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On the Advancement of BTF Measurement on Site

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Abstract

We present our progress to the on-site measurement of the spatially varying surface reflectance represented by bidirectional texture function (BTF). This requires a physical realization of a portable instrument that can be brought to the sample, outside the laboratory. We discuss our motivation, the main issues, and challenges for making such an instrument possible. We focus on the design of the mechanical parts that are required for an easy manipulation of the device on site and describe our experiences with the instrument in practice. The design uses a miniaturized rotary light stage. It allows for measurement of HDR images with the acquisition rate of 1000 HDR images per minute, where one HDR image consists of 4 individual exposures.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture I.4.1 [Image Processing and Computer Vision]: Digitization and Image Capture—Reflectance

1. Introduction

The measurement of spatially varying surface reflectance is required for reproducing real world appearance in various applications. We focus on the measurement of a surface reflectance represented as a bidirectional texture function (BTF). For this representation the images are taken for many combinations of a light direction and a viewing direction against the measured planar sample which gives 6-dimensional function (2 parameters for incoming direction, 2 for outgoing direction and 2 more for the position on a planar sample). While there are other dependencies such as wavelength, light polarization, temperature and air pressure, mostly used BTF measurement instruments neglect that and use trichromatic (RGB) cameras. The BTF is generally a powerful model of surface reflectance that allows for capturing fine details of non-local effects such as subsurface scattering, masking, self-shadowing etc. For the recent survey on the measurement devices with the focus on the development of stationary devices at the University of Bonn we refer to Schwartz et al. [SSW*14].

Although the measurement of BTF is time demanding by principle as we need to sample six or seven dimensional function, the modus operandi of the measurement for the laboratory conditions is relatively easy. A material sample is fixed on the holder in the stationary instrument and the measurement of raw image data is carried out in order of tens of minutes to hours. This modus operandi is not suitable for cases where we cannot extract the sample from its surroundings or where such extraction is almost infeasible. This is for example in the case of buildings and archaeological sites. Even when the sample extraction is feasible and allowed, it may require various mechanical methods for a successful extraction in dependence on the material type. This could be also rather time demanding. The extracted material sample can be for example fragile and the sample can be easily damaged or broken during the attempt of the extraction. In some cases such as for virtual reconstruction of buildings and the furnishings (e.g. for [HZDS09]), the sample extraction would cause a physical damage of the building including at least aesthetic changes. For cultural heritage artifacts such as sculptures or surfaces that become specific due to weathering [XDR11] this is simply not allowed.

Some applications such as machine learning require massive campaign of surface reflectance measurement on site for creation of hyper-realistic images that could be used for rendering of images as the input. These measurements are difficult to implement by the use of stationary instruments. Below, we review the state of the art and focus on some issues based on our experiences with the portable instrument prototype for measuring BTF on site that was described in detail in two former publications [HHN*17a,HHN*17b]. We describe the issues found out during testing the instrument, how they were resolved and some themes for future work.

2. State of the art of portable on-site measurement instruments

As the problem of appearance measurement is difficult due to data dimension and size, only a few approaches for measuring surface reflectance were proposed, in particular, for measuring BTF. There is a survey by Schwartz et al. [SSW*14] describing the options for measuring surface reflectance for computer graphics, including many details for the prototypes developed at the University of

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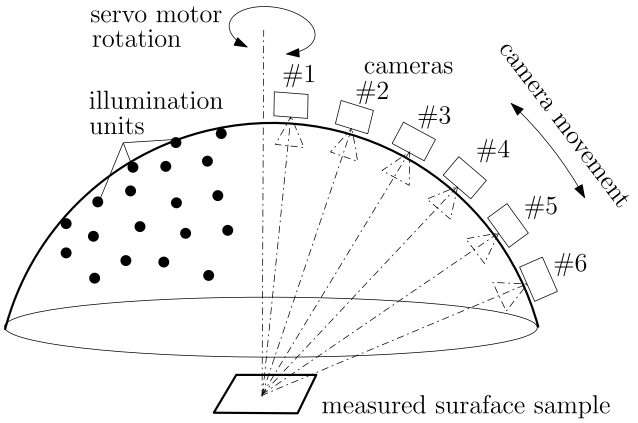

Figure 1: *Lightdrum concept: LED illumination units with optics are located on the hemispherical dome. The acquisition of images is done with six USB 3.0 cameras. The cameras can be moved together along meridian. The instrument is rotated by precise servo motor with zero backlash gear.*

Bonn. Other older surveys are by Filip and Haindl [FH09], Weyrich et al. [WLL*08] and Mueller et al. [MMS*05], updated recently by Weinmann and Klein [WK15]. Some devices for SVBRDF measurement [RPG16, AWL13] utilize Helmholtz reciprocity which is not possible for BTF acquisition.

Portable instruments allowing for on-site measurements for six or seven-dimensional BTF are indeed rare due to the difficulty of putting the illumination and image sensors into a small space and weight, in particular, where the device is to be used for on-site measurement.

The first proposal for a portable instrument was outlined by Dana [Dan01]. It uses an ellipsoidal mirror, a structured light source, and a beam splitter that allows for the separation of the incident light from the reflected light. Using a motorized XY stage which moves the gantry over the surface sample in scan-line order allows, in principle, the measurement of the surface reflectance variation over the whole surface. However, the set of input and output directions is limited by the shape of the ellipsoid and the beam splitter and to our knowledge this device has never been built.

Another principle uses a kaleidoscope and was proposed by Han and Perlin [HP03]. The idea is to use the reflections inside the tapered kaleidoscope to achieve a variety of viewing and illumination directions. The separation of optical paths of incident and outgoing light is again achieved by an optical beam splitter. Although the prototype with a 3-sided kaleidoscope was built in [HP03], the gantry allows for a rather limited and discrete choice of viewing and illumination directions and it achieved low spatial resolution. The prototype was tested only under laboratory conditions.

The measurement instrument design published in [HHN*17a, HHN*17b] and further discussed below has a principle outlined in Figure 1. It was motivated by several previous works including the technique for measuring BRDFs in situ proposed by Ben-Ezra et al. [BEWW*08] that uses a hemispherical setup, containing a set of LEDs. In that setp the measured sample is located in the center of the instrument, the LEDs were used for both the illumination and sensing of the light reflected from the sample. This is close to a so called light stage that was proposed by Debevec at al. [DHT*00]. First this principle was adopted for BTF measurement by Malzbender et al. [MGW01] for polynomial texture maps providing low resolution reflectance acquisition for a single camera at the surface normal. Mueller et al. [MMS*05] used this principle for the design of a stationary dome based instrument for measuring BTF data. It contains 151 off-the-shelf cameras whose flash lights serve for illumination. This setup was modified by Schwartz et al. [SSWK13] by adding a rotary stage on which the measured sample is put. Then only 12 cameras at fixed positions, on a meridian stage, were needed. These two dome based setups [MMS*05, SSWK13] are movable but they require a re-calibration after transport. Further, they do not allow for measurement on site as they are bulky and they cannot be positioned against a stationary sample. An extracted sample is put into the instrument.

Another work is by Filip et al. [FVK14] who proposed a possibly portable device with one camera at fixed elevation direction and two light sources that can be set at azimuth to arbitrary angle by stepper motors. This device achieves very limited directional resolution in the elevation direction and has a low dynamic range. As the rigidity of mechanical construction is not sufficient and the device does not protect the sample to be illuminated by the surrounding illumination, the prototype is impossible to use for measurement on site.

3. Key design requirements on a portable BTF measurement instrument

Originally, the need for a portable measurement instrument was motivated by the completion of the project of MPI Informatics Building Model [HZDS09]. After the geometry completion, it appeared in year 2010 that there is no method to measure the BTF of the material surfaces in the building. We stated several main design issues not achieved by stationary instruments to make a prototype useful in practical scenarios of on-site measurements:

- decrease the time of measurement to the order of minutes while keeping a high acquisition rate as in [SSWK13, MMS*05],
- decrease the size and weight of the instrument to be operated by one or two persons and to allow for an easy transportation through 600mm wide doors,
- make a robust mechanical construction that does not require any re-calibration after moving the instrument and is thermally stable,
- provide the technique for image data registration as there is no holder with marks as for stationary instruments,
- make easy to position the instrument against the stationary sample for common real-world situations,
- achieve a sufficient spatial size of sample being measured to capture sufficient surface reflectance variety,
- provide at least trichromatic image data acquisition allowing for a color calibration, a sufficient color gamut and a sufficient intensity range for majority of surfaces,
- attain a high quality accurate data acquisition with usable spatial resolution useful in computer graphics and vision applications,
- minimize the number of instrument components and operation

steps during the measurement (such as avoiding the use of additional notebook running the application),

- minimize the power consumption: a high one would produce excessive heat, causing instrument failures. This includes also the risk of a circulation of warm air in front of the cameras that could deteriorate the quality of acquired images.

Also, the work on the prototype was restricted by the financial budget under the time constraints of the project funding by the end of year 2016. As no instrument design can serve universally for all imaginable scenarios, we needed to set some basic design trade-offs (such as sample size, image resolution) that were following the limits of optical design and allow for relatively general application scenarios needed by the project [HZDS09]. We have opted for imaging a planar object size of 80 × 80mm from which we can use a sample with a diameter of 51mm. Then the spatial resolution is 150 DPI (e.g. 5.9 lines per mm) on the measured sample when viewed in the direction of surface normal.

The work on the prototype required very careful co-design in optics, mechanics, electronics and software with the extensive research on available off-the-shelf components. Some parts had to be custom manufactured. The whole project realization took 30 months since the initial design steps. The design split the instrument into two parts connected by cables to improve on the manipulation operability. The first part is a power box with electronics such as power supply units and Ethernet router. The power box weighs 10 kg and is connected to the second main part. The three cables provide the data connection by 1 GBit Ethernet, the DC power supply at 5V/40 Amps and a cable required to power a servo motor.

The second part is the main body of the measurement instrument and is called a lightdrum. A servo-motor with a zero backlash gear operates a cylinder ended up with an aperture that is positioned against the measured sample. The servo motor rotates the dome with LED modules and cameras above the measured sample around measured surface normal. The interior alloy frame provides a mechanical rigid support for most of parts in the lightdrum such as cameras and electronic parts. The instrument is protected by a custom carbon cover against the external impacts and stray light. The lightdrum is equipped with six fast USB 3.0 cameras with Bayer filter that can be moved together along the meridian from the hemisphere pole (elevation angle $\theta = 0^o$) towards the equator ($\theta = 75^o$). The cameras elevation is set by the stepper motor moving all the cameras together along a linear rail in a range of 12.5 degrees so that the angle of view of the neighboring cameras overlap in the end positions. While the cameras' motion is only approximately circular, this design decreases the instrument weight [HHv*15].

Small custom LED modules with an adjustable direction are used for illumination. They are affixed to the hemispherical dome made of PMMA that is mounted to an interior alloy frame with a camera subsystem. The number of LED modules is 139 and 5 of them are located between the cameras. The instrument main axis is set perpendicularly to the sample by means of an autocollimator that uses a laser and a small additional camera as outlined in [Hav16].

The USB 3.0 cameras are connected to microcomputers that process the data from the cameras and composite high dynamic range (HDR) images, each from four individual images of different exposures. These six microcomputers are connected to the control microcomputer that controls LED lighting and synchronizes the LED flashes with the camera data acquisition. The control microcomputer is also connected to the camera for the autocollimator, switches on/off the laser for the autocollimator, and operates the stepper-motor. All seven microcomputers are connected via an embedded network switch that also allows for data transfer from the instrument to an external storage where the images are processed. The weight of the lightdrum body including the geared servo-motor is 12.5 kg.


(a) (b) (c,d)

Figure 2: *Concepts of the holders, original realization in year 2016, (a) a tripod based holder for the position high above the floor, (b) a tripod based holder for the measurement on the ceiling, (c,d) table-top frame holder for the position on the floor and a vertical wall close above the floor.*

4. Measurement application scenarios

The instrument was designed to offer a number of real-world application scenarios. Therefore it must be placed on a mechanical holder that allows for the setting and fine adjustment of the instrument position against a stationary sample. We have classified the real world measurement scenarios into four cases depicted in Figure 2 showing the use of proposed holders for measurement of a stationary sample (a) on a vertical wall high above the floor, (b) on a ceiling (or on a tilted wall so the case between (a) and (b)), (c) on a floor or a desk, (d) on a vertical wall close above the floor.

For the four application cases we designed and realized two different instrument holders shown in Figure 3. Since the publication of [HHN*17a, HHN*17b] we improved on the functionality of these holders to facilitate the instrument positioning. Below, we detail the description of these modifications. The problem of instrument setting is known as positioning a 3D object in space. It requires to set 6 degrees of freedom, 3 of them for position (x, y, z) and 3 of them for rotation, the angles (α, β, γ). The one degree corresponding to the angle γ is naturally resolved by rotation of the servo motor. The 5 other degrees of freedom require the elements for mechanical adjustment to be included in the instrument holders. Note that the holders with the adjustment elements should be rigid enough to keep 12.5 kg of the lightdrum, minimize the vibration after the servo-motor rotation, and suppress the external vibrations.

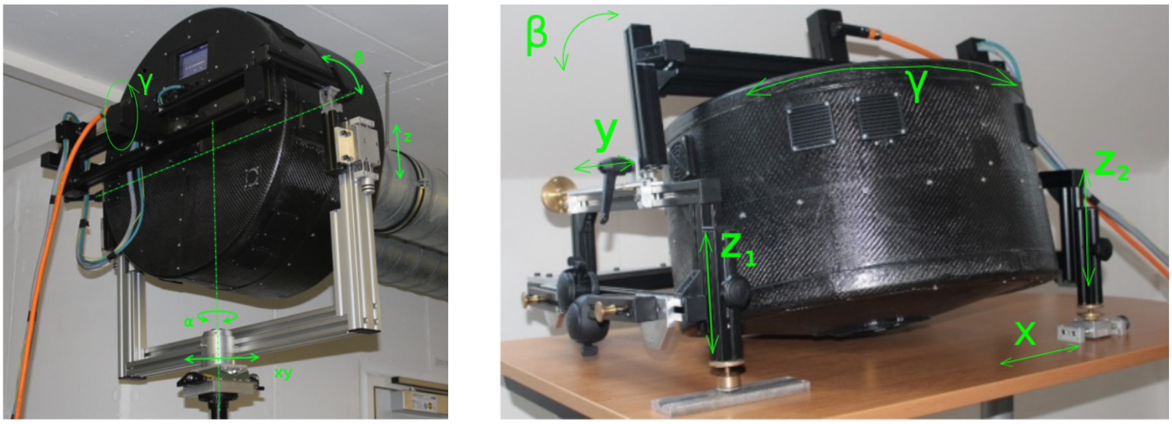

Figure 3: *(left) tripod based holder (right) table-top frame holder. The 6 degrees of freedom are depicted in green.*

4.1. Tripod based holder – case (a) and (b)

The first holder is based on a heavy duty and stiff tripod that itself allows for rough adjustment of z axis. It was completed by XY linear stage (x, y position) and U-shape frame on which the lightdrum is mounted. The ends of U-frame are equipped by two linear stages allowing for fine adjustment along z axis. The angle α is achieved by rotating the devices at the tripod's axis, the angle β at the end of U-shaped frame. All the adjustment knobs allow either for direct manipulation by linear or angle position setting, or for release, angle adjustment, and fixing (angles α and β). The holder can be used in two different cases in which the adjustment elements may have a different effect. In order to be stable the design of the holder must keep the center of mass of the lightdrum approximately in the tripod's axis.

4.2. Table top frame based holder – case (c) and (d)

The second holder is designed to be used for the measurement on a horizontal plane such as a floor or table. The aluminum frame holding the servo motor with the lightdrum is only kept, the rest of the frame is specific. The frame uses three legs to be stable. The movement in x-axis is achieved by a linear guide fixed to one leg while two other legs use ball transfer units at their ends. The second leg is constrained in one direction by a part with V-groove to which the ball of ball transfer unit is engaged into. Both linear stage and V-groove part a put on the horizontal plane. The last ball unit in the third leg is freely sliding over a flat metal pad. The second sliding motion in y-axis is achieved by motion over the frame at both sides using screws with a travel range of 80mm. The movement along z-axis is accomplished by leveling three set screws in the frame's legs independently for two front legs. The difference in positions of these two legs along z axis allows for a fine adjustment of the tilt angle α. The tilt in the perpendicular direction along angle β is realized by fixing the aluminum frame with the servo motor against the base frame on both sides of the frame with miniature clamp levers.

5. Results and discussion

The lightdrum prototype was tested. The initial holders proposed in [HHN*17a, HHN*17b] were extended as described in Section 4 and successfully tested at the building of MPI Informatik on measurement of 25 flat material samples (all 4 positions in Figure 2). The utility of the autocollimator with fixing the mirror on the top of measured sample was confirmed; although it requires some effort, it provides the most accurate results. The time needed for setting up a single measurement fluctuates between 10 to 15 minutes, when operated by a single person. The use of the touch display facilitates the operation with the instrument. For some measurement scenarios it is convenient to flip the display content vertically. The use of a vibration sensor inside the instrument to repeat some measurements is necessary.

Based on our experience we believe that for keeping the chosen sample size and the quality of measurement it is extremely difficult or infeasible to decrease the instrument size. This is mainly due to the optical design: optimally we should use an orthographic camera instead of a perspective one. It would be possible to decrease the footprint and weight of the instrument at the detriment of decreasing the number of LED modules and the measured sample size.

6. Conclusion and future work

We believe that when the instrument measurement time gets to approximately 5 minutes for the same image quality and data size, it would become highly acceptable by a wide range of users, including the movie industry. The current bottleneck of the lightdrum includes the speed of camera capture, the transfer and processing the data and the storage speed limits for saving 40 GBytes needed for 16680 images taken.

In the future it makes sense to extend the device to allow for at least sparse spectral measurements. There is also likely that the recent LED technologies with better white spectrum will improve on the color fidelity. To decrease the measurement setup time it would make sense to allow for more automated instrument adjustment against a stationary sample using electrical actuators embedded in the holders. The measurement time will be decreased by newer and faster camera and computer hardware.

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