Přednáška 05

Prostorově proměnné materiály

Měření a modelování texturovaných materiálů pomocí SVBRDF a BTF

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Spatially-Varying BRDF Measurement

[McAllister 02]



$$SVBRDF(\lambda, x, y, \theta_i, \varphi_i, \theta_v, \varphi_v)$$

- **7 dimensional data** ⇨ 4 dimensions depend on camera, light & sample positioning
- Restricted to opaque, flat surfaces where BRDF reciprocity holds

Measurement setup with **4 mechanical degrees of freedom**:

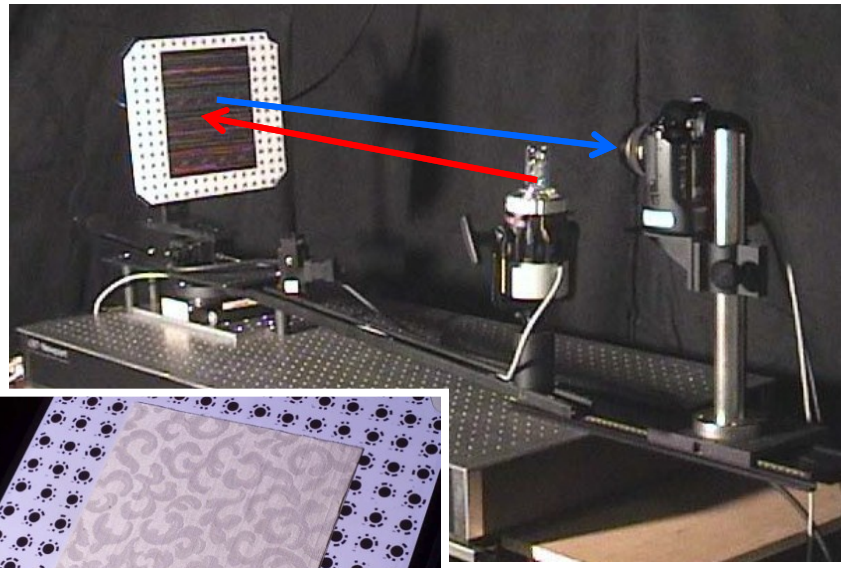
Gonio-reflectometers	sample/light/camera **1/2/1**
Image-based setups	sparse view/light sampling **2/2** + known geometry
Light-stages	many lights/cameras **2/2**
Portable setups	registration of BRDF measurement to sparse object images

SV-BRDF Sample Acquisition

Gonio-reflectometers

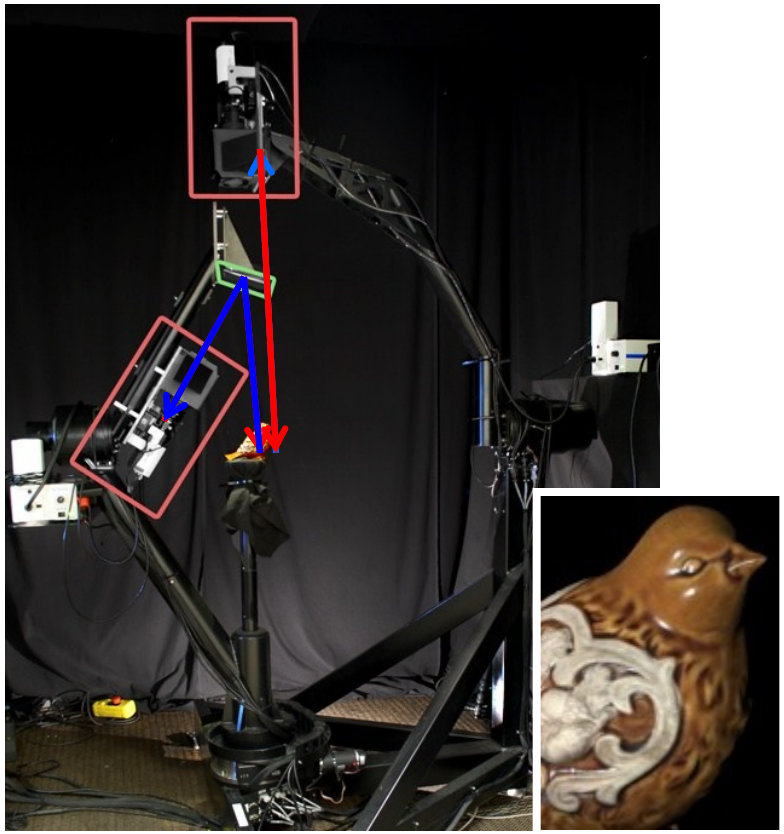
[McAllister GH 02]

- moving light, tilting sample



[Holroyd et al. TOG 10]

Simultaneous measurement of geometry and SVBRDF



SV-BRDF Sample Acquisition

Light stages

Facial SVBRDF measurement

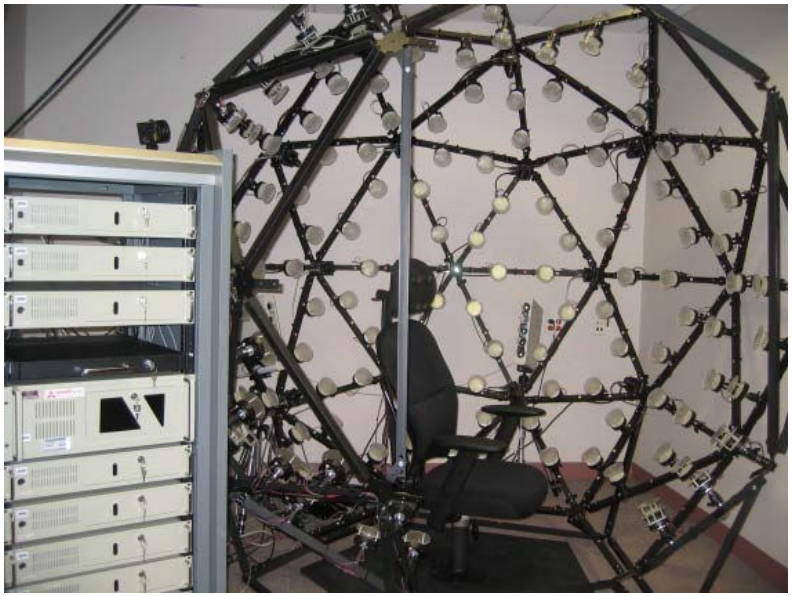
- 156 lights, high-speed camera

[Debevec et al. SIG 00]



- 150 lights, 16 cameras
- structured light for geometry capture

[Weyrich et al. SIG 06]



SV-BRDF Sample Acquisition

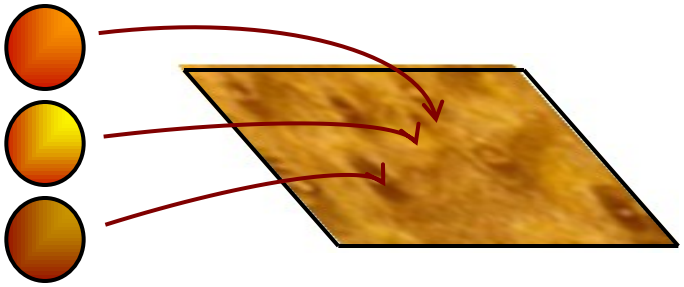
Portable setups

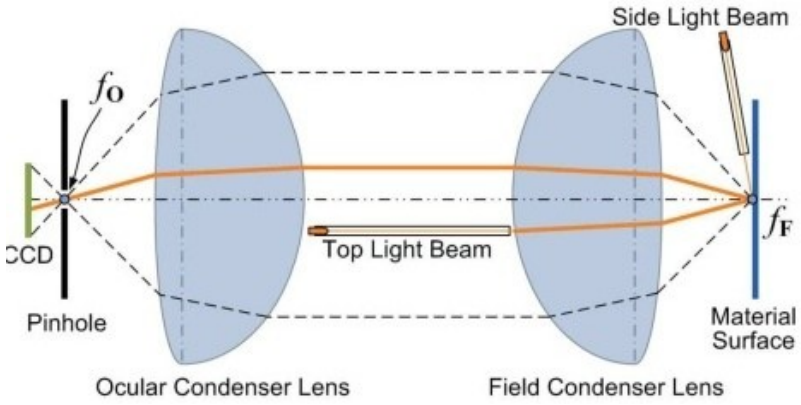
[Dong et al. SIG 10]

Fast measurement, compromise accuracy:

- Sparsely measured BRDF registered to measured object reflectance map (single view, many lights)
- Anisotropic BRDFs

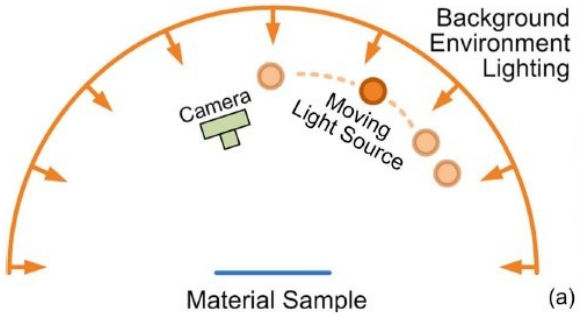
BRDF 1
BRDF 2
….
BRDF n

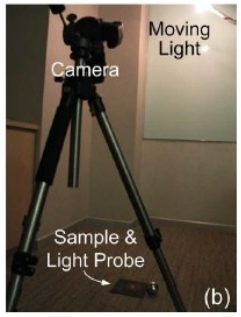




BRDF measurement





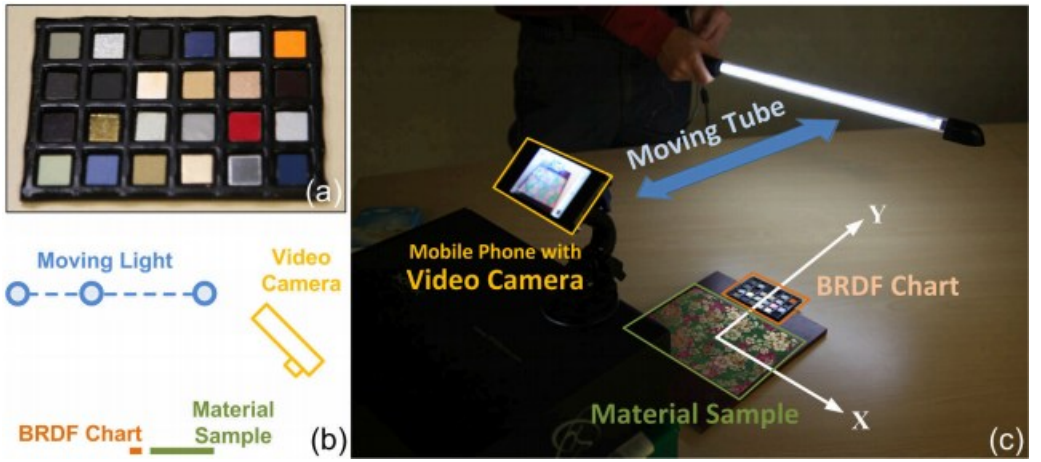


Reflectance-map measurement

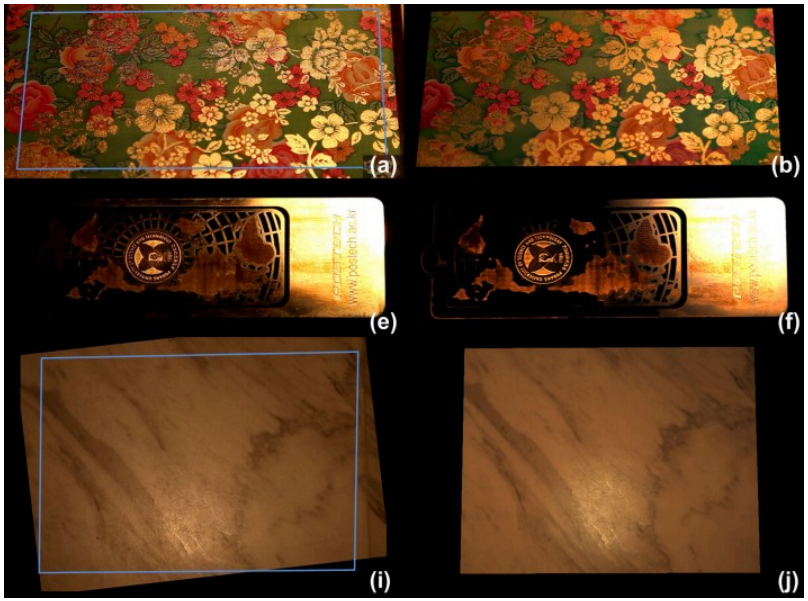
SVBRDF Capture & Modeling

Portable setups

- [Ren et al. TOG 11] - “pocket reflectometry”: SVBRDF from movie of static object lit by linear light source captured by a static mobile phone camera
  - Use set of BRDF reflectance targets (selection is important)
  - Measured reflectance fitted as a mixture of target’s BRDFs



[Ren et al. 11 ACM]



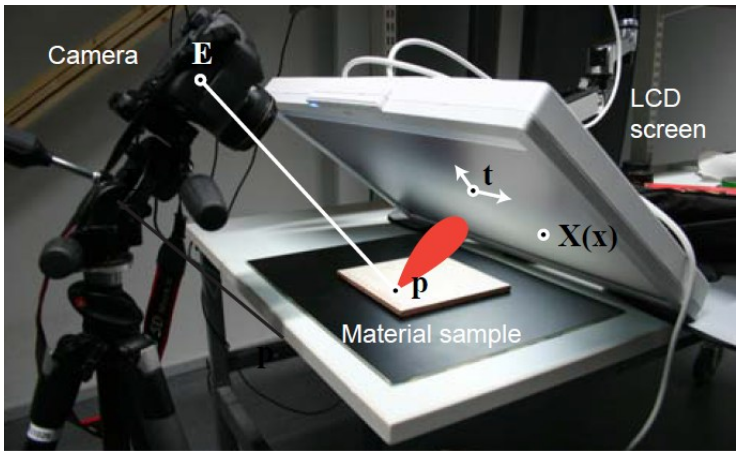
SV-BRDF Sample Acquisition

Portable setups

[Aittala et al. SIGGRAPH 13]

SVBRDF Capture In The Frequency Domain

- reflection of Fourier basis patterns emitted from the screen ⇨ fitting reflectance by Gaussian mixture models
- different sampling frequencies ⇨ 131 images
- viewing rays reflecting into the screen as reflectance lobe
- each captured pixel ⇨ integral of the product of this projected lobe and the illumination pattern





SV-BRDF Sample Acquisition

Portable setups

[Aittala et al. SIGGRAPH 15]

Two-Shot SVBRDF Capture for Stationary Materials

- smartphone a capturing device
- acquisition limited to retroreflective BRDF slice ⇨ camera close to illumination
- fitting micro-facet BRDF model
- assumption od stationary texture in the material ⇨ repeatable structure

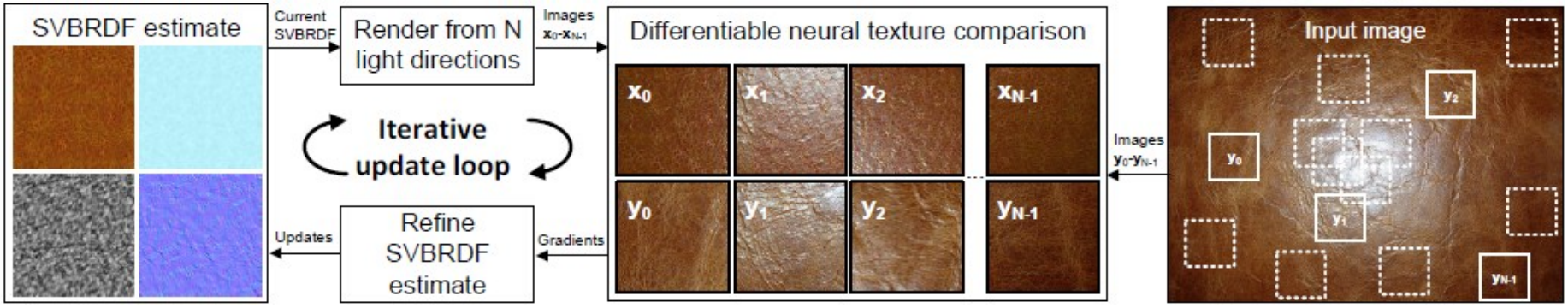


SV-BRDF Sample Acquisition

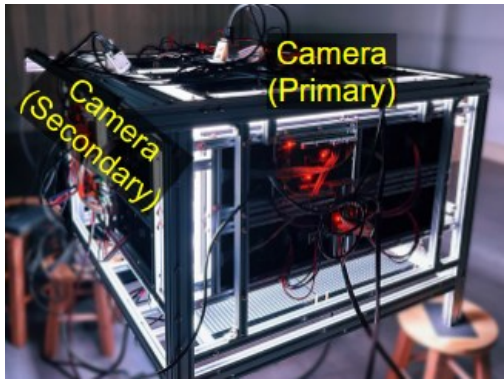
Portable setups **[Aittala et al. SIGGRAPH 16]**

Reflectance Modeling by Neural Texture Synthesis

- spatially varying parametric reflectance models from a single image taken with flash illumination
- materials with stationary texture
- decomposition of image into local tiles
- deep convolutional neural network ⇨ fitting diffuse and specular coefficients maps



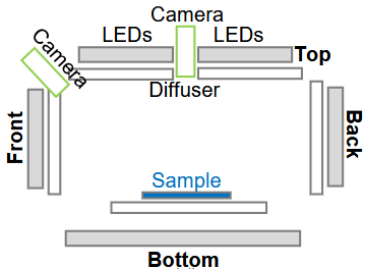
SV-BRDF Sample Acquisition

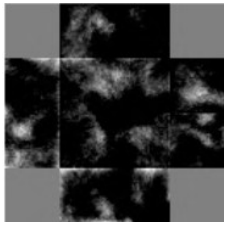


Portable setups

[Ma et al.23]

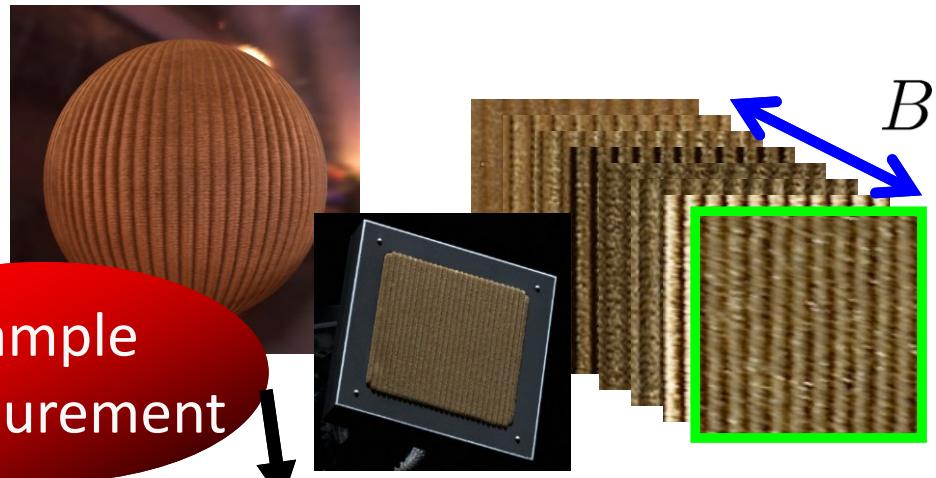
- **Capture setup**: Near-field light stage with 16,384 programmable LEDs and two 24 MP cameras (frontal and oblique views).
- **Illumination multiplexing**: 64 jointly optimized lighting patterns
- **Two views image registration**: Dense SIFT/PatchMatch pixel correspondences.
- **Neural reconstruction**: A pretrained network estimates per-pixel (lumitexel) reflectance as a compact 56D latent representation.
- **Reflectance refinement**: Additional measurements under 63 linear lighting configurations enable per-pixel optimization.
- **SVBRDF fitting**: Anisotropic GGX model fitted to the recovered reflectance, including diffuse/specular albedo, roughness, normals, and tangent directions.
- **Performance**: 193 HDR photographs per sample (15 minutes of acquisition).
- **Dataset**: 1,000 measured materials across 9 categories, with 1024 × 1024 SVBRDF parameter maps: https://opensvbrdf.github.io/







BTF Measurement Setups Taxonomy



Sample Measurement

$$BTF(\lambda, x, y, \theta_i, \varphi_i, \theta_v, \varphi_v)$$

7 dimensional data ⇨

4 dimensions depend on camera, light & sample positioning

Measurement setup with **4 mechanical degrees of freedom**:

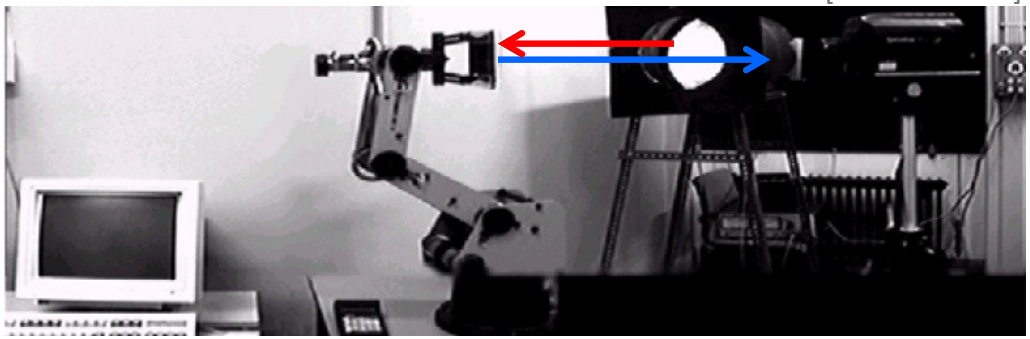
- **Gonio-reflectometers**
  - Moving Sample & Camera — sample/camera **3/1** (**1/1** + many lights)
  - Moving Sample & Light — sample/light **2/2**
  - Moving Sample, Light & Camera — sample/light/camera **1/2/1**
- **Mirrors, domes**
  - Moving Sample — sample **1** + many lights & cameras
  - Static Measurement Setups — many lights & cameras (real/virtual)
- **Portable setups**

BTF Sample Acquisition

Gonioreflectometer – Moving Sample & Camera

CURET-Columbia&Utrecht University
[Dana et al. ACM TOG99]

[Dana et al. 99]



Database: 61 samples

Illu./View directions:

55/max.205 = 215 img.

Max. illu./view elev.:

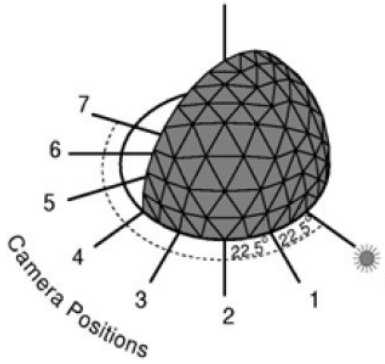
85°/85°

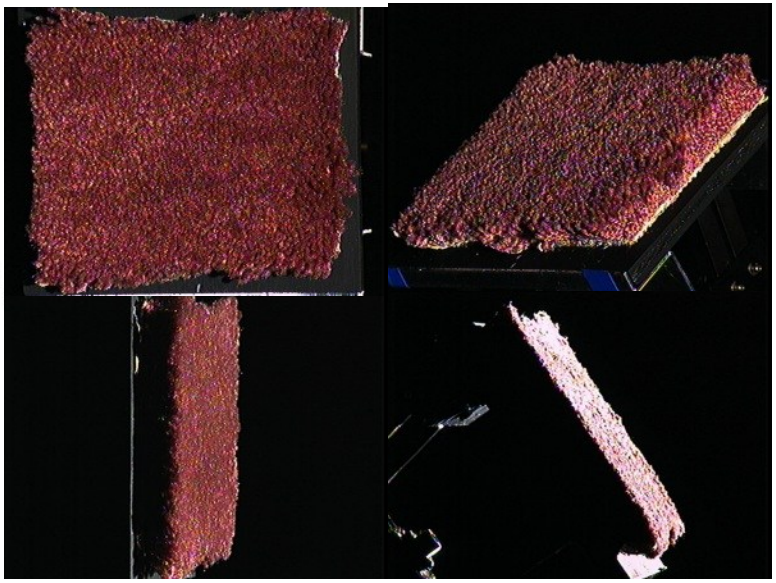
Rectified images:

400 x 300 pixels

Measurement time:

n/a





http://www1.cs.columbia.edu/CAVE/software/curet

BTF Sample Acquisition

Gonioreflectometer – Moving Sample & Camera

Bonn University
[Sattler et al. EGSR 03]

Database:

10 samples (4 HDR)

Illu./View directions:

81/81 = 6 561 img.

Max. illu./view elev.:

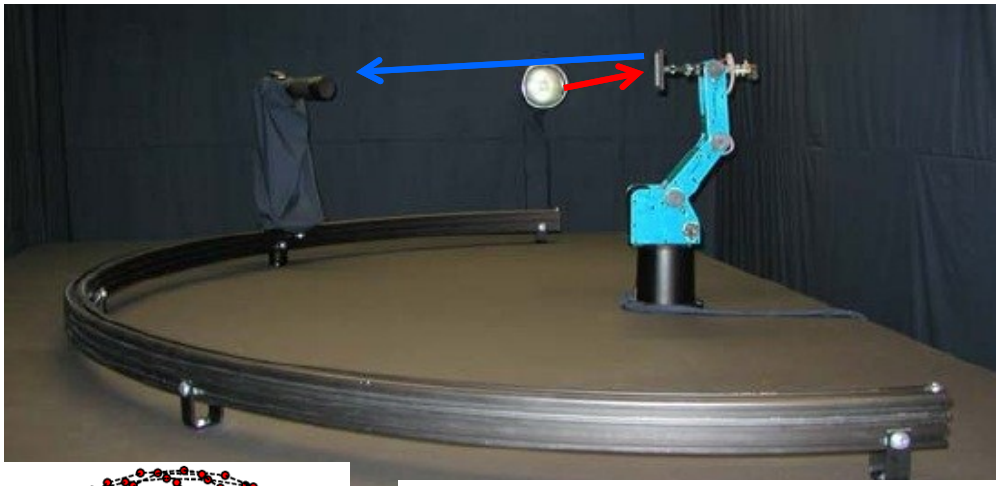
75°/75°

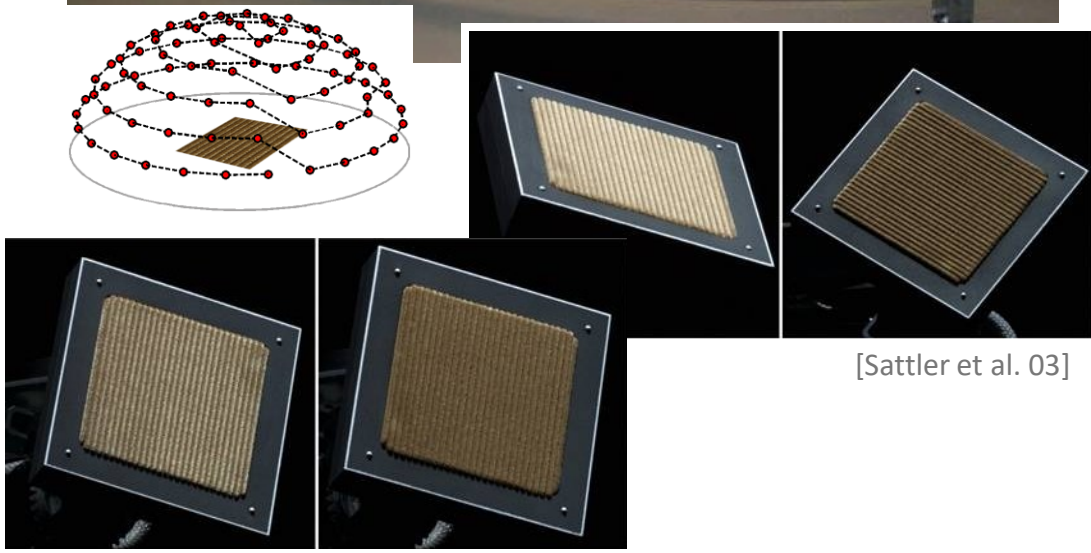
Rectified images:

800 x 800 pixels

Measurement time:

~ 14 hours





[Sattler et al. 03]

http://btf.cs.uni-bonn.de/

BTF Sample Acquisition

Gonioreflectometer – Moving Sample & Light

Yale University [Koudelka et al., TEXTURE 03]

[Koudelka et al. 03]

Database: 17 samples

Illu./View directions:

120/90 = 10 800 img.

Max. illu./view elev.:

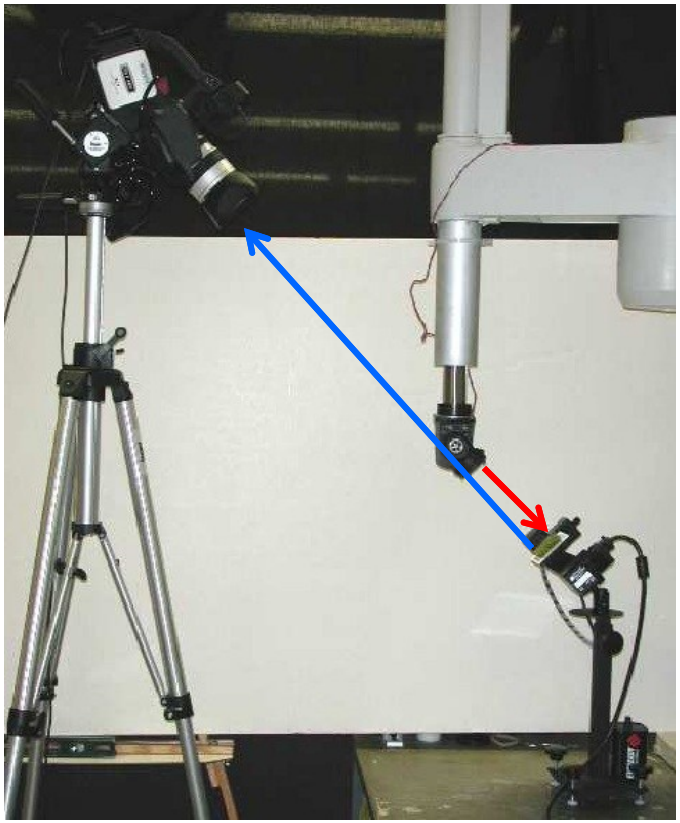
80°/75°

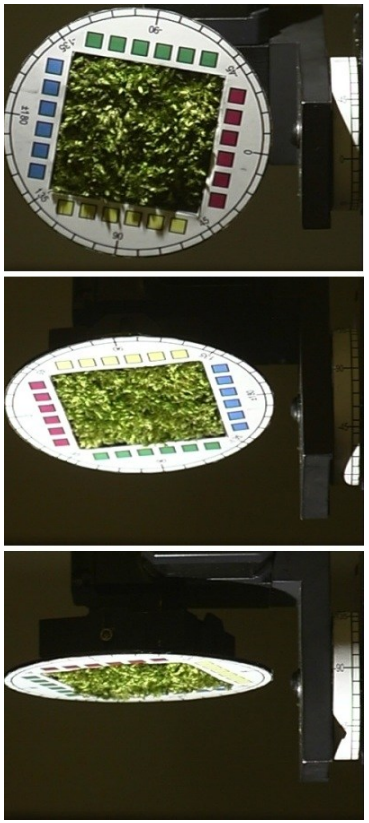
Rectified images:

192 x 192 pixels

Measurement time:

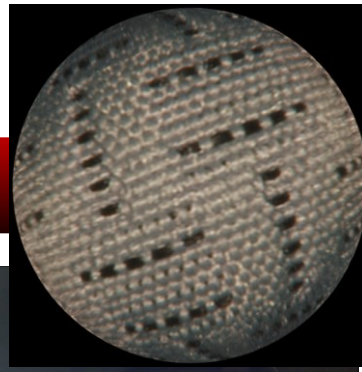
~ 10 hours





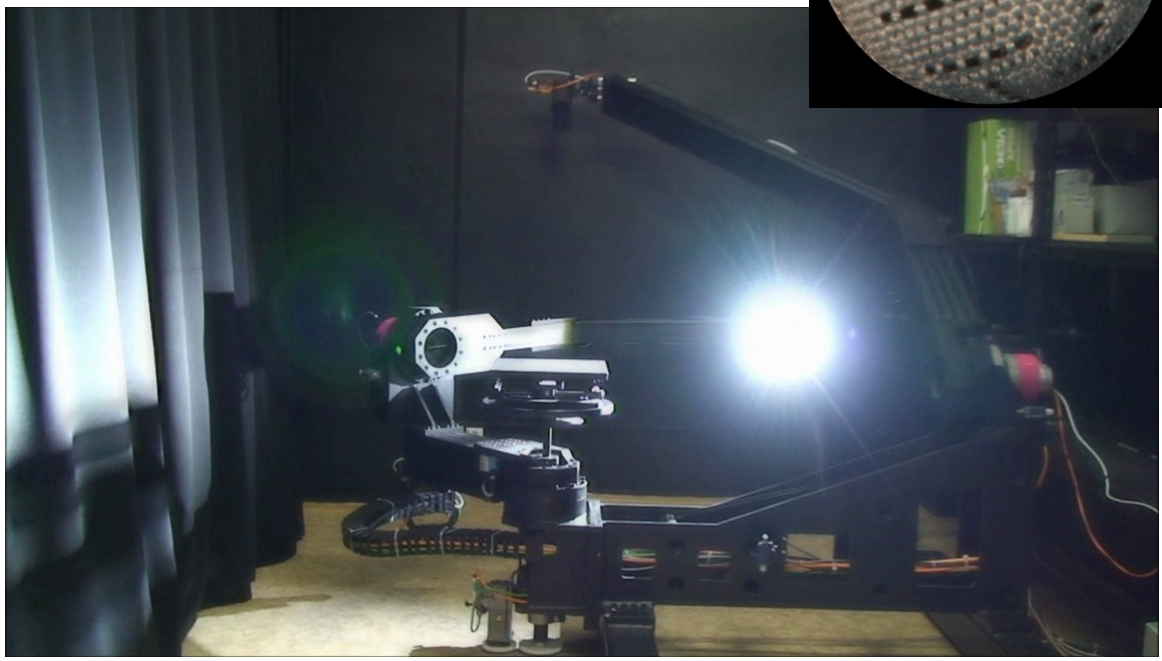
http://vision.ucsd.edu/kriegman-grp/research/vst

BTF Sample Acquisition



Gonioreflectometer – Moving Sample, Light & Camera

UTIA AS CR
[Haindl&Filip CVPR13]



Illu./View directions:
arbitrary/arbitrary (81/81)
Max. illu./view elev.:
90°/90°
Rectified images:
2000 x 2000 pixels
Database: publicly available
Measurement time: ~10 hours

- Spectral & HDRI measurements
- Arms angular accuracy: 0.03°
- Resolution: over 1000 DPI

http://btf.utia.cas.cz

BTF Sample Acquisition

Mirrors – Moving Sample & Light

Rutgers University
[Dana & Wang, JOSA 04]

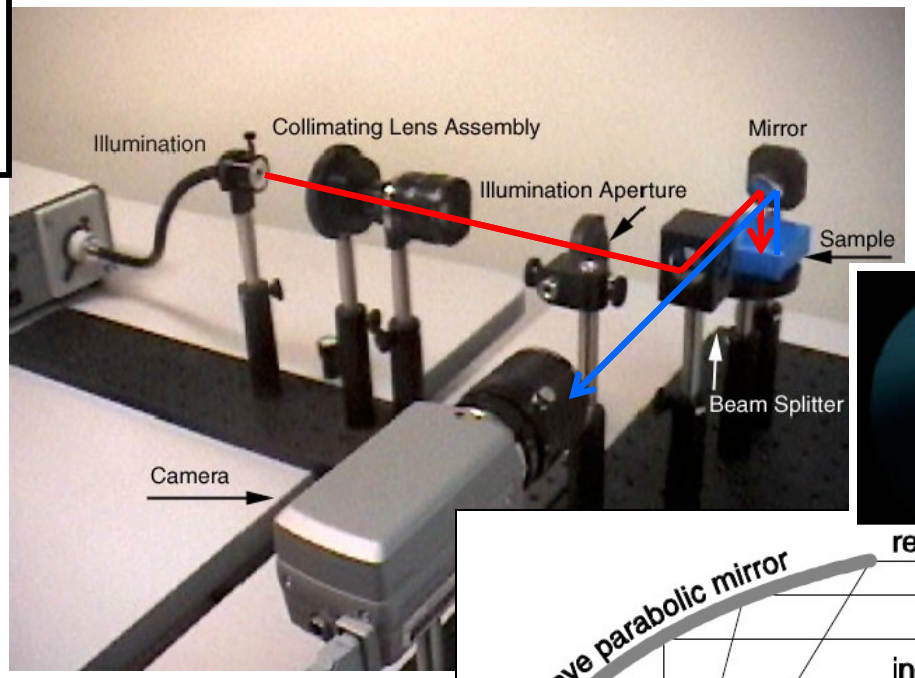
Database: n/a

Illu./View directions:
continuous

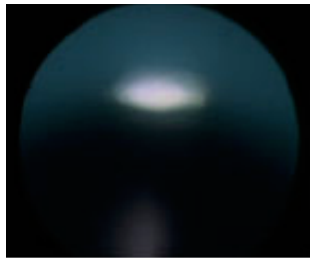
Max. illu./view elev.:
23-37°/23-37°

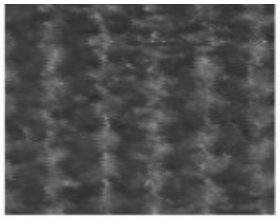
Rectified images:
~ 200 x 200 pixels

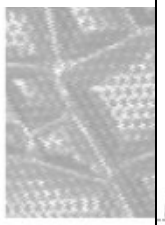
Measurement time:
~1 hour

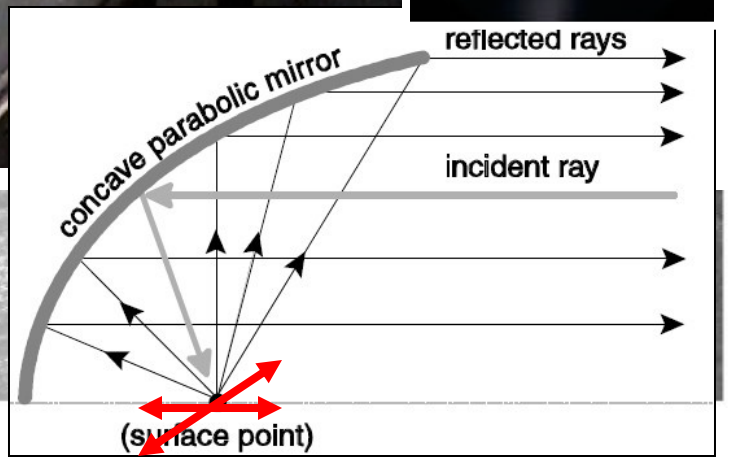


[Dana & Wang 03]









Material moves below mirror

BTF Sample Acquisition

Mirrors – Static Measurement Setups

New York University
[Han et al., ACM TOG 03]

Database: n/a

Illu./View directions:

22-79/22-79 =

484 – 6241 img.

Max. illu./view elev.:

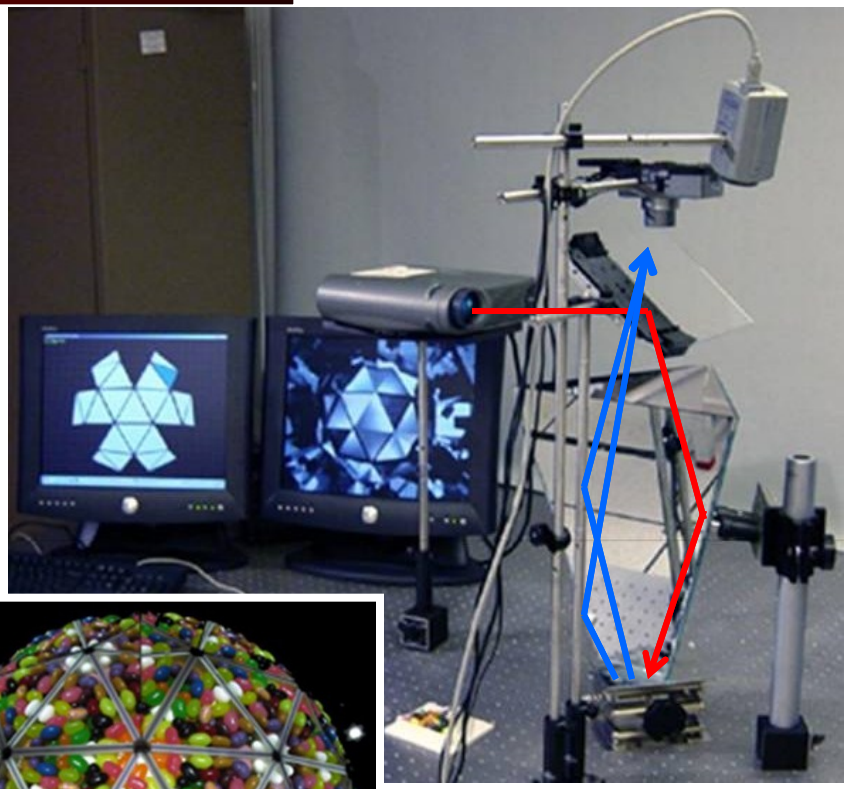
76°/76°

Rectified images:

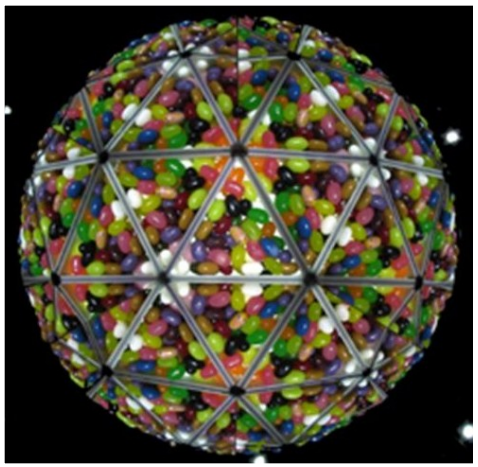
~ 200 x 200 pixels

Measurement time:

~1 hour



[Han et al. 03]

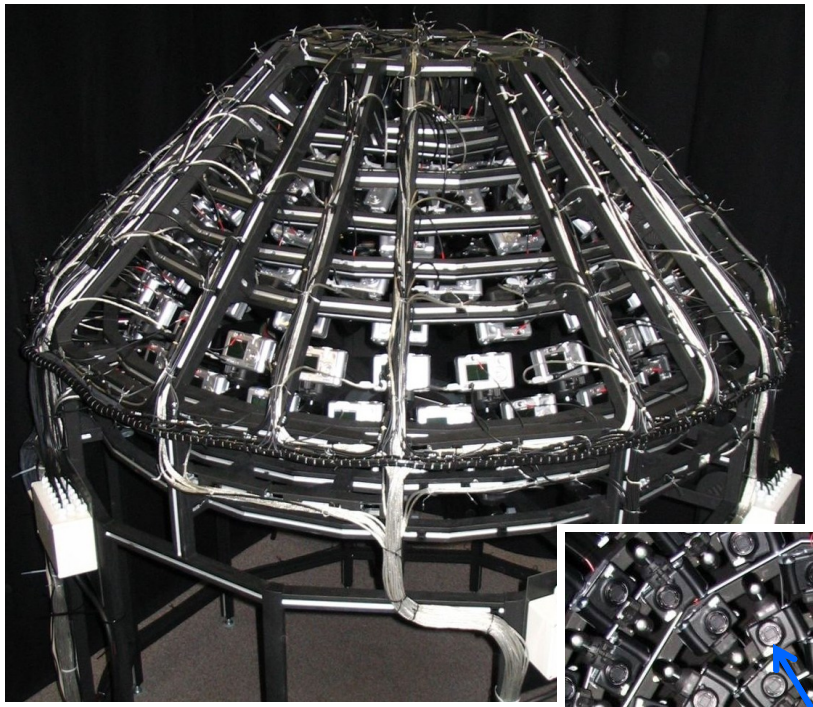


BTF Sample Acquisition

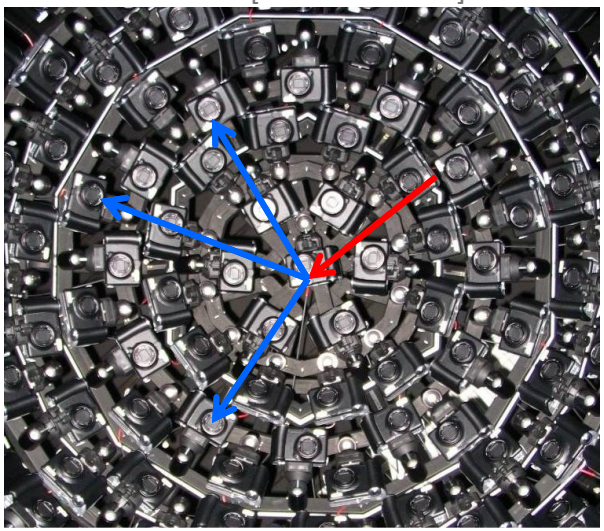
Dome – Static Measurement Setups

Bonn University
[Müller et al. 05]

Illu./View directions:
151/151 = 22 801 img.
Max. illu./view elev.:
n/a
Rectified images:
1024 x 1024 pixels
Database: n/a
Measurement time:
~1 hour



[Muller et al. 03]



BTF Sample Acquisition

Dome – Moving Sample, portable

Bonn University
[Schwartz et al. 14]

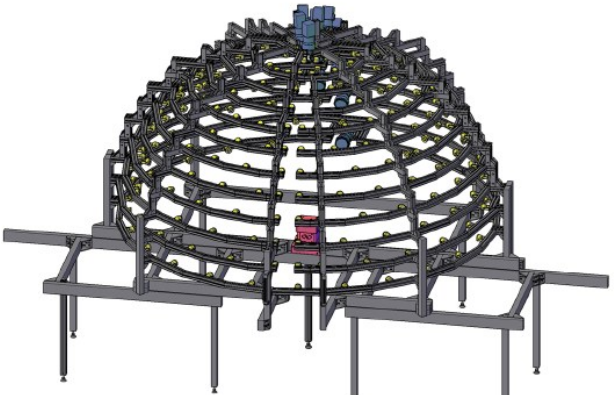
- Dome setup used in industry

Illu./View directions: 198/264 = 52 272 images

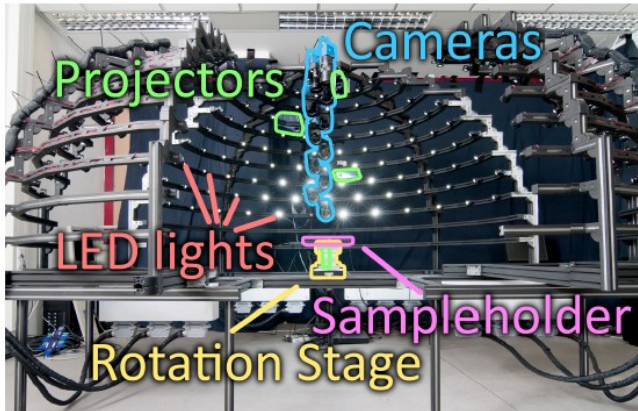
Max. illu./view elev.: 75 degrees

Rectified images: 1024 x 1024 pixels

Measurement time: 4-10 hours

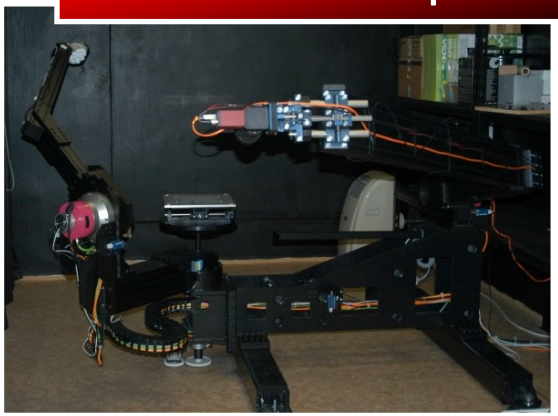






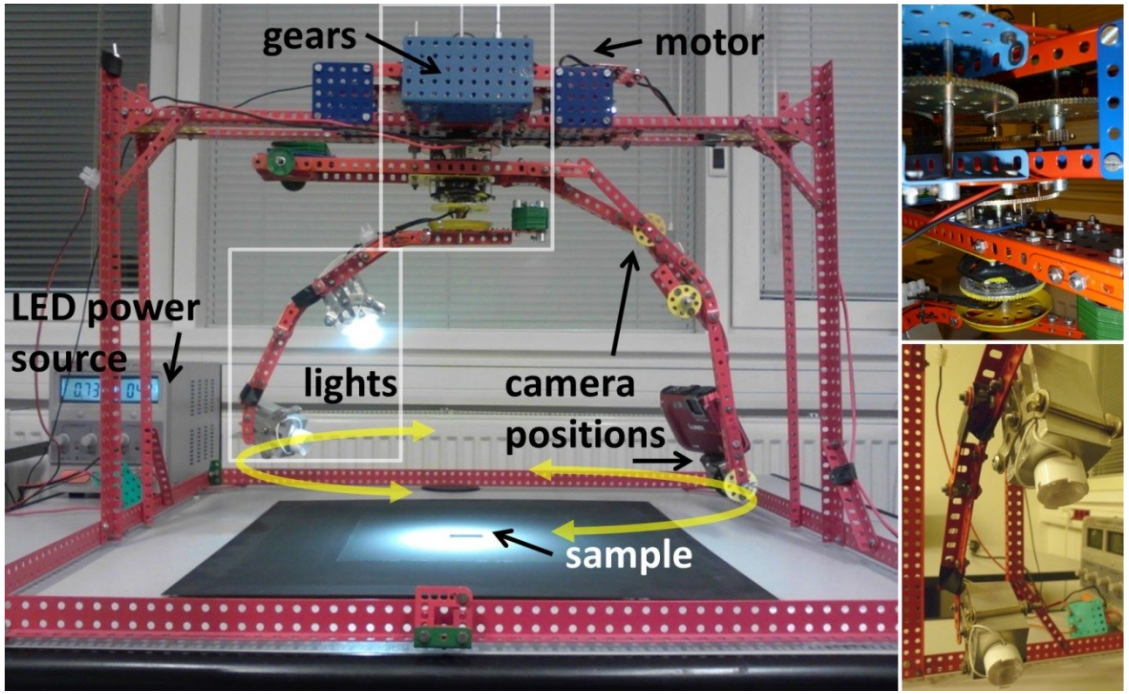
Rapid Measurement Approach

Portable Setups



[Filip et al. 14]

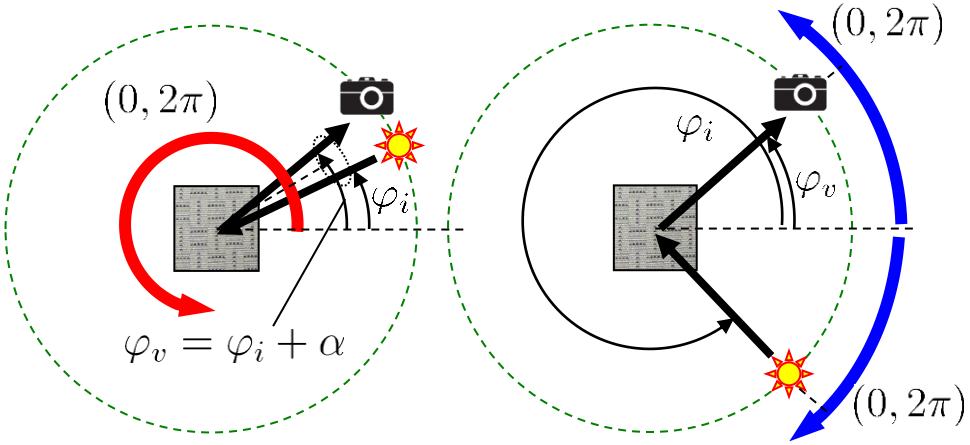
- Measurement of BTF 6561 images ⇨ 20 hours
- **Faster solutions needed for practical usage**
- Proof-of-concept prototype ⇨ construction set

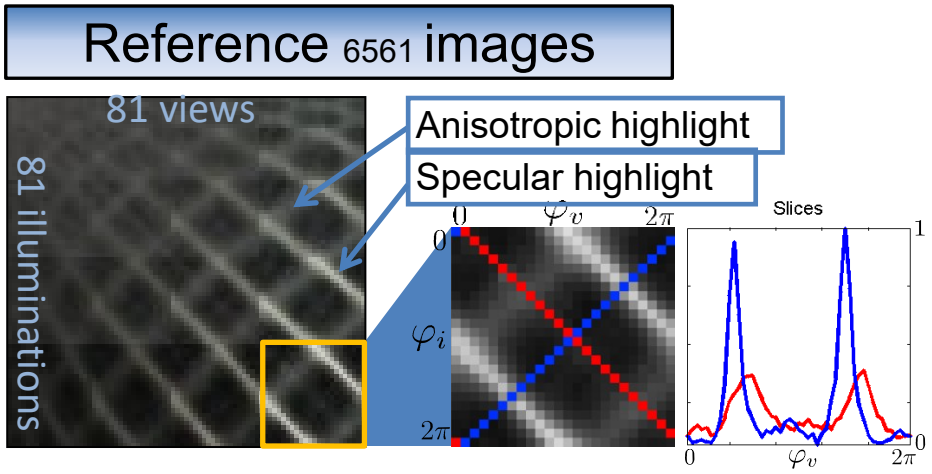


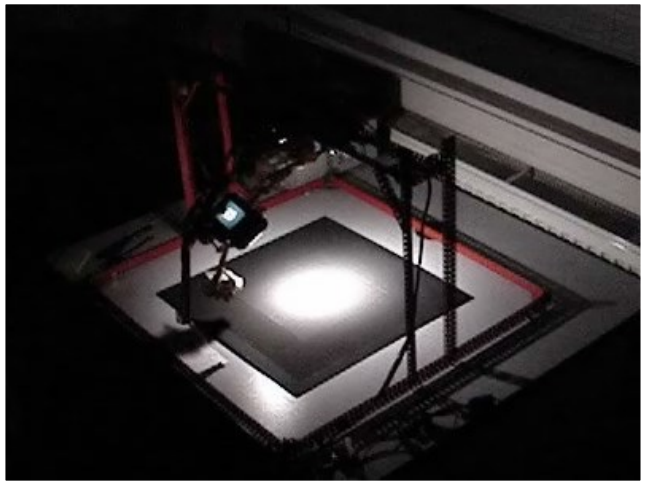
- 2 LEDs
- compact camera
- approximate BTF ⇨ capturing time 4 minutes

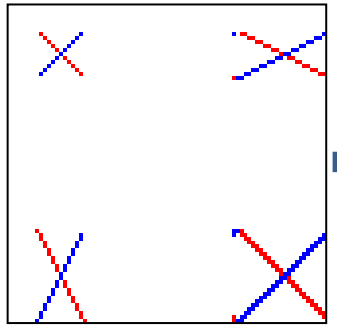
Rapid Measurement Approach

measurement procedure

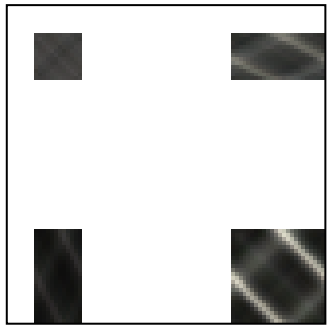




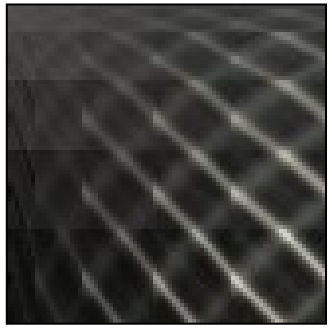




8 slices 169 images



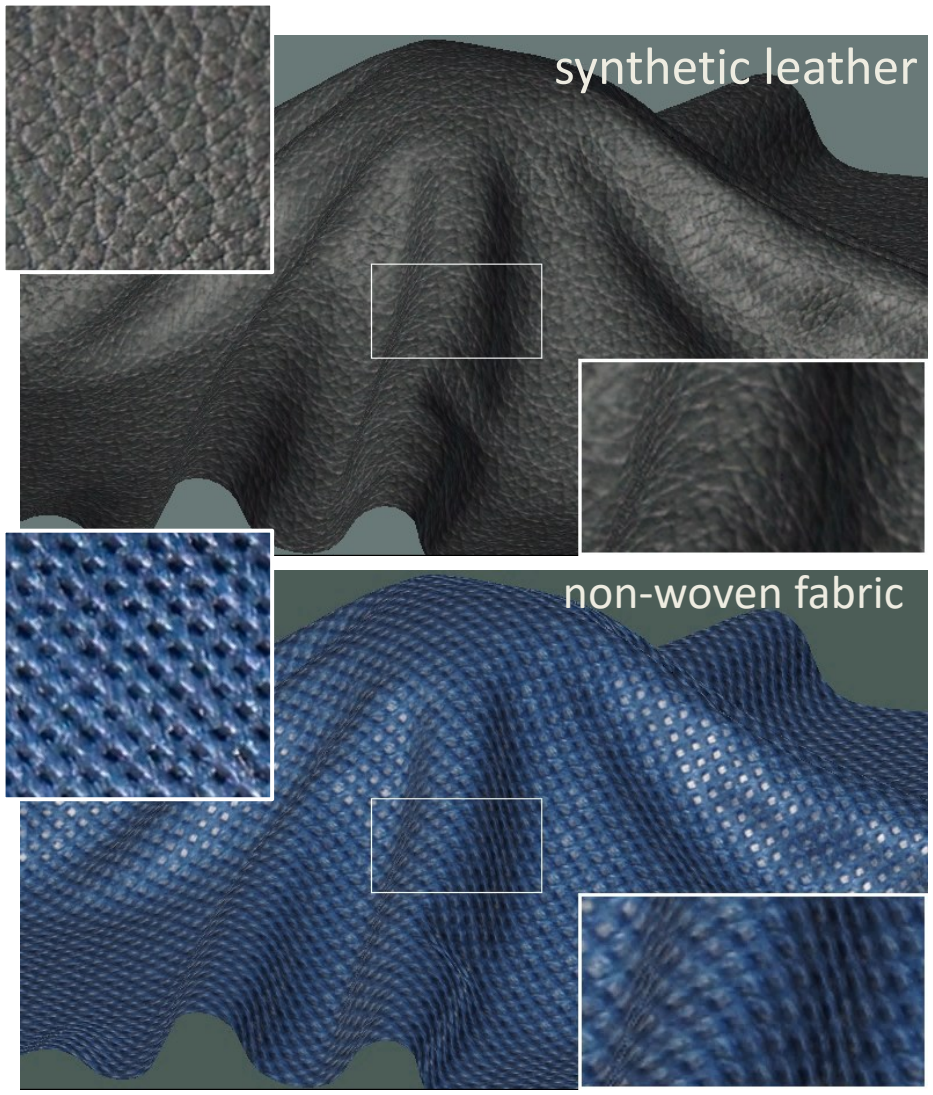
subspaces reconstruction

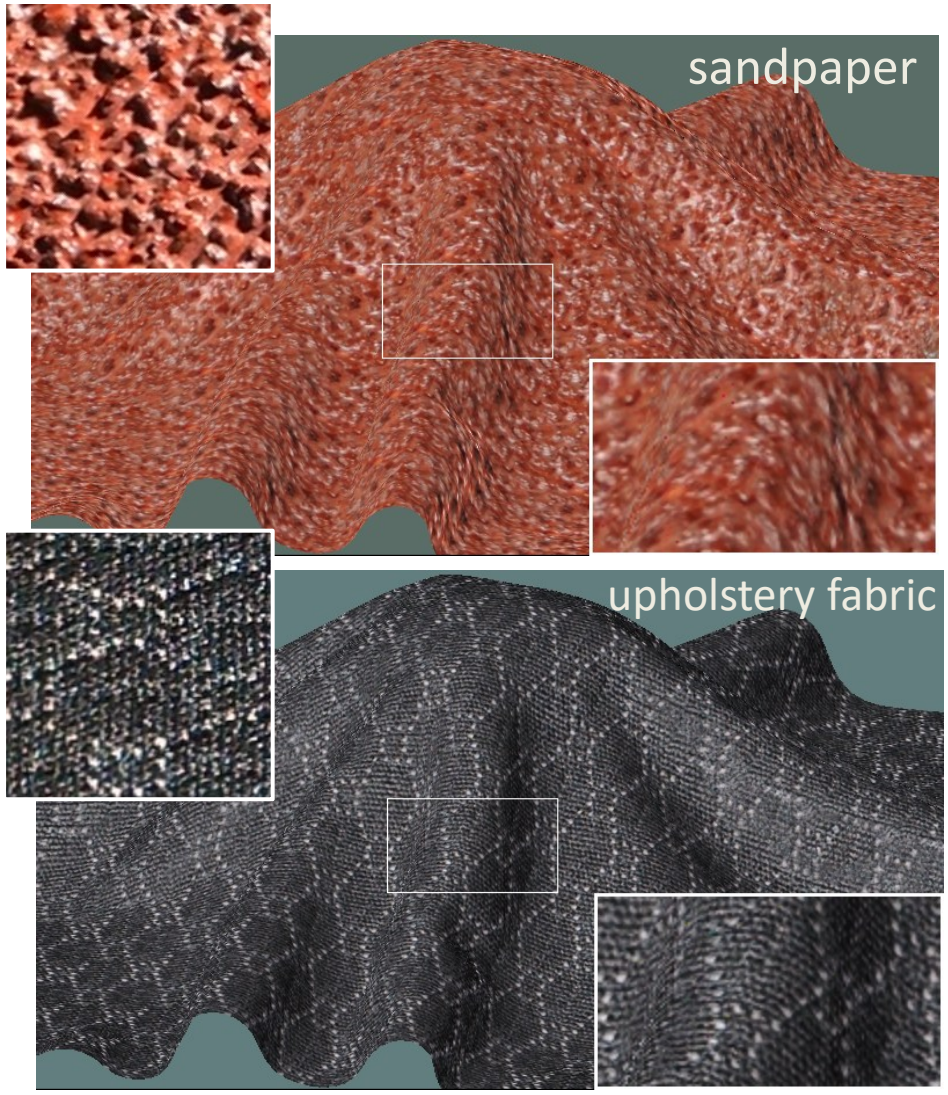


missing images interpolation

Results of Portable Setup

materials photo & measured appearance (169 images)





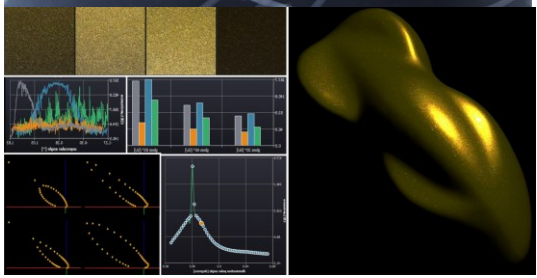
Rapid Measurement Approach

Portable Setups

[Filip et al. 14]







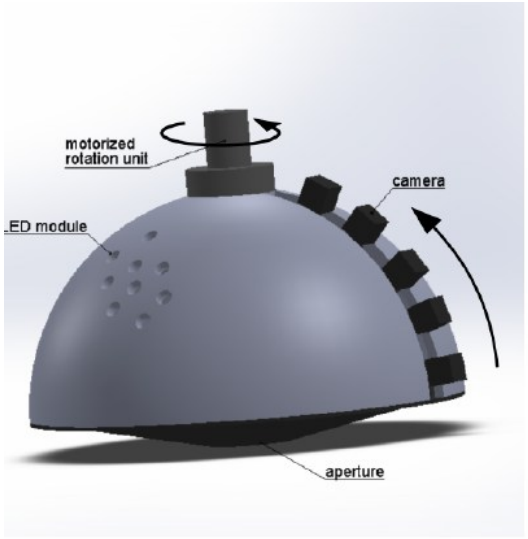


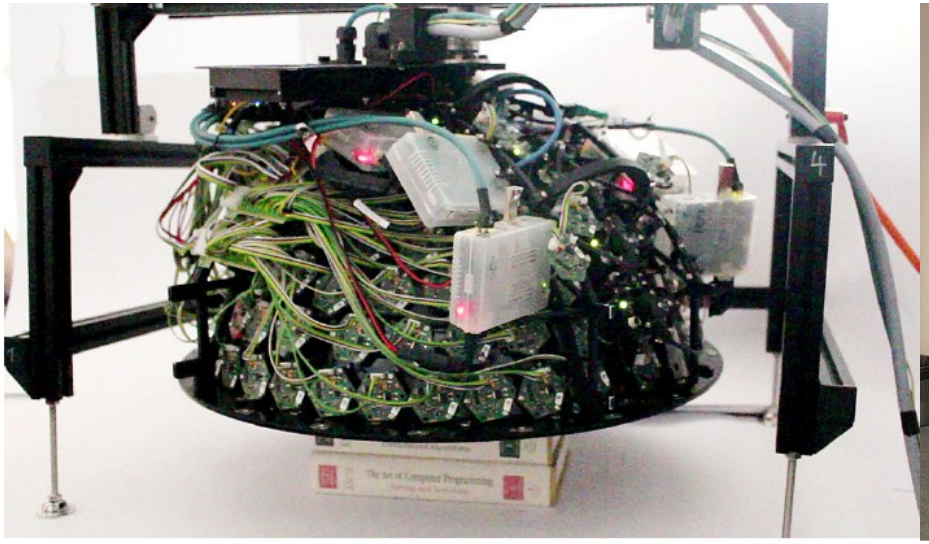
- **SIGHTTEX Q** –Multi-camera, multi-light goniometric acquisition of material appearance (BTF).
- Optical setup: 5 industrial RGB cameras at elevation angles of 15°, 30°, 45°, 60°, and 75°, HDR acquisition
- Illumination: 28 directional LED sources, distributed at 3° elevation intervals (0°–81°).
- Angular sampling: Independent azimuthal rotation of cameras and lights over 360° (0.1° positioning repeatability)
- Spatial resolution: Up to 1500 DPI (17 µm/pixel)
- BTF sampling: Example configuration: 15° elevation / 30° azimuth sampling -> 3 660 HDR images
- Calibrated BTF data for photorealistic visualization, material comparison (gloss, sparkle, graininess, and anisotropy).
- Compact flatbed-scanner-like design; configurable measurements (5–40 minutes)

Rapid Measurement Approach

Portable Setups

- **LightDrum** [Havran et al. Sensors 2016]
- Portable solution for fast on-site BTF measurement
- Body with lights and cameras rotates above the measured material





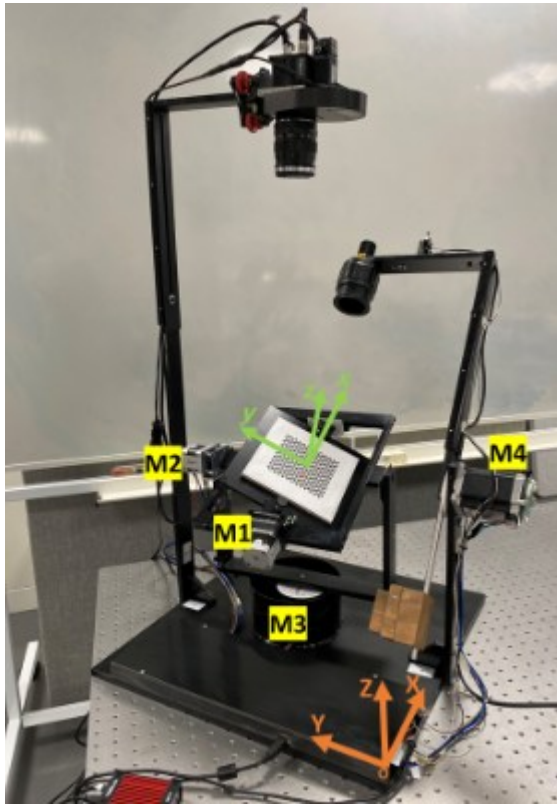


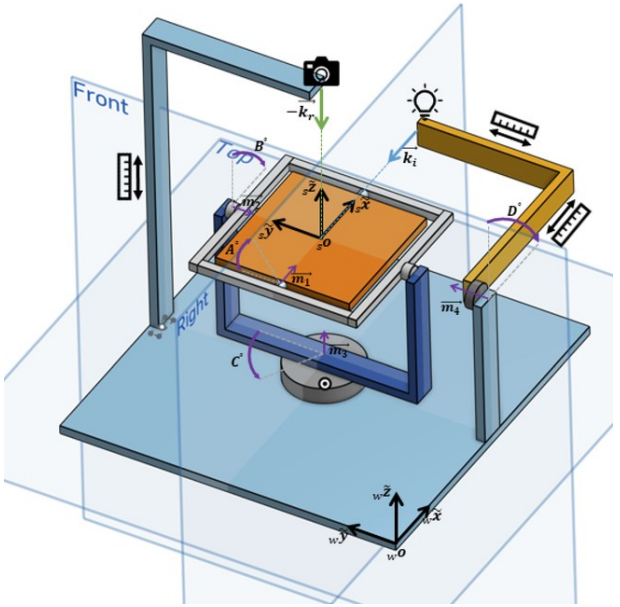
Rapid Measurement Approach

Portable Setups

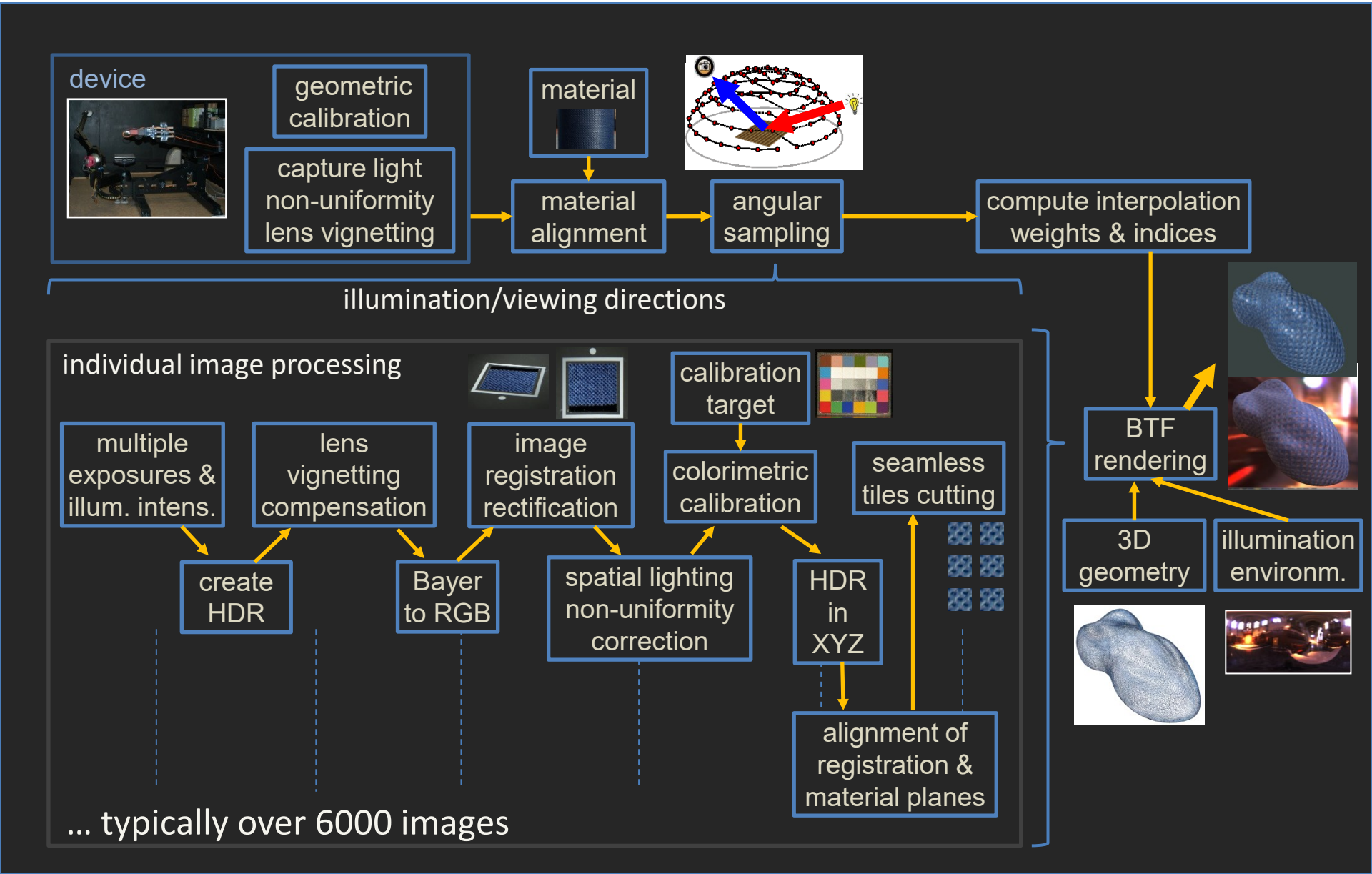
[Ansari-Asl et al. 24]

- Goniospectrophotometer-inspired system: SVBRDF and BTF data.
- 4 degrees of freedom - rotations: sample 3, illumination source 1.
- Multispectral acquisition: SpectroCam camera (2456 × 2058 pixels), using 6 visible spectral bands, HDR: Exposure bracketing
- Illumination: Single broadband white LED (6500 K) with adjustable collimator.
- ChArUco markers, camera calibration, and homography-based image alignment.
- Reduced hardware cost using only one camera and one light source, while enabling spatially and spectrally resolved reflectance measurement.





BTF Capturing & Visualization Pipeline



BTF – HDR and Spectral Measurement

- Most system measure RGB data in 8-bit/colour channel
- University Bonn Database (UBO) – 4 HDR architectural samples
- Materials appearance depends on light's spectrum ⇨ need for full spectral measurements.
- **[Lyssi 09]** – full spectral BTF measurement and calibration on **[Sattler et al. 03]** setup.
  - Spectral Filter ⇨ 30 wavelength bands (430 – 720 nm)
  - 30 x 81 x 81 images ⇨ enormous measurement times (3 days)
  - sample in OpenEXR = **1 TeraByte**
- **[Rump et al. 10]** – GT data for multispectral BTF

[Sattler et al. 03]



Bayer CFA to full-color RGB

Demosaicing reconstructs two missing color channels at each sensor photosite

01 MEASURED MOSAIC

One color sample per photosite

R	G	R	G	R	G
G	B	G	B	G	B
R	G	R	G	R	G
G	B	G	B	G	B
R	G	R	G	R	G
G	B	G	B	G	B

50% G | 25% R | 25% B

RGGB repeats every 2 x 2 pixels

02 INTERPOLATE CHANNELS

Example: center is a red pixel

B	G	B
G	R	G
B	G	B

R = measured

G = mean of 4 axial G

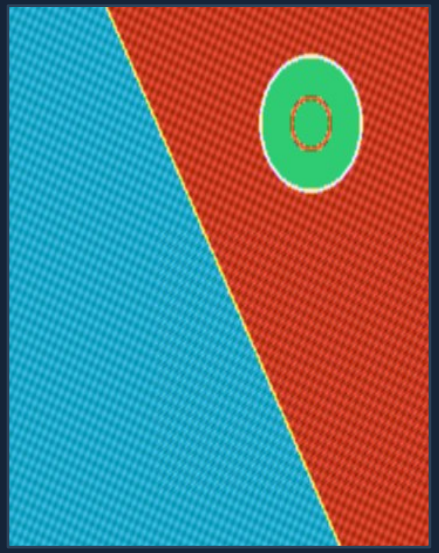
B = mean of 4 diagonal B

Bilinear interpolation

The red pixel keeps its measured R; G and B are estimated from neighbors.

03 RECONSTRUCT RGB

RGB values at every pixel



Synthesized color can contain false colors and zipper artifacts.

LINEAR RAW black level / WB > demosaic > color correction > sRGB display encoding

Standard Bayer demosaicing methods

From simple interpolation to spatially adaptive and learned reconstruction

SIMPLE INTERPOLATION

Nearest neighbor; bilinear

Fast baseline; blur and color aliasing.

LINEAR CROSS-CHANNEL FILTERING

Malvar-He-Cutler (MHC)

Efficient 5 x 5 linear correction filters.

GRADIENT / EDGE-AWARE

Hamilton-Adams; VNG; EA

Interpolate along, not across, edges.

ADAPTIVE DIRECTIONAL

AHD (homogeneity-directed)

Select a locally coherent direction.

STATISTICAL / FREQUENCY-BASED

LMMSE; frequency methods

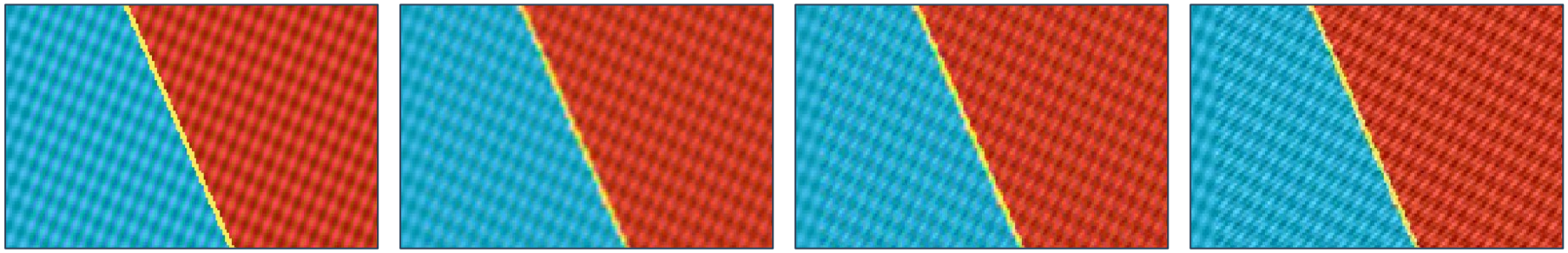
Model noise, color difference, aliasing.

ADVANCED / DATA-DRIVEN

AMaZE; CNN-based models

Higher complexity and detail recovery.

SAME SYNTHETIC RGGB IMAGE - CLOSE-UP OF TEXTURE AND SLANTED EDGE



RGB reference | Bilinear | Edge-aware (EA) | VNG

Illustrative, not a benchmark: errors depend on edge orientation, texture frequency and camera noise.

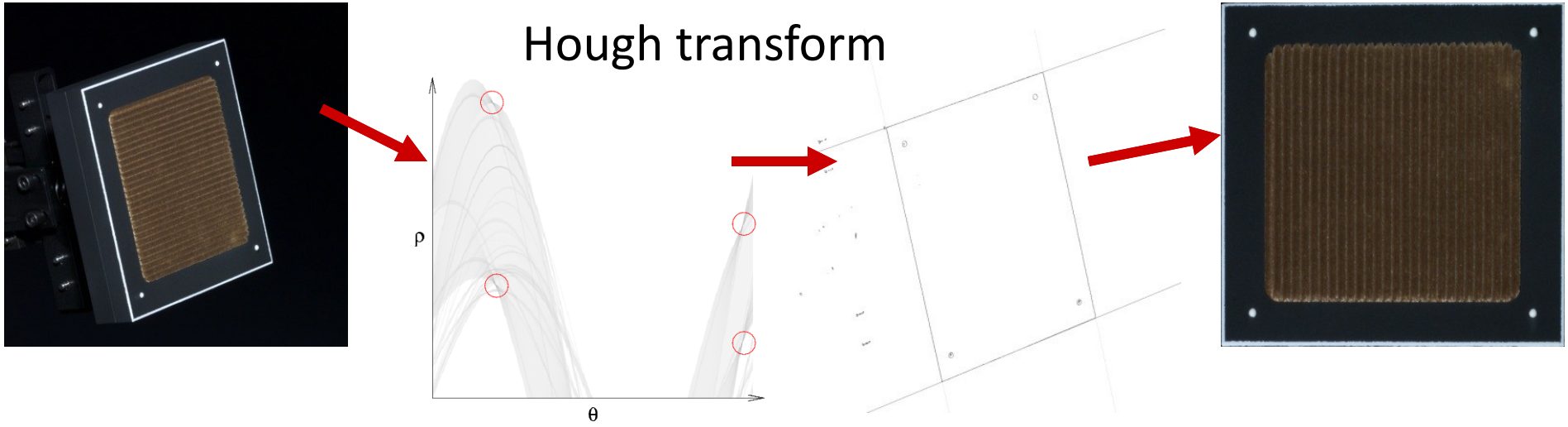
Spatial Reflectance Data Rectification

- **Registration and resampling** images of different views ⇨ same size images, surface normal aligned with viewing direction

Using:

- Registration marks
- Intersection of sample borders
- Predefined geometric transformation (static setups)

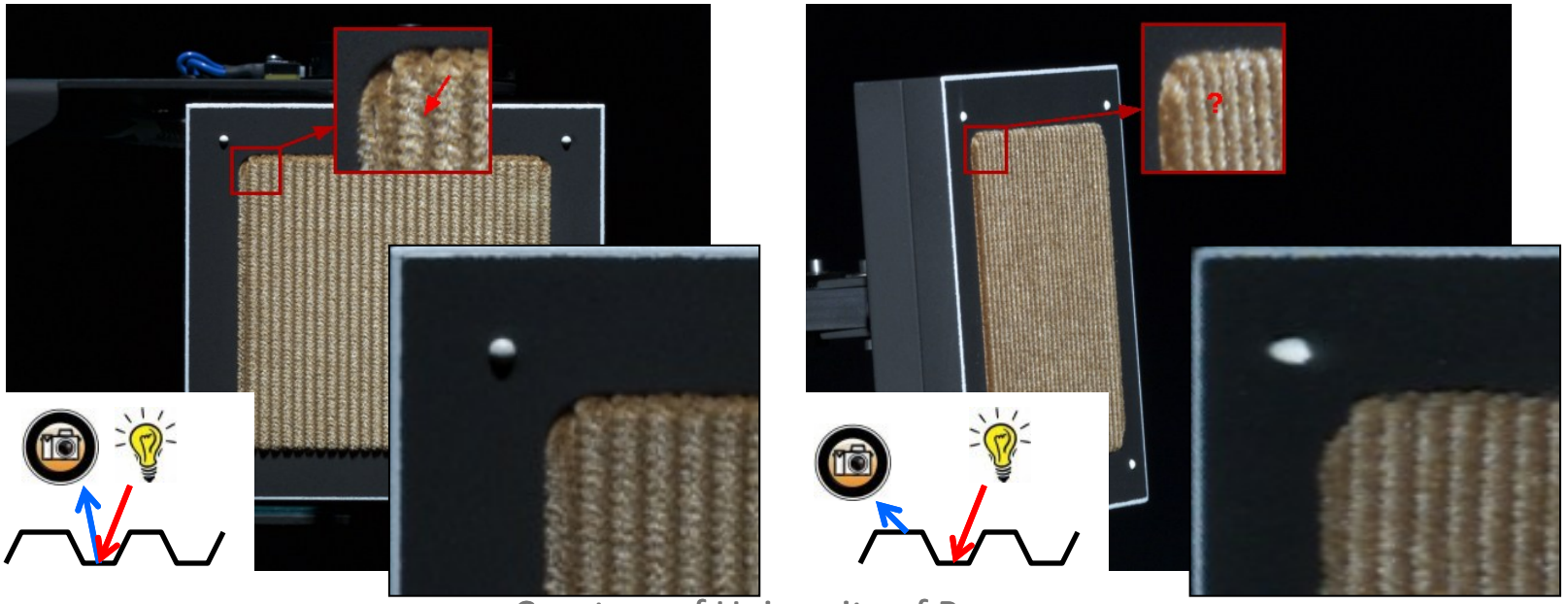
Lines detection
Hough transform



BTF vs. SV-BRDF

Contrary to SVBRDF, BTF face problem with rough structure samples

- Different views ⇨ **Pixel-wise misalignment**, due to occlusion
- Solution ⇨ process individual views separately



Courtesy of University of Bonn

BTF - no geometrical information ⇨ no material profile at object edges

UTIA BTF database – 22 materials



BTF database

- 6 BTFs as collection of images
- 16 BTFs in BIG data format

http://btf.utia.cas.cz

Conclusions on Appearance Measurement

- Measurement **setup design depend on** the required **application**
- source of errors ⇨ images registration, angular parameterization, angular sampling
- **High accuracy** ⇨ **no moving parts** or simple mechanical elements
- Maximum **sample size** ⇨ influences distance of light & camera (directional light, orthographic projection)
- Maximum **sample height** ⇨ influences selection of measurement technique (e.g. SVBRDF vs. BTF)
- Special treatment of specular and anisotropic materials
- Data-consistency-critical applications ⇨ non-uniform or adaptive sampling strategies

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