 6: Cross-sectional view of mirror used in prototype. The focal points is a distance f from the vertex of the parabolic mirror and $f = 12.7$ mm. The mirror aperture is given by $d = 25.4$ mm. The angles defining the off-axis parabolic segment are $\theta_1 = 36.5°$ and $\theta_2 = 22.8°$.

of the mirror there is an associated illumination direction such that the sample's surface normal is the bisector of the illumination and viewing direction. Therefore, there is a significant specular component of reflectance. On the bottom of the mirror the viewing angles represented extend to -36.5 degrees. For the range of -22.8 to -36.5 degrees, the incident illumination direction that would cause a specular reflection at this part of the mirror is not present. Therefore the diffuse component of reflection dominates here. Indeed we can observe in the first image of Figure 7 that the top portion corresponds to specular reflection as it is the color of the source and the bottom part corresponds to primarily diffuse reflectance components. The second image in Figure 7 is the aggregate reflectance measurement for human skin. Notice that the characteristic arced stripe present for the specular sample is nearly absent in this measurement. The third image in this figure illustrates the aggregate reflectance from a diffuse brick sample. Notice again a relatively diffuse reflectance behavior. The last image in Figure 7 shows the reflectance from the back of a CD (compact disk) that was tilted so that the multicolor reflectance could be observed. On a CD, diffraction causes reflectance color to vary with viewing angle and this multi-color reflectance pattern is clearly observed in the figure.

Figures 8 and 9 illustrate the illumination addressing capability of the device, i.e. the aperture is positioned to choose a particular illumination direction. To demonstrate the effect of illumination addressing, six different illumination aperture positions are used with the glossy blue cardboard sample. Figure 8 shows the measured reflectance when the illumination aperture is moved so that the incident ray changes from the top center of the mirror (left image) toward the bottom center of the mirror (right image). Notice the specularity moves in the opposite direction as one would expect from the mirror geometry. Figure 9 shows the measured reflectance when the illumination aperture is moved so that the incident ray changes from the right side of the mirror (left image) to left side (right image). Notice the specularity moves in the opposite direction because the aperture position controls the incident angle and the emmitance angle must lie on the opposite side of the surface normal for specular reflection. Highly specular samples are useful to obtain exact calibration between image coordinates, aperture position and viewing angles. This type of illumination addressing is a key feature of the device, since the illumination direction is changed in a fairly simple way. Responses recorded from this device can also be used to determine slant and tilt of a surface whose reflectance is known or approximately known.

In Figure 10 a set of images of human skin is shown as the mirror is adjusted so that its focal point corresponds to the skin surface. Observe that when the surface is below focus, one can view a region of the surface to get the context of the overall texture. Then as the focal point is lowered to be coincident with the surface, the observed images show an incremental magnification toward a single point on the surface. This trait is useful for visual navigation, i.e. the focal point can be directed visually to the precise position of interest on the surface.

5 Applications

The work described here is motivated in part by the application of skin texture measurement in a clinical setting. Clinical evaluation of a skin surface is typically done by visual observation. A physician observes the skin surface at different viewing/illumination angles by instinctively tilting his/her head or tilting the skin surface. This information cannot be conveyed in a single image. Instead, bidirectional measurements of skin BTF can be used to fully characterize the skin surface for use in computer-assisted diagnosis or quantitative evaluation of treatment efficacy. Prior BTF measurement methods as in [6] are too cumbersome for clinical use. The device described here enables fast and convenient data capture and will be applied in dermatology studies in collaboration with the Robert Wood Johnson Medical School, New Brunswick NJ.

While the structure of the skin is three-dimensional, the characteristics are quite different from other 3D structure imaged in clinical settings. Typically, 3D medical imaging is equated to MRI or CT volumetric imaging. But neither of these modalities is appropriate for imaging the fine scale structure at the skin surface. Furthermore, the structures of interest are visible and thus no internal imaging methods are required. Yet although the skin structure is visible, imaging the skin surface is not equivalent to merely taking a picture because a single image cannot capture depth variations on the surface. Stereo imaging only works well for macroscopic surface shape and cannot accurately describe the complex fine-scale geometry of the skin surface. Laser profiling can be used to obtain depth maps, but for complex surfaces like skin the precision is not sufficient. Also, this depth information alone ignores the very important quantity of surface reflectance that is captured via imaging.

Figure 7: Images of the aggregate BRDF obtained for four samples. From left to right the samples are (1) glossy blue cardboard, (2) skin surface of the author's hand, (3) diffuse brick, (4) the surface of a CD (compact disk).

Figure 8: Illumination addressing. The illumination aperture is moved so that the incident ray changes from the top center of the mirror (left image) toward the bottom center of the mirror (right image). Notice the specularity moves in the opposite direction as one would expect from the mirror geometry.

Figure 9: Illumination addressing. The illumination aperture is moved so that the incident ray changes from the right side of the mirror (left image) to left side (right image). Notice the specularity moves in the opposite direction.

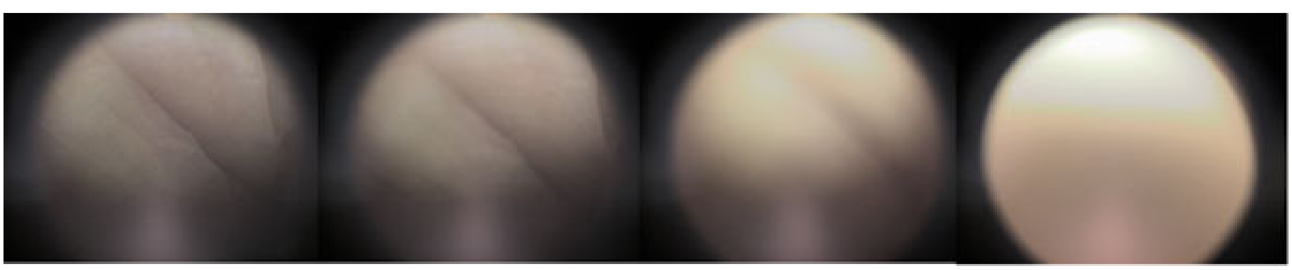

Figure 10: Images from camera as mirror focuses on skin surface. When the focal point is above the surface, surrounding texture is discernible. The images from left to right depict the camera view as the focal point approaches the surface. These views can be used to navigate the mirror focus to the desired surface point.

In medical imaging, texture analysis has been typically limited to 2D analysis of medical images (e.g. evaluation of microcalcifications in mammograms) or volumetric texture analysis (e.g. analysis of volumetric data from magnetic resonance imaging). The study of surface BTF is of clear interest to the field of dermatology for evaluation and diagnosis of skin cancer and other disorders; yet this area remains largely unexplored. The research problems that need to be addressed for this application include appropriate imaging devices, surface models and recognition/detection algorithms. The result of this research would lead to a new protocol for computer-assisted diagnosis of skin disorders. In addition the approach could lead to an invaluable tool to quantify treatment efficacy.

There are many additional areas in which measurements from this device have considerable utility. For instance, in industrial settings BRDF/BTF of textiles and coatings should be measured for quality control and inventory characterization. Also in the industrial setting, measurements of BRDF/BTF of materials can be used in design and planning, e.g. automotive interiors. Watermarking of items for preservation and security can be planned and executed with a BRDF/BTF measurement device. Interior design applications can use BRDF/BTF measurements for visualization purposes. This is especially useful for e-commerce solutions that require the consumer to view the appearance of fabrics, wallpaper, wall coatings, etc. under a variety of pose and illuminations. BTF measurements enable a true digital representation of the object that captures all the essential observable features of an object. In fact, marketing any product with a digital representation is assisted with BRDF/BTF measurements so the appearance of the product can be better evaluated by the consumer without the need to see the item. The BRDF/BTF measurements are also useful in the military for camouflage design and evaluation. In general, any application that could use computer vision to recognize and/or classify a surface needs a BRDF/BTF measurement device to design/test algorithms. Also, any application that uses computer graphics rendering to synthesize the object's appearance (e.g. on a computer screen) may use a BRDF/BTF measurement device to find out how appearance should be rendered.

6 Summary

A device is described which enables economical, compact and convenient measurements of spatially vary BRDF. A concave curved mirror enables variations of viewing and illumination direction without the need for complex mechanical equipment to orient the source and sensor over a hemisphere of possible direction. The utility for such a device is widespread in many areas of computer vision and computer graphics. Experimental results are provided which show reflectance measurements of real-world samples using the device.

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