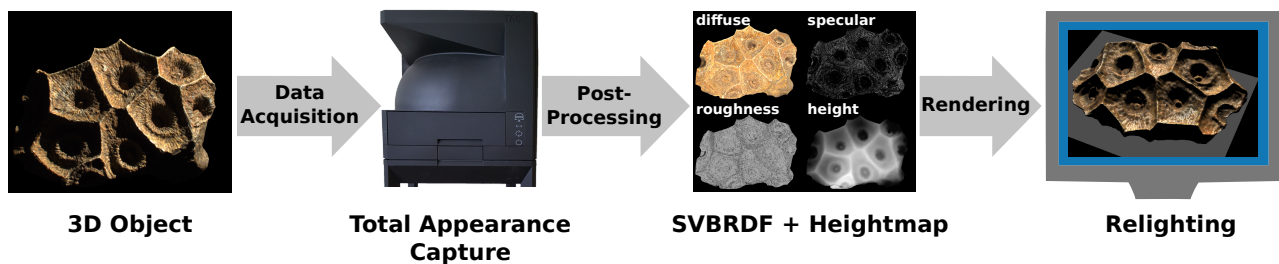


# High-Quality Multi-Spectral Reflectance Acquisition with X-Rite TAC7

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**Figure 1:** Overview of the proposed pipeline: In a first step, the TAC7 device is used to capture the surface geometry of the considered artifact, as well as multi-spectral reflectance data from multiple view and under different illumination directions. This is followed by a post-processing step, in which a multi-spectral SVBRDF representation is fitted, which can finally be used for real-time relighting in novel environments.

## Abstract

When relighting digitized objects, strong color deviations can arise depending on the illumination conditions if the object's reflectance is only captured in RGB. To guarantee color-correct simulations, it is therefore of great importance to perform appearance capture with a finer spectral sampling than the three broad band RGB channels. Capturing both shape and multi-spectral reflectance at a high quality is a challenging task and – to the best of our knowledge – has not yet been performed at the quality and speed of our approach. We acquire surface geometry and multi-spectral spatially varying reflectance of objects of up to a few centimeters height with the TAC7 device, which is available commercially as of lately. We demonstrate the improvements in color-accuracy and the overall quality of the appearance capture by relighting our accurately digitized objects under varying illumination conditions.

## 1. Introduction

Digital representations of three-dimensional objects have found their way into many industries. Examples are the movie and game industry, as well as TV-commercials, virtual prototyping and cultural heritage applications like digital museums. To allow for artistic freedom during the reproduction regarding viewpoint and illumination conditions, an object needs to be captured in its entirety, i.e. taking a single photograph or even a video is not sufficient. For a photo-realistic reproduction it is therefore crucial to capture both the object's geometry, as well as the spatially varying surface reflectance at the highest possible quality. Furthermore, as it has been repeatedly demonstrated throughout the literature, for a realistic reproduction of the object colors under arbitrary light sources, it is insufficient to capture and represent the digitized object in RGB.

Instead, a much finer sampling of the visual part of the electromagnetic spectrum is necessary than the three broadband channels of an RGB camera. Apart from artistic aspects, many fields in science greatly benefit from the ability to inspect digital copies of real world objects. In the fields of archeology, paleontology and also the arts, reflectance transformation imaging (RTI) has been used for many years to allow for enhanced inspections of object surfaces.

Though great progress has been made in recent object digitization pipelines [Sch15], they usually record only RGB data. Such an RGB acquisition essentially reduces continuous reflectance spectra  $L(\lambda)$  to three discretized values  $C_i$  by computing integrals for the red, green and blue channels of the reflected spectra, weighted by

the corresponding camera color matching functions  $f_i(\lambda)$ :

$$C_i = \int_{\lambda} L(\lambda) f_i(\lambda) d\lambda. \quad (1)$$

Though such a discretization is able to represent all possible colors by a linear combination of the three primaries, problems arise as soon as the illumination conditions change. Even if acquisition setups are carefully radiometrically calibrated and the outputs are whitebalanced, it becomes impossible to recreate the true object colors under arbitrary light spectra. Figure 2 exemplarily shows a digitized object under four standard illuminants and a light spectrum acquired in a forest canopy [dC00]. The differences between the renderings in row **A** and **B** are immediately visible for four of the five illumination spectra, and are sometimes as drastic as a change from reddish to green colors (HP1). These differences are the result of performing the object relighting in RGB (row **B**), as opposed to a much more accurate relighting with spectra discretized into 30 waveband bins (row **A**). Such drastic color errors are a nuisance for artists, but they become a severe problem in certain industries that digitally present their products to customers and therefore have a strong interest in color accuracy. When digitally archiving cultural heritage artifacts, their true appearance might be lost forever if not captured accurately enough, once the originals deteriorated due to erosion or other aging effects.

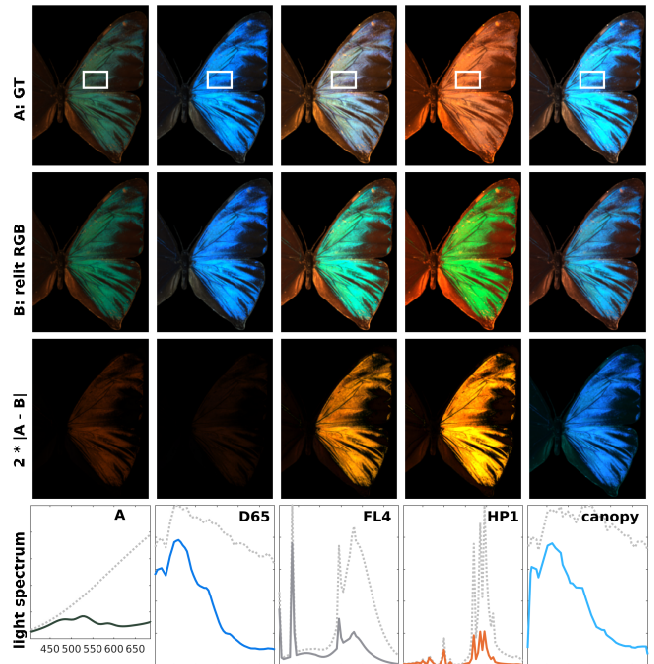
The challenges of capturing multi-spectral images are the high costs, limited spatial resolution and reduced light sensitivity of snapshot devices, which entered the markets only a few years ago [GTL14, IME]. In contrast, the longer established scanning spectral cameras [HSB02] increase acquisition times by a significant factor, as multiple images are necessary to capture one multi-spectral image.

In this paper we examine the applicability of the commercially produced Total Appearance Capture material scanner (TAC7) [XR16] by X-Rite Incorporated for the digitization of objects that fit into the device’s measurement bay. This device offers a readily calibrated setup that allows to quickly capture high quality surface geometry and reflectance of materials with multi-spectral resolution. The obtained accurately digitized objects are represented as a heightfield geometry and a multi-spectral, spatially varying BRDF. We show the benefit of a multi-spectral over an RGB-based representation in several relighting experiments.

## 2. Related Work

Related work can be categorized into efforts regarding accurate reflectance acquisition and multi-spectral imaging.

**Reflectance Acquisition:** Detailed surveys regarding the progress in reflectance acquisition are provided by Haindl and Filip [HF13] and Weinmann et al. [WLGK16]. As the use of simple 2D texture representations parameterized over the object surface does not capture the view and light dependency of the surface reflectance, this approach is not capable of accurately preserving characteristics of material appearance that determine the impression of the object [SWRK11]. Instead, surface light fields [LH96, GGSC96], capture the appearance of objects under fixed illumination from multiple viewpoints. In turn, surface reflectance fields [DHT\*00,



**Figure 2:** Visualization of errors resulting from relighting in RGB vs. spectral ground truth under different illuminations. **Top row:** object digitized in our pipeline, illuminated under varying light sources: CIE illuminants A, D65, FL4 and HP1, and sunlight filtered through a forest’s canopy (taken from de Castro [dC00]); **second row:** object digitized in RGB, relit under RGB illumination; **third row:** absolute RGB differences between A and B, scaled by 2 for better visibility; **bottom row:** illumination spectra (dotted lines) and resulting averaged reflection spectra (solid lines) from the highlighted regions in A. The color errors resulting from the RGB discretization are not negligible.

[MGW01] allow the representation of material appearance from a single static viewpoint under varying illumination conditions.

Furthermore, both the view and illumination dependent characteristics of spatially varying surface reflectance behavior have been captured as spatially varying bi-directional reflectance distribution functions (SVBRDFs) [HLZ10, NJRS13, SRT\*14] and bi-directional texture functions (BTFs) [SSW\*14]. While SVBRDFs are only suitable for modeling local light scattering, BTFs are capable of capturing mesoscopic effects of light exchange such as self-occlusions and interreflections within their data-driven representation. However, this is achieved at the cost of long acquisition times and high memory requirements. To keep the acquisition practical and fast, we rely on SVBRDFs in this work. In contrast to the aforementioned approaches that only consider RGB acquisition, we combine multi-spectral imaging with SVBRDF acquisition by using the recently released acquisition device TAC7 [XR16] to acquire multi-spectral SVBRDFs, along with the an acquisition of the surface geometry based on structured light.

**Multi-Spectral Imaging Techniques** Sampling the spectral domain based on tunable filters or filter wheels leads to an increasing acquisition time in comparison to non-spectral acquisition. This becomes particularly costly for reflectance acquisition, where thousands of different view-light configurations have to be taken into account. Using reconstruction algorithms allows to circumvent densely sampling the spectral domain at the cost of a high sensitivity to noise and possibly resulting unreliable reconstructions. The latter might occur particularly when short acquisition times are necessary and the illumination cannot be increased. Multi-spectral cameras typically do not meet the requirements of both a high spectral and a high spatial resolution at short acquisition times [SH14]. Though recently introduced commercially available multi-spectral snapshot cameras offer video frame-rate acquisition of spectral images, they typically provide only a limited spatial resolution and suffer from a lack of light sensitivity [IME].

In contrast, hybrid approaches [IB98, HSB\*99] combine spatially dense high-quality RGB measurements and sparse spectral measurements for a trained pseudo-inverse which they apply for a dense reconstruction of the full spectral data. The practicality of these approaches is limited by bad reconstruction results obtained when applying the pseudoinverse of the RGB filter matrix [IB99] by not being suitable in the presence of multiple materials in the scene [HSB\*99]. Other approaches require sparsely measured low-noise spectra, e.g. given by a spectral line-camera, which need to be registered to dense RGB measurements [RK10]. Such registrations pose a challenging problem, which rules out the applicability of such methods in practice. To facilitate the registration problem, Merzbach et al. [MWRK17] simultaneously captured spectral band images at short acquisition times, accepting the resulting high noise levels, in combination with RGB images. Using a fusion of those two modalities, they are able to reconstruct multi-spectral BTFs.

In this work, we employ a recently released commercially available reflectance acquisition device [XR16] that allows spectral SVBRDF measurements. This device is designed for industrial needs, i.e. acquisition times are practical, calibration is performed automatically and there are readily available processing protocols.

### 3. Methodology

Figure 1 gives an overview of our method. We use the recently released material scanner TAC7 [XR16] to acquire both surface geometry and multi-spectral images under different view and light configurations for objects with a height of a few centimeters. This is followed by a processing of the acquired data in which the collected reflectance data is used to fit multi-spectral SVBRDFs. This combination of geometry and SVBRDF representation allows for color-correct real-time renderings under arbitrary light spectra. In the following, we provide a more detailed description of these steps.

#### 3.1. Data Acquisition

The TAC7 has originally been designed for measuring planar material samples. For geometry acquisition, it is equipped with a structured light system consisting of a projector that projects Gray code patterns onto the surfaces observed by four cameras. These cameras are mounted in an arc at inclination angles  $5.0^\circ$ ,  $22.5^\circ$ ,  $45.0^\circ$  and

$67.5^\circ$ . To capture images from varying azimuth angles, the objects are placed on a turntable in the center of the gantry. The hemisphere above the turntable is equipped with 30 LED light sources and additionally a movable linear light source. Most of the LEDs are white and the cameras are monochromatic, i.e. they are sensitive over the entire visible range of the spectrum. To capture the surface colors, wheels with ten different spectral filters can be rotated in front of four white and colorful LEDs. Per view and light configuration the cameras acquire images with several exposure times. These low dynamic range images are later combined into high dynamic range (HDR) images, which is necessary to capture the full dynamic range of the surface reflectance.

Before the acquisition begins, the user must select the dominant surface type from a selection of presets. These vary from low to high gloss and consider either isotropic or anisotropic reflectance. The user can specify which of the following modalities should be acquired: monochrome LEDs, polychrome LEDs, structured light, linear light source. Each of them can be fine-tuned individually, e.g. by specifying the rotation increments of the turntable, the angular steps of the linear light source, and in particular the exposure bracketing steps of the cameras. Depending on the selected preset and the manual user settings, the acquisition effort can be influenced. If for example a mostly diffuse and isotropic object is to be captured, the storage requirements are about 15 GB and the total acquisition time amounts to about 15 minutes. For the other extreme, i.e. an anisotropic and very glossy object, about 100 GB are necessary and the measurement takes about 70 minutes. A reason for the increased acquisition effort is that the sharp specular peaks need to be sampled densely by moving the linear light source in small angular increments, and the anisotropy requires finer rotation increments of the turntable.

The only necessary preparation is a fixation of light or deformable objects. We used an inflexible black anodized aluminum plate as a base and attached such objects with double-sided tape to keep them in place while the turntable moves. Objects are inserted on a sliding mechanism that does not offer much space above. Therefore, objects cannot stick out more than half a centimeter above the sample holder. However, the entire sample plate can be fixed at an arbitrary height level up to a few centimeters below the sample holder's reference plane. Abusing this mechanism allows to measure objects of at most 4 cm height. The sample holder features a circular boundary with an inner diameter of 14 cm.

#### 3.2. Data Post-Processing

Once all the data has been acquired, the post-processing starts by detecting Aruco [MS13] markers on the sample holder. This allows for a geometric calibration, where the camera positions w.r.t. the objects can be determined accurately. Next, the surface height field is determined by decoding the projected structured light patterns. For each of the considered views, a decoding of the pattern observations per pixel is performed, which results in binary bit codes that can be matched across different images. These correspondences are triangulated via bundle adjustment to obtain a three-dimensional point cloud and the scattered 3D points are subsequently interpolated into a rasterized height map. For this, the points' height values are determined by projection onto the sample holder's reference plane,

which leaves only 2D scattered samples with their corresponding height values that need to be interpolated.

With the reconstructed geometry, the parameters of a multi-spectral SVBRDF, consisting of a diffuse Lambert and a specular anisotropic Ward model [War92] with bounded albedo [GMD10], are determined from the data:

$$\rho(\omega_i, \omega_o) = \frac{k_d}{\pi} + \frac{k_s (\mathbf{h} \cdot \mathbf{h})}{\pi \alpha_x \alpha_y (\mathbf{h} \cdot \mathbf{n})^4} \exp \left\{ - \frac{((\mathbf{h} \cdot \mathbf{x})/\alpha_x)^2 + ((\mathbf{h} \cdot \mathbf{y})/\alpha_y)^2}{(\mathbf{h} \cdot \mathbf{n})^2} \right\}, \quad (2)$$

where  $\omega_i$  and  $\omega_o$  denote the incoming and outgoing light direction,  $\mathbf{n}$  denotes the local surface normal and  $\mathbf{h}$  denotes the unnormalized halfway vector defined as the bisector of  $\omega_i$  and  $\omega_o$ . The parameters that need to be estimated during the fitting process are the surface normal  $\mathbf{n}$ , the diffuse and specular albedos  $k_d$  and  $k_s$  and one or two surface roughness parameters  $\alpha_x$  and  $\alpha_y$  along the local surface coordinate system's x- and y-axes, depending on the state of anisotropy of the surface. For suitable surfaces, this specular component can optionally be modulated by a Fresnel term [Sch94]. The resulting data is stored in AxF-files [ML15]. This appearance exchange format is supported by several widely used rendering platforms such as Autodesk VRED [Aut].

The initial orientations of the surface normals are estimated via photometric stereo, or for specular surfaces via shape from specularity. The remaining BRDF parameters are first obtained from an initial clustering step. Subsequently, a refinement is carried out per pixel over several iterations using nonlinear optimization with a relative error metric.

### 3.3. Rendering

The spatially varying reflectance parameters from the fitting step are stored as parameter textures, along with height and normal maps. Using this representation, the acquired objects can be rendered in real-time using displacement mapping. Each surface point's reflectance function is evaluated by looking up the corresponding parameters in the stored parameter maps.

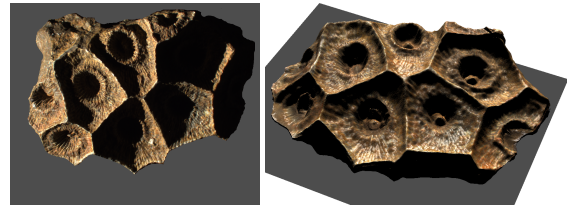
## 4. Results

We captured a variety of different objects to validate the capability of the device and the reconstruction pipeline. Our choice of objects was limited by the working dimensions of the acquisition setup. Those are restricted both physically and due to a limited depth of field of the cameras. Examples are presented in Figures 3, 4, 5 and 6, and range from coins and small jewelry objects, over a fossil to organic structures like a conserved butterfly or even living plant leaves.

Our acquisition times varied from about 20 to 90 minutes, depending on the granularity of the turntable and linear light source rotation steps. The post-processing times depend on the amount of the acquired images, the selected region of interest and the mode of reflectance fitting. They range from about 30 minutes (ficus leaves) to half a day (ceramic buttons & coins). The height map



**Figure 3:** A collection of ceramic buttons and historic coins, photographed (left) and rendered from a different viewing direction (right). We are able to faithfully capture fine geometric details and a wide variety of surface appearances.



**Figure 4:** Photograph of a fossil acquired by the measurement device and spectral rendering. This object had the strongest height variations of about 3.5 cm among the objects we acquired for this study.

and SVBRDF have an upper resolution limit of about  $2000 \times 2000$  pixels if the full sample area is processed.

To validate the visual quality, we compare renderings of the digitized objects to actual photographs. The achieved quality of the renderings is very high regarding the spatial resolution and the faithfulness of the fits. In Figure 2 we impressively demonstrate the importance of a multi-spectral acquisition of the surface colors. The color errors between the spectrally relit butterfly and an RGB relighting are clearly visible. Depending on the illumination spectrum, the results can even look green instead of red, as it happens under illumination from a high pressure discharge lamp (HP1).

## 5. Conclusions

In this paper, we show how a recently released, commercially available multi-spectral reflectance acquisition device can be used for the digitization of small objects and demonstrate that high quality reconstructions can be achieved with a current state-of-the-art in



**Figure 5:** Photograph of a shimmering butterfly under sunlight and spectral rendering under equal energy illumination.





**Figure 6:** Rendering of ficus leaves. This reconstruction proves that the TAC7 device has acquisition times that are short enough to capture temporally variable organic objects, e.g. shriveling leaves.

the industry. The resulting digitized objects are accurately reconstructed regarding both surface geometry and spectral reflectance behavior. This, in turn, allows photo-realistic and color-correct digital depictions of the objects under arbitrary illumination conditions. With this investigation, we demonstrate the importance of considering spectral characteristics in reflectance behavior for applications in 3D content generation, virtual product presentation and cultural heritage.

The main limitation of our current approach is its capability of handling only relatively small objects with a height of up to four centimeters and a horizontal diameter of about 14 centimeters that fit into the working volume of the TAC7 device. This is a result of the original design objective of measuring only flat material samples.

With current toolset the geometry of the digitized objects is therefore only represented as a heightmap instead of actual 3D meshes. This means that lower parts of the captured objects currently cannot be reconstructed without customized software. Finally, transparencies or fine gaps in the surfaces as well as fluorescence effects are not taken into account.

Future work has to be spent on taking transparencies or fluorescence effects into account and digitizing a larger collecting of 3D objects.

## 6. Acknowledgements

We would like to thank Max Herrmann and Christopher Schwartz for their helpful comments and instructions.

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