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STUDY ON CLOSE RANGE DIGITISATION TECHNIQUES INTEGRATED WITH REFLECTANCE ESTIMATION

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COSCH WORKING GROUP 2: SPATIAL OBJECT DOCUMENTATION
COSCH WORKING GROUP 5: VISUALISATION OF CH OBJECTS AND ITS DISSEMINATION

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ABSTRACT:

As 3D imaging techniques gain popularity in non-invasive cultural heritage (CH) digitisation, additional modalities, such as spectral and microgeometric properties of surface, are introduced to the resulting models. Reflectance estimation enables visualization of CH objects with photo-realism and increases the descriptiveness of a digital copy. The optical behaviour of surfaces can be visualized by creating textures from multiple viewpoints or by retrieving intrinsic optical properties of the surface's material using photometric techniques and by utilizing physically based rendering. The developed method concentrates on structured light projection combined with multidirectional illumination in order to retrieve reflectance information along with surface geometry. The goal of this approach is to provide quantitative description of objects in accordance with human perception and to enable realistic visualisation of virtual 3D models under arbitrary illumination conditions.

1. INTRODUCTION

In the advent of digital 3D imaging technology, documentation of cultural heritage objects (CHO) can readily be performed by a range of optical methods: using industrial laser scanners, structured light scanners and digital photogrammetry, including structure from motion. One of the aspects of documentation is the ability to reconstruct the object with due resemblance, either in the virtual or the physical realm.

1.1 Shape and reflectance

A visual representation of CHO requires (or intuitively implies) that the photographic properties of the surface should also be registered and assigned to the geometric structure. Image-based methods operate on photographic data and inherently provide this kind of information. The registered values result from a combination of radiometric quantities and the extent to which it determines reflectance information is sometimes unclear.

1.2 Aid of Computer Graphics

Once the object is digitized, common rendering techniques can be used to create graphical representation of the model. The model can then be viewed statically or interacted with in a virtual scene.
The basic rendering pipeline consists of consecutive stages – at first the geometry is projected onto the virtual image plane and then the output frame is generated on a per-pixel basis.
Even without reflectance information, the model can be represented using surface primitives and a uniform shading model.
The particular choice of models used for describing a virtual scene defines the set of visual qualities of the CHO that can be represented by the digital copy.

1.3 Documentation and Visualisation

While the introduction of optical properties can be considered an extension or 'the next step' from the geometrical model, some of the referred methods treat data primarily as visual representation, while the shape can be retrieved derivatively during later processing stages. Here I would like to compare these methods and comment on different aspects of each of them.

2. REFLECTANCE INTERPRETATION

In radiometry, reflectance is defined by the ratio of incident and outgoing radiation. Further specification of this ratio, whether spectral or spatial is defined by the context in which it is used.
In an image-based optical system, the resulting intensity that is registered by a matrix detector and represented by pixels values, comes from the combined radiometric properties of the light source, the medium, the object, the imaging system and the sensor itself. This statement is true for both transitive and reflective materials, therefore it is required that the class of investigated CHO is narrowed down to non-emissive and non-translucent solids, transmittance, surface reflectance and the performance of the imaging optics as well as the respective geometry of every mentioned element. From this combined response, only the spatial and spectral distribution of reflectance is intrinsic to the object and this portion of information has to be separated from all other factors. In this paper reflectance is referred to in a photometric aspect, but the following discussion can be extended to the hyperspectral domain. It has been shown that image-based registration

outside of visible spectrum can also be used in CHO documentation (Delaney, 2010).

The photometric approach in image-based methods is an extension to a single sensor and light source reflectometry. Reflectance, however, is often treated as a tag word in different contexts and is used for expressing the following grades of surface properties:

- Albedo,
- Material,
- Appearance.

2.1 Albedo

A property that can easily be attributed to a particular solid is its diffuse reflectivity. In a simplified form, the reflectance is described only by the Lambertian component and as such, it does not change while the viewing direction changes. Only the incident angle changes the intensity, resulting in natural shading gradients of a non-planar surface. This interpretation of reflectance is more common for colorimetric and spectral analysis.

2.2 Material

The intrinsic optical properties of an object correspond to its physical/chemical nature. The general distinction can be made between metallic and non-metallic minerals. It may be the optimal description for CHO documentation because it allows physical analysis and may also include microgeometric information such as roughness and diffractive structure.

2.3 Appearance

On the other hand, the object can be represented by its overall appearance as acquired by the imaging device, without separating extrinsic factors. This includes the spectral and spatial distribution of illumination as well as shadows cast on the object. It may result in more photo-realistic and visually pleasing details. Some methods particularly favour this photographic aspect.

2.4 BRDF

To specify an arbitrary reflectance characteristic, a function can be defined by taking all possible infinitesimal solid angles of incidence and all viewing directions over the whole hemispherical domain (Ω) of a surface fragment. The following ratio of radiance and irradiance is the definition of the bidirectional reflectance distribution function (Nicodemus, 1965) in a radiometric sense:

$$f(\omega_i, \omega_o) = \frac{dL(\omega_o)}{dE(\omega_i)} \quad (1)$$

The photometric analogue is the ratio of luminance to illuminance (incident luminous flux per unit area). The two physical properties of this function are the Helmholtz reciprocity (2) and energy conservation stating that the total reflected energy cannot be greater than the incoming.

$$f(\omega_i, \omega_o) = f(\omega_o, \omega_i) \quad (2)$$

2.5 Simplified description

To demonstrate basic discrepancies between reflectance models, a simplified 2D view can be used, in which the incoming and outgoing rays are shown.as depicted in Figure 1.

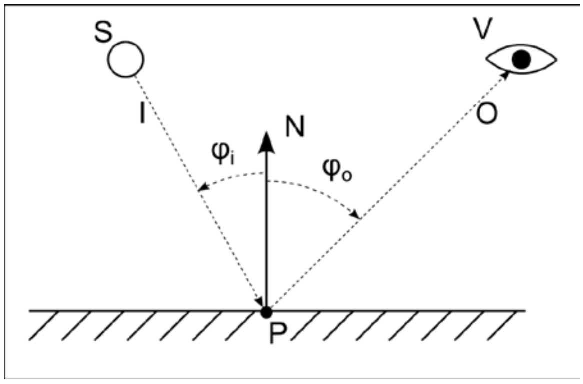

Figure 1. A simplified 2D view of reflectance estimation at point P with incident and outgoing directions of light source S and viewer V.

In reality, light is scattered in all directions and not limited to one plane, while the incident and outgoing rays are described by solid angles. This simplified view should be enough to compare some basic properties of reflection and to discuss limitations imposed by the chosen model.

2.6 Normal vectors

From a set of intensity responses sampled at a given pixel under varying incidence angles, a normal to the corresponding fragment of the surface can be recovered. This operation is based on the basic law of reflection and assumes that the maximal reflectance value can be observed from a single direction of reflection (Figure 2) with the following property:

$$\varphi_i = \varphi_o \equiv \varphi_r \quad (3)$$

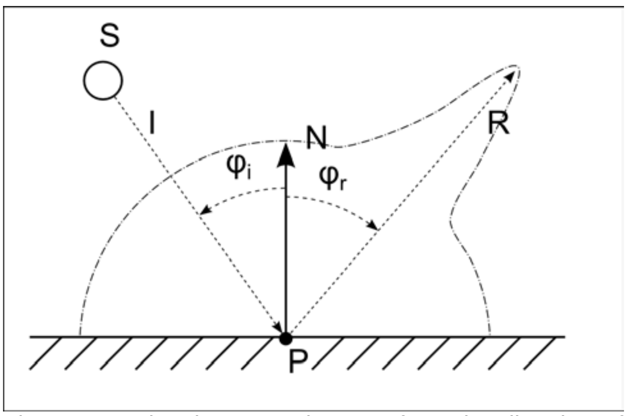

Figure 2. Estimating normal vector from the direction of maximal reflectance.

2.7 Anisotropy

For anisotropic materials, the reflectance distribution changes when the sample is rotated around the normal (N). It should be explicitly stated whether the proposed method accounts for such a property and whether there is a well-defined coordinate system to visualize this behaviour in the CHO model.

2.8 Off-specular reflection

For high values of the incidence angle, the maximum reflectance is not observed at the theoretical angle of reflection. This is caused by the reduced effective roughness of the surface and is shown in Figure 3. Depending on the refractive index of the material, the Fresnel term increases the reflectance ratio at such tangent angles of incidence.

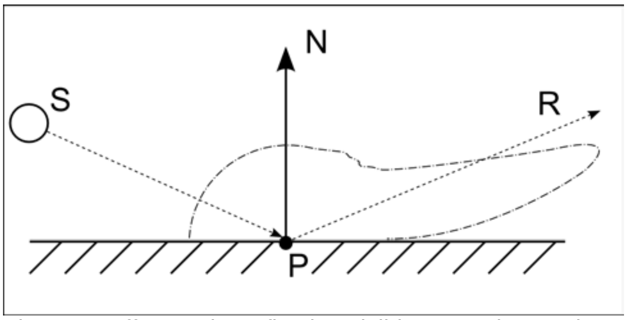

Figure 3. Off-specular reflection visible at grazing angles.

3. AVAILABLE METHODS

Among the various methods used in documentation evaluated by participants of the COSCH Action, the following group constitutes the commonly researched approaches:

- Polynomial Texture Maps (PTM),
- Reflectance Transformation Imaging (RTI),
- Photometric stereo,

The mentioned methods are active, meaning that they introduce additional luminous energy to the observed volume. External lighting conditions may interfere with the acquisition process and the illumination has to be strong enough to overcome the intensity of background light sources.

3.1 PTM and RTI

Originally developed at HP Labs, the PTM approach requires a single camera position with multiple illumination directions (Malzbender, 2001). A second order polynomial is fitted to intensity values at every pixel parameterized by the angular position of the light source.
To determine light positions, either a predefined illumination geometry is used (placed on a dome) or a specular sphere is placed within the field of view of the camera (highlight-based). In the latter case, the light direction is retrieved from specular highlight on the reference sphere.
This approach strongly favours the CHO appearance and photo-realistic quality over quantitative material interpretation.
Modifications to this algorithm resulted with RTI that allows for normal vectors’ retrieval and improves model rendering. In this sense it is similar to the next method.

3.2 Photometric Stereo

For a Lambertian surface, the geometry of the object can be figured out from shading. This implies additional assumptions about imaging conditions, namely that the illumination and viewing directions are the same for every pixel of the image. Using multiple illumination directions, the shape can be retrieved even if the reflectance is viewer dependent (Goldman, 2010). This method, called photometric stereo, can work in consecutive approximations, first to determine light source positions, then to retrieve the normal vector map over the image, integrate it to get surface geometry and finally refine the data to fit a reflectance distribution function. Multidirectional illumination can be simultaneous and also constant, since the employed light sources can emit in separate spectral channels (Brostow, 2011).

3.3 Derivative geometry

Although geometry can be retrieved along with photometric data, these methods are not applicable to more complex shapes of CHO, such as those with step-like or steep edges as well as concave (suffering from self-occlusion).
These systems would require further geometrical calibration and correct scaling of the resulting geometric model. Another problem is the systematic error caused by normal integration, depth sensitivity and bas-relief ambiguity.
Several attempts have been made to overcome such problems and to utilize optimization algorithms for retrieving geometry, normal map and reflectance, including the spatially varying reflectance of complex shapes (Ruiter, 2012). A hybrid approach was used by Nehab et al (Nehab, 2005) to combine structured light scanning and photometric stereo. Other methods exist for merging multi-view photography with dense 3D models (Callieri, 2008).

4. COMMON GROUND

To be able to compare several methods that allow simultaneous retrieval of shape and reflectance, it is crucial to distinguish them by their applicability and limitations.
Each of the described methods introduces its own processing schemes and prior assumptions about the geometry or optical properties of the investigated surface or both. More often than not, drawbacks that arise due to these assumptions are difficult to realize in the overall view. For example, to what extent do the lighting conditions need to be controlled, what are the geometrical and photometric confines of the surface?

4.1 Point of reference

Although there are many models of reflectance distribution, it is difficult to propose an etalon for verification and error estimation between the available methods. It is still possible to acquire reference data empirically for a selected surface sample by means of a more precise device, i.e. a gonioreflectometer and then to evaluate the performance of the image-based device. However, there are no well-established materials, other than the extreme cases of perfectly diffuse or mirror-like samples which are standardized and repeatedly mentioned in literature. This makes it harder to compare

existing solutions, because no universally available ground truth exists for a wide range of materials. Current research aims at reproducing surfaces of arbitrary BRDF (Matusik, 2009; Malzbender, 2012).
The applicability of reflectance information as one of the documentation aspects requires investigation. It is also uncertain whether particular BRDF models correspond well to human perception, although recent studies have shown that the interaction with an object aids perception of such qualities as gloss (Lichtenauer, 2013).

4.2 Interchangeability

Another issue that should be addressed is the correspondence and interchangeability of data resulting from various methods. Geometrical models can be merged in a common metric space and can be converted to multiple coexisting data formats, but photometric data are less transferable and much less consolidated. In CAD/CAM environments it is possible to map additional information to 3D models such as photographic textures but a format in which photometric quantities can be stored is not standardized.

5. THE DEVELOPED SYSTEM

An integrated system for CHO documentation was already developed at author's Institute (Sitnik, 2012). The original setup consisted of a multispectral camera, a digital projector, a directional illumination array and a flash lamp. The spectral and angular characteristic of the reflectance were captured independently and combined at a later stage of 3D data processing.
It is important to point out that all modalities were registered by a single 4872x3248 CCD matrix assuring spatial correspondence between 3D and photometric samples that did not require alignment. However, the reflectance distribution was treated as an additional modality, meaning that the core of the device could operate solely as a structured light scanner. Geometric calibration was performed using a flat calibration target (Sitnik, 2005).

5.1 Examples

The described system has been used to document CHO consisting of various semi-specular materials. Some examples have been provided and shown in Figure 4.

Figure 4. Examples of 3D models rendered in real-time from triangle meshes textured with parameterized BRDF.

5.2 Mobile setup

The existing setup was modified to use a colour camera to perform out of laboratory experiments with angular reflectance estimation. To reduce the dimensions and increase acquisition tempo, both the projector and the camera were designed with a limited resolution of 1280x720 and 1928x1448 pixels respectively. The assembled mobile setup is shown in Figure 5.

Light sources used in this setup consist of high powered light emitting diodes (LED). To ensure even illumination of the whole scene, every source is diffused with a celluloid sphere of ca. 40 mm diameter. This allows for easier rearrangement of lights depending on the size of the CHO. In this particular setup a set of 8 spheres was used, covering roughly 40 degrees field of view.
Light source positions as well as the relative intensities of the LEDs need to be determined in order to retrieve photometric information. This is done by means of a modified calibration procedure, by utilizing the same flat target used for geometric calibration (Krzesłowski, 2013). This procedure assumes that light sources can be approximated by points which can introduce aliasing errors – especially for mirror-like surfaces.
To create a full 3D model a rotating stage is used. The angular step between consecutive views is chosen excessively so that most reflections on the surface are registered. This causes partial redundancy of geometric data, and has to be filtered out during the final stage of data merging.

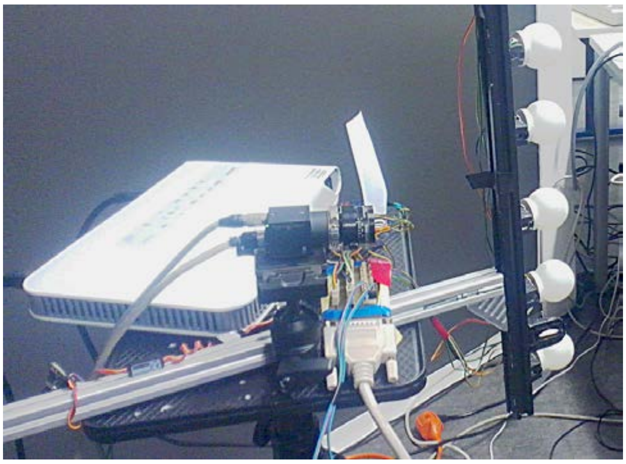

Figure 5. Side view of the experimental mobile setup with a 2.8 Mpx camera (only some illuminators are visible on the right).

5.3 Projector cover

Since both structured light projection and photometric illumination are active methods, they can interfere with each other. To allow continuous scanning, the digital projector cannot be turned off completely. For this reason, there is a background light coming from the lowest intensity level of the projector. To eliminate this light during multidirectional illumination, a projector cover was added to the device. The system automatically controls this cover using the already available hardware (Figure 6).

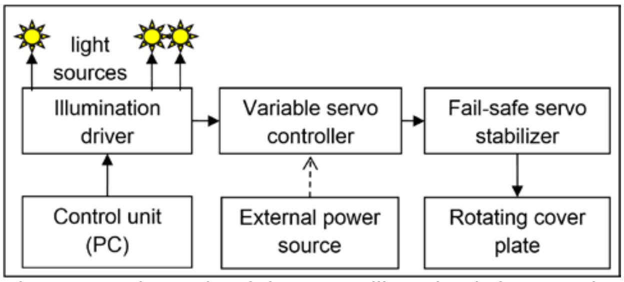

Figure 6. Schematic of the controlling circuit for covering the projector during photometric registration.

6. SETUP LIMITATIONS

At the current stage, the system cannot account for anisotropic materials because the sampling is too sparse. Due to the compact hardware form, it is also impossible to illuminate and observe the surface at grazing angles, so the increased specularity caused by the Fresnel term cannot be estimated.

6.1 Limited Intensity

The light sources used in this setup are too weak to perform outdoor registration. Therefore, the environment has to be controlled. Stronger light sources or an additional covering dome should be used in a future design.

6.2 Angular Sensitivity

The size of a particular light source and the spatial configuration of the illumination array determine the angular resolution in the reflectance domain. Although this can be scaled up and more sources can be used, it would complicate the construction and increase the acquisition time.

7. CONCLUSION

Several existing photometric methods have a chance of becoming accepted and standardized tools for digital documentation of cultural heritage. Information about surface reflectance as an additional modality contributes to the perceptual representation of the resulting model. In the emergence of innovative 3D imaging technologies further work is needed to test different photometric strategies involving structured illumination. It is equally important to establish a common ground for comparing results between such methods for different classes of CHO materials.

8. REFERENCES

Brostow, G. J., Hernández, C., Vogiatzis, G., Stenger, B., Cipolla, R., 2011. Video Normals from Colored Lights. IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 33(10), pp. 2104–2114.

Callieri, M., Cignoni, P., Corsini, M., Scopigno, R., 2008. Masked photo blending: mapping dense photographic data set on high-resolution sampled 3D models. Computers & Graphics-Uk, vol. 32(4), pp. 464–473.

Delaney, J. K., Zeibel, J., G., Thoury, M., Littleton, R., Palmer, M., Morales, K. M., de la Rie, E. R., Hoenigswald, A., 2010. Visible and infrared imaging spectroscopy of Picasso's Harlequin musician: mapping and identification of artist materials in situ. Appl Spectrosc. 64(6), pp. 584–94.

Goldman, D. B., Curless, B., Hertzmann, A., Seitz, S. M., 2010. Shape and Spatially-Varying BRDFs from Photometric Stereo," IEEE Transactions on Pattern Analysis and Machine Intelligence 32(6), pp. 1060–1071.

Krzesłowski, J. F, Sitnik, R., Mączkowski, G., 2013. Novel calibration procedure for SVBRDF estimation of 3D objects using directional illumination and structured light projection. Proc. SPIE 8650(1), Three-Dimensional Image Processing (3DIP) and Applications p. 86500G.

Lichtenauer, M. S, Schuetz, P., Zolliker, P., 2013. Interaction improves perception of gloss. Journal of Vision 13(14):14 pp. 1–13.

Malzbender T., Samadani, R., Scher, S., Crume, A., Dunn, D., and Davis, J., 2012. Printing reflectance functions. ACM Trans. Graph. 31(3), 20.

Malzbender, T., Gelb, D., Wolters, H., 2001. Polynomial texture maps. In Proceedings of the 28th annual conference on Computer graphics and interactive techniques (SIGGRAPH '01). ACM, New York, NY, USA, 519–528.

Matusik, W., Ajdin, B., Gu, J., Lawrence, J., Lensch, H. P. A., Pellacini, F., and Rusinkiewicz, S., 2009. Printing spatially-varying reflectance. In ACM SIGGRAPH Asia 2009 papers (SIGGRAPH Asia '09). ACM, New York, NY, USA, Article 128.

Nicodemus, F. E., 1965. Directional Reflectance and Emissivity of an Opaque Surface. Applied Optics. 4(7), pp. 767–773.

Nehab, D., Rusinkiewicz, D., Davis, J., Ramamoorthi, R, 2005. Efficiently Combining Positions and Normals for Precise 3D Geometry. ACM Transactions on Graphics 24(3).

Ruiters, R., Schwartz, C., Klein, R., 2012. Data Driven Surface Reflectance from Sparse and Irregular Samples. Computer Graphics Forum (Proc. of Eurographics) 31(2), pp. 315–324.

Sitnik, R., Krzesłowski, J., Mączkowski, G., 2012. Processing Paths from Integrating Multimodal 3D Measurement of Shape, Color and BRDF. International Journal of Heritage in the Digital Era 1(1), pp. 25–44.

Sitnik, R., 2005. New method of structure light measurement system calibration based on adaptive and effective evaluation of 3D-phase distribution. In: Proc. SPIE 5856, Optical Measurement Systems for Industrial Inspection IV, 109, Munich, Germany, June 13, 2005.

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