

# CAPTURING AND 3D RENDERING OF OPTICAL MATERIAL BEHAVIOR

The **physical** approach to **realism**

- Towards **high-end** automated **geometry & color** acquisition
- **Optical material behavior** acquisition & 3D rendering



**Martin Ritz**

[Martin.Ritz@igd.fraunhofer.de](mailto:Martin.Ritz@igd.fraunhofer.de)

Deputy Head

Competence Center

**Digitization of Cultural Heritage**

Fraunhofer Institute for

**Computer Graphics Research IGD**

Fraunhoferstrasse 5

64283 Darmstadt, Germany

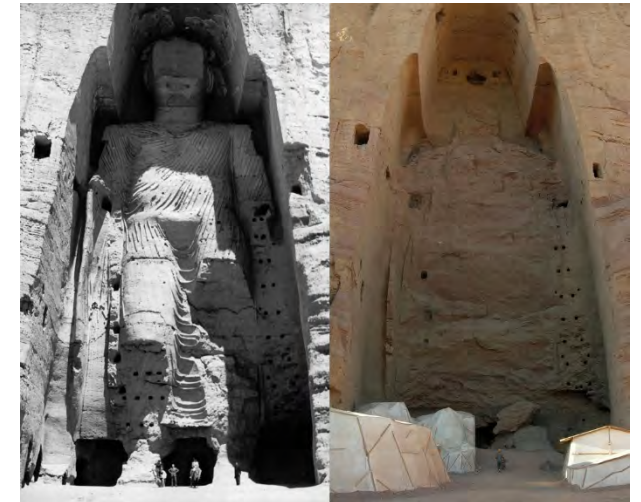
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# WHY 3D DIGITIZATION?



Natural and man-made disasters, flow of time,...



2018-01-12\_IGD-Folien\_de



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# POTENTIAL USE CASES OF FAST & HQ 3D DIGITIZATION

## ...both for Cultural Heritage and the Industry

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- **Cultural Heritage:** Many more use cases for 3D digitization beyond „Digital Conservation“:
  - **Documentation** of preservation status over time
  - Virtual/real **reconstruction** of fragmented or destroyed artifacts
  - Offering science and the public **worldwide access** through digital libraries and archives
  - New **exhibition** concepts (e.g., hybrid exhibitions, virtual/real restitution of geograph. disjunct collections)
  - **Reproduction** instead of transporting fragile originals (e.g., 3D print)
  - Entertainment and **tourism** (e.g., games, documentaries)
- **Industry:** Equally challenging objects (highly reflective, cavities):
  - Tracking of **material integrity** or **geometrical changes** to tools **over time** (e.g., car manufacturing)
  - **Quality assurance:** CAD model vs. real manufactured part (set-actual comparison)
  - Reconstruction of **missing 3D/CAD models** from parts (e.g., cars/old timers)
  - **Guiding robotic systems** along real object surfaces w/o known geometry (e.g., painting, coating)

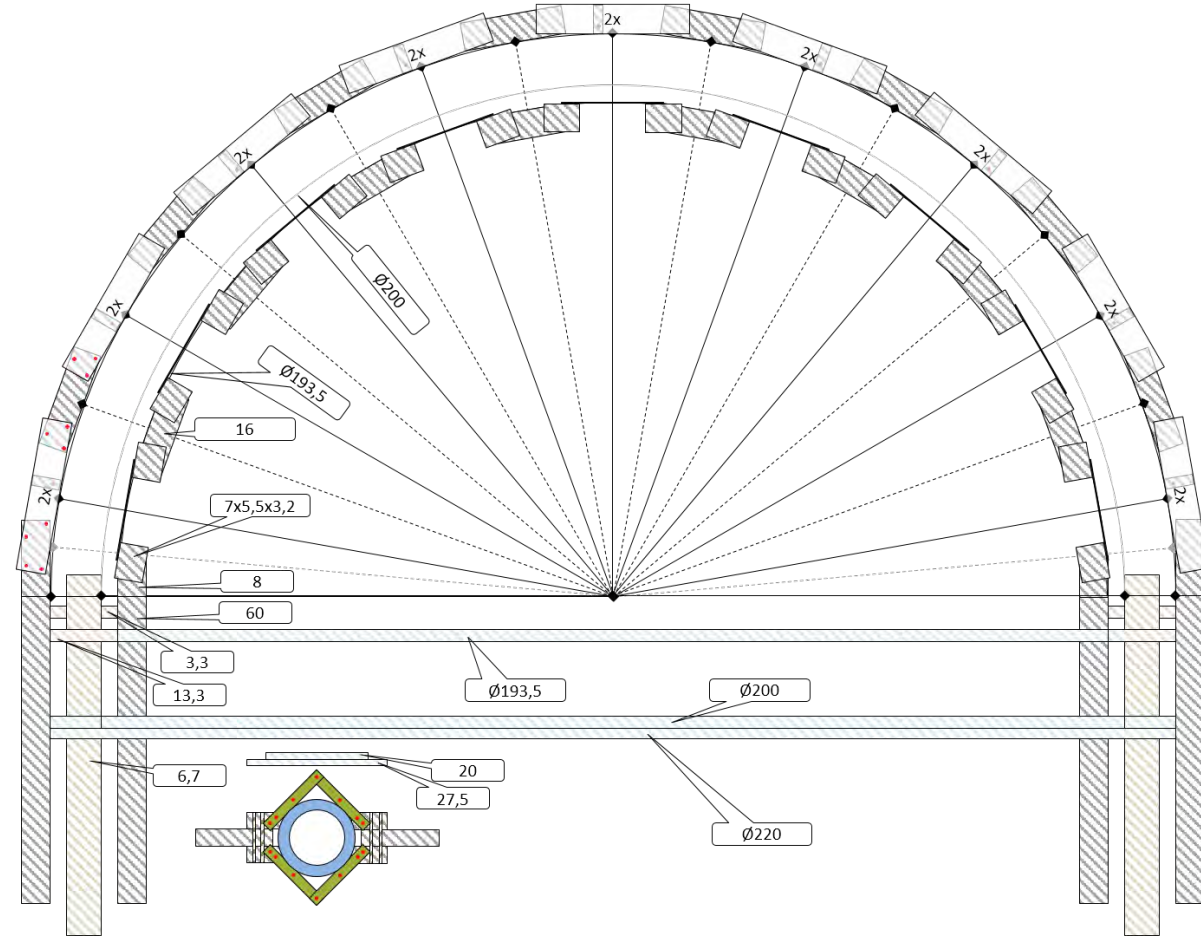
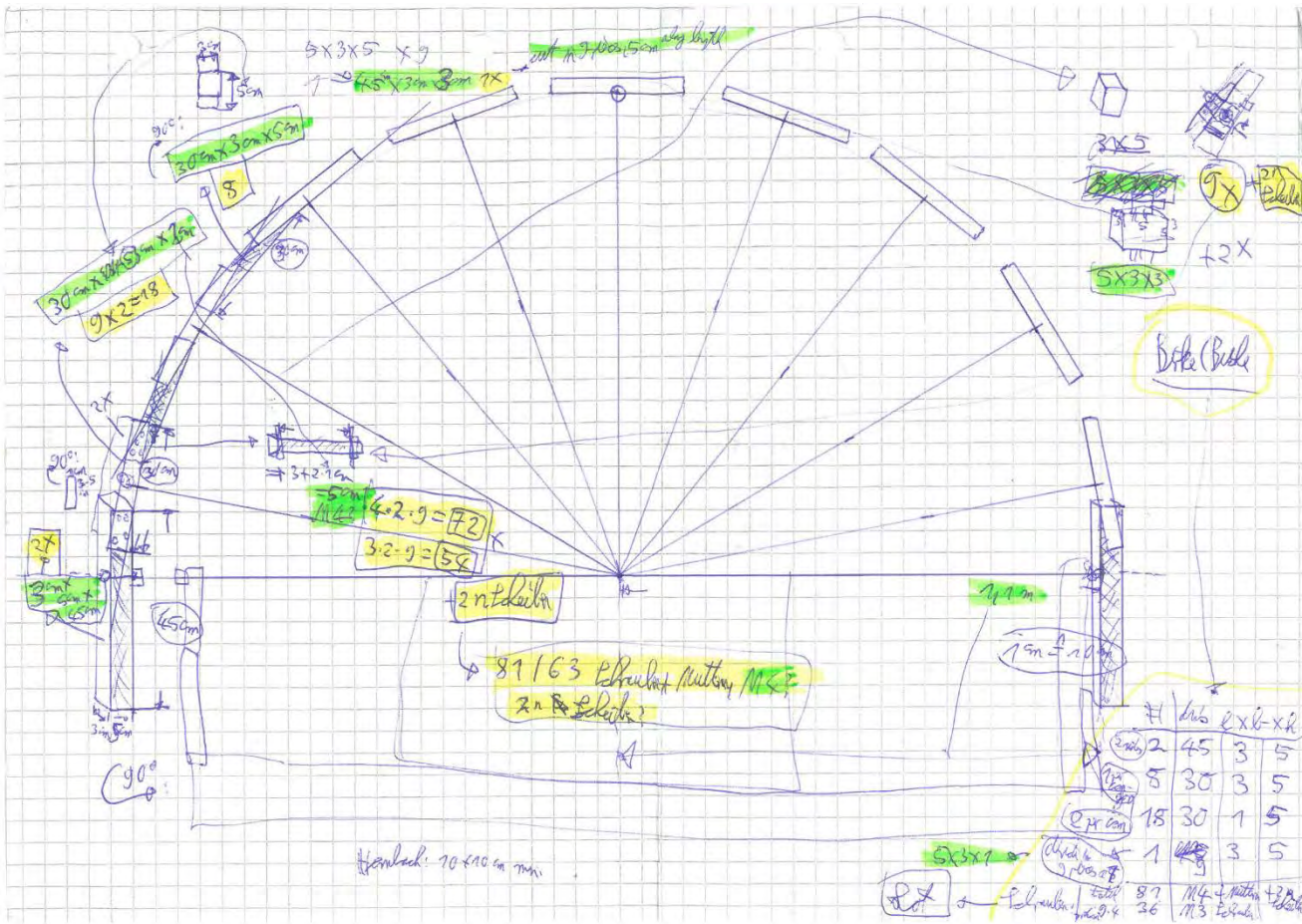
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# A VISION FORMING FROM PRESSING NEED

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- Situation
  - Huge numbers of artifacts waiting to be digitized
  - Need for sustainable digitization
    - Sufficient quality, different aspects / dimensions, e.g. optical material behavior
  - Manual digitization: too much time and effort
  - No commercial autonomous and color-calibrated 3D scanning systems available
  
- Our vision:
  - Fully automatic system, one-button solution
  - High throughput, high quality
    - Geometry+texture, also acquisition of optical material behavior
  - Tradeoff to solve: digitization time vs. hardware cost
    - Single camera on robotic system ↔ dome-like structure with hardware redundancy

# REALIZING OUR VISION



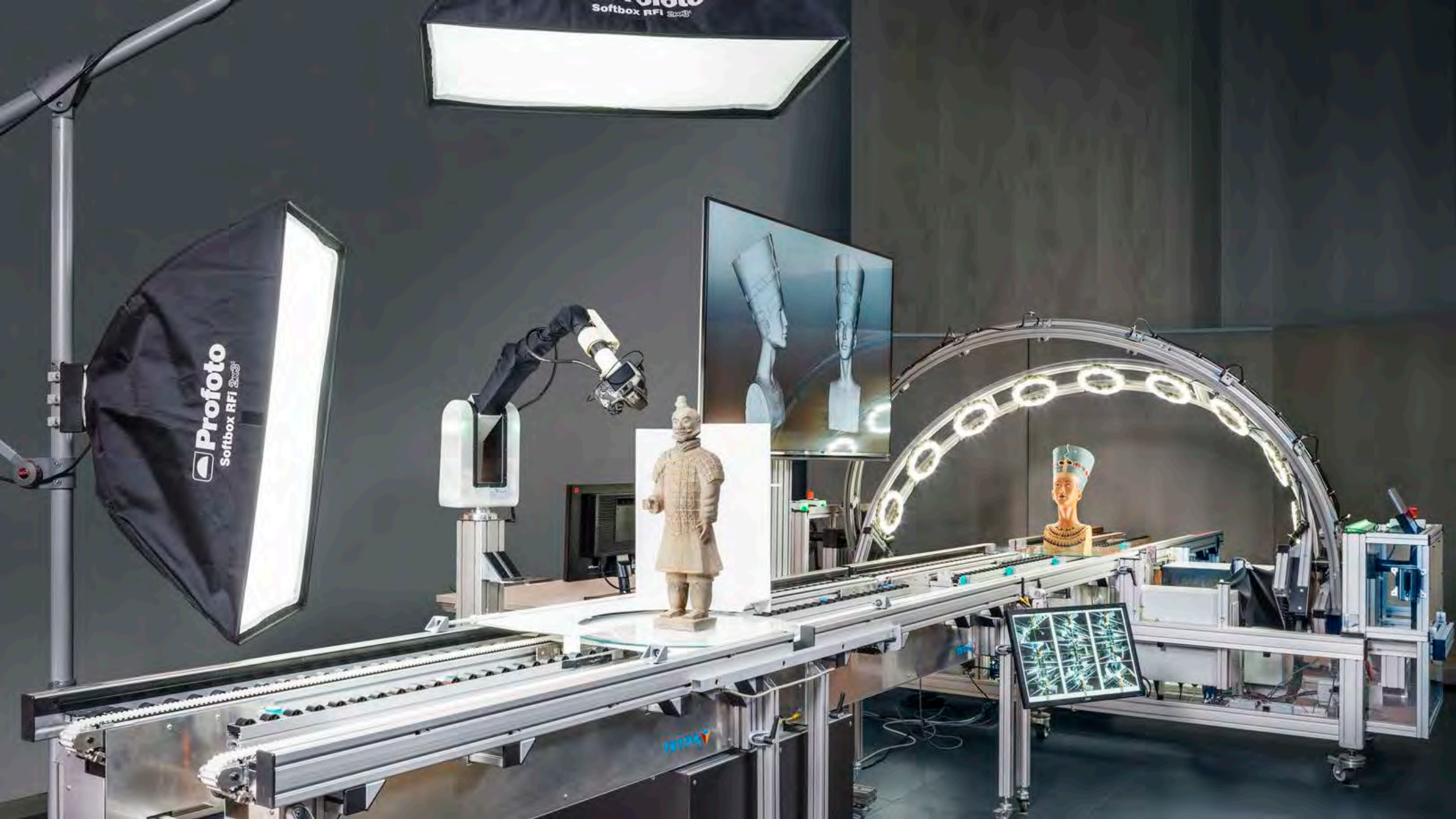


# REALIZING OUR VISION



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Profoto  
Softbox RFI 2x3

TRIMA



# EU PRIZE FOR CULTURAL HERITAGE / EUROPA NOSTRA AWARD 2018 FOR CULTLAB3



EUROPEAN HERITAGE AWARDS  
CEREMONY 2018  
Berlin Congress Center, 22 June

2018-01-12\_IGD-Folien.de





EUROPEAN UNION  
PRIZE FOR  
CULTURAL HERITAGE  
EUROPA NOSTRA  
AWARD  
2018

# TOWARDS HIGH-END AUTOMATED GEOMETRY ACQUISITION

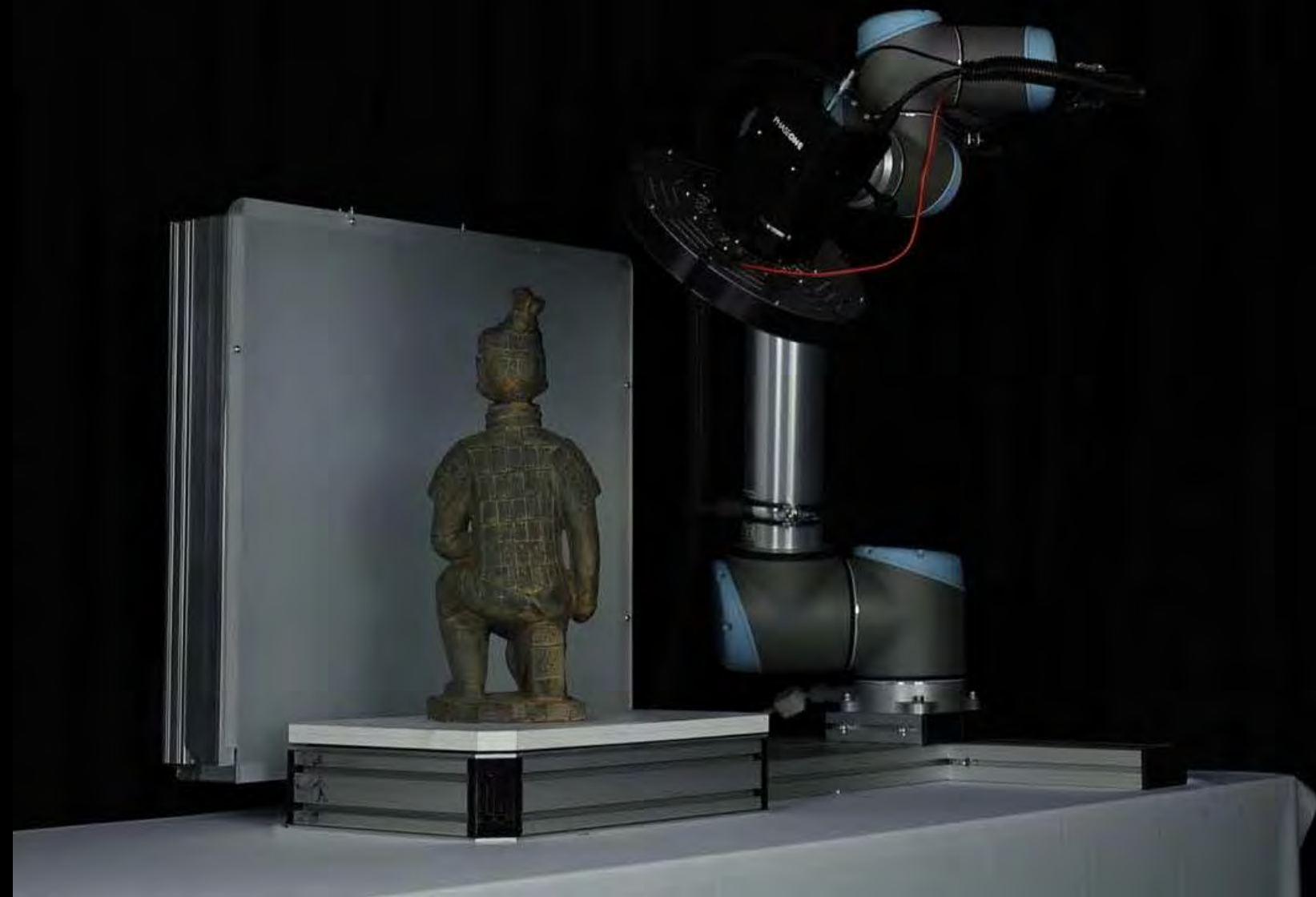
## Scanning shiny/complex objects directly

- No coating/spraying
- Hardly any post-processing
- Using optical and algorithmic tricks
  - Optically decoupling diffuse from specular
  - Next-best View Planning: automatically avoiding angles of total reflection



© CES / 3D-model: Fraunhofer IGD, rendering: United Screens GmbH











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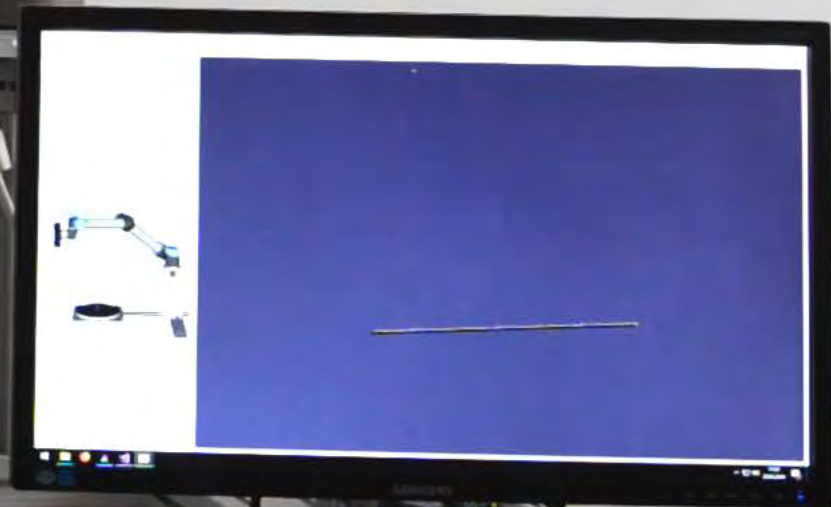
# TOWARDS HIGH-END AUTOMATED GEOMETRY ACQUISITION

## Scanning shiny industrial objects in real-time

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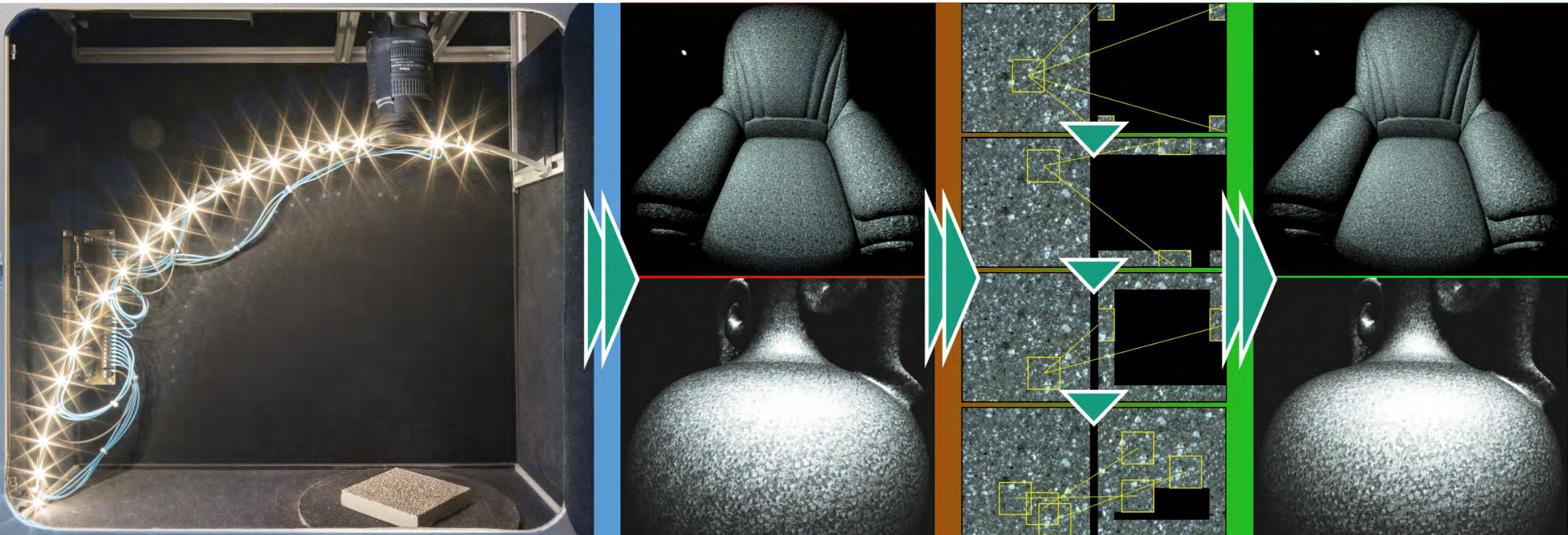
- Laser-line scanning
- Result geometry appears instantly after laser line sweeps over object





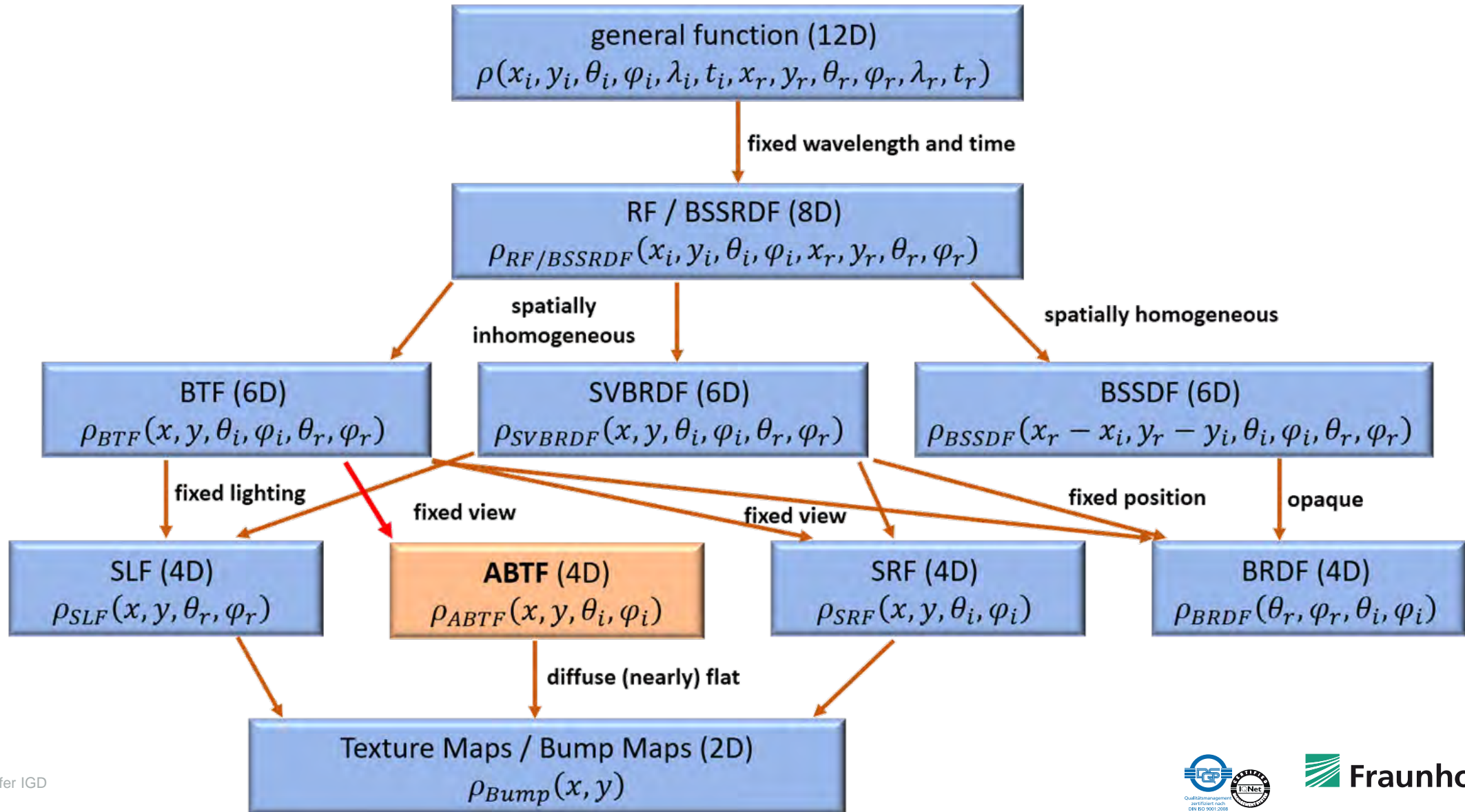


# OPTICAL MATERIAL BEHAVIOR ACQUISITION & RENDERING of flat surface samples



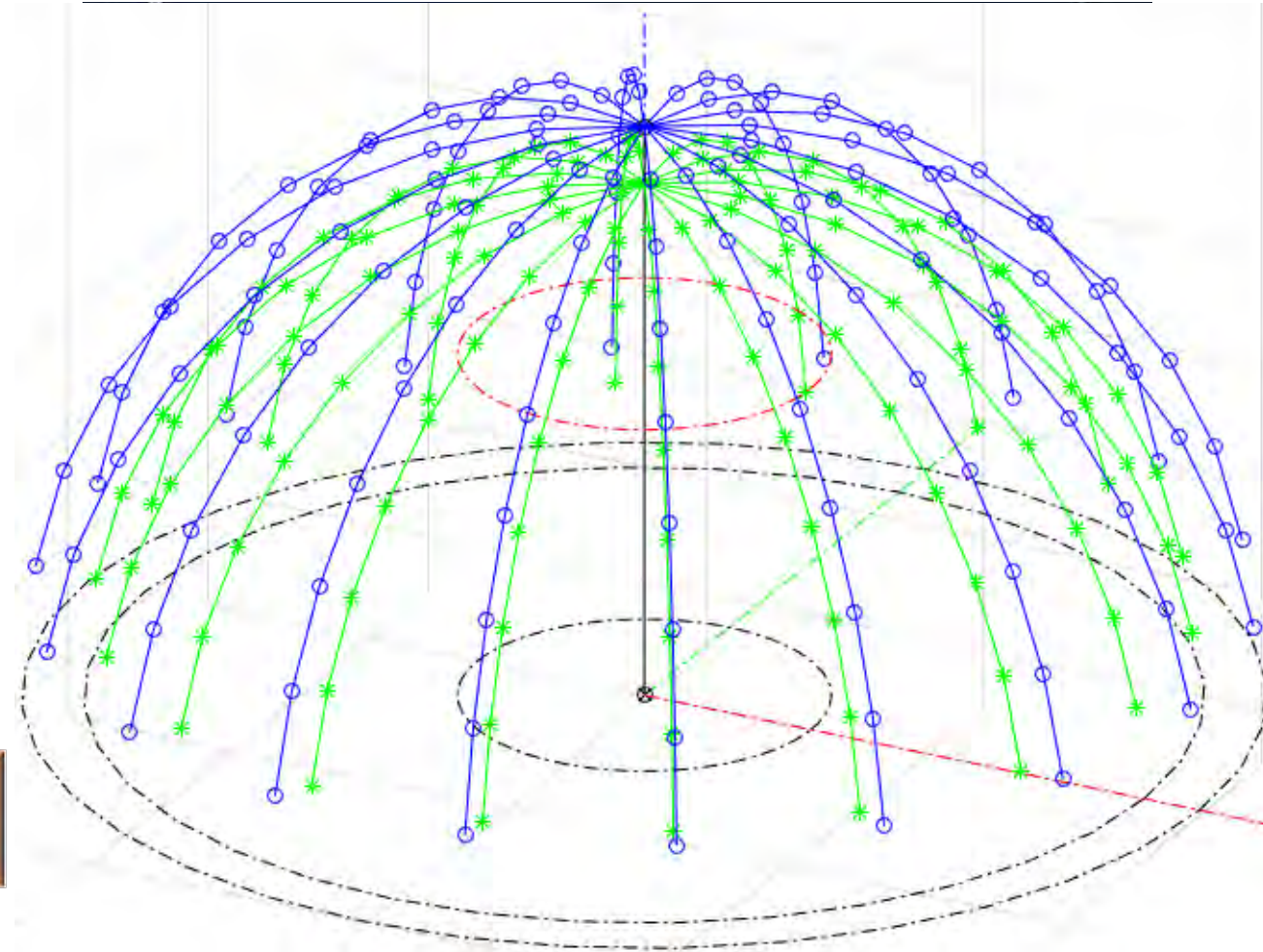
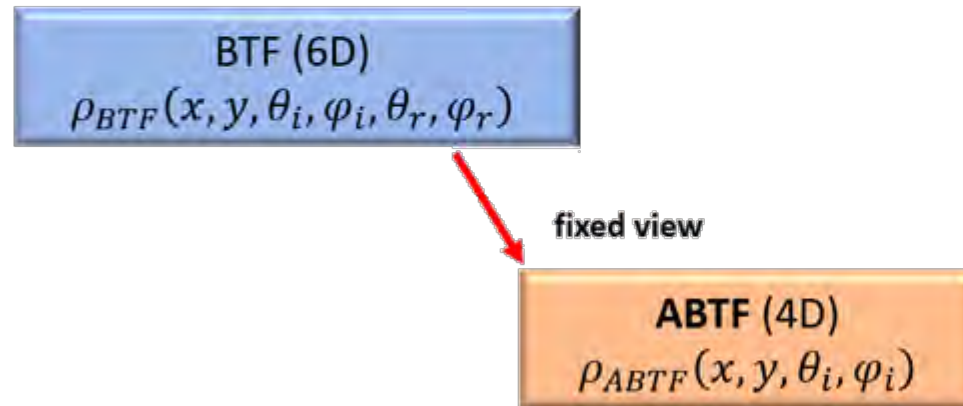


# Physically Measured Optical Material Behavior



# Physically Measured Optical Material Behavior


## BTF vs. A(pproximate)-BTF






# Physically Measured Optical Material Behavior

## A(pproximate)-BTF



Automated Acquisition and Real-time Rendering of Spatially Varying Optical Material Behavior



Martin Ritz<sup>1</sup>, Pedro Santos<sup>1</sup>, Dieter Fellner<sup>2,3,4</sup>  
<sup>1</sup>Fraunhofer IGD, <sup>2</sup>TU Darmstadt, <sup>3</sup>TU Graz

### Problem

Photorealism in 3D rendering is expanding across different fields of applications, including 3D games industry and rapid prototyping in many domains already in early design stages, e.g. in the automotive and textile industry. But **where** do the specifications come from that define **realistic materials**? Manual design of material models has been perfected over a long time to deliver quite good results. The only way, however, to bring out the **physically correct light interaction behavior** for each individual (or mixture of different) materials) on a surface, is **actual measurement** under **systematic illumination** from a set of different perspectives to reveal the **actual optical reaction**. One reason to go this far is material behavior **faithful to reality**, and individual rather than defining abstract classes of materials. Another reason is **damage assessment**, e.g. for industrial quality control.

### Implementation: Measuring & Rendering ABTF<sup>1</sup> Materials

Followed by a user-defined selection of the region of interest on the sample surface, the acquisition process is entirely automatic.


**Capturing**

- ✓ Capture image set  $I$  for virtual light hemisphere
- For each lighting situation  $(\theta, \phi)$ :
  - $t = \bigcup_{\theta \in \Theta, \phi \in \Phi} \text{Capture}(\theta, \phi, \mathbf{x}_p)$
  - $\theta$ : incident light angle (reverse elevat. in)
  - $\phi$ : rotary angle (azimuth w.r.t. surface normal)
  - ✓ Back-projectable!
- ✓ Crop  $I$  to user-defined area of interest
- ✓ Write into ABTF file  $\mathbf{x}_p = [x_p, y_p, \theta, \phi]$

**Rendering** (for each pixel):

- ✓ Decompose vector to virtual light source:
  - $\theta$ : (incident light angle, reverse elevation)
  - $\phi$ : (azimuth w.r.t. surface normal)
- ✓ Map  $\theta$  and  $\phi$  to nearest lighting situation  $(\theta_{i,j}, \phi_{i,j})$  in  $T_k$
- Interpolate from available neighboring lighting situations
- ✓ Shade current pixel using
  - $J, V$ : texture coordinates, available to shader
  - $T_{k,i,j}$ : texture (lookup into  $T_k$  in sample space)

...and results in a **4D texture** that is passed to the renderer and accessed by the shader during rendering. ABTFs are basically textures (with dimension 4) and thus can be mapped on arbitrary 3D models that have texture coordinates.



### Related Work & Motivation


In the initial idea [Kautz et al. 2004], a **fixed quarter arc** equipped with equidistantly spaced LED light sources was used to illuminate a sample and capture its response from a camera vertically above.

This approach was **extended** and entirely **automated** to produce results within minutes [Santos et al. 2010]. Rendering already produced realistic impressions under the assumption of **isotropy** (invariance of material behavior to rotation around the sample surface normal). However, it is exactly **anisotropic materials** that show especially compelling material-specific effects.

Our approach breaks this limitation entirely by introducing a rotary. The combinatory set defined by 2D equiangularly positioned high power LEDs on a quarter light arc, combined with a number of rotary turns to specific angles, constitutes a **virtual hemisphere of illumination**.

### Results & Comparison to Conventional Texturing

ABTF material models are more than BRDFs<sup>1</sup>, as they capture the **spatially varying** material behavior of a sample, which is achieved by capturing using a matrix sensor, giving **every single pixel its own life**, independent of its neighbors. The 'A' (Approximate) indicates that there is one abstraction, which taxonomically places the ABTF under the BTF<sup>2</sup>. There is only one camera, straight above the sample. Most material-specific behavior can already be reproduced thanks to the hemispherical illumination, while the abstraction allows for **realistic rendering** and **interactivity in real-time**.



### Technical Approach

We created a **fully automatic system** for acquisition of **spatially varying optical material behavior** of real object surfaces under a hemisphere of individual incident light directions. The resulting measured material model is flexibly applicable to **arbitrary 3D model geometries**, can be **photorealistically rendered** and interacted with in **real-time** and is **not constrained** to isotropic materials.

### References

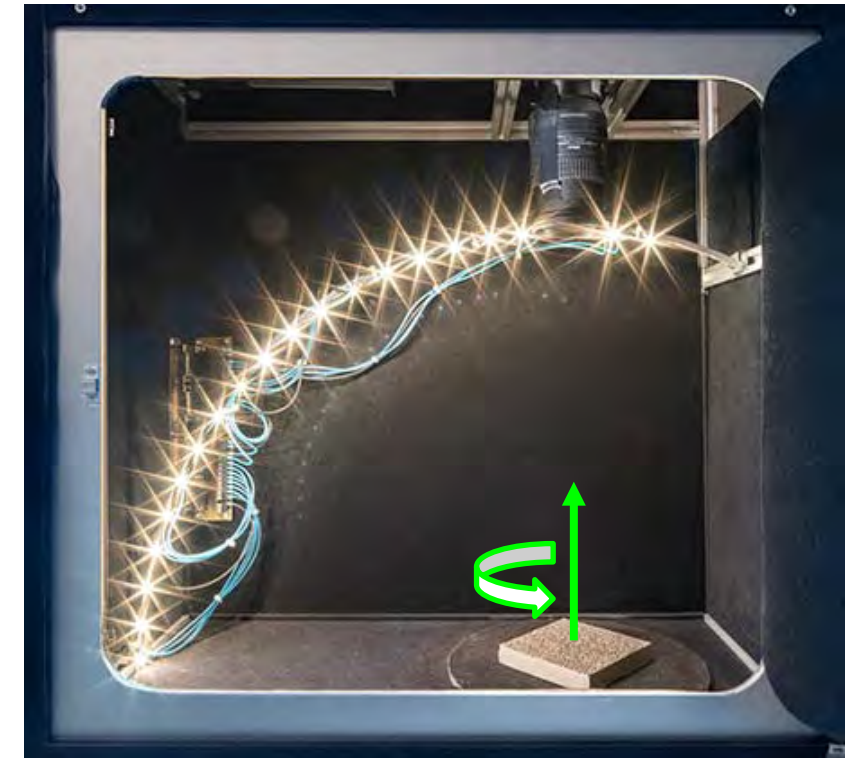
<sup>1</sup>Kautz et al. 2004, in: Kerz, Mike J., Sam Leifer, Sam Leifer, and Sam Leifer. 2004. Decoupling shaders from surface descriptions. In Proceedings of SIGGRAPH 2004. ACM Press, New York, NY, USA, 177-185.

<sup>2</sup>Santos et al. 2010, in: Proceedings of SIGGRAPH 2010. ACM Press, New York, NY, USA, 177-185.

<sup>3</sup>Santos et al. 2010, in: Proceedings of SIGGRAPH 2010. ACM Press, New York, NY, USA, 177-185.

Martin.Ritz@igd.fraunhofer.de  
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- SIGGRAPH 2018 Canada:
- Measuring & Rendering ABTF Materials



# White reflective stone (before texture periodization)





# Metal plate with reflective patches (before texture periodization)



Rendering of measured ABTF material by Fraunhofer IGD using InstantReality  
Material sample: Foster and Partners - thanks to Francis Aish

# Weakness of Approach so far

## 4D Texture (ABTF material model)

- **Strengths:**

- Flexible mapping of measured material behavior on **arbitrary geometry**
- Photo-realistic rendering and interaction in **real-time**

- **Weakness:**

- Common problems of texturing, striking in 2 levels:
  1. Non-seamless textures create visible **border artifacts**
    - At transition to neighbors
  2. Even perfectly seamless textures show **repetition artifacts**
    - Distribution in large numbers side by side over 3D surface





Martin Ritz,  
Pedro Santos  
Cultural Heritage Digitization,  
Fraunhofer IGD, Germany

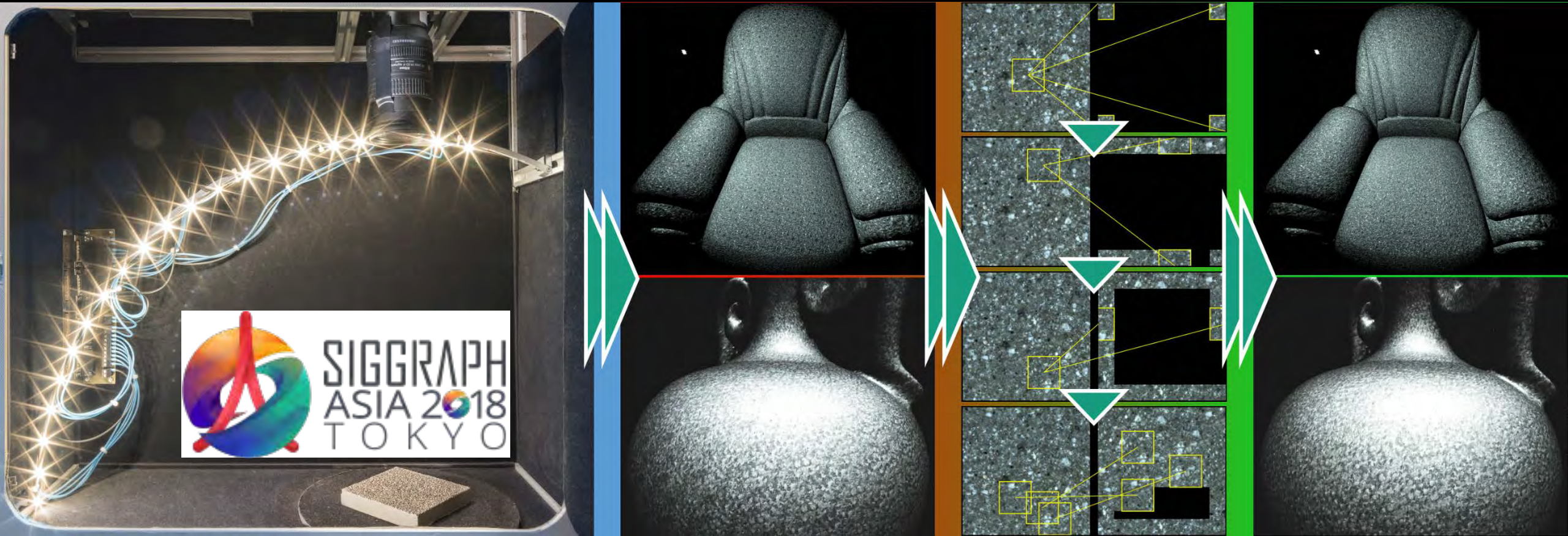
# Synthesis and Rendering of Seamless and Non-Repetitive

# 4D Texture Variations for Measured Optical Material Properties

Dieter Fellner  
Fraunhofer IGD, Germany  
TU Darmstadt, Germany  
TU Graz, Austria

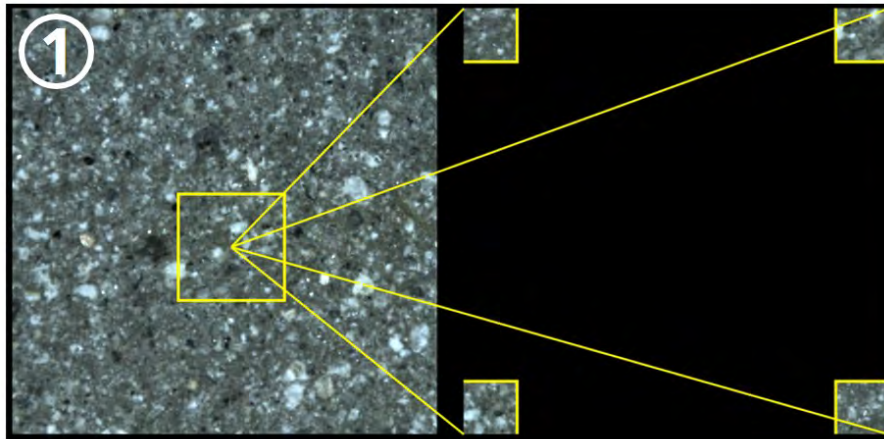
Simon Breitfelder  
TU Darmstadt, Germany

Arjan Kuijper  
Fraunhofer IGD, Germany  
TU Darmstadt, Germany



# Texture Synthesis

Establishing Seamless Transitions → Periodicity





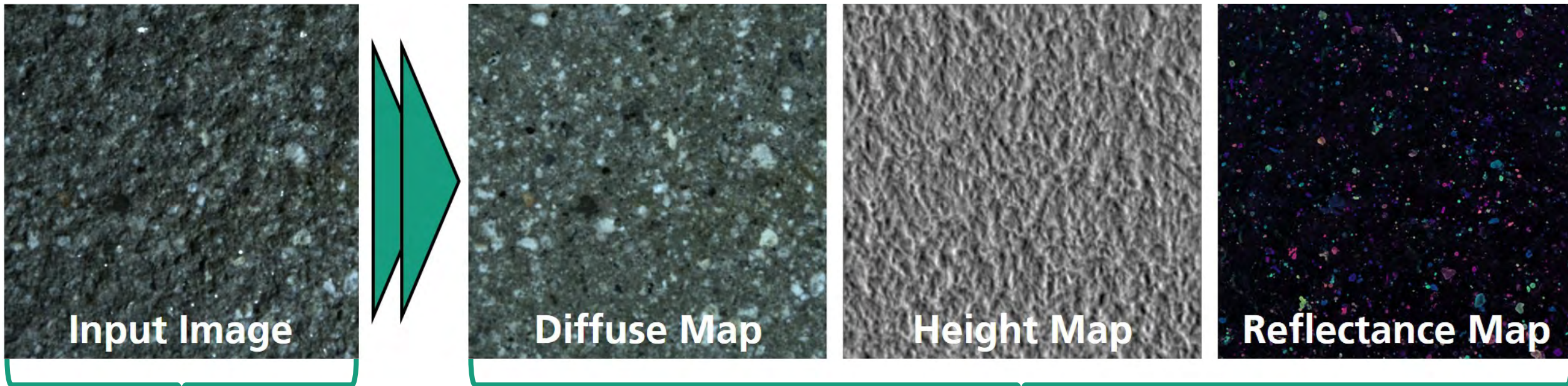
# Texture Synthesis

## Finding the Best-matching Patch for Transfer: Free-form Boundary Cut



# Texture Synthesis

## Maintaining Material Behavior Consistency across the Dimensions of Light



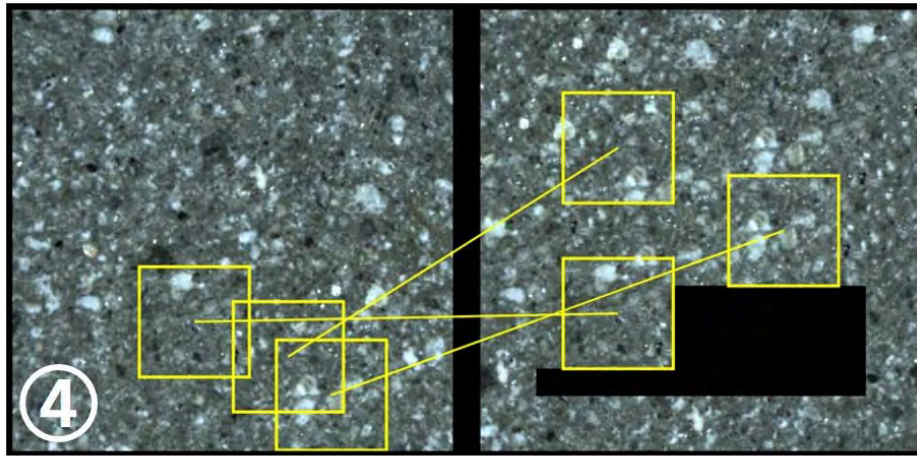
1 sample image  
from  
measured ABTF dataset

3 computed images  
representing characteristics of the  
**entire measured ABTF dataset**

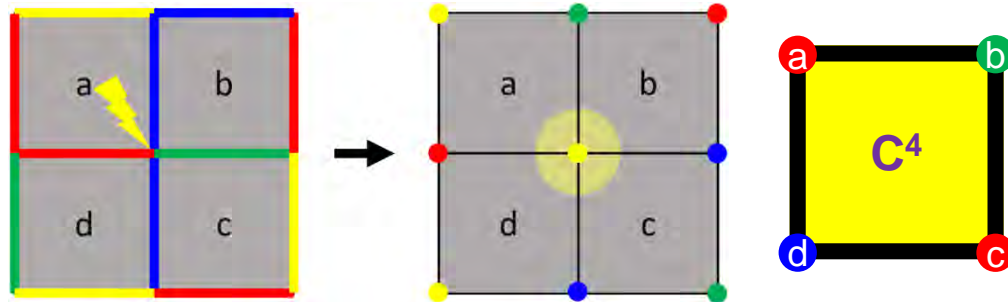


# Texture Synthesis

## Disrupting Repetition Artifacts



- Generation of a texture is non-deterministic
- New distribution every time
- Set of Texture Variations
  - Compatible at edges → seamless transitions
  - C corner types → C<sup>4</sup> different textures
  - C<sup>4</sup> =<sub>C=2</sub> 16 variations already sufficient
- Apply generating rule set from each variation to the **entire ABTF dataset**



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# Results

Texture Synthesis stage 1 (non-periodic texturing vs. **seamless texturing**)



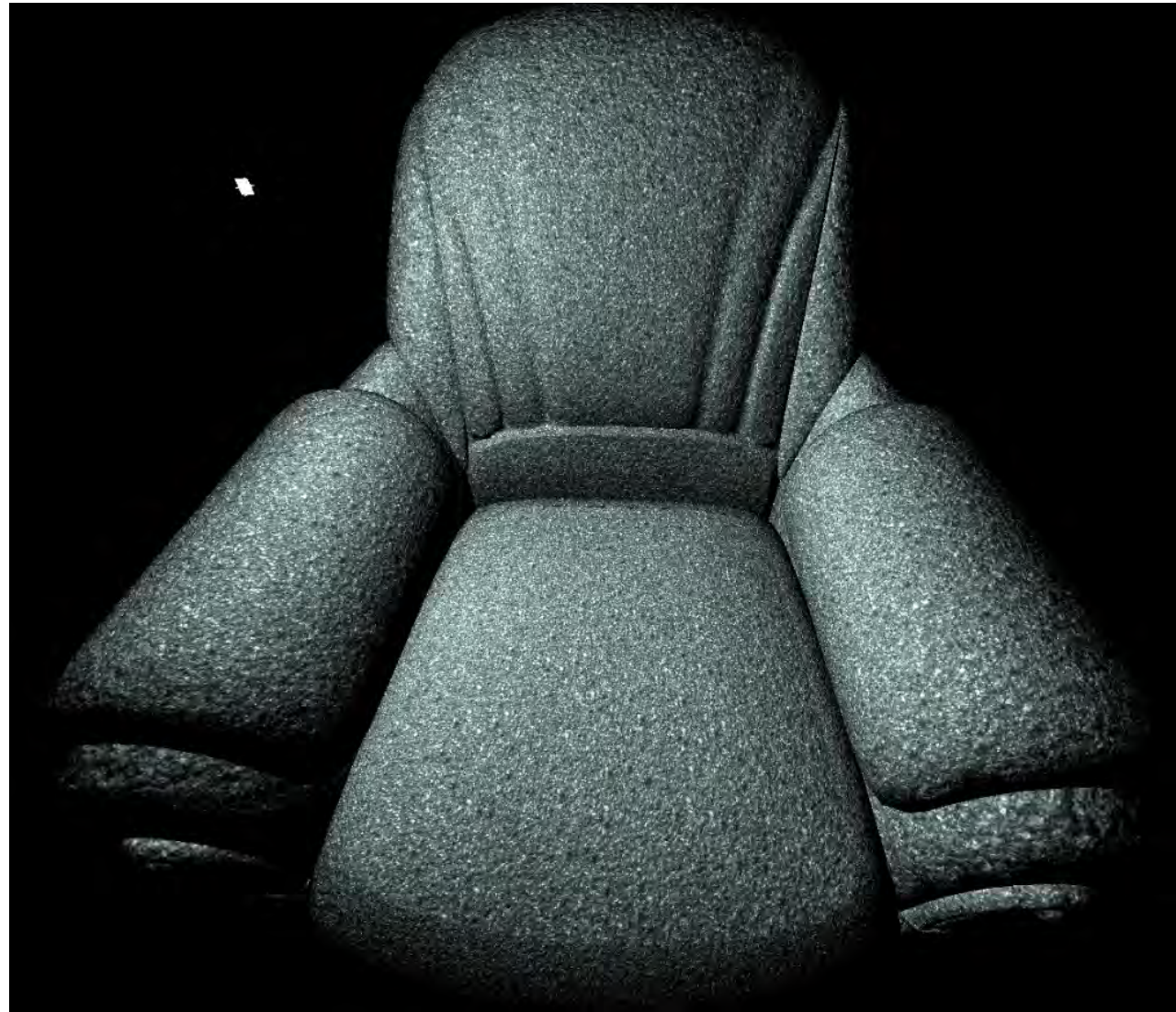


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# Results

Texture Synthesis stage 2 (seamless texturing with repetitions vs. **texture variations**)

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# Results

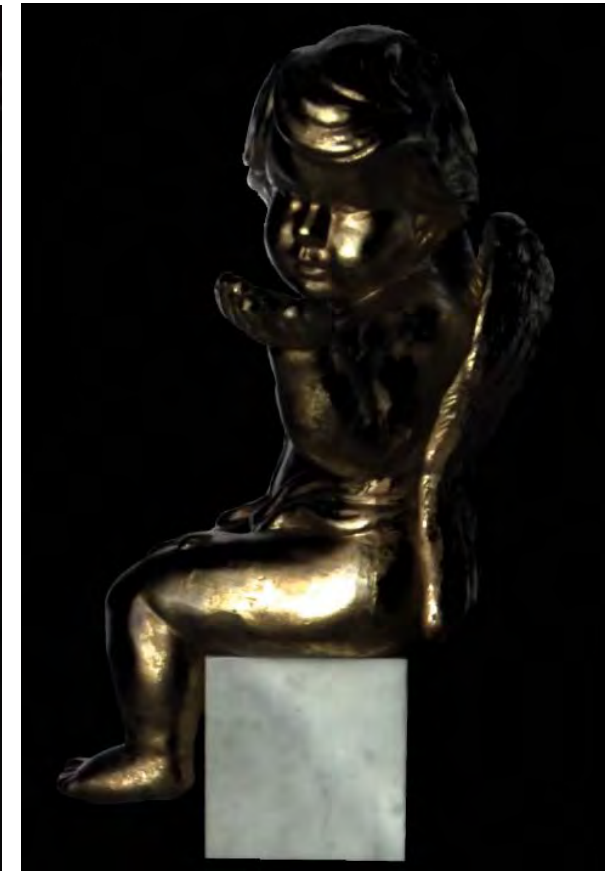
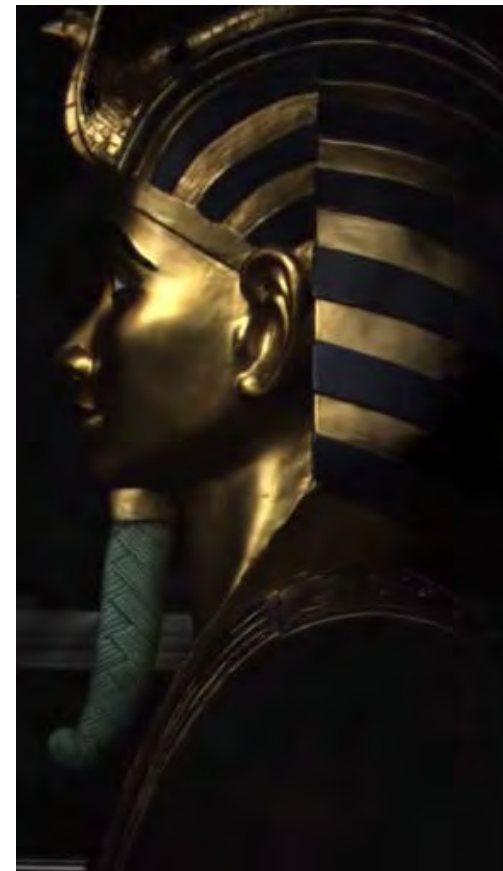
Target geometry for ABTF material transfer

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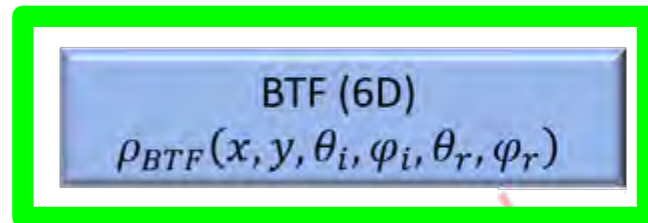
# OPTICAL MATERIAL BEHAVIOR ACQUISITION & RENDERING of entire objects



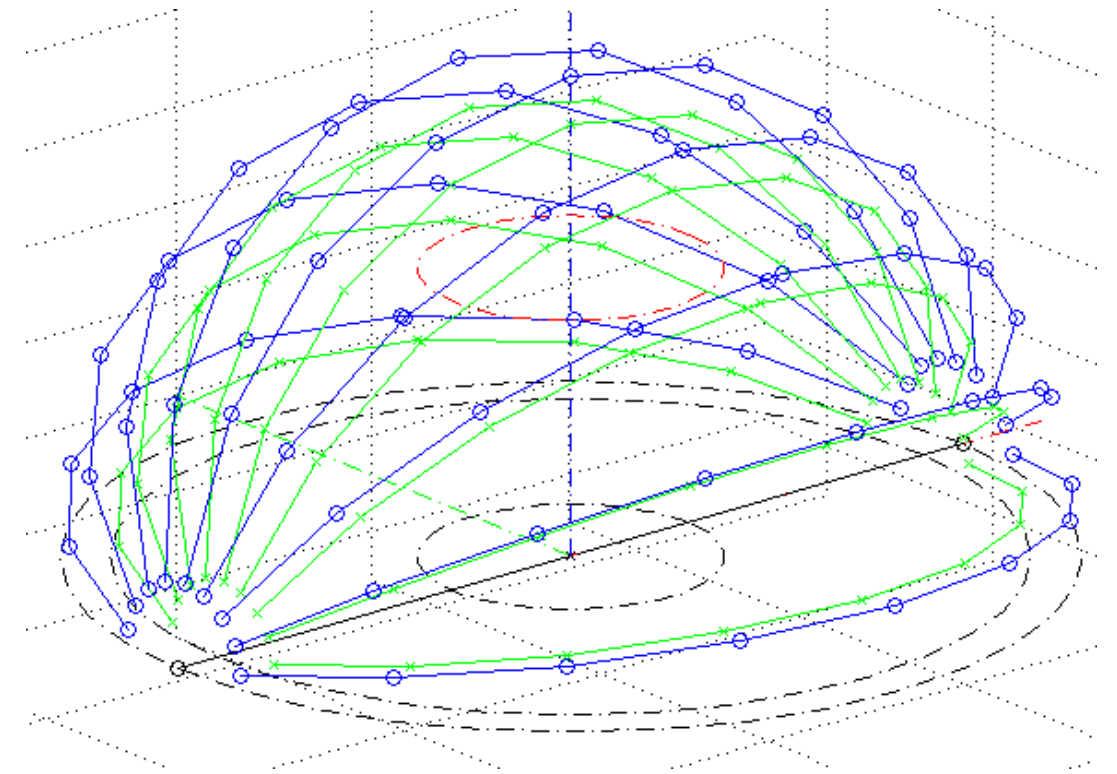
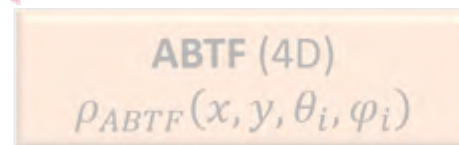
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# OPTICAL MATERIAL BEHAVIOR ACQUISITION & RENDERING of entire objects

Capture **combinatorial set**:  
{all views} x {all light directions}



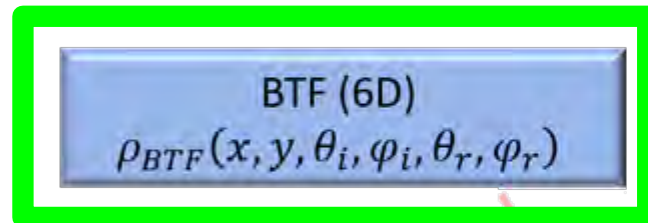
fixed view





# OPTICAL MATERIAL BEHAVIOR ACQUISITION & RENDERING of entire objects

Capture **combinatorial set**:  
{all views} x {all light directions}



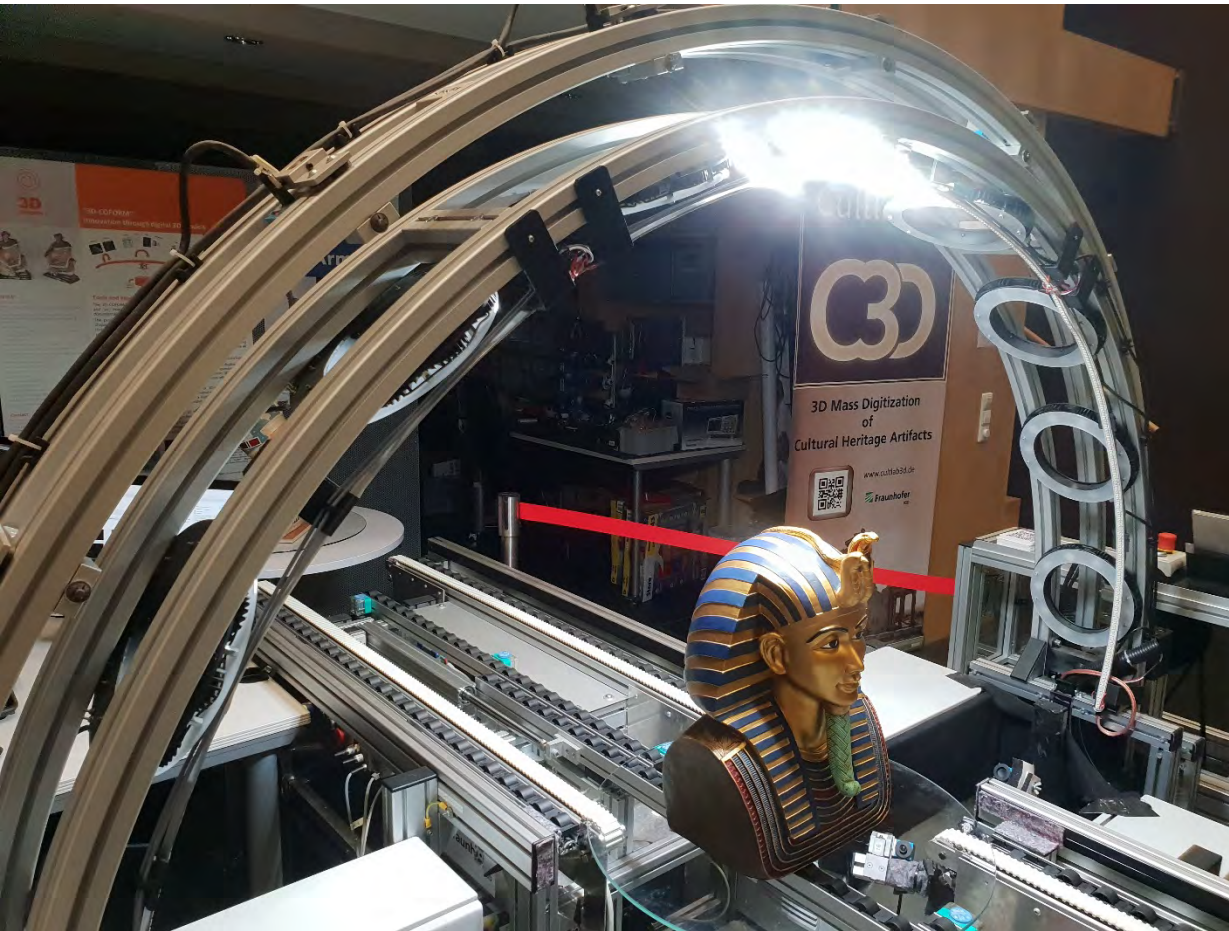
fixed view





# OPTICAL MATERIAL BEHAVIOR

$9^2$  cam perspectives x  $9^2$  discrete light angles







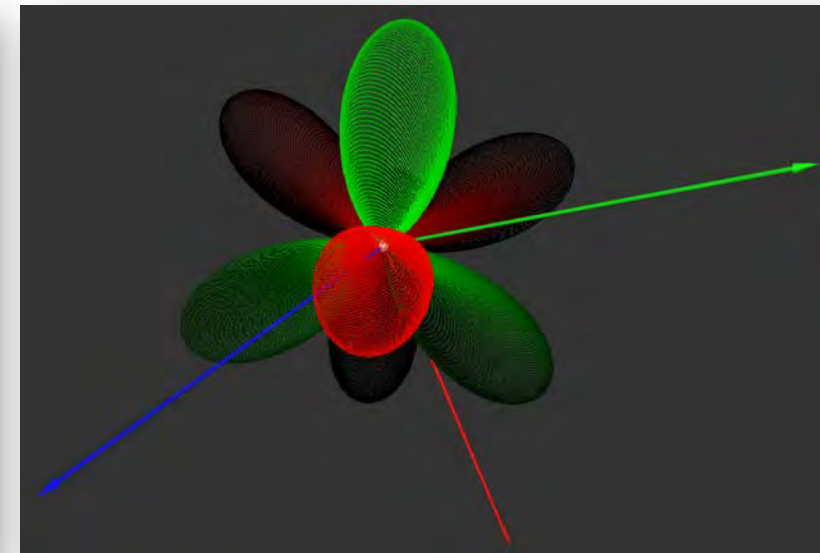




# OPTICAL MATERIAL BEHAVIOR

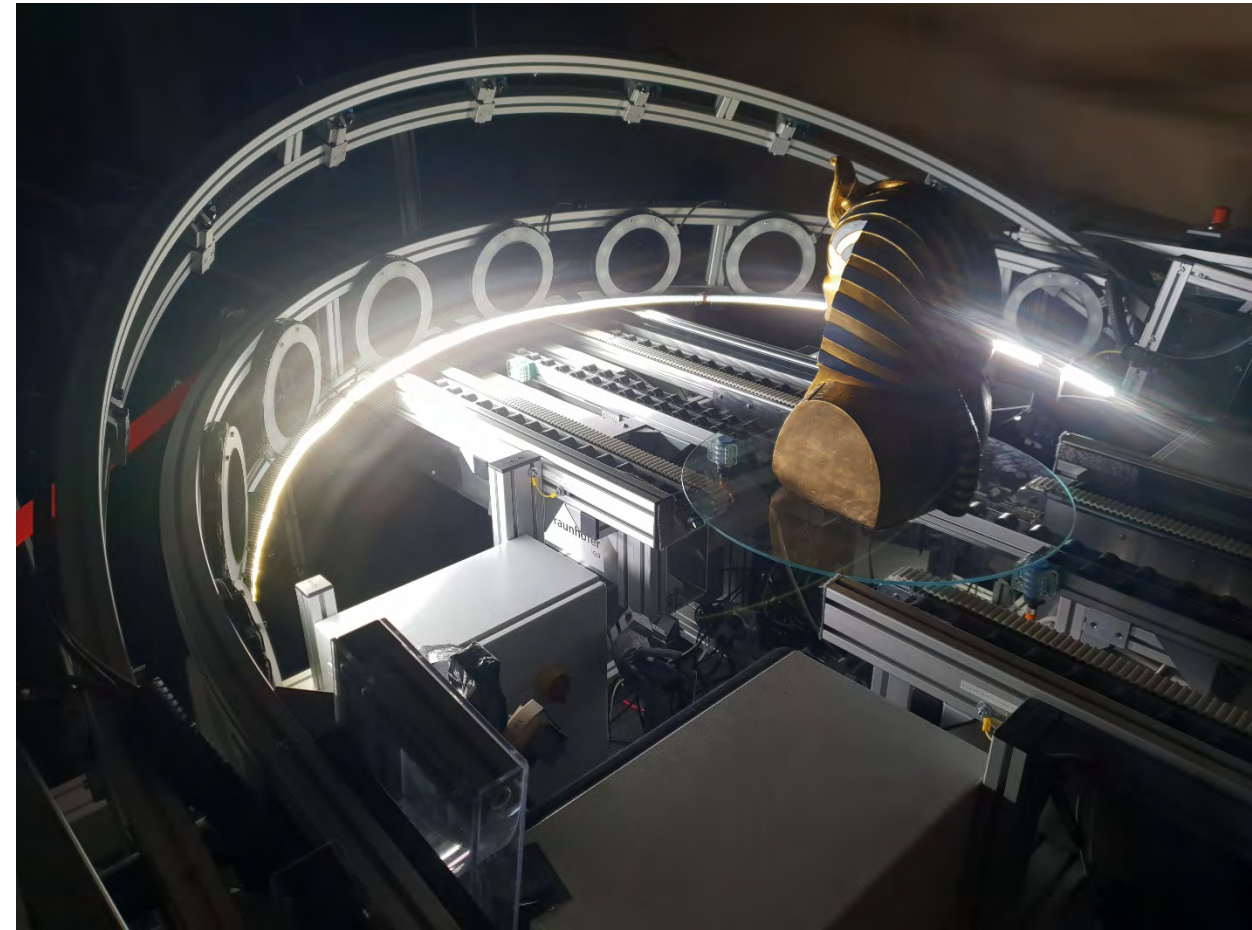
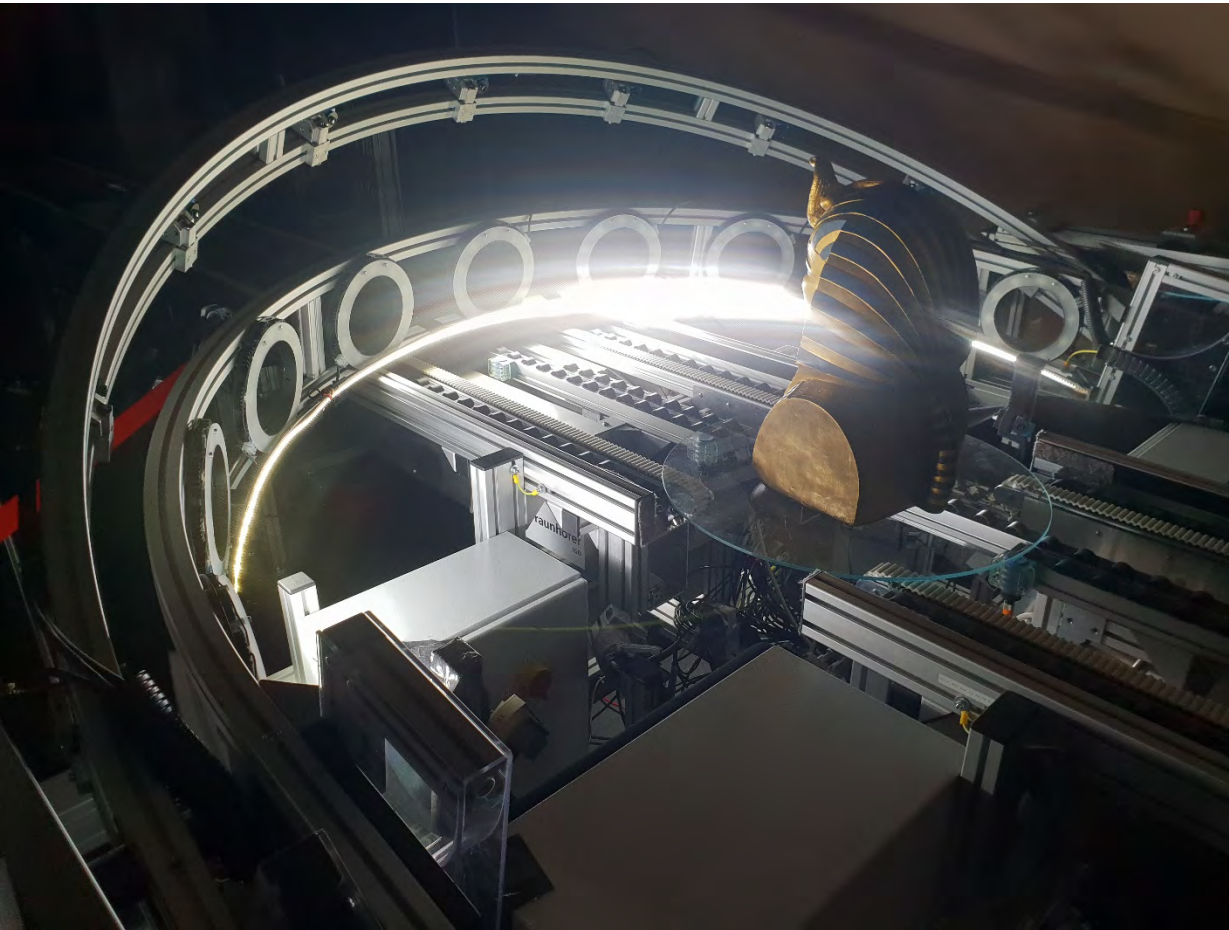
## $9^2$ camera perspectives x continuous SH light encoding

- SH = Spherical Harmonics
  - Set of base function used to efficiently encode illumination distributed over (hemi)sphere



# OPTICAL MATERIAL BEHAVIOR

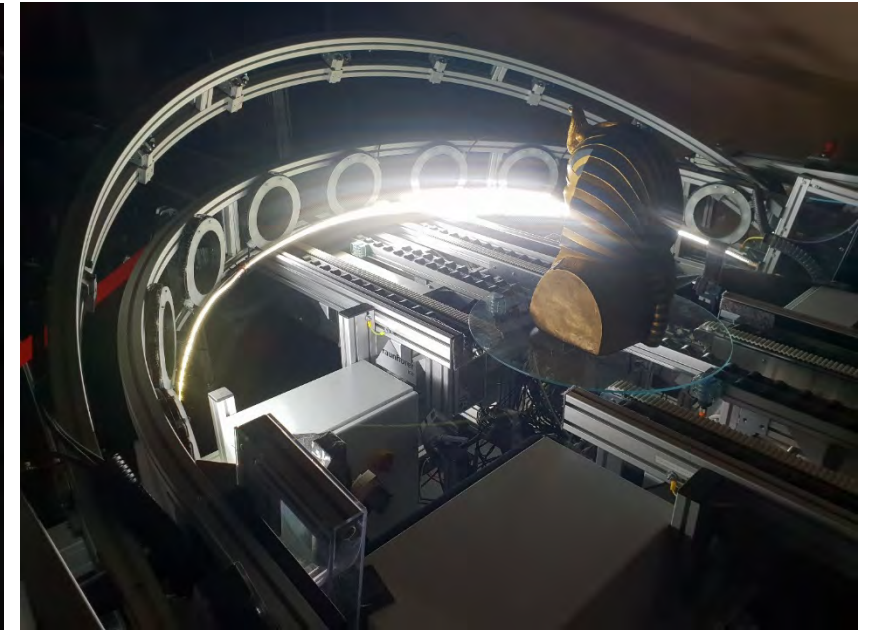
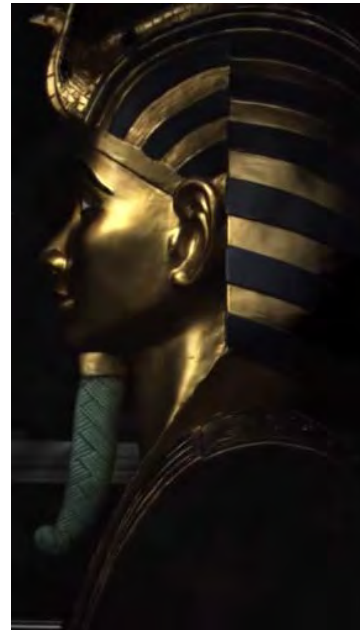
$9^2$  cam perspectives x continuous SH light encoding





# The Message

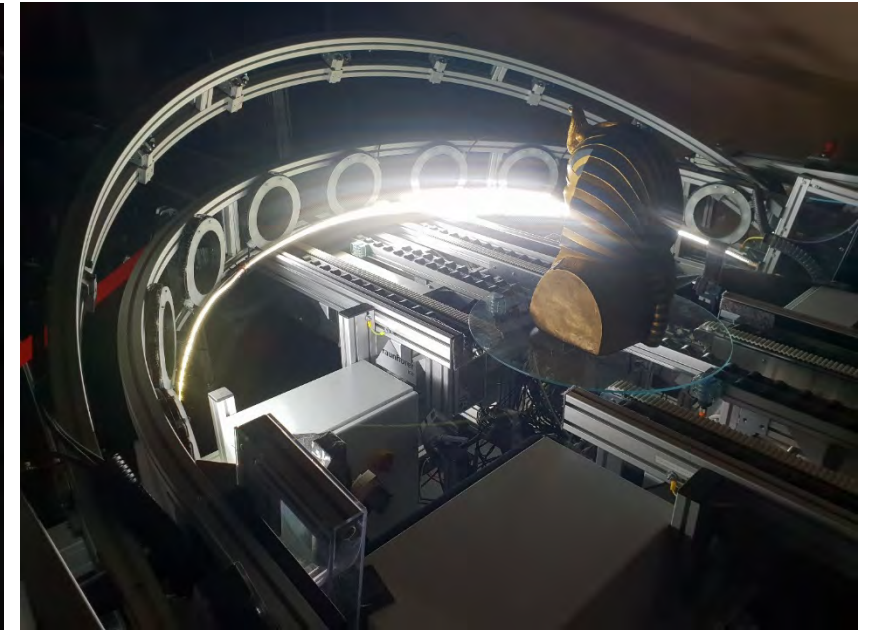
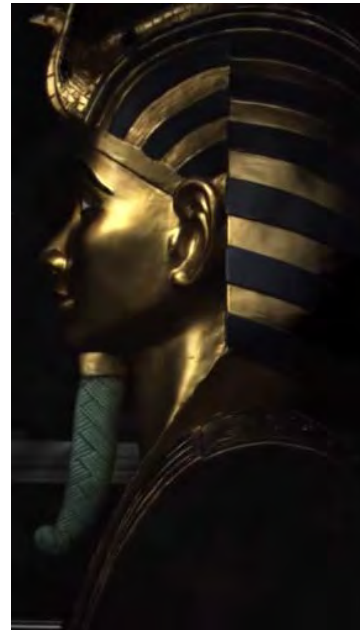
- 3D digitization is important
  - Maximize **quality**
  - Minimize *human effort*
- 3D is **incomplete** without optical material behavior
  - **Parameter-tuned** models look nice, but...
  - ...only methods based on **physical measurements** provide ultimate realism and reference to reality



# Thank you for your attention...

...please visit us...

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- on [www.cultlab3d.de](http://www.cultlab3d.de)
- or *directly* at our Fraunhofer-Institute close to Frankfurt (Germany) to see our latest developments in action.



**Martin Ritz**

[Martin.Ritz@igd.fraunhofer.de](mailto:Martin.Ritz@igd.fraunhofer.de)