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How to capture aesthetic features of complex cultural heritage objects – active illumination data fusion

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Abstract

In the process of digitization of cultural heritage objects with differentiated shininess it is difficult to reproduce faithfully the aesthetic of the original. The aim of the presented research is to address simultaneous capturing of shape, color and reflection features in order to digitally reproduce the appearance of the real object. We focus our work on a study of a ceramic furnace tile which exhibits complex shape, color and varying reflection properties. To achieve the goal we use a specially designed automated acquisition setup and provide a dedicated data processing pipeline. The collected geometry conforms to metrological uncertainty validation and the diffuse component is colorimetrically calibrated. The reflection properties are measurement-based, modeled with Blinn-Phong and visualized with an OpenGL shader. Close integration of capturing devices and a single data processing pipeline allows to fully utilize multidimensional raw data in order to get faithful final appearance model.

Research background

Cultural heritage artifacts with complex geometry and reflection properties are very difficult to digitize faithfully both in terms of shape and color. On one hand methods such as structured light projection provide high quality 3D point clouds [1, 2, 3]. Unfortunately directional illumination during acquisition leads to uneven light distribution on surface, self-shadowing and multiple reflections (Fig. 1). Thus, stitching data captured from different directions gives a false appearance of unbalanced brightness and numerous reflections embedded in the object's color texture.

On the other hand solutions which provide high quality colorimetric calibration and highlights compensation are often developed for flat samples only and do not allow for shape acquisition [4, 5]. Capturing reflection properties in the form of a BRDF model is an entirely different problem and is often neglected in shape and color acquisition. It turns out that for objects with differentiated shininess even very precise 3D scan does not reproduce faithfully the aesthetic of the original. Therefore the aim of the presented research is to address simultaneous capturing of shape, color and reflection features in order to digitally reproduce the appearance of the real object.

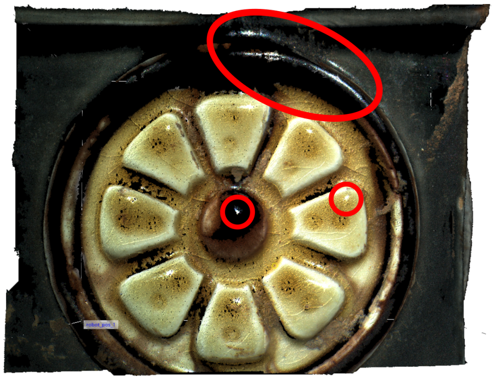

Figure 1. *Raw high resolution point cloud. Indicated some of specular highlights embedded in color texture.*

Several approaches have been used to enrich shape acquisition with color and appearance properties. A comprehensive solution by Tonsho et al.[6] uses a separate multispectral camera and 3D scanner. Mansouri et al.[7] filters out the specular component, considering the diffuse color only. Nielsen et al.[8] provides an evaluation of BRDF estimation in a structured light setup but focuses on simulations. Simon et al. [10] proposes an extensible framework for capturing different features of a 3D surface such as shape or multispectral color and focuses on mutual calibration between different acquisition devices within a single rig. Our previous solutions[9] suffer from small number of illumination directions and poor sampling of reflectance.

Another approach is to use the reflectance transformation imaging technique (RTI) [11]. It allows to recover a map of normal vectors from a single viewpoint with the use of multiple illumination directions. A fitted model of reflectance can be used to model object appearance for arbitrary illumination conditions. Many solutions report usefulness of this technique in cultural heritage documentation, visualization [13, 14, 15] and even quantitative aging analysis [12]. The limitation is that RTI does not give a full 3D model but rather a view from a single direction which makes it unsuitable for complete 3D documentation.

Here we propose a practical extension to an automated structured light projection setup which makes capturing shape along with color and reflectance properties possible. The main advantage and contribution is that the look of a resulting 3D model is based on physical data rather than a subjective vision of a graphic designer. Our aim is to make 3D models not only look good but also to achieve close correspondence with the original so that the result is more useful for conservation and documentation purposes.

Use case

We focus our work on a study of a ceramic furnace tile which exhibits a complex shape, color and varying reflection properties on its glazed but partially brushed front surface (Fig. 2). The object is a part of a tiled stove from Museum of King Jan III Palace in Wilanów. It was made in the majolica technique in the second half of the XIX century in Rörsrand in Sweden (project from Ernst A. Jacobsson).

Figure 2. *Investigated object: furnace tile from the collection of King Jan III Palace in Wilanów.*

Our main focus is a demonstration of a digitized tile with the emphasis on colorimetrically reconstructed diffuse component and BRDF response approximated with the Blinn-Phong model. The object appearance in arbitrary artificial illumination conditions is visualized with an OpenGL shader. The collected geometry conforms to metrological uncertainty validation and the diffuse color component is calibrated and available in CIE XYZ or CIE LAB color space. The reflection properties however enrich the appearance impression and do not aim to infer on the object's material. To achieve the goal we use a specially designed automated acquisition setup and provide a dedicated data processing pipeline.

The setup

A state of the art acquisition setup called Rotlite (Fig. 3) is the effect of joint efforts of Warsaw University of Technology and King Jan III Museum Palace at Wilanow. Built as a part of Documentation and Digitization Division in the museum it serves as a platform for multimodal data acquisition. It integrates a structured light projection 3D scanner mounted on a 6-axis robot [2] along with a turntable and multispectral illuminator. It is equipped with a rotating arm with RGBW LED illuminators. Therefore it is able to register a number of responses from varying illumination directions at each point. Each response comes in 6 spectral bands within a visible range thanks to multiplexing between camera and illuminators' RGB channels [17]. Apart from this, multiple exposure is used to capture high dynamic range required to register a diffuse reflection component as well as specular highlights straight from the resulting radiance map [16].

The setup is capable of capturing point clouds with the sampling density of 1600 points per mm^2, in the volume of 80×60×40mm. The machine is controlled with a specially developed software which allows for automatic capture of a predefined sequence of camera and illumination positions. The operator plans an acquisition sequence by choosing a set of robot positions and a number of turntable steps for each robot orientation. After that the process may be conducted automatically without manual supervision. During operation, consecutive point clouds appear in preview one by one after being simplified on the fly. This way the progress can be monitored in real time. Such preliminary 3D model is used for assessment and planning of next scanning directions so that the full object's surface is covered.

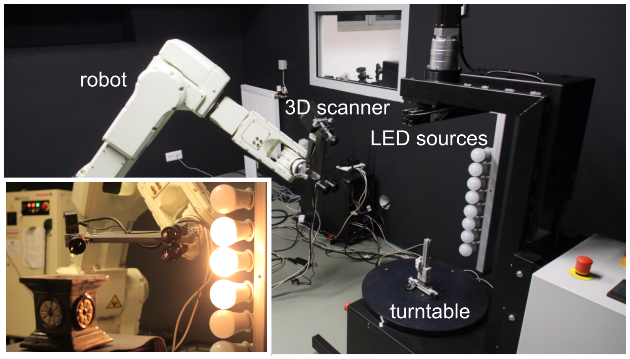

Figure 3. *Rotlite measurement setup.*

Data processing

Recovering a final 3D model requires several processing steps which can be divided into two main pipelines. The first one focuses on 3D point cloud reconstruction whereas the second one is responsible for extracting color and reflectance information.

Geometric pipeline

Input data for the point clouds processing pipeline come straight from structured light projection 3D scanner. The device produces dense point clouds with additional information gathered per point. These complementary features include normal vector directions estimated from local point's neighborhood and camera pixel coordinates. The latter indices greatly simplify data organization because points in the cloud can be ordered according to their corresponding pixel coordinates and it is possible to map color information from images to the cloud and back.

The outline of the processing pipeline is illustrated in Fig. 4. During the acquisition process raw dense clouds are stored while their simplified equivalents are created on the fly and loaded into data processing application. This approach allows for maintaining visual representation of the whole model for large number of scanning directions. Working on the dense model would not be feasible because serious memory capacity limitations occur at this scale of data capture. Therefore most of the processing steps are conducted on the simplified data, greatly improving time of operations.

First step is filtering which uses k-means clustering algorithm for removal of spurious points and small groups of points not connected with the main dataset. This prepares the cloud for precise fitting step with iterative closest points algorithm. The crucial feature of the automated setup is the ability to recover clouds' initial positions from scanner orientations given by the robot. Its kinematics supplemented with a hand-eye calibration of the 3D scanner along with turntable axis calibration gives preliminarily fitted clouds, ready to be refined with an automatic ICP algorithm.

Once the clouds are adjusted their transformations are

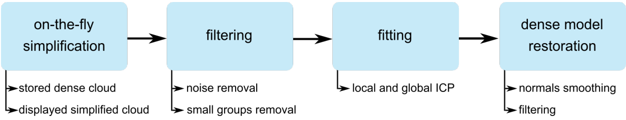

Figure 4. *Outline of the point clouds processing pipeline.*

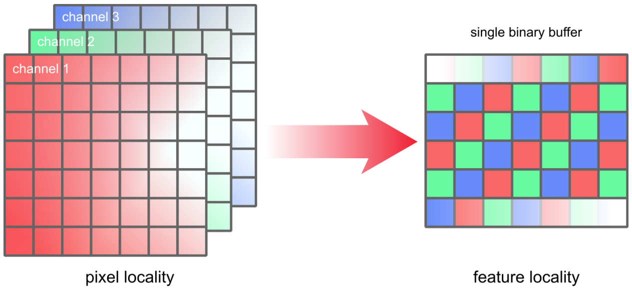

Figure 5. *Data reordering concept: left – input images per feature (channel); right – output binary buffer.*

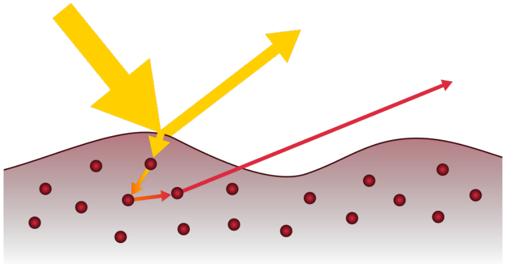

Figure 6. *Dichromatic reflection model. Reflection has two components: Lambertian body reflection and specular interface reflection.*

brought back to the dense model which is also being filtered from noise. One additional operation is to smooth the normal vectors because their stability is essential for correct reflectance estimation. Normal vector directions, being calculated from very limited neighborhood, suffer from significant variability. To overcome this they are averaged within the radius of 0.5mm which effectively diminishes their noise variation.

Photometric pipeline

Color and reflectance information is recovered from a sequence of images captured with the directional illuminator. For each scanning (observation) direction a set of images with 44 illumination angles, 2 exposures and 6 spectral bands is associated. It comprises a significant amount of data which is extremely poorly ordered from the processing perspective. For the efficient pipeline it should be easy to access different features (channels) for each point instead of different pixels of each feature, as is the case with storing band images (Fig. 5). Therefore the first step in the photometric processing pipeline is data reordering which converts a set of images to binary buffers with the desired data locality. This process is optimized with the use of parallel computations based on OpenMP. Once the data is reordered it is possible to load feature sets for different pixels on demand in a stream-like fasion which greatly reduces memory usage and increases caching performance.

Consecutive operations in the photometric pipeline are calculated per point in cloud. First a high dynamic range radiance map is found for each spectral channel. It requires knowledge about camera response function which is being estimated in advance from a picture of a ColorChecker target in the same illumination and exposure conditions. This way the radiance map is consistent for all point clouds.

In the next step it is necessary to extract diffuse and specular component of reflection. Here we follow common assumption of a dichromatic reflection model which states that light energy scattered from a surface consists of two components [18]. The body reflection component carries information about material color and conforms to Lambertian reflection and the interface reflection component has specular properties and spectral response of a light source (Fig 6).

To incorporate both reflection components in the final 3D model we need to provide a rendering equation which tells what intensity would be perceived for a given illumination and observation geometry. Many different approaches can be utilized for this [19] but we currently focus on a simple, empirical BRDF model by Blinn-Phong [20]. It combines Lambertian diffuse reflection and specular component described with two parameters K_s and K_e (Eq. 1). The first coefficient describes how much energy the surface reflects whereas the second, exponential one, indicates how selective is the reflection.

$$I_p = I_d K_d(\vec{n}\cdot\vec{l}) + I_s K_s(\vec{h}\cdot\vec{v})^{K_e} \tag{1}$$

The Lambertian (diffuse) component is parametrized with a cosine between a normal vector and illumination direction and the specular component depends on a cosine between a normal and a so-called half-way vector direction. The half-way vector is the average vector between illumination and specular reflection direction (Blinn-Phong parametrization). With the above assumptions the task is to recover reflection parameters (K_d, K_s and K_e) from images collected along with each point cloud.

Having a big amount of redundant data from many illumination directions it is possible to estimate both reflection components from simple statistics. The diffuse component for each point and in each spectral channel is calculated as the average response from all images excluding minimum and maximum values. The extrema are considered outliers because they may indicate lack of illumination or specular reflection respectively. Mean diffuse component radiance maps are used as input for color reconstruction with the aid of linear colorimetric calibration based on the ColorChecker target [17]. This way the product $I_d K_d$ from Eq. 1 is estimated separately for each of the R,G,B color channels.

A procedure for specular components estimation is presented in Fig. 7. In order to estimate them the radiance value for each illumination direction has to be normalized by the cosine forshortening factor: $E_i' = E_i/(\vec{n}_i \cdot \vec{l}_i)$ first. Next, responses from angles over 90° and with values below a selected threshold are dropped as outliers. Maximal response prepared this way is considered a measure of the K_s coefficient. This reasoning is based on the assumption that the maximum value corresponds to the amount of energy reflected in a specular way.

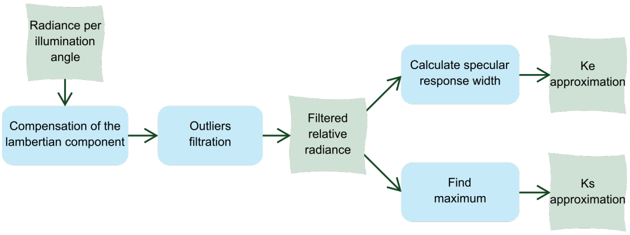

Figure 7. *Specular reflection components' calculation procedure.*

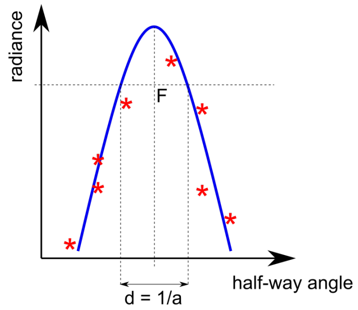

Figure 8. *Angular radiance responses for a single point and its parabola approximation for the* K_e *coefficient estimation.* K_e *is modeled as the highest power coefficient of the polynomial which is inversely proportional to the focal width of the parabola.*

Figure 9. *Visualization of the point cloud virtual model of the furnace tile: left – the diffuse component only; right – diffuse and specular components according the the Phong shading model.*

Simultaneously all the valid angular radiance responses are used as samples for a parabola (second order polynomial) approximation. The resulting highest power coefficient which indicates the width of the angular response lobe is considered to be an approximation of the K_e coefficient (Fig. 8).

Specular reflection coefficients are calculated for each point in the cloud and stored as a separate data layer. During the rendering process this additional layer is used by an OpenGL shader which implements the Phong reflection model and provides real time shading for the actual observation and illumination in a virtual scene.

Results

The resulting point cloud model was created from 144 fitted point clouds. The first approximation of the furnace tile appearance is the rendering of a diffuse component (Fig. 9 on the left). It does not include specular highlights embedded in the surface color but at the same time the presentation of the object is flat and not realistic. The second approach to visualization uses the described Phong reflection model calculated from the real world data (Fig. 9 on the right). This time the object looks more realistic and pleasant. The important fact to emphasize is that the model parameters were not tuned manually but rather estimated from the captured images.

Fig. 10 shows the closeup of the surface rendered with the chosen reflection model and Fig. 11 presents maps of the specular reflection coefficients Ks and Ke respectively.

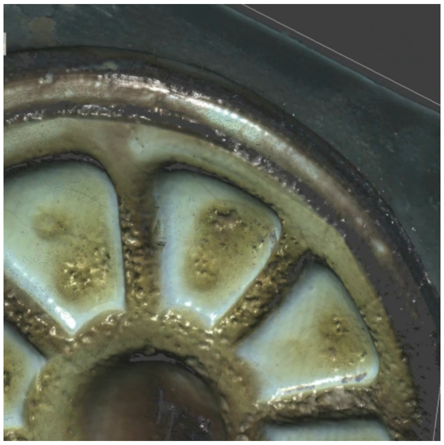

Figure 10. *Closeup of the surface rendered with the reflection model.*

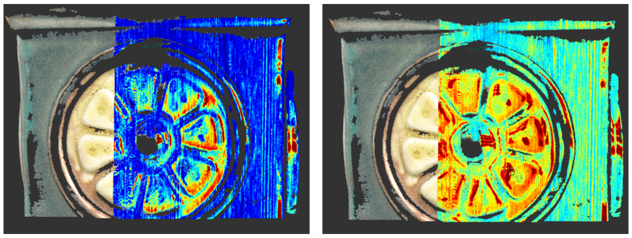

Figure 11. *Visualization of the reflection model coefficients* Ks *(left) and* Ke *(right) for a single point cloud.*

Conclusion

The presented solution provides a full-scale approach with automated high resolution capturing setup, many illumination directions and dependable processing pipeline. It is a great platform for future research in this area. We show that by utilizing such system it is possible to achieve results beyond capabilities of off-the-shelf scanners. The presented data fusion is more than a sum of shape and color components. Close integration of capturing devices and a single data processing pipeline allows to fully utilize multidimensional raw data in order to get faithful final appearance model.

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Author Biography

Grzegorz Mączkowski, PhD, works currently as an adjunct professor at Virtual Reality Techniques Division, Warsaw University of Technology. In 2016 he defended his doctoral thesis focused on combined 3D and multispectral imaging of cultural heritage artifacts. His research addresses multimodal 3D acquisition techniques with practical applications developed at the academia and in cooperation with King Jan III's Museum Palace in Wilanów.

Jakub Krzesłowski received his MS in Engineering from Warsaw University of Technology (2009). Since then he has worked at the Institute of Micromechanics and Photonics on reflectance modelling applied to Cultural Heritage. He is mainly focused on hardware integration, 3D visualization and data processing.

Eryk Bunsch, M.Sc., dipl. conservator of art. Collaborates with National Institute for Museums and Public Collections and National Audiovisual Institute since 2011 as an expert in the field of modern 3D documentation of cultural heritage. Head of Laboratory for 3D Documentation at Museum of King Jan III's Palace at Wilanów. His scientific interest considers developing technology of precise 3D scanning of cultural heritage objects. He has managed many research projects related to 3D documentation.