pixel+: integrating and standardizing of various interactive single-camera, multi-light imagery

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ABSTRACT

Multi-light, single-camera imaging techniques like Reflectance Transformation Imaging (RTI, including PTM, HSH, and PCA-RBF) and the Portable Light Dome (PLD) have been used by cultural heritage scholars and collection curators extensively because of the extra interactive visual information that can be revealed on artefacts when compared to standard digital photography. Besides a virtual relighting of the scanned object, these techniques offer filters to accentuate different aspects of the studied surface. The main focus of RTI, developed at HP, CHI and among others elaborated by ISTI CNR, is aimed at photo-realistic virtual relighting. PLD, developed at KU Leuven, on the other hand, is aimed at extracting surface properties such as surface color (albedo), surface gradient (normals), 3D surface features (height profiles) and reflectance distribution (reflectance maps). PLD and RTI both produce interactive pixel based file formats, which are dissimilar, resulting in incompatible datasets. The pixel+ project (Art and History Museum, KU Leuven, and KBR, Belspo BRAIN-be funded) aims to merge both technologies into one web-based consultation platform, allowing existing PLD and RTI datasets to be viewed in one web environment with their respective viewing filters as well as to illuminate the virtual model. Moreover, as both methods are alike in terms of required input and processed output, pixel+ focuses on other types of integration, resulting in new viewing modes for processed data as well as a novel reprocessing pipeline for existing source images. In addition, for sustainable and flexible web consultation a new open format, based on glTF, is suggested and a first elaboration is presented.

Keywords: RTI, PLD, single-camera multi-light imaging, 3D imaging, heritage scanning, multispectral imaging, relightable images, multi-light reflectance imaging

1. OVERVIEW OF SINGLE-CAMERA, MULTI-LIGHT TECHNOLOGIES

The diversity of acquiring, processing and viewing single-camera, multi-light (SCML) data sets is extensive. Equally, the terminology defining this technology is diverse: among many Multi-Light Image Collections (MLICs), Relightable Images, Multi-light Reflectance Imaging (MLR), Reflectance Transformation Imaging (RTI); all focusing on a particular aspect of the acquisition, processing or viewing. As the starting point of all interactions within this technology is the data collection, throughout this paper the physical description of how these data sets are created is used: single-camera, multi-light. Thus, the pixel+ project is aimed at bringing together data

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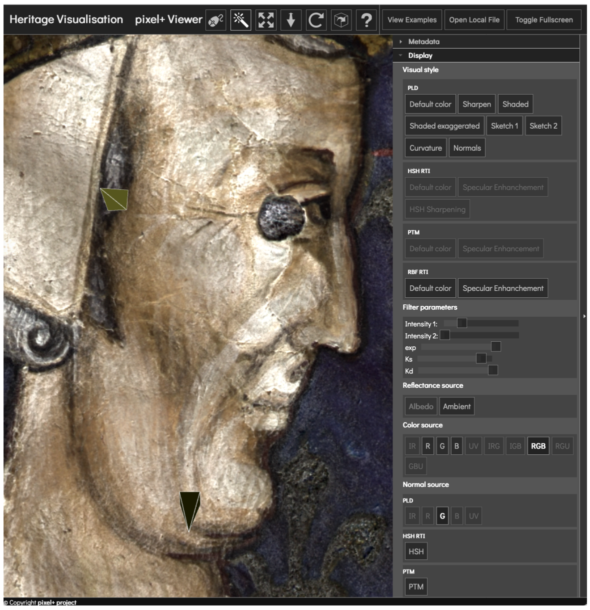
(a) PLD's *sketch1* style on a PLD SCML dataset with simultaneously 5 views active of a 21st c. BCE cuneiform tablet with both written characters (sunken relief) and a seal impression (low relief) (© Art and History Museum: O.181 - KU Leuven)



(b) Novel *Specular enhancement* style on a PCA+RBF RTI processed PLD SCML dataset of a section on folio 3 verso of the Bible of Anjou, ca. 1340 (© KU Leuven: Ms. 1))

Figure 1: Two interactive visualizations with varying shaders in the pixel+ viewer

sets where the position of the incident illumination is changed from image to image, and more specific on PLD,[1] PTM,[2] HSH RTI,[3] and RBF RTI.[4] The focus is laid on PLD, PTM and HSH RTI as many existing data sets have been captured and processed using one of these methods. RBF RTI is included as well, as it is a novel and promising RTI interpolation method.

1.1 PLD

PLD's processing technology[1,5–12] is based on the principle of photometric stereo.[13] By observing an object from the same point of view under varying illumination directions, the local surface gradient and albedo can be determined. For ideal matte (so called Lambertian[14]) materials, the observed light intensity depends on the cosine of the angle between the incident light ray and the local surface gradient (i.e. normal). Although only 2 (if the albedo is known) or 3 different light directions are needed,[13] photometric stereo acquisition setups typically use many more light directions to handle outliers caused by self-shadowing, interreflections, non-Lambertian behaviour, image noise, non-linear camera response, etc.[15] PLD's minidome has 260 white light LED (white light version) or narrow band NIR, R, G, B, NUV LED (multi-spectral version) emitters. Their smaller microdome has 228 white light or multi spectral LEDs.[12]

PLD supports several output formats. The CUN format is optimized for data transfer and consultation with PLD's desktop application[16] The ZUN format is similar to CUN, but sacrifices some compression efficiency in return for faster parsing by a web browser. Both formats contain a normal and albedo map,[13] and an ambient map (a weighted average of the input images). A multi-spectral CUN/ZUN stores these maps for each of the sets of input images obtained with one of the 5 spectral bands. Up to six views (f. ex.: top, bottom, front, back, left and right of a 3D object) can be stored, and are simultaneously displayed in the viewer application as nets of a cube. The desktop viewer is needed to calculate height profiles, depth maps, histograms, and reflectance maps. The latter requires the set of original images.

PLD files can be viewed using several visual styles, each one accentuating certain aspects of the object's material. The default color mode allows virtual relighting using Lambertian shading, which can be seen as the inverse of photometric stereo. By removing the local color information, small surface detail is more easily visualized in the *shaded* style. The local surface gradient can be artificially boosted by scaling the normals along the viewing direction (*shaded exaggerated*) The *sketch* style visualizes areas where the normal changes quickly, like the steep indentations in clay tablets. Note that in all PLD (and RTI) viewing styles self shadowing and interreflections are (explicitly) not modeled.

1.2 RTI

1.2.1 PTM

RTI starts from a similar data set, i.e. a sequence of images in which the incident illumination is changed. RTI's objective is however different. It is a data fitting method that tries to find a (compact) interpolation-based formulation that describes the changing pixel values as a function of the light direction. Polynomial Texture Maps[2,17] store this information in a 6 degree polynomial (per color channel). This can be compressed further by observing that for many materials the color doesn't change much when the direction of the incident illumination is changed. Instead of 18 numbers per pixel, LPTM (Luminance PTM) only requires 9 (6 for the polynomial describing the change of luminance and 3 for the static RGB color information). It results in smaller file sizes, one of the evident reasons why it is often preferred.

The principal visual style of PTM is photo-realistic relighting. However, it has been demonstrated a 6th degree polynomial can't properly capture specular highlights and shadows.[18] For this reason, higher order PTMs have been developed, but as they are more prone to overfitting, causing the interpolation results at novel light directions to suffer, high order PTM coefficients need to be calculated with more robust fitting methods.[19,20]

The local surface gradient (normal) can be calculated by finding the direction with the maximum luminance, i.e. finding the maximum of the polynomial.[2,18] This however only holds true for diffuse surfaces. Many materials are not ideal-diffuse and have e.g. a specular component.[21] In the case of specular reflections, the normal will be halfway between the viewing ray and the illumination ray. In contrast, photometric methods like PLD are based on a physical model[13] and tend to provide better surface gradient estimations.

A number of viewing styles have been developed to accentuate particular surface detail. The *Specular enhancement* style artificially accentuates the surface gradient by introducing a specular Phong term in the rendering equation.

1.2.2 HSH RTI

Another popular RTI approach uses hemispherical harmonics.[3] Data fitting and relighting is more accurate than PTM, especially when using 2nd or 3rd order HSH. 2nd order HSH RTI suffers from an artificial increase in brightness at grazing angles.[18]

HSH RTIs are typically saved in the RTI file format.[22] Besides the *default color* style for photo-realistic relighting, HSH can also be viewed with the same *Specular enhancement* style. Next to the HSH coefficients, this style requires the calculation of the surface orientation.[18]

1.2.3 RBF RTI

A novel approach[4] combines Principal Component Analysis (a data reduction algorithm) with Gaussian Radial Basis Functions (an interpolation algorithm) and attains higher PSNR on the relightable images while keeping the total amount of data to a minimum. The data is contained in a JSON file and several JPEGs, containing the compressed versions of the coefficients.

1.2.4 OTHER RTI TYPES

Other SCML methods are based on Discrete Modal Decomposition,[23] Neural Networks[24] or the Light Transport Matrix.[25] This paper will not further elaborate on these methods as they are used less frequently and the calculation of the surface gradient, a necessary requirement for the first integration type (*infra*), is not always possible.

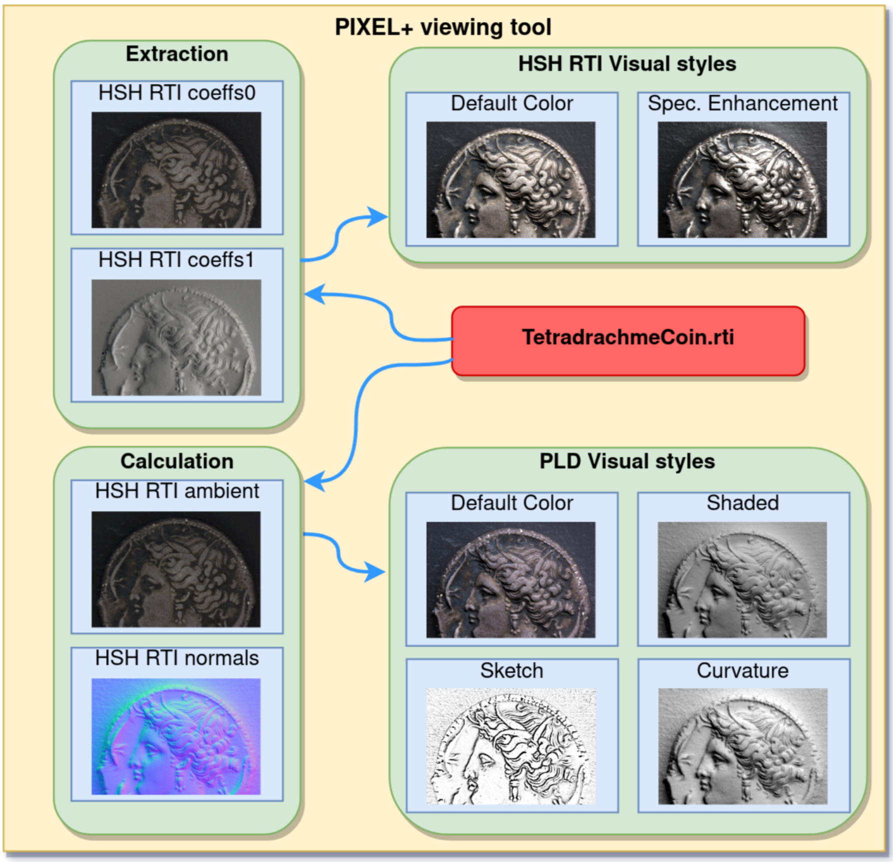


Figure 2: First type of integration as implemented in the pixel+ viewer. Processed PTM, HSH RTI, RBF RTI, and PLD files (example in red, face of coin 2A112_32, ©KBR - KU Leuven) can be opened and viewed with their original viewing styles. The ambient and normal maps are calculated by the web viewer in the background. When the calculation of these maps is finished, other viewing modes become available.

2. RELATED WORK

Up till now, PLD's CUN- and ZUN-files have been created with the at KU Leuven custom made PLDDigitize software interface[16] and with data sets obtained with one of PLD's domes. PTM and HSH RTI files have been created with an RTI dome,[26–28] or by using the Highlight-RTI.[29] In terms of processing RTI, RTIBuilder, part of a set of open source, well documented RTI tools,[30] has been frequently used. Newer RTI approaches require other software,[31] but follow the same convention of storing a list of photos and the corresponding light directions in a text file.

A number of tools to visualize SCML files already exist. Desktop viewers include CHI RTIViewer,[30] (web) PLD Viewer,[16] APTool,[32] and ImageViewer.[18] Web based viewers include Oxford RTI Viewer,[33] Relight RTI Viewer,[31] Web RTI Viewer.[34] Web based RTI viewers offer conversion tools to convert PTM and RTI files to a (custom) web friendly format. Desktop viewers have potentially more features, whereas web viewers require no additional software to be installed and can be well integrated into online SCML databases.[35] Besides the in this paper discussed pixel+ viewer, currently no viewer can work with the results and files derived from both the PLD and RTI approaches.

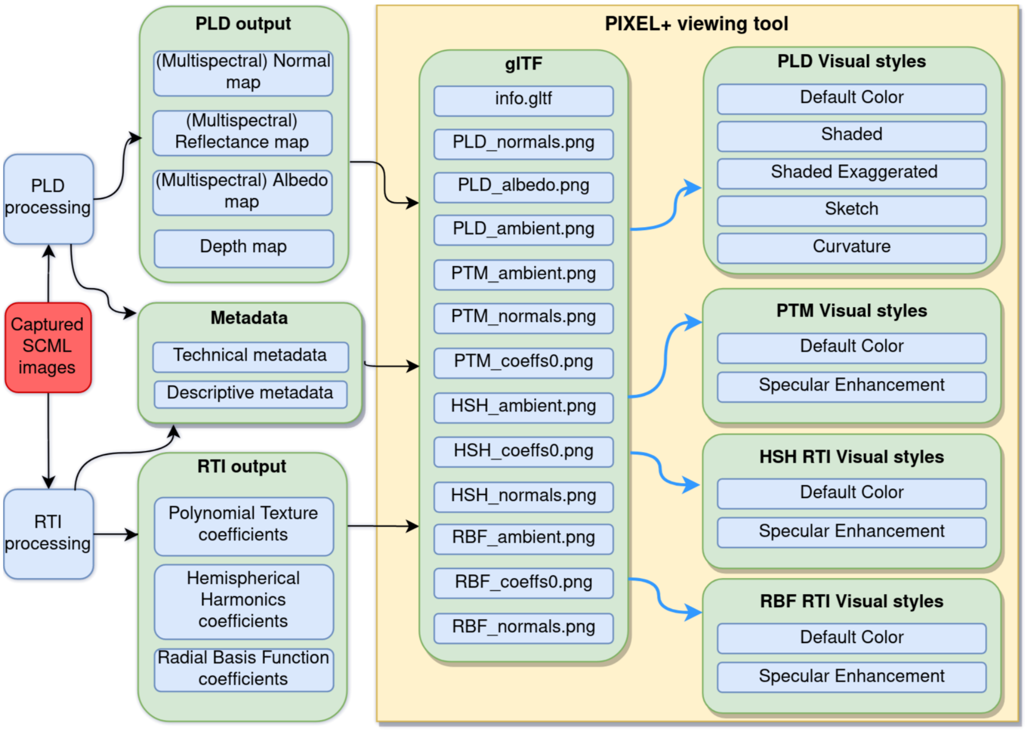


Figure 3: Second type of integration addressed by the pixel+ project: original source files (in red) can be processed using multiple methods. The resulting data is stored in glTF. For the sake of clarity, only a subset of available visual styles and glTF assets is shown in this diagram.

3. INTEGRATION OF PLD AND RTI

The pixel+ project focuses on 2 types of integration. The first type (figure 2) is aimed at existing processed data. Currently most of the processed RTI and PLD data sets are spread across various online or offline, open or limited access databases. Because PLD and RTI files have to be consulted in separate viewers, with separate viewing styles, users are less likely to perform cross PLD and RTI data base examinations. To address this issue, the pixel+ viewer is able to parse and visualize PTM, HSH RTI, (multi-spectral) CUN, (multi-spectral) ZUN and RBF RTI files with their proper visual styles; all in one and the same viewing interface. This should boost inter-compatibility studies between results derived from both platforms and make it possible the output can benefit from both approaches' strengths.

More in particular, since a normal map and an ambient map can be calculated in the web viewer for these aforementioned RTI types, they can be viewed with PLD's visual styles as well.

The second type of integration (figure 3) is aimed at the original source images (acquisition data set). SCML processing technologies have improved over the past decade and will improve in the future. Therefore, if storing these data sets is not an issue, it must be recommended to keep the original source images together with the corresponding light positions/directions (and calibration files). The second type of integration consists of a reprocessing step of the original source images using the various RTI or PLD approaches. When the original source images are available, this type of integration is preferred as by processing the set of images in a particular SCML way, some information will inherently be lost. To store this information in a web friendly, open, flexible and efficient way, we propose a new file format for SCML data: glTF.

3.1 A new web format for SCML datasets

Existing SCML file types, i.e. CUN, ZUN, PTM, and RTI are foremost designed to be opened on a desktop viewer. Opening and extracting data from these files in a browser environment is also possible (cfr. first integration type), however some pre- and post-processing steps may require CPU/GPU resources that exceed web capability. Table 1 shows a comparison of SCML file types, opened with the pixel+ viewer (*infra*). All but PLD's ZUN format have high parsing times. Note that many more RTI and PTM file types exist (e.g. with JPEG compression or a higher order HSH RTI). This will affect the file sizes, though the parsing time will remain high. Instead of parsing such a file and calculating intermediate data, such as ambient and normal maps from PTM or HSH coefficients, we propose to store this information in a new, more flexible, web optimized file format.

glTF[36] is based on widely used file types that can be easily processed by a browser, designed to keep the processing time of 3D assets before the data is sent to the GPU to a minimum.

A glTF file, formatted as JSON, contains technical and other meta data, various nodes for the imagewide RTI and PLD parameters, and links to the per-pixel data.

The per-pixel data is stored in PNG/JPG files. The local surface gradient is e.g. stored in a normal map, the six PTM coefficients are stored in 2 RGB images, etc. To minimize quantization errors, the data is scaled between the min and max value that this image type can contain (0 - 255 (JPG, 8 bit PNG) or 0 - 65535 for 16 bit PNG).

An other benefit of the glTF file format is that it will allow saving pixel+ viewer parameters (e.g. which visual style should be active during opening of the file) in the glTF file.

Other web RTI file formats[31,34] equally choose to store their per-pixel data in images and the general information in a JSON file. As this is de facto the same as glTF, the next step for the SCML community should be to agree and write a specification for a SCML web format. Next to the relightable image data itself, unfortunately often overlooked, more attention should be invested in defining and structuring the metadata and how annotations can be supported. A strategy with both embedded and separate JSON file can be followed.[34] Metadata not only is important in a linked web context, it also provides insights for a user browsing through SCML collections to comprehend the acquisition and applied processing steps; and provide a path towards the reproducibility and replicability of the initial imaging effort.

Table 1: Comparison of existing SCML file types, opened with pixel+ viewer.

Type	File Size (Kb)	Parsing Time (s)
LRGB PTM	48371	42.4
HSH RTI	64494	56.9
CUN	18692	35.3
ZUN	24045	1.2

4. PIXEL+ VIEWER

The pixel+ viewer* (fig. 1) is a web viewer for SCML imagery. It is based on WebGL, capable of opening both existing RTI and PLD files. Compared to these (legacy) formats, the proposed web optimized glTF format (see 3.1) requires less pre-processing and offers more flexibility. A source SCML dataset, processed using PTM, PLD, HSH RTI and RBF RTI, can be converted into glTF. On such a glTF file, the pixel+ viewer can offer a user studying the virtual object a plethora of visual styles. For an up to date list of implemented styles in the pixel+ viewer, the reader is referred to viewer's website.[37]

The internal WebGL scene consists of a virtual camera, 2 virtual directional lights and 1 or more rectangles. GL textures are created for the per-pixel information (e.g. normal maps and RTI coefficients). The visual styles are written as webgl shaders in GLSL.

The in the pixel+ viewer implemented processing methods all produce similar but nonetheless distinct different results, figure 4 provides a comparison. The top row consists of a virtual relighting, processed with PTM,

*http://www.heritage-visualisation.org/viewer

PLD, HSH RTI, and RBF RTI, using their default relighting visual styles. For PLD this corresponds to a Lambertian shading, giving the object a diffuse appearance and removing any shadows. Since the RTI methods are optimized for virtual relighting, they will appear as more photo-realistic. RTI's interpolation quality depends on the fitting algorithm, the interpolation method, the shape and material appearance[15] of the object, as well as the number and distribution of the light sources. In this example, RBF RTI provides the most realistic virtual relighting. Pintus et al.[38] provides an objective and subjective evaluation on the relighting of these RTI methods. The bottom row provides an overview of the recovered surface gradient with the different methods. PLD recovers the surface gradients based on a physical model and is robust to under- and overexposure, whereas RTI approaches solve for the maximum of the luminance equation,[2] but cannot properly handle outliers caused by e.g. non-Lambertian reflectance (specular highlights) and interreflections. The algorithm implemented in the pixel+ viewer to calculate the surface gradient from PTM and HSH RTI coefficients produces the same output as RTIViewer.[30] The Relight software package[31] has been used to calculate RBF RTI files, which include a normal map.

A 3D (in the form of a depth map or mesh) visualisation can be reconstructed by integrating the surface gradients.[15] Figure 5 shows the resulting 3D mesh obtained with PLDViewer from PTM, PLD, HSH RTI, and RBF RTI normals. To obtain better results for PTM, instead of the classical algorithm to calculate PTM normals, the relight software package was used. If a depth map is added to the glTF file, the pixel+ viewer is capable of rotating the object. As the capabilities of WebGL are lacking w.r.t. OpenGL (e.g. no support for displacement shaders), this functionality was built in javascript (subdiving the rectangle in a grid) and the vertex shader (per vertex displacement, depending on the depth map)

Viewer settings that have to be applied when opening a file, e.g. which visual style is active, virtual light positions, rotation of the object) can either be saved directly in glTF or - for legacy PTM, HSH RTI and (multi-spectral) CUN/ZUN files - passed on in the URL as parameters.

Multi-spectral recordings with narrow band spectral emitters result not only in separate albedo and ambient maps, but also in separate normal maps. The latter because the local surface orientation depends on the spectral interaction and distribution of the emitted light. The pixel+ viewer has the possibility to change not only the albedo or ambient source, but also the normal source that is being used by the visual styles.

The pixel+ viewer is hosted on an Apache web server, requiring no special configuration. Museum curators who want to disseminate their SCML collection can choose to host their own version of the viewer or deep link directly to our maintained version. For the latter, cross-origin network access needs to be enabled. The pixel+ viewer has been tested on the most recent versions of Mozilla Firefox and Chrome on Windows 10, Mac OS X, Fedora and Android.

5. DISSEMINATION SITE

SCML imaging is useful and popular within the heritage field because of its potential to visualize surface features not registered by standard photography and its multi-functionality (in terms of recording, processing and viewing). The downside of this flexibility is that it can be difficult for actors in the heritage field to asses the quality of a SCML file (the included dataset and the output). Above has been discussed a variation of processing methods for SCML datasets exists. Pixel+ has now incorporated a number of them within one viewing interface. To further improve the scientific understanding and valorization of this technology, the pixel+ viewer comes together with a dissemination website[†]. The aim of this website is twofold: Next to providing solid and technical (relevant background) knowledge to users working with SCML technologies to understand the underlying principles and parameters of the various visual styles of their high dimensional data, this website also aids in democratising the SCML imaging with the broad audience and open a communication channel towards the SCML imaging community.

[†] http://www.heritage-visualisation.org

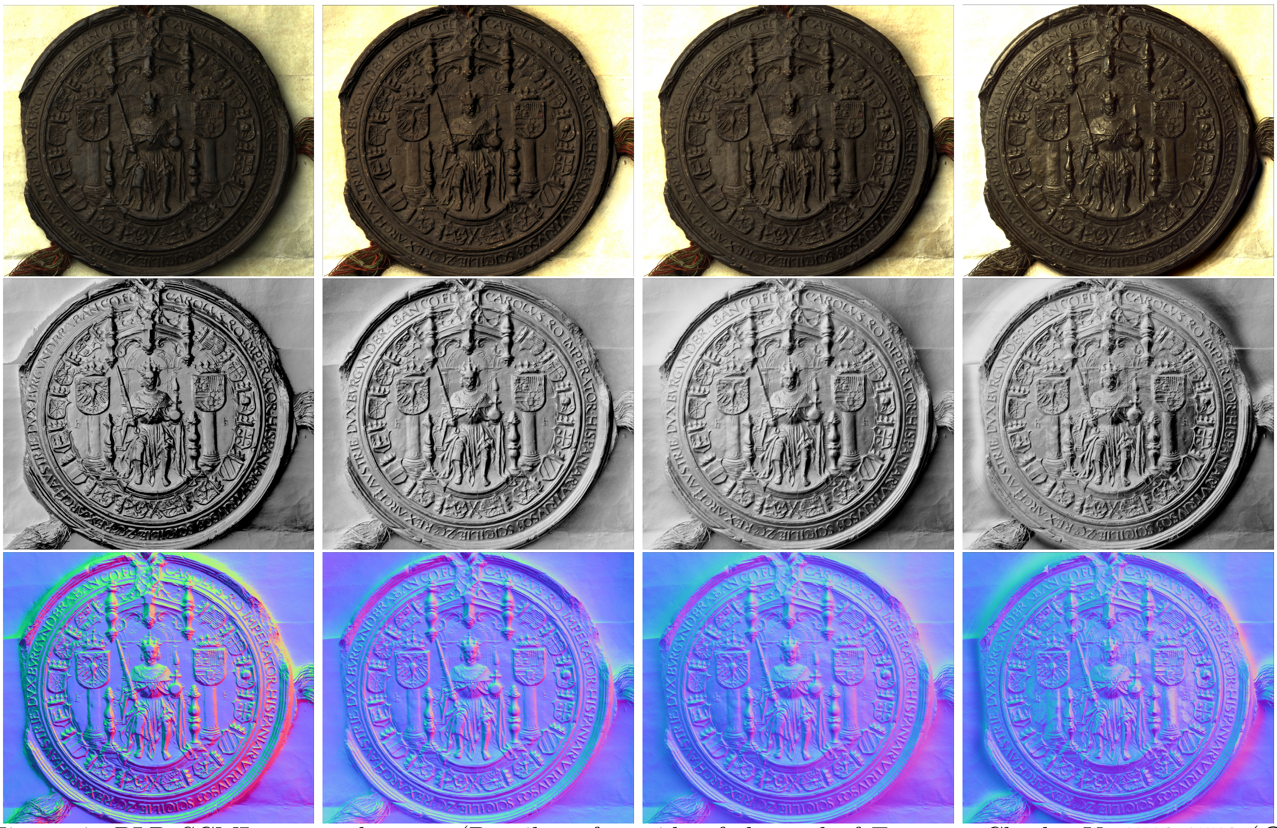


Figure 4: PLD SCML source data set (Detail on face side of the seal of Emperor Charles V, 1519-1556 (© KU Leuven Archives)), processed with (from left to right) PTM, PLD, HSH RTI, and RBF RTI. Top: default viewing style, middle: surface gradient, visualized in the pixel+ viewer with PLD's *shaded* viewing style, bottom: false color surface orientation

Figure 5: 3D mesh based on the same SCML dataset, calculated with from left to right: PTM normals, PLD normals, HSH RTI normals, and RBF RTI normals (example on obverse of slight convex cuneiform tablet O.181, © Art and History Museum - KU Leuven), visualized with the pixel+ viewer.

6. FUTURE WORK

We recognize the importance of user-friendly annotation support. Annotations in the form of user generated PNG files with a transparency channel as proposed by[34] can be easily added to the glTF file and displayed as extra layers on top of the WebGL Canvas element. The implementation is foreseen for the near future.

Together with other SCML developers and content providers, the proposed web format needs to be further improved and refined. It is our conviction single or similar viewing approaches as described in this paper and a technology agnostic SCML web optimized file format will only succeed if it is the result of an interdisciplinary community effort.

7. CONCLUSIONS

This paper has presented an overview of how the pixel+ project has allowed the PLD and RTI approaches to grow together and how, in general, we believe and foresee the SCML technology for the heritage field should be addressed in the future. The first implemented steps towards integration, interchangeability, intercompatibility of SCML datasets have been made to invigorate this process. To unleash the full potential of SCML imaging in a linked web context, the further standardization of the SCML file format, including technical and other metadata, easy-yet-powerful annotation, and high-resolution support will need to be developed and discussed with the SCML community. The source code for the dissemination site as well as the pixel+ viewer can be found online[39,40]

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