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Enhanced RTI for gloss reproduction

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Abstract

The Digital Humanities Lab (DHLab) is a technological oriented research group within the faculty of Humanities of the University of Basel. The research profile of the DHLab integrates computer science, digital imaging, computational photography, the accessibility of digital objects and solutions for digital preservation with the aim to support scholars in the emerging field of humanities research. The project Digital Materiality, a collaboration with the Seminar of Art History, examines how new imaging and visualization methods can be applied to describe the reflection of light on surfaces of artworks. Of main interest are mosaics and early prints; both types of artworks have a strong interaction with light that can not captured adequately by standard photographic approaches. Conventional photographic processes are not able to capture the dynamic component of the light-surface interdependence that is specific for this kind of art.

The technical part of the project focuses on improving the methodology that is in general described as Reflectance Transformation Imaging (RTI) techniques. RTI is an approach based on a mathematical model, that is fitted in image data derived from photographs. By modifying the mathematical model that is used to represent the light-surface interaction, the digital reproduction can be improved so that relevant attributes of artworks can be transported into the digital domain in such a way that the requirements and needs of humanities researchers to a digital representation can be fulfilled. The improvements take into account more sophisticated but still robust and simple reflection models for the realistic visualization of localized diffuse and specular surfaces within the same digital reproduction. For humanities research the most important aspect is the compatibility to web-based Virtual Research Environments (VRE). The presented approach can be integrated in such environments because the client-side visualization is implemented in WebGL. For flexibility, performance and data permanence aspects the server side will be an enhanced image server layer following the International Image Interoperability Framework (IIIF) image based environment.

Introduction

Images play a vital part in art historical research, especially in terms of communication and documentation. Reproductions enable art historians to develop theories, discuss them with fellow scholars and they are also important for the documentation of the current state of artworks, e.g in the process of a restoration. This is particularly useful, if the object is not easily accessible, e.g. because it is kept in a museum or archive in a country far away, or collaboration shall be simplified. In this case a common solution is to work with photographs. They document the visual impression of objects and they can be a precise tool to capture the state of an original for example before and after a restoration. This has become even simpler with digital photography, because digital images can be easily shared, disseminated and given access to. Due to all of these advantages digital images are an important part not only of art historical research, but of our cultural heritage in general, and they account for a constitutive part of our contemporary multimedia output in social, scientific and economic fields [1].

However, when it comes to special kinds of artworks like mosaics, these static and two-dimensional images are not able to reproduce the actual visual impression of the object; the purpose the artwork was created for. Therefore, new technologies and methods are needed to transfer characteristic features of an original into the digital domain. The changes in photography due to technological advance and the transition to the digital domain have not only brought a new standard in quality. Now, there are also new possibilities to apply digital technologies and computer technology to digital imaging. Following this approach of integration, new digital methods that go far beyond conventional photography have been developed. Our approach of computational photography is a promising approach for a more comprehensive way to capture, communicate and disseminate digital images of mosaics and art in general (reference [2] shows several examples).

The challenge concerning the digitization of mosaics lies in their complex surface properties and reflection behavior. Their specific materiality is a result of countless tesserae that are composed in a setting bed to form the mosaic. All of these small parts reflect light in a particular way, causing an impressive sparkling effect that cannot be visualized appropriately using normal photographic images. Besides, ancient or medieval mosaics are usually placed on the walls of a church and therefore they are meant to interact with their individual surroundings by purpose. Examples are the shape of the walls as well as the lighting conditions inside such a building. Similar considerations apply for early prints, books, parchments and textiles. The visual impression that these objects convey can hardly be delivered by photographs. Metallic inclusions and the interplay of different materials give the object a dynamic appearance caused by the localized change of reflectance behavior.

A promising method to solve those limitations is Reflectance Transformation Imaging [3] [4]. RTI is a set of computational photographic methods that capture a subjects surface shape and color and enables the interactive re-lighting of the subject from any direction based on a mathematical model. The method was originally developed by HP-Labs [5]. Polynomial Texture Mapping (PTM) best describes the principal technique HP has followed. The reflection of light is in a first step captured by multiple photographs illuminated from different positions. In a second step a simple mathematical term, typically a polynomial of second order is fitted to the measured reflection for each pixel position. This approach is convenient from several points of view: Only little amount of hardware and software is needed to acquire a PTM, stability and reproducibility are easy to guarantee because of a reliable fitting procedure and only relatively little knowledge to operate the tools is required. The major drawback of PTM is the limitation of the applied mathematical model. A second order polynomial is able to reproduce reflection of diffuse surfaces, also called a lambertian surface, while the realistic reproduction of gloss is not possible. A lambertian surface scatters the incoming light in such a way that the apparent brightness does not depend on the observer's point of view. Although the radiance of the surface depends on the angle between the normal and the illuminating source, following the lambertian cosine law, it does not depend on the angle between the normal and the observer; it has a uniform reflection. A glossy surface, on the other hand, has a component of specular reflection. Specularity means that light is reflected only in one direction, defined by the law of reflection (also called Snell law). A mirror is a perfect example for specular reflection[8]. The limitation of the second order polynomial is crucial for the reproduction of many artworks like e.g. mosaics. A mosaic is constructed to interact with light and in most cases diffuse and glossy materials are placed on purpose to constitute the artwork in a specific manner. Another drawback is the RTI imaging workflow and the fact that display of RTI needs a particular stand-alone application [9]. The most promising way to work with RTI renderings is certainly a web-environment, based on standard technology, without plug-ins or other add-ons. There are basic approaches to integrate an RTI viewer in web environments. Most of those implementations are still in the prototype-phase and, most importantly, all of them are not able to reproduce objects composed of diffuse and glossy materials properly. Therefore RTI has been improved by the following means:

- Using a data-driven scientific approach to find a better model or acctually a combination of multiple models to be able to reproduce lambertian and glossy materials with as few parameters as possible.
- Using WebGL, a subset of the common and well-known graphics library "OpenGL", to render RTI images in any standard web-browser, even on most mobile devices. Such a solution opens various new applications and the possibility for collaborative work because the viewer can be embedded in a web environment.
- Embedding RTI in Virtual Research Environments (VRE) for annotation and interlinkage of multiple originals stored in one or more repositories.

The data-driven scientific approach takes into account two different processes:

- Acquire data and use RTI methodologies to distinguish between glossy and lambertian materials in an arbitrary object.
- Modeling gloss reflectance behavior referring to art historians' impressions; therefore the model must have adjustable parameters to allow the customization to the needs of the experts.

Furthermore the scholar may want to integrate information coming from other types of scientific photographs, such as infrared or ultraviolet illuminated or induced fluorescence photography to enrich the visual impression of renderings of artwork by usually non-visual aspects. Especially the combination of such scientific photographs with RTI images is advantageous because multiple visual impressions can be combined in a way that would not be possible in reality. Thus, an appropriate workflow is needed to capture the important attributes of the light-surface interaction of the original and to produce an image that can be made accessible, e.g. in a Virtual Research Environment, for scientific collaboration.

As a last consideration, it is important to provide the users, e.g. scholars and researchers, a plug and play solution, easy to set up and to work with.

Hardware

Our experimental setup consists of a dome structure (see figure 1) made of a composition of aluminum and acrylic glass. The device is equipped with 48 high luminance white-light LEDs powered by external custom-made electronics for calibration, automated control of the measurement process and increased reproducibility. The structure is approximately 50 cm in diameter and 35 cm in height. A high resolution digital SLR is mounted on the structure. The full setup can be calibrated before operation. Calibration includes intensity, white-point and color-correction. The LEDs can be synchronized with the camera by standard TTL flash-trigger signals. Besides LEDs in the visible range, also UV or IR LEDs can be controlled and therefore integrated in the measurement process to create a extended acquisition.

The demonstrated setup is mobile, highly flexible and especially

Figure 1. *The dome structure developed by DHLab*

designed for the purpose of RTI capturing. The system can be configured to control the LED intensity by pulse width modulation. In addition continuous light with all LEDs activated is possible for very homogeneous illumination of the object in conventional digital photographs. The continuous full-light mode is optimal for various reproduction set-ups. The advantage of our approach is the compatibility with other standard "of the shelf" equipment. It can be easily be configured to automatically do sequential interval triggering with any standard digital camera. For the application of RTI image capture the whole system is triggered and controlled by a remote capture software, that is available from most camera manufacturers. The system allows automatic image capture and data transfer to any storage system, e.g. a fast RAID system. The main advantages of this setup are its simplicity and robustness that leads to reproducible and calibrated results of high quality. Calibration is very important for RTI image data because of the relevance of the exact knowledge of the position of the light source. The system is first calibrated in optimized conditions. The calibration data is in a second step stored as technical meta information that is applied to measurements in situ. In this way larger collections of objects can be captured without any additional unnecessary human interaction in a standardized, reproducible way. Apart from the light position, the already mentioned light intensity, the light color and the distance of the target can be measured and taken into account for even better calibration. In our case the system is located in a calibration lab for any pre-configuration process, assuring that no ambient light is affecting the measurements. These characteristics make the setup an very well suited structure for examination and modification of basic principles of RTI. As a consequence it allows the study of light reflection on numerous types of surfaces and materials. Because of the identical capture situation for all images, results from various objects can be compared and conclusions can be drawn on the basis of precise and valid data. In addition a well documented and calibrated system is the key element for data sustainability. Only a reproducible, well-documented physical measurement process can lead to RTI image data files of sustainable scientific value.

The structure has other positive features: It is stable, can be

Figure 2. *Inside view of the dome structure*

aligned to the object plane and since it is lightweight, it is mobile, can be easily moved and transported to any location; the LEDs have a high reproducibility and can be operated with a short cycle time.

Software

For simplicity and reliability, the software in our set-up is divided in three parts:

- Calibration and image elaboration: In this step already existing software is mainly used, a short list includes: CHI RTIBuilder [6] for the calibration of the lights direction; camera specific proprietary software for remote capture and Adobe Raw Converter® for raw image data transformation.
- PTM and gloss coefficient elaboration: All the computational work related to the analysis of the captured image data, consisting of the PTM fitting procedure and the gloss coefficient estimation, is based on a program written in C++ and Python, with the use of the SWIG library [11]. The prototype was developed with Matlab [12] for first experimental development. For reasons of performance and accessibility the code will be integrated in an image server compliant with the International Image Interoperability Framework (IIIF). This server is implemented with multi-threaded code written in C++.
- Visualization: The rendering of RTI data can either be done in any modern standard web-browser (Chrome, Safari or Firefox) with rti.js, a software written by the DHLab [18]. The already existing CHI RTIViewer software [9] has also been modified to enable the display of the final result with the new enhanced technique proposed later in this document.

Methodology

To capture an RTI image the procedure described in reference [3] and in reference [4] has been followed, while integrating it with standard image correction techniques.

- the calibration of the light source position is performed with a black glossy sphere. With such a black glossy surface it is possible to detect the highlight caused by the specular reflection of a specific light source. This is a standard approach coming from CHI [7].
- capturing a color target and applying the profile to the image data for color space transformation into a standard color space like sRGB or AdobeRGB
- the object of the acquisition is placed in position and a photo for each flash light is acquired;
- the photos are converted from the RAW format to 16bit RGB-TIFF. In this process lens distortion correction, white balancing and lens color aberration correction are applied to the acquired image data.

Layering approach

The presented approach is not following the path of finding a complex mathematical model to reproduce matte and glossy surfaces. The solution to be able to visualize various types of materials is layering the problem (patent pending). The diffuse

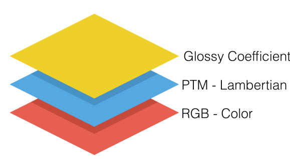


Figure 3. *The layering model*

component of matte object parts is modeled by a polynomial that is calculated using the data collected from each light direction. Similar to PTM [5], the result of this first step is a set of parameters from a best-fit second order polynomial or any other function that is appropriate to be fitted into the data acquired. In addition a vector that represents the surface alignment is calculated, e.g. a normal vector [10]. The coefficients of the functions are defined for each pixel position. The presence of gloss is estimated by data analysis in a second step within a gloss-layer. As we described in the introduction, gloss can be distinguished from diffuse reflection by the distribution of the data points acquired. The visual appearance of a realistic surface is then composed in a three stage process:

- the diffuse component is calculated by a mathematical function (second order polynomial or any other appropriate function) and the coefficients found for diffuse reflection [5],
- the normal vectors of the surface are generated using the coefficients of the mathematical function [10],
- the glossy component is generated synthetically by overlay of a reflection model derived from computer graphics. If the gloss coefficient is > 0, such virtual specularity is added based on e.g. the Phong reflection model [13] [14] or a similar model [15]. The parameters of this model can be changed, within a range, by the user and based on the physics of the material of the original.

Glossiness Model

To test our hypothesis several objects have been captured: a small mosaic with gold and stone tesserae, a oil painting, a matte white surface, some examples of fabric, a leaf, and a wooden mask. This collection of examples allows to have a wide set of test materials, showing a variety of glossy and matte surfaces.
A small mosaik made by Laboratorio di Mosaico e Pintura, Domenico La Malta is used a show object for this work. A comparison of the result obtained with the old and new approach is shown in figure 4, where light is coming from the same direction. This mosaic can be considered the perfect example of an object composed of several materials with different materiality appearances.
The analysis performed shows that it is possible to construct a function that distinguishes the diverse grade of glossiness in a custom target. It is particularly effective when combined with conditions imposed on other variables. For a proper representation of glossy and matte surfaces and their reflection characteristics an algorithm has been developed that allows to separate the glossy material from the matte material in the acquired image data. Combining this algorithm with the function that represents the matte surface elements gives very promising results. To estimate the diffuse characteristic of the material, only the parameter

(a) New method (b) Old method

***Figure 4.** Comparison between old PTM fit method and the new proposed approach - the golden tesserae behave different from the matte tesserae, gold is glossy, stone matte*

of the fitted model are used. The matte part is described by the PTM two dimensional function [5], as follows:

$$f_{matte}(l_u,l_v,x,y) = p_1^{(x,y)} l_u^2 + p_2^{(x,y)} l_v^2 + p_3^{(x,y)} l_u l_v + p_4^{(x,y)} l_u + p_5^{(x,y)} l_v + p_6^{(x,y)} \quad (1)$$

defined by n parameters $p_i^{(x,y)}, i:1,...,n$, where the pair of coordinates (x,y) represent a single pixel on the picture and l_u, l_u are the coordinates of the normalized vector describing the light direction as described in [5]. Therefore for each pixel we obtain a set of n coefficients. The distance between the matte function value and the intensity of the pixel for all lighting directions is computed for each pixel. To do so a function is defined

$$f_G(x,y) = \frac{1}{N} \sum_{(l_u,l_v)} \left(f_{matte}(l_u,l_v,x,y) - I((l_u,l_v),x,y)\right)^2, \quad (2)$$

or

$$f_G(x,y) = \frac{1}{M} \sum_{(l_u,l_v)} \left|f_{matte}(l_u,l_v,x,y) - I((l_u,l_v),x,y)\right|^3, \quad (3)$$

where N and M are normalization factors, and

$$I((l_u,l_v),x,y) \quad (4)$$

is the intensity of the pixel (x,y) in the photo defined by the flash light (l_u,l_v). This function has values between 0 and 1 on all the pixels and is used as a glossy coefficient. The $f_G(x,y)$ coefficient varies between 0 and 1. A specific cut is made using the values of the mean value of the intensity:

$$\text{meanvalue}(x,y) = \frac{1}{N_p} \sum_{(l_u,l_v)} I((l_u,l_v),x,y) \quad (5)$$

where N_p is a normalization factor. The histogram of the mean value calculated on the whole image is shown in figure 5. By

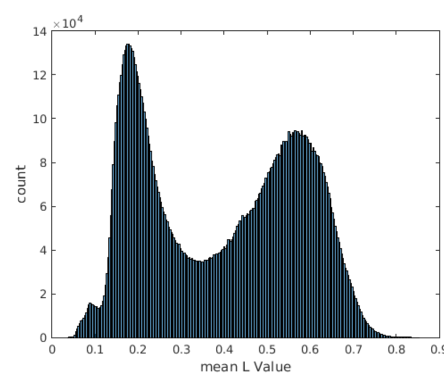


***Figure 5.** Distribution of the* meanvalue(x,y) *of each pixel in mosaic*

defining two or more threshold levels on the mean value, it is possible to distinguish between different material appearances. For example, dividing the histogram in figure 5 in three different regions provides a material map of the different components. The result of a possible choice of two thresholds is presented in figure 6 a, b, c. The points that belong to each region are colored in white, while the rest of the point are colored in black. The mean value is used as an additional information to define what parts should be treated as heavily reflecting or not. If a pixel has mean value below a defined threshold it will be treated as belonging to a glossy part and so a glossy coefficient will be calculated, always different from zero. The result of this calculation is shown in figure 7. As a conclusion it can be said that the full rendering of the

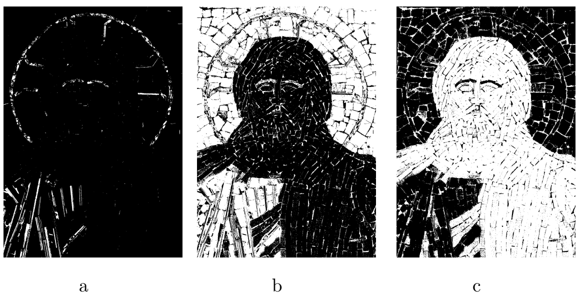


Figure 6. *Test mosaic - in each image the white pixels are the selected ones while the black one do not satisfy the condition.*

reflectance is the result of the matte plus the result of gloss layers multiplied by the gloss coefficient. In this way it is possible to render multiple degrees of gloss in the same image.

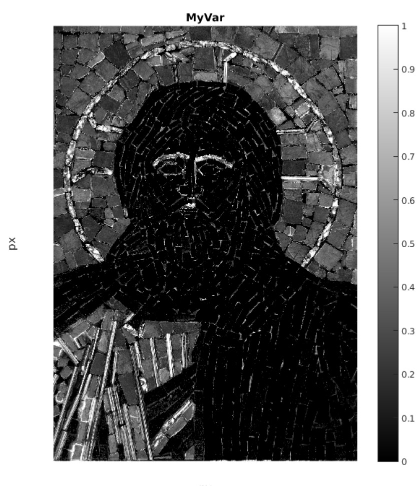


Figure 7. *Distribution of the parameter $f_G(x,y)$ representing the amount of gloss for each pixel the mosaic*

Viewer and User interaction

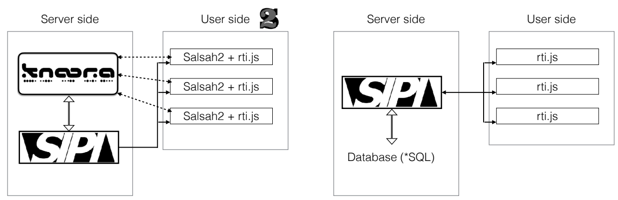
The strength of RTI is the possibility, for the user, to interactively change the light direction. This interaction is important in order to perceive the quality of a glossy surface. Therefore a set of tools for rendering and interacting with RTI/PTM data in a web browser[18] has been developed. The javascript library and the viewers are IIIF compliant, three.js-based and supporting multi-resolution. Three.js is a JavaScript computer graphics library for web platforms. It uses WebGL [21] (Web Graphics Library) for real time rendering. WebGL is a 3D computer graphics and 2D graphics JavaScript API (application program interface), compatible with a variety of web browsers without the use of plug-ins. WebGL allows GPU (graphics processing unit) accelerated image processing and 3D effects as part of the web page canvas. Therefore, it is possible to interact with other HTML elements or other parts of the page. Inspiration has been taken from the existing RTI Viewer [9] [20], a C++/QT software released in General Public License version 3, and the existing WebRTI Viewer, a web application written mainly in JavaScript using the SpiderGL[22] library.

The Viewer implements controls that allow the user to change the magnitude of the specular and diffuse part of the digital representation. These are updated in our viewer and allow the user to modify the three typical parameters: α, which is a shininess constant for this material, which is larger for surfaces that are smoother and more mirror-like, when this constant is large the specular highlight is small, k_d which is a diffuse reflection constant, and k_s which is a specular reflection constant.

A web-based approach opens many new possibilities for e.g. the dissemination of digital reproductions and the collaborative work between researchers. A specific binary executable stand-alone application is limiting any scientific discussion to a workstation. The required software infrastructure to support such collaborative work goes beyond a standard web-server solution. Besides Regions of Interest (ROIs) and linked comments and annotations the full set of viewing parameters must be stored as technical metadata within the system. Furthermore any time dependent changes of those viewing parameters must be tracked for reproducibility and traceability as a reference for any future discussion. Such traceabiltiy is also necessary to be able to cite a specific situation a scholar wanted to highlight. Therefore, the WebGL is the key to integrate RTI in a fully featured web-based Virtual Research Environment. In this regard the DHLab has been developing KNORA (Knowledge Organization, Representation and Annotation) [23] and SALSAH (System for Annotation and Linkage of Sources in Arts and Humanities) [24]. Knora is a software framework for storing, sharing, and working with primary sources and data in the humanities. SALSAH is the graphical user interface, currently the version 2 is under active development.

Web-based work with such dynamic image sources as RTI renderings, requires a high performance image server. To give the viewer full flexibility for the viewing conditions a image server that is compliant to the International Image Interoperability Framework has been implemented. The IIIF server is also capable to serve RTI customized images following the requirements of performance, maintainability and stability. An IIIF web service returns an image in response to a standard HTTP or HTTPS request. The URI (Uniform Resource Identifier - an array of characters used to identify a resource) can specify the region, size, rotation, quality characteristics and format of the requested image. A URI can also be constructed to request basic technical information about the image to support client applications[17]. This server will be able to compute RTI image data based on uploaded single images and it provides the web viewer with the necessary image data. A IIIF server, as a distinguished layer in the server architecture, is in the final stage of development and a working beta version of the code can be found at [25].

The software architecture has been developed allowing two main scenarios: a VRE set-up, represented in figure 8(a) and a simpler stand-alone set-up, represented in figure 8(b).



(a) (b)

Figure 8. *Schematic representation of two developed software architectures*

Conclusions and Future work

The interdisciplinary project has various important aspects. On one hand it shows, that for most work in humanities research and for the adequate documentation of a objects surface an approach going beyond conventional RTI is needed. The dialog with humanities researchers shows that the distinction between different materials is crucial for most work that usually would be done with the original. Also for documentation of an artwork the rendering of different materials is very important, to get closer to a digital facsimile. On the other hand simplicity is crucial for operating an RTI workflow. Only if a complex technical method is encapsulated by a simple user interface its operation is reasonable. The concept of IIIF for example is simplifying image access, the pre-calibrated hardware allows fast capturing of complete image sequences and the support of web-browsers means that no specific application has to be installed. Our future work will focus on the visualization of RTI textures on 3D surfaces, the stability of the fitting method will be further improved by using the robust regression method s suggested in [26]. Besides that we will try to improve the fidelity of color reproduction by implementing ICC-compliant RTI color-management. Of general importance is the quality control within the workflow and the comparison of state-of-the-art photographs with RTI images regarding attributes like sharpness. For this task we apply standard imaging quality procedures like imatest [27]. Finally humanities researchers will use the integrated RTI/VRE solution to explore the value-added of collaborative work with the presented new technique.

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