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PIONEER PROJECTS

PIXEL+
UNIVERSAL WEB INTERFACE FOR INTERACTIVE PIXEL BASED FILE FORMATS

CONTRACT - BR/PI/175/PIXEL+

FINAL REPORT

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SUMMARY

Context

Interactive Pixel Based file formats have been produced over the course of the last two decades by many stakeholders active in the Heritage sector. It is a global story. Its use has facilitated research and dissemination strategies for vast numbers of artefacts, conservation interactions and scientific studies. The technology has been explored and elaborated via varying technical strategies; each one of them delivering specific results with visual benefits and paths for computational research (Pintus et al. 2019). This situation is also reflected in the many naming conventions used for this technology: Relightable Images, Multi-Light Image Collections, Reflectance Transformation Imaging, Multi-Light Images, Multi-Light Reflectance, … . It has been the aim of the pixel+ project to bring the existing spectrum of these technologies closer together, by

- A. creating a universal web interface for its most popular processed output formats (*objective 1*),
- B. finding solutions to store and disseminate these type of multi-layered datasets in a new open, web optimize file format (*objective 2*),
- C. providing a conversion tool allowing stakeholders to optimize their existing datasets into the new file format (*objective 2*). Throughout the pixel+ project the general collective term for the targeted technology is Single Camera Multi-Light (SCML), the newly proposed file format: .scml.

SCML techniques have been used extensively to study objects under varying light conditions. Intuitively, we humans perform this technique to study local surface detail, the shape of an object or reflectance properties, e.g. by using a flash light at raking angles to reveal the tiny surface details. These visual cues that change under varying light conditions are captured with cameras and serve as input for various algorithms that model this light dependent pixel intensity (i.e. formulate the final pixel color as a function of the light direction) or even learn surface and material properties from these cues.
Two major SCML approaches lay in the scope of the pixel+ project. On the one hand the Belgian system of the Portable Light Dome (PLD) and on the other hand the US solution with Reflectance Transformation Imaging (RTI); sometimes also known as Polynomial Texture Mapping (PTM), piloted by Cultural Heritage Imaging (CHI, San Francisco). The latter includes the axe expanded by mainly ISTI/CNR researchers in Italy. Both approaches have proven their added value over the last 20 years for the visual documenting, study and multi-layered digital preservation of heritage objects. In the meantime countless past and ongoing research and imaging projects, initiated and funded all over the world, illustrate this clearly. For all these projects and their outcomes pixel+ has provided new solutions.

Both platforms have been developed by separate research groups, with a different focus. This resulted in dissimilar interactive pixel based file formats, making it challenging to interchange the information processed and stored in their respective output datasets. Therefore, the pixel+ project aimed to merge the technologies of both approaches into a single consultation platform

that will be capable of displaying all existing interactive pixel based file formats with their respective viewing modes and metadata. This viewer has the ability to illuminate the virtual model of the heritage object and consult the processed datasets with visual styles developed within the research spheres of both platforms. Moreover, as both methods are alike in terms of required input and processed output, pixel+ focusses on other types of integration, resulting in new additional visual styles for processed data, as well as a novel reprocessing pipeline for existing source image sets.

Because RTI and PLD are still relatively young technologies, knowledge of their technicalities and wide range of potential benefits is still sub-par. A new dissemination website has been launched which explains these technologies and their derivatives. It contains best practices and use cases, and shares community updates. As it's in the interest of the whole community, the website doesn’t shy away from discussing other future computational photography techniques to further elaborate viewing, processing and/or digital preserving interactive pixel based file formats. The source codes of both the pixel+ viewer and this companion website are on GitHub.

Objectives

Objective 1: Integration of RTI and PLD

Both targeted methods with their underlying software, computing structure and strategy have laid their focus differently, a consequence of their historical development process. The RTI branch is originally engineered to perform as a flexible and robust interactive visualisation system. Whereas the PLD system aims at mining these pixel-based datasets by – besides interactive visualisation – processing them in a manner that the results permit a full study of the physical dimensions of the artefact and an extensive analysis of the reflective properties of every pixel (e.g. to be processed into histograms and reflection maps). The first objective is to combine the power and advantages of both systems into one interface so that the data generated by the various acquisition sequences can benefit from the achievements by both development axes.
The combination of both technologies results in a web based Single Camera Multi-Light viewer in which both RTI and PLD files can be consulted with their own viewing modes. Moreover, by leveraging intermediate maps that can be calculated from these processed scml files, novel viewing modes are made possible.

Objective 2: Developing a framework for the future

Being aware of the constant development of ICT technologies, where staying compatible over longer periods asks for almost unlimited resources. To resolve this, often the Open Source approach is used. The Open Source approach is also in line with Belgian Federal government policy regarding software procurement. In order to allow for such development, thorough documentation is needed. This documentation, written with the end user and the FAIR principles (Wilkinson et al. 2016) in mind, also enabled a swift development of the first versions of the pixel+ web-based viewer software.

Note that, with reference to the original proposal, which only stated a single web plugin, pixel+ has resulted in a full grown **web viewer**, a **novel file format**, a **format conversion tool**, and a **dissemination site** containing much needed background information about the scanning, processing and viewing stages of SCML technologies. Furthermore, the **integration** of RTI and PLD was performed on **more levels** than anticipated, allowing for a transparent user interaction on the level of import, preprocessing, and viewing of the different RTI and PLD based formats and recordings scenarios.

Conclusions

The pixel+ project produced the following deliverables:

- Web based viewing environment (Technology readiness level 9): pixel+ viewer
- Dissemination/knowledge base website
- Source code and documentation
- Novel open, web optimized file format specification (.scml)
- Windows/Linux conversion software to convert Legacy PTM/RTI/PLD formats and source image sets into scml-files
- Knowledge transfer between various stakeholders of SCML technology

These technical and other outcomes will help cultural heritage researchers in analyzing datasets that are spread across various incompatible Single Camera Multi-Light databases (with their own incompatible viewing platforms).

The web viewer is capable of viewing and interactively relighting legacy files (i.e.. PLD's: .cun & .zun and RTI's: .ptm and HSH .rti) by in-browser calculation of intermediate maps, viewing methods of the other's technology become available.
The novel file format specification for the scml-files, optimized for web viewing, was designed in collaboration with ISTI/CNR researchers. A format conversion tool converts legacy files into the novel scml-file. Both processed RTI and PLD files as well as RTI and PLD source datasets can be converted. The novel format consists of widely used, open building blocks (i.e. zip, png, xml, json) and has several benefits: decrease of parsing time, addition of metadata, storing viewer specific settings, storing ultra high resolution files in a pyramidal image tiles, etc; all together a robust future-oriented solution.
Together with the web viewer, the scml-file format introduces some IIIF image server capabilities, without the need to install a seperate - currently non existing - SCML IIIF image server software on the content provider's data server. Only those bytes that are needed to render the current WebGL scene will be transferred. This decreases loading times and traffic in between the data server and user exponentially.
Much attention has been paid in order to not impose constraints or complicated setups for content providers hosting legacy RTI/PLD or novel scml-files to disseminate their content via the pixel+ viewer. This was achieved by having thorough discussions with the digital asset managers and ICT services of the project's partners during the execution of the project.

Knowledge on SCML technologies in the heritage communities is typically limited, incomplete and even outdated (not evolved along with the newly developed technical abilities of recent years). Most users of SCML imaging results stick uniquely to the interactive visualization aspect of the technology. A dissemination site, www.heritage-visualisation.org, bundles historic and state-of-the-art information about RTI and PLD and provides the necessary background information to aid researchers and scholars in quality assessment and improving their understanding of what can be seen in scml-files. 2D+ and 3D scanning or (other) advanced photography methods are becoming more popular and easier to use. To better appreciate such virtual objects, it should contain how it was captured and processed. Together with the intrinsic knowledge about the physical object, knowledge base systems that describe in end user's terms these various stages (capture, process, view) will help them to interpret the virtual objects these novel powerful forms of scanning produce.

Keywords

Portable Light Dome (PLD), Reflection Transformation Imaging (RTI), 3D Scanning, Software Development, Computer Vision, Technology integration, Conservation Technology, Heritage Visualisation.

1. INTRODUCTION

In recent years advanced imaging techniques have been introduced to study, document, curate, and preserve our heritage. Pixel+ focuses on a particular subset that exploits the fact that when an artifact is observed under varying lighting conditions, it is possible to extract information on the shape and material characteristics of the artifact's surface. This computational photography assisted technique is throughout this report labeled as Single Camera Multi-Light (SCML) imaging. The acquisition of the source image set, needed to process the interactive virtual output file, can be obtained via various methods, devices and strategies. The majority of them can be differentiated as the Dome method and the Single Mobile Light Method, see figure below.

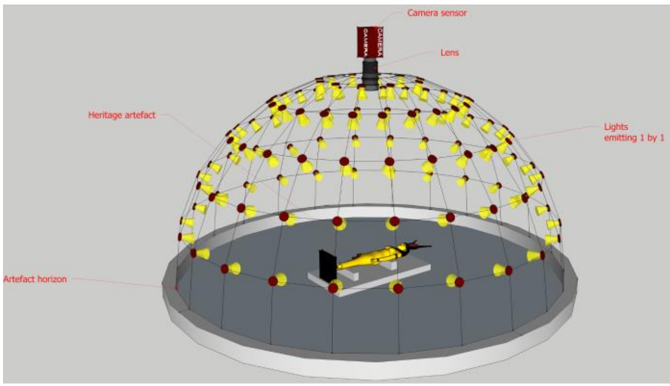

Fig. 1a - Dome Method: Theoretic setup of a dome acquisition device with fixed light source positions (as published on AIC-wiki).

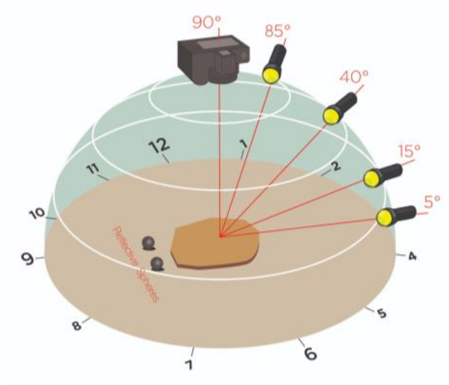

Fig. 1b - Single Mobile Light Method: Theoretic setup for highlight acquisition indicating four angles of light and twelve locations around the object for a manually positioned light source (as published on AIC-wiki).

Two known processing methodologies that are based on this technology are Reflectance Transformation Imaging/Polynomial Texture Mapping (RTI/PTM: Malzbender, Gelb, Wolters 2001; Mudge et al. 2008) and the Portable Light Dome (PLD: Willems et al. 2005a; 2005b; Verbiest et al. 2006). Both methods provide an interactive image model that can be re-lit from any direction or used to study the shape and reflection characteristics of the artifact's surface. Various filters (visual styles) can be applied to cater specific needs. Some users are purely interested in the surface shape (e.g. cuneiform tablets), others in the reflective properties (e.g. to investigate pigments). Or, stakeholder want to disseminate to beholders interactive, photo-realistic, virtual models. This can even be combined with multispectral applications (Van der Perre et al. 2016; Hanneken 2016; Giachetti et al. 2017;). Depending on the processing method and the applied visualisation filters all such variation of output is possible. However, a major challenge is found in providing the means to combine all these outputs via one integrated platform. A challenge taken on by pixel+.

RTI and PLD have been developed and elaborated by different research groups, and from different perspectives. The RTI pipeline by CHI (Cultural Heritage Imaging) has a strong focus on low-cost solutions and ease of use; since their Single Mobile Light Method / highlight methodology requires only a single light source, a standard DSLR camera and a reflective sphere, it became available for a large audience (Schroer et al. 2013 & 2019), a major contribution to the field of heritage studies. Related to this method and the first to analyze the processed data visually was based on PTM (Polynomial Texture Mapping). More recently, other interpolation techniques have been proposed (cf. infra), applied on multi spectral data (e.g. Giaghetti et al. 2017).

From the start in the early 2000s the PLD-domes were designed to accommodate the need for large scale recordings. Since, the initial design has evolved into several industrial prototypes, for various applications. The starting point of the technology is based on photometric stereo (Woodham 1980). This has been studied in applied settings since 2005, but has matured substantially in parallel with the hardware developments. As PLD’s core is built around physically modelling how light interacts at the material surface, object/material properties such as local surface orientations and reflectance behaviour can be examined.

Because of the different research and development tracks, both methods are similar, but at the same time divergent in terms of processing, output format, viewing software, etc. Pixel+ merges these various tracks, grown side by side over time, by developing a web viewer that is capable of displaying their existing file formats with their respective processed shaders and metadata, and has the ability to re-lit the virtual model. This web viewer uses novel web technologies (e.g WebGL, WebWorkers, HTTP 206 partial content) and facilitates sharing these file types and allows content providers (e.g. museums) to open up their collections with SCML imaging datasets to the public. By combining the benefits and functionalities of the existing SCML methods, pixel+ aims to overcome the disadvantages of the pre-pixel+ situation. See below the section ‘RTI's and PLD's strengths and weaknesses’, under 2. Methodology and Results, where this issue is further explored.

To further support this approach, after project internal and after collaborative discussions with ISTI/CNR researchers specialized in advanced SCML research topics, the need was defined to develop a novel open web optimized file format. Its result (.scml) is based on widely available standards and together with the web viewer it provides IIIF image server-like capabilities, without the necessity to install extra software on the servers of the data providers and certainly not on the consultation devices of the client end-users. Below in the section ‘SCML: a novel file format’ a closer look at the architecture is given.

The combination of the pixel+ viewer and the new .scml file format allows to consult and explore processed SCML source image datasets as never before. To assure as many stakeholders as possible of the worldwide heritage community can benefit from these new abilities when possessing such, whether or not, processed resources, a free OS conversion tool has been built. With the tool, processed legacy files are converted into the novel scml-file. Beside the legacy PTM, HSH RTI and PLD (.cun, .zun) files also RTI and PLD source image sets can be converted.

Because RTI and PLD are still fairly new technologies, awareness of their existence and knowledge of its possible benefits is still limited. A dissemination website: https://www.heritage-visualisation.org/, was launched explaining the involved technologies, it discusses best practices and use cases and shares technology updates from all developers. As it's in the interest of the whole community, the website doesn't shy away from discussing other computational photography techniques as well.

2. METHODOLOGY AND RESULTS

Project execution

Organisation

Every month a core workgroup came together to discuss the progress, define the challenges and set out the future strategies (i.e. physical or online meetings). The participants are Chris Vastenhoud (RMAH, promotor), Vincent Vanweddingen (RMAH, KU Leuven, project employee), Marc Proesmans (KU Leuven, formal partner), Lieve Watteeuw (KU Leuven, formal partner), Frédéric Lemmers (KBR, formal partner), Paul Konijn (KU Leuven), Bruno Vandermeulen (KU Leuven), Athena Van der Perre (RMAH, KU Leuven), Hendrik Hameeuw (KU Leuven, RMAH). This group consists of a mix of digitisation managers, scientific software engineers, DH scholars, and scientific photographers.

The follow-up committee consists of representatives of the partners and supplemented with (international) stakeholders and SCML experts:

- Mr. Chris Vastenhoud, RMAH (Coordinator Data Management projects)
- Dr. Marc Proesmans, KU Leuven (Leading engineer behind PLD system)
- Dr. Hendrik Hameeuw, RMAH-KU Leuven (Coordinator PLD and RTI projects)
- Prof. Dr. Lieve Watteeuw, KU Leuven (Coordinator PLD projects)
- Dr. Athena Van der Perre, RMAH-KU Leuven (Imaging specialist)
- Prof. Dr. Kirk Martinez, University Southampton (Coordinator Digital Imaging & RTI projects)
- Dr. Patrick Semal, RBINS (Coordinator Imaging & Data Management projects)
- Mr. Frédéric Lemmers, KBR (Coordinator Digitalization Projects)
- Mr. Bruno Vandermeulen, University Library KU Leuven (Coordinator Digital Lab)
- Prof. Dr. Jacob Dahl, Oxford University (Coordinator RTI & Data Management projects)

Of these, Prof. Dr. Kirk Martinez, Dr. Patrick Semal, and Prof. Dr. Jacob Dahl, Oxford University are consulted and kept up-to-date through informal contacts.

The Follow-up committee had meetings on:

- 21/06/17
- 06/07/17
- 07/09/17
- 16/01/18
- 27/02/18
- 29/03/18
- 14/06/18
- 17/10/18
- 16/01/19
- 28/02/19
- 02/04/19
- 14/05/19
- 11/06/19
- 05/09/19
- 21/10/19
- 16/12/19
- 28/01/20
- 25/09/20
- 22/10/20

Overview of progress and general strategy

The project was split into 2 main phases: Phase 1 consisted of the analysis of how RTI and PLD can be combined and a working implementation of this, i.e. pixel+ viewer. For this phase, the project hired a project employee working full time and based at the RMAH with special accreditation allowing frequent worksessions at KU Leuven - ESAT-PSI (formal partner). The milestone event ending this phase was the publication of the first version of a fully functioning online pixel+ viewer; including a first version of the new file format.
Phase 2 consisted of further development and fine tuning of the developed tools, i.e. pixel+ viewer, .scml file format and converter tool. This phase was stretched in time to allow involved partners and interested external parties (CHI (San Francisco), ISTI-CNR (Pisa)), Faculty of Oriental Studies at Oxford) to test the software, give feedback and update the software toolchain. Based on that first fine-tuning, slightly pushed forward in time due to COVID-19, a public launch of the pixel+ viewer (May 2020) marked a first interim milestone during this phase. Making the converter tool available online was the second milestone.

Background and Deepening

The project kicked off with a thorough literature study on the origin and evolution history of both the PLD and RTI branches, i.e. in terms of viewing software, existing file formats and architecture, data compression strategies, specific acquisition and processing techniques. As one of the project partners, Departement Elektrotechniek (ESAT) - KU Leuven, are the developers of the PLD system, the information on PLD was already available. The information on RTI, on the other hand, proved to be spread across various resources and research groups.

As discussed in-depth below, RTI presents itself as a popular light field interpolation technique with various flavors. As the pixel+ project's spotlight is mainly on creating better ways of **disseminating existing datasets** and **building bridges** with PLD's existing datasets and processing methods, the focus was laid on (L)PTM, HSH RTI, and the promising novel RBF+PCA RTI sub-branches.

The first integration tests were made in C++ in the already existing PLDviewer desktop interface and in javascript in the already running PLD webviewer, which was originally found on www.minidome.be. The latter was heavily modernised, extended and eventually converged into the pixel+ viewer.

As the pixel+ web viewer leverages WebGL to visualize the scene, the next step, after writing a javascript parsing code, was to rewrite the visual styles of PTM and HSH RTI, as they can be seen in RTIViewer in GLSL, in the OpenGL Shading Language. At this stage, PLD's (incl. bundled multispectral recordings) CUN/ZUN, PTM and HSH RTI files could be viewed in the web viewer. This was considered to be the **first form of integration**. The next step towards the **further integration** of PLD and RTI was to visualize PTM and HSH RTIs with the already existing PLD's visual styles. This was performed by writing a javascript web worker that calculates the normals and the ambient maps starting from HSH or PTM coefficients. Similarly, RTI's specular enhancement style was written for PLD files.

The focus of the project was not only on the technical aspects of integrating PLD and RTI into a single viewing platform, but also in the **dissemination of both technologies**. These two paths can also be observed in the project's communication efforts (publication list, blogs, …). A broad audience ranging from optical engineers and computer vision researchers to museum curators and various heritage scholars that are or could be interested in SCML technology. By already targeting certain dissemination channels at an early stage in the project, we could actively listen to various stakeholders in the heritage community and adapt our strategy accordingly to maximize the outcome of the project. By actively seeking them out and contacting them directly, we could tackle their needs. This was an important focus of this second phase.

What was often mentioned by members of the heritage community was the ease with which datasets in online databases could be opened in a web viewer environment. For SCML datasets, up till the start of the pixel+ project, that was almost uniquely made possible with the in 2013 developed WebRTIViewer by Visual Computing Laboratory - ISTI-CNR (Palma 2013). Also at KU Leuven a webservice (www.minidome.be) was made available for processed PLD source image sets. Such types of online consultation requires fast loading of the data and clever data management. For grayscale and RGB photos, and to a certain extent multi-spectral imagery, the IIIF ecosystem has provided several options. This includes a source file containing a high resolution file (e.g. jpeg 2000), an image server that creates on demand derivatives of this source file (e.g. Cantaloupe) and a web viewer that can display these derivatives (e.g. Mirador).

The need for faster loading into the web viewer was tackled by adding an intermediate step. By converting the legacy formats into a web optimized version that was inspired by glTF the processed data in the files can be uploaded and consulted much smoother. Deep zoom functionality was added by saving stacked piramidal versions of the textures, and adapting the pixel+ viewer. The data delivery software stack of some content providers requires all data belonging to a specific object to be stored into a single file. ZIP with compression flag 0 (store) was chosen, as it is an open, widely used format that can be parsed in browsers with very small overhead. This novel file format was named .scml.

Based on the decisions made to build a functional pixel+ viewer that meets both the technical and the end-users needs a format SCML converter was written and made available for free to stakeholders via the dissemination website of the project. The tool converts legacy processed PTM, HSH RTI, ZUN and CUN files and RTI (when a light position file is available) and PLD source image sets into the novel .scml format. In these newly obtained files the number of processed functionalities can be determined: pyramidal tiles, depth data, ptm data, pld data, HSH RTI data, RBF RTI data and orientation of the image. The converter also takes a first step to add additional metadata to the .scml file in a structured way. Needless to state, the number of applied functionalities influences the file size. The converter tool also includes a downsample function.

The Portable Light Dome branch

Information on the different PLD file formats (.cun, .zun, multispectral .cun and multispectral .zun) is, because it has been developed and maintained by a single group, easy to acquire. The various acquisition devices, processing and visualizing techniques are described in Willems et al. (2005a, 2005b), Verbiest et al. (2006), Hameeuw et al. (2011, 2020), Watteeuw et al. (2015).

PLD's main outputs structured in the processed files are 1. an Albedo map, containing the Lambertian color, 2. an Ambient map, containing the average color when the object is lit from all directions and 3. a Normal map, which encodes the local surface orientation. For the multispactral .cun and .zun seperate albedo, ambient and normals maps are included x-times corresponding to the x-number of source image sets that came with the acquisition process; in case of the MSmini- and MSmicro-domes the five included narrow band spectral datasets are nearIR, R, G, B and nearUV (Van der Perre et al. 2016). This information is efficiently compressed in the aforementioned proprietary file formats. Next to this output, information on the surface reflectance properties (the Bidirectional Reflectance Distribution Function) in so-called reflection maps are gathered as well, but this isn't stored in the compressed files, but in an intermediate format.
PLD supports up to 6 different sides of an object (corresponding to the 6 theoretical sides of a cube, i.e. a standard volume) into one file (Hameeuw & Willems 2011). This ability was created to assist assyriologists in examining the writing on all sides of 3D cuneiform tablet (which could start on the front and continue on the sides and back); but the function can equally be used to image the face and back of a coin and join it in the same viewing environment.
The PLDviewer desktop interface, as described in Hameeuw et al. (2020), has several viewing styles or shaders to examine the object, e.g. by switching off the color, to only focus on the object's shape. The sketch shader can accentuate where the local surface orientation changes dramatically, a visualization enhancement which has proven its benefits for a variety of research questions (Van Lerberghe and Voet 2009; Watteeuw and Vandermeulen 2014). A default color shader (albedo or ambient) can be applied to virtually relight the object.
Next to these viewing modes, across the years the PLDviewer has also introduced several measuring tools. A histogram (whether or not based on white light or various spectral recordings) of a region, per pixel reflection maps can be generated and height profiles in milimeter can be drawn on the object. An option to export the virtual model to 3D is also available. Version 7.0.05 including all these functionalities of the PLDviewer desktop viewer is available via https://portablelightdome.wordpress.com/software/.

The Reflectance Transformation Imaging branch

Reflectance Transformation Imaging (RTI) has been developed and elaborated by different groups, resulting in dispersed information. The main purpose of all RTI techniques is data

fitting, i.e. modelling a (compact) interpolation-based formulation that describes the changing pixel values as a function of the light direction.
RTI was originally developed at HPLabs by Tom Malzbender (2001) in the form of Polynomial Texture Mapping (PTM). Work by Cultural Heritage Imaging (San Francisco) and the Visual Computing Lab of ISTI-CNR (Pisa) resulted in a novel and now widely used RTI file format: HSH RTI.
RTI needs as input a same source image set as described for any SCML approach, it can be captured using Light Domes methods (e.g. Martinez 2011) or via an accessible Single Mobile Light method (Schroer et al. 2013). The latter is mostly referred to as highlight RTI (in the source image set on all recordings a reflective sphere registers the spatial position of the light source, visual information to be used during processing to produce the light position file/data), but in fact, both the Light Dome (when the fixed light sources are not pre-programmed in the processing software) as the Single Mobile Light methods (can) make use of this approach.

The RTI format supports the following interpolation techniques:

- Polynomial Texture Mapping (PTM), Malzbender et al. (2001)
- (Hemi)Spherical Harmonics ((H)SH), Mudge et al. (2008)
- Discrete Model Decomposition (DSM), Pitard et al. (2015)
- Principal Component Analysis + Radial Basis Function (PCA + RBF), Ponchio et al. (2019)
- Based on (Convolutional) Neural Networks, Ren et al. (2015), Xu et al. (2018)
- Light Transport Matrix, Thanikachalam et al. (2017)

This list is not exhaustive, as constantly novel techniques are also being introduced. Of these, however, only PTM and HSH are widely used in practice, as RTIBuilder, the software the cultural heritage sector typically uses to produce RTI files, only supports the processing of these two light field fitting and interpolation algorithms. Multi view RTI, multi spectral RTI and novel shading modes for the HSH RTI have been proposed but, save for in house development at some research groups, have not been implemented yet. The PTM file format (see Sustainability of Digital Formats: Planning for Library of Congress Collections 2018a), can store the polynomial coefficients per color channel (RGB PTM), only on the luminance channel (LRGB PTM), using YCbCr (LUM PTM) or using a lookup table (LUT PTM). Each of these types can also be saved with JPEG. The PTM file format does not save metadata.

Focussing only on PTM, HSH, and RBF RTI these coefficients can be used to virtually relight an object, similar to PLD, but using different shaders, so revealing other types of information. RTIViewer doesn't have measuring tools.

POLYNOMIAL TEXTURE MAPS (PTM)

Polynomial Texture Maps compress the information that is in the changing pixel values with reference to the changing light direction into 6 coefficients per color band, resulting in 18 planes. Many materials however don’t change their reflecting color depending on the angle of reflected light. Only the luminance changes. LPTM (Luminance PTM) exploits this fact by only encoding the changing luminance into a 6th degree biquadratic polynomial. The color information that is stored in a LPTM doesn't change with varying illumination directions. As this results in smaller file sizes (9 planes instead of 18) without sacrificing much quality, LPTM is often preferred over regular PTM.

The principal visual style of PTM is photo-realistic relighting. However, Macdonald (2015) has demonstrated that a 6th degree polynomial struggles to incorporate difficult light field effects like specular highlights and shadows. This has been partially solved by introducing higher order terms, though one has to be aware of overfitting, which will show up as artifacts in the synthetic interpolated image at novel light directions. More robust fitting methods to calculate higher order PTM coefficients can potentially solve this, see Drew et al. 2012 or Pintus et al. 2017.

The local surface gradient can be calculated by finding the direction with the maximum luminance, i.e. finding the maximum of the polynomial, see Malzbender et al. 2001 and Macdonald 2015. This, however, only holds true for diffuse surfaces. Many materials are not ideal-diffuse and have more complicated reflectance behaviour, as described in Matusic et al. (2003). 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 (beit a purely Lambertian surface as in Woodham et. al 1980 or more complicated ones, as in Ackermann et al. 2015) and tend to provide better surface gradient estimations.

HEMI-SPHERICAL HARMONICS (HSH RTI)

(Hemi-)Spherical Harmonics are a set of basis functions that can efficiently describe functions on a (hemi)-sphere. With respect to PTM, HSH tends to provide more realistic relighting (especially for challenging objects that hold specular reflections) when using 2nd or 3rd order HSH. As many HSH RTIs are produced with only 2nd order HSHs, it is important to stress that they can suffer from an artificial increase in brightness at grazing angles (Macdonald 2015). The amount of coefficients per order is 4, 9 and 16 for a first, second and third order HSH respectively, typically per RGB color band. Note that the minimum amount of texture units that can be accessed in webGL is 8, though most modern systems support at least 16. Rendering a >1 order HSH could therefore require more than 1 draw call.
HSH RTI can be stored in an HSH or RTI file, see Sustainability of Digital Formats: Planning for Library of Congress Collections 2018b. Next to HSH, the RTI file format also supports PTM, Spherical Harmonics and Adaptive Basis. Metadata can be stored in an RTI file as an XMP packet.

Strengths and weaknesses RTI and PLD

PLD is based on the principle of Photometric Stereo, which has been introduced by Woodham (1980). When a light shines on a Lambertian (i.e matte, diffusely reflecting) surface (e.g. a clay cuneiform tablet), the reflected intensity depends on the intrinsic intensity (albedo) and the angle between the surface orientation and the light direction. By lighting an object from several different directions, one can extract the surface orientation (represented as surface normals) and Lambertian intensity (albedo). The albedo is typically represented as a grayscale or RGB color image, except for multispectral recordings, which have an albedo value per spectral band. This technique has been improved to include non-Lambertian surfaces, having specular reflections (e.g. shiny metal coins) as well, as described in Verbiest (2008).

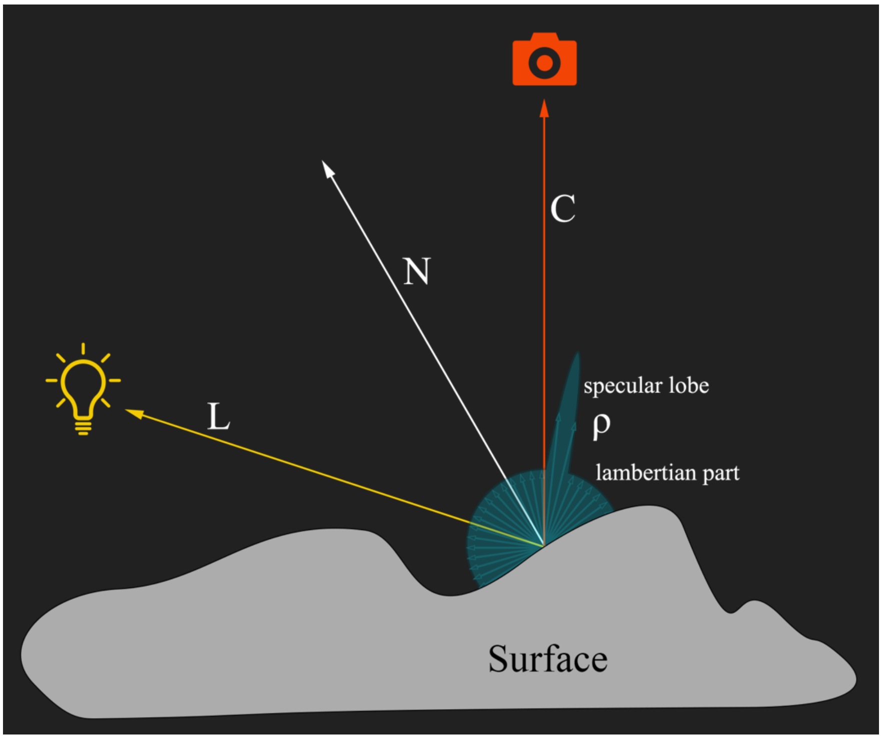

Fig. 2 - From recorded conference presentation Vanweddingen et al. 2020. **L**: Light vector; **N**: Local surface gradient (normal); **C**: Camera vector; **ρ**: BRDF for specific light L, i.e. how the light is reflected. In traditional PS, ρ is uniformly distributed. PLD processing has been adapted to handle materials with specular lobes.

The output of PLD is based on physical models of reflection. The extracted surface characteristics (Lambertian albedo, surface orientation, reflection properties) can be studied independently. Typically the recovered surface orientation is very detailed, in line with the resolution of the used light sensor. The (multispectral) histogram and (multispectral) reflectance maps can be used to cluster and classify certain regions (e.g. differentiating different pigments with visual similar appearance).

Because PLD depends upon Lambertian photometric stereo, some of the color relighting will not look photorealistic. Effects like interreflections and self shadowing aren't taken into account. On the one hand an advantage as shadow and specularity obscure information at the pixel level, but again, it makes the overall appearance of the image less photorealistic. Therefore, surfaces with a complex BRDF (e.g. highly specular reflections, color changing reflectance etc.) will in the default relighting mode have a slight artificial look, as only the Lambertian color component is used.

RTI, on the other hand, doesn't study surface properties. Given a set of images of an object, each time lit from a different direction, this interpolation technique aims to find a mathematical function to predict the per pixel color, given a virtual light direction.
Effects like self shadowing, interreflections and non-Lambertian reflectance are implicitly taken into account, causing the relighting of some objects to be more photorealistic, though not perfect. Especially results in between samples (i.e. a virtual light direction that doesn't coincide with a real recording), interpolation artifacts may occur. HSH has the potential to cope with this better than PTM, but still performs worse than the more recently introduced PCA + RBF fitting algorithms.
Surface orientation can be extracted from the PTM or HSH coefficients, but the result will not be as good as photometric stereo. Self shadowing, interreflections and non-Lambertian reflectance will introduce errors in the calculations of the surface normals.

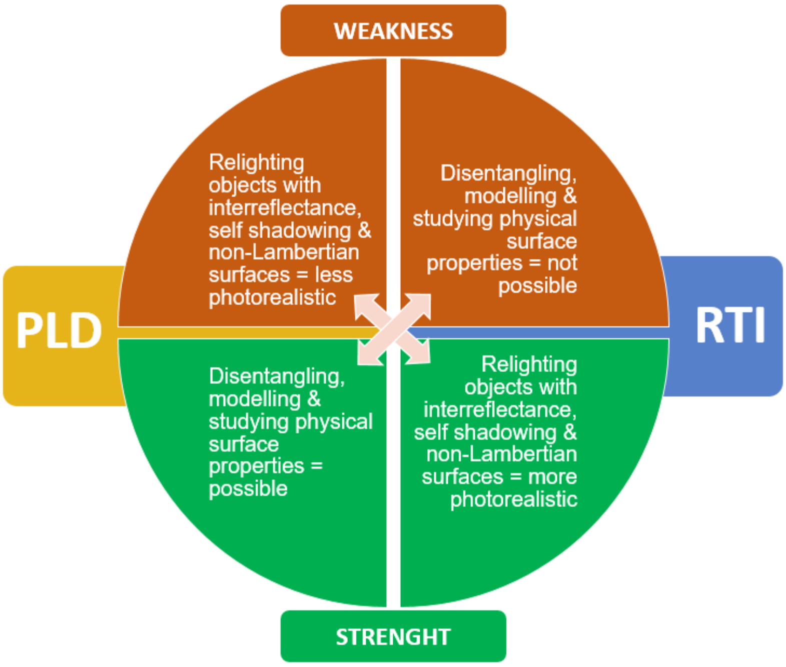

Fig. 3 - Main strengths and weaknesses of processed SCML source image sets of standard PLD & RTI branches.

When comparing, the strengths of one technology can be defined as the weaknesses of the other, and the other way around. But in terms of required input, both technologies are in essence similar, i.e. a set of images taken with a stationary camera and each time lit from a different direction. However, as PLD has focussed on extracting as accurate and precise as possible surface properties, its hardware has been designed to substantiate this and based on that its acquisition and processing pipeline is therefore geometrically and radiometrically calibrated to a high degree. PLD takes into account the physical position of the light source and camera (and not assuming them being placed at infinity), nor assuming the light sources to be equally powerful ideal point light sources (and thus modelling the LED dependent and direction dependent light intensity). One could apply (some of) these pre-processing steps on RTI data as well, however, it is to be stressed that a typical source RTI dataset doesn't include

the necessary data to perform thorough calibration. This lack of properly calibration of RTI source data has to be kept in mind for the integration (e.g. this will negatively influence the quality of the surface orientation estimation)
Beside other incentives was RTI developed with ease of use in mind (that includes, a method accessible and executable by most stakeholders in the heritage studies), and can in terms of hardware be as simple as one stationary camera, one flash light and one or more reflective spheres (to extract the light direction), the latter whether or not combined with the Light Dome or the Single Mobile Light Method.

Based on the above insights, we developed the following types of integration of PLD and RTI:

- Existing processed RTI, PTM and PLD files are to be opened in one web viewer with their respective viewing modes (**first level of integration**).
- Existing processed RTI, PTM and PLD files can be remapped so that the viewing modes of the other technologies become available, insomuch as that will bring additional benefits (**second level of integration**).
- Existing RTI, PTM and PLD source image sets can be processed in both an RTI/PTM and a PLD pipeline (**third level of integration**).

The first two levels of integration work with already processed data. As it is to be expected that most RTI and PLD content will only reside in their processed, final form, much attention to this important use case was given when designing the viewer. When the original source image sets are available and can be reprocessed, the third form of integration will provide the best results. The first and the second level of integration, as processing source image sets through the original PLD and RTI pipelines inherently means losing or ignoring information of importance for the other pipeline, will therefore deliver the less perfect results.

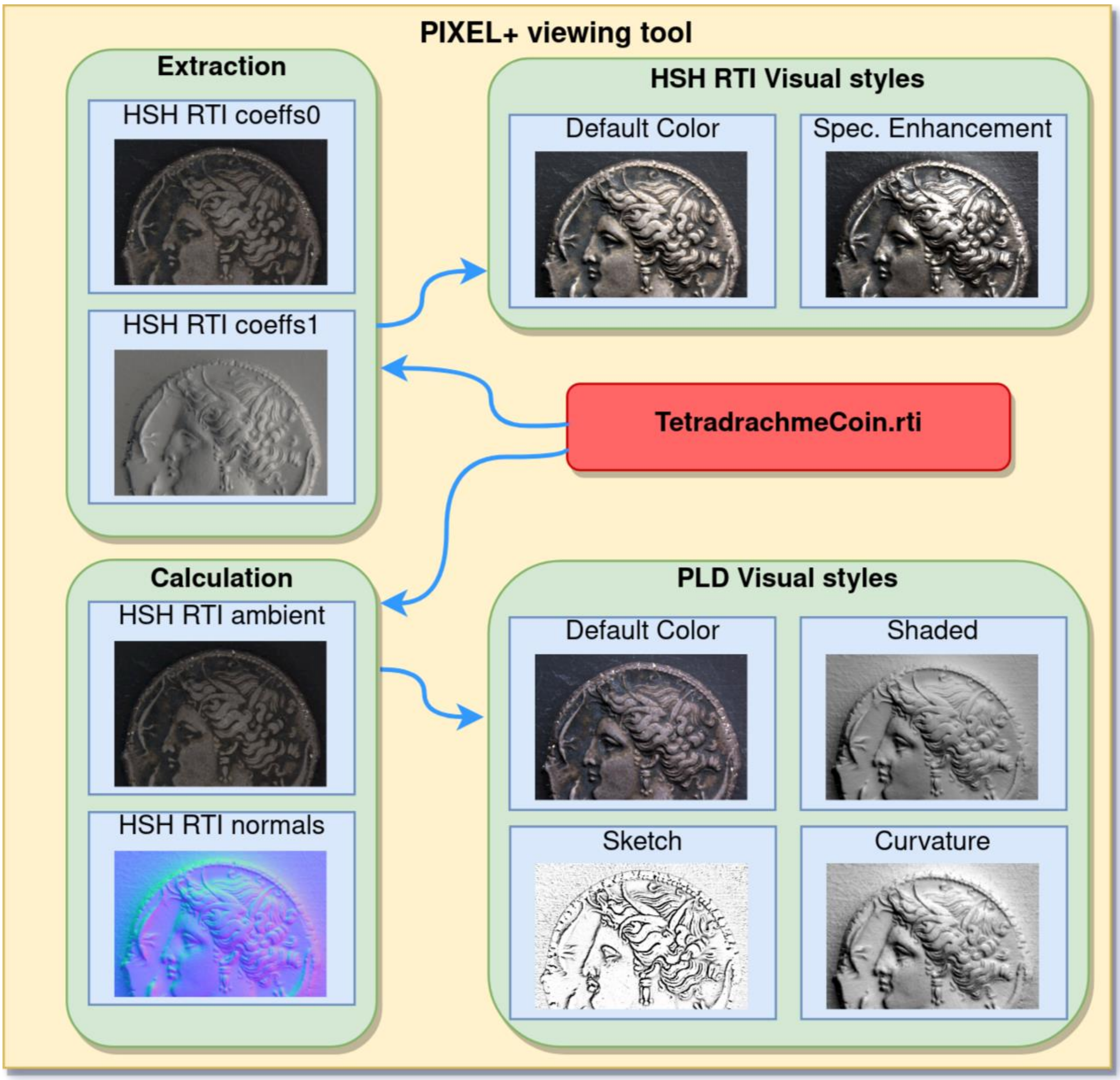

Fig. 4 - Given the multitude of heritage collections and individual objects that have been scanned with both technologies, pixel+ allows to view processed files (.cun and .zun for PLD and; .ptm and .rti for RTI) with filters of both technologies. It achieves this by calculating intermediate data file formats like normal maps and ambient maps.

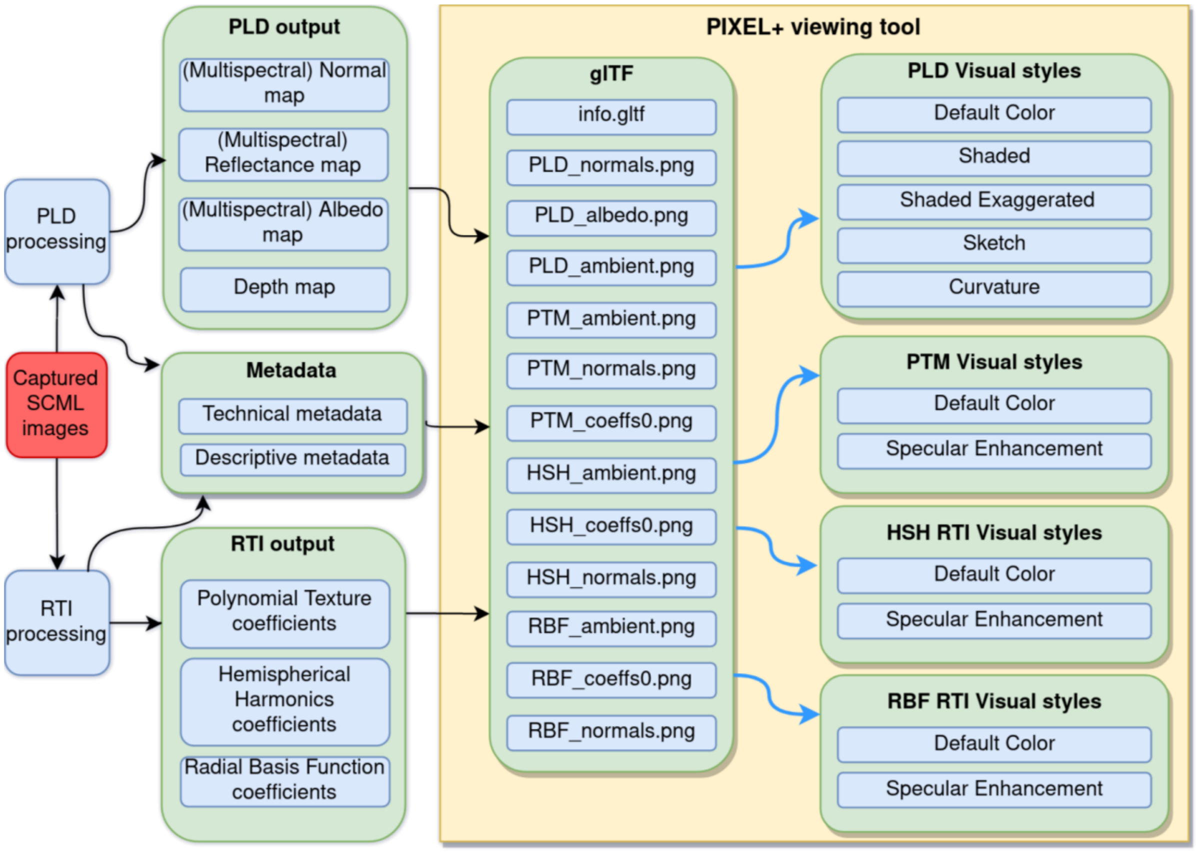

Fig. 5 - The best possible form of integration starts from the original input images as, compared to integration methods 1 & 2, no information is thrown away. Because both technologies require the same sort of input, i.e. a set of images lighted from various light directions, pixel+ allows to apply both the PLD as well as the RTI pipeline on both RTI and PLD input source image set.

PLD and RTI software

PLD's processed files, i.e. CUN and ZUN, have been created with the Portable Light Dome software set (Hameeuw 2020). This includes software for the acquisition, processing and viewing stage. A web viewer also exists that has, with respect to the desktop viewer, less functionality. The acquisition software outputs a folder of linear images and a metadata file that contains amongst other things which LED light was switched on per frame. This information can be used by the PLDDigitizer tool that also performs calibration routines, and outputs a .cun or .zun file, which can be viewed with the viewer. The desktop viewer is capable of viewing more data or calculation intensive results like reflection maps (which are a lower dimensional representation of a bidirectional reflectance distribution function) and 3D depth maps.

PTM and HSH RTI files have been created with an RTI dome (Pawlowicz et al. 2006, MGiachetti et al. 2017, Martinez et al. 2019), or by using a movable flash and one or several reflective spheres, so called Highlight-RTI (Cultural Heritage Imaging 2013). PTM and HSH data fitting code is available online, but most results are obtained with the popular RTIBuilder, which is part of a set of open source, well documented RTI tools (Schroer 2019). Newer RTI approaches require other (processing) software (Ponchio et al. 2019), and can handle other RTI source datasets as well, as they are following the same convention for their input, i.e. a folder with the images and a text file of a list of photos and the corresponding light directions (a so called *.lp or light positions file).

RTI Viewer, a desktop application of CHI, is typically used to view PTM and HSH RTI files. It has several viewing styles, i.e. a default color style for photo realistic relighting, and a specular enhancement style which further accentuates the surface orientation. Other RTI desktop viewers include APTool (Giaghetti et al. 2020), and ImageViewer (Macdonald 2015). Web based viewers include Oxford RTI Viewer (Goslar 2020), Relight RTI Viewer (Ponchio 2019), Web RTI Viewer (Jaspe 2019). Web based RTI viewers offer conversion tools to convert PTM and RTI files to a (custom) web friendly format.

Neither a web viewer, nor a desktop viewer, is capable of opening both PLD and RTI files.

Pixel+ viewer

The pixel+ viewer can be accessed on https://www.heritage-visualisation.org/viewer. It's primary features are:

- Parsing and viewing of and regular (i.e. consisting of processed results of only one source image set) and multi-spectral CUN and ZUN files (PLD's principal output) with all of PLDViewer's visual styles.
- Parsing and viewing of LPTM, PTM, HSH, relight RTI files.
- Calculation of normal and ambient maps from the RTI coefficients of processed legacy RTI data so that PLD's other visual styles become available.
- Encoding default viewing options in the URL (for legacy PLD and RTI files);
- Parsing and viewing the novel SCML format;
- Very fast loading and visualising of SCML data;
- Capable of visualizing extremely high resolution SCML files on modest hardware, without the need to downsample the original dataset.

It uses web technologies like HTML, CSS, JQuery, WebGL, Javascript, web workers, File API, XMLHttpRequest, Query string, HTTP 206 Partial content, HTTP Content Length. Examples of legacy RTI and PLD files (i.e. CUN/ZUN/PTM/RTI) are shown on the landing page.

Content providers can generate a link (string) that will directly open their processed legacy RTI/PLD or novel SCML files into the viewer. CORS will have to be enabled on the web server that hosts the file. As this allows tight linking with their content providing systems without the need to install extra software, nor extra steps for the user who wants to view the files. The pixel+ project sees this dissemination approach as the principal way of opening all sorts of SCML files. Both the KU Leuven and KBR formal partners have implemented this approach with their institute’s Digital Asset Management systems. The second way of implementation uses the File Api to open a local SCML file, stored on the device of the person. This approach has been used (i.e. tested) on the https://www.heritage-visualisation.org/examples.html page of the project’s dissemination website.

The preferred file type for the pixel+ viewer is the novel .scml, as this is web optimized, has many additional viewing benefits and is future oriented (see below).
However, for legacy files, some extra support can be added as well by adding viewing options to the URL. This includes changing the default rotation, a mirroring option (e.g. when the subject is a stamp), a default viewing style and light directions when opening this particular legacy RTI or PLD file in the web viewer. This helps in the use case that a researcher cannot convert a legacy RTI or PLD file to the novel SCML file, or does not have access to the file server on which this file has to be stored, yet wants to share a specific viewing mode when opening the file. The default viewing mode when opening a SCML file can also be changed by adding these URL parameters, or by specifying them during conversion. In the latter case, all the information is contained in 1 container format, whereas in the first, part of the information is encoded in the URL (that is typically placed on a different server than the data server).

The 3D WebGL scene consists of a virtual camera, 2 directional white light (i.e. #ffffff) lights (represented by pyramids of which the color is representative for the intensity according to the Planckian locus).

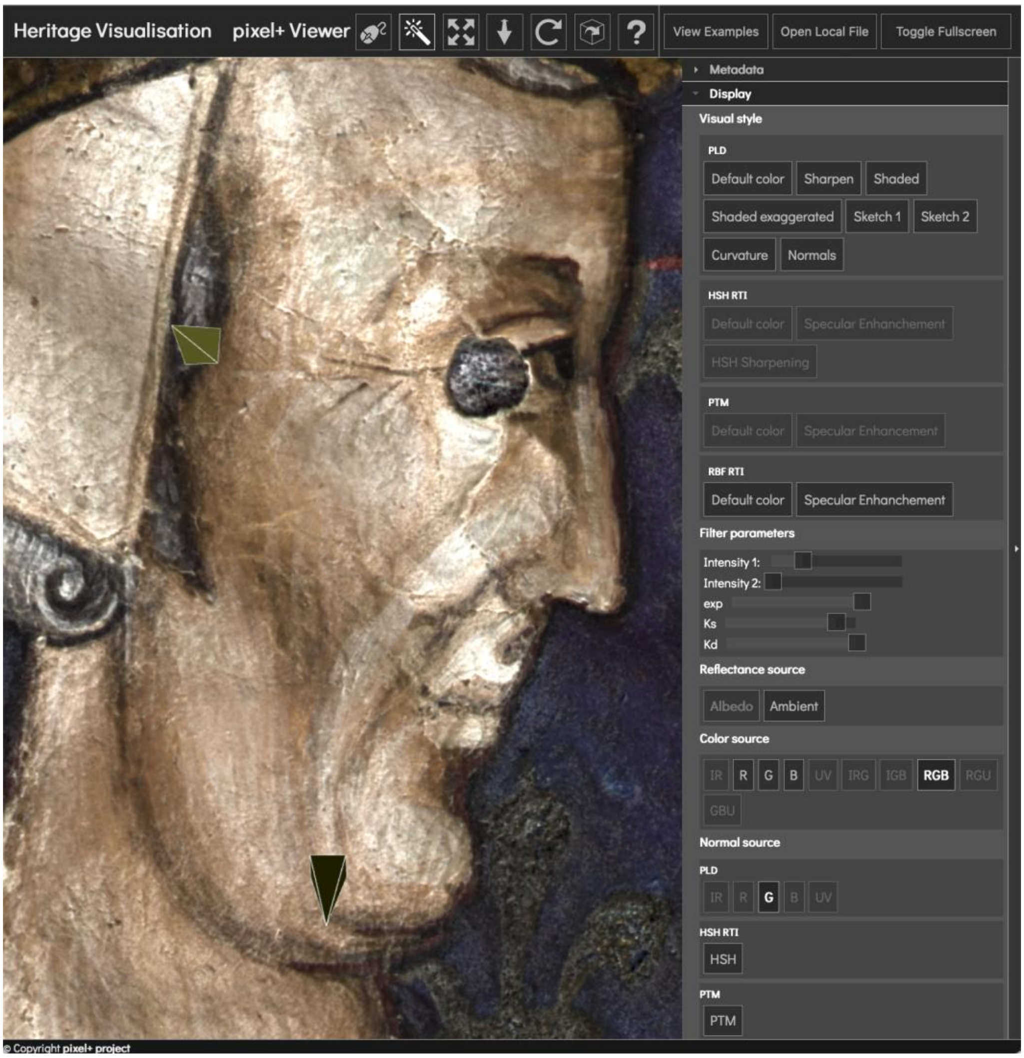

Fig. 6 - Large section on folio 3 verso of the Bible of Anjou, ca. 1340 (© RICH project KU Leuven: Ms. 1). Example of an RBF RTI file viewed with the Specular enhancement style. Example can be consulted via http://www.heritage-visualisation.org/viewer/?ds=data/samples/KUL_bible_of_Anjou/GBIB_MS1_001V_MS_01.scml.

The pixel+ viewer has the following visual styles implemented (i.e. Summer 2021):

- PLD:
    - Default color (Lambertian shading)
    - Specular Enhancement (Lambertian shading + additional specular phong term)
    - Sharpen reflectance
    - Exaggerated normals (Exaggerating the surface orientation deviation from the viewing axis)
    - Shaded (Lambertian shading with a vfg-uniform albedo, allowing a more careful study of the surface orientation)
    - Shaded Exaggerated
    - Sketch 1 (mimicking pencil drawings - where the local surface orientation abruptly changes, the rendered pixel color is darkened)
    - Sketch 2
    - Curvature 1
    - Curvature 2
    - Normals
    - Reflectance
- HSH RTI:
    - Default color
    - Sharpened normals
    - Sharpened HSH
    - Specular Enhancement
- PTM RTI:
    - Default color
    - Specular Enhancement
- RBF RTI:
    - Default color
    - Specular enhancement

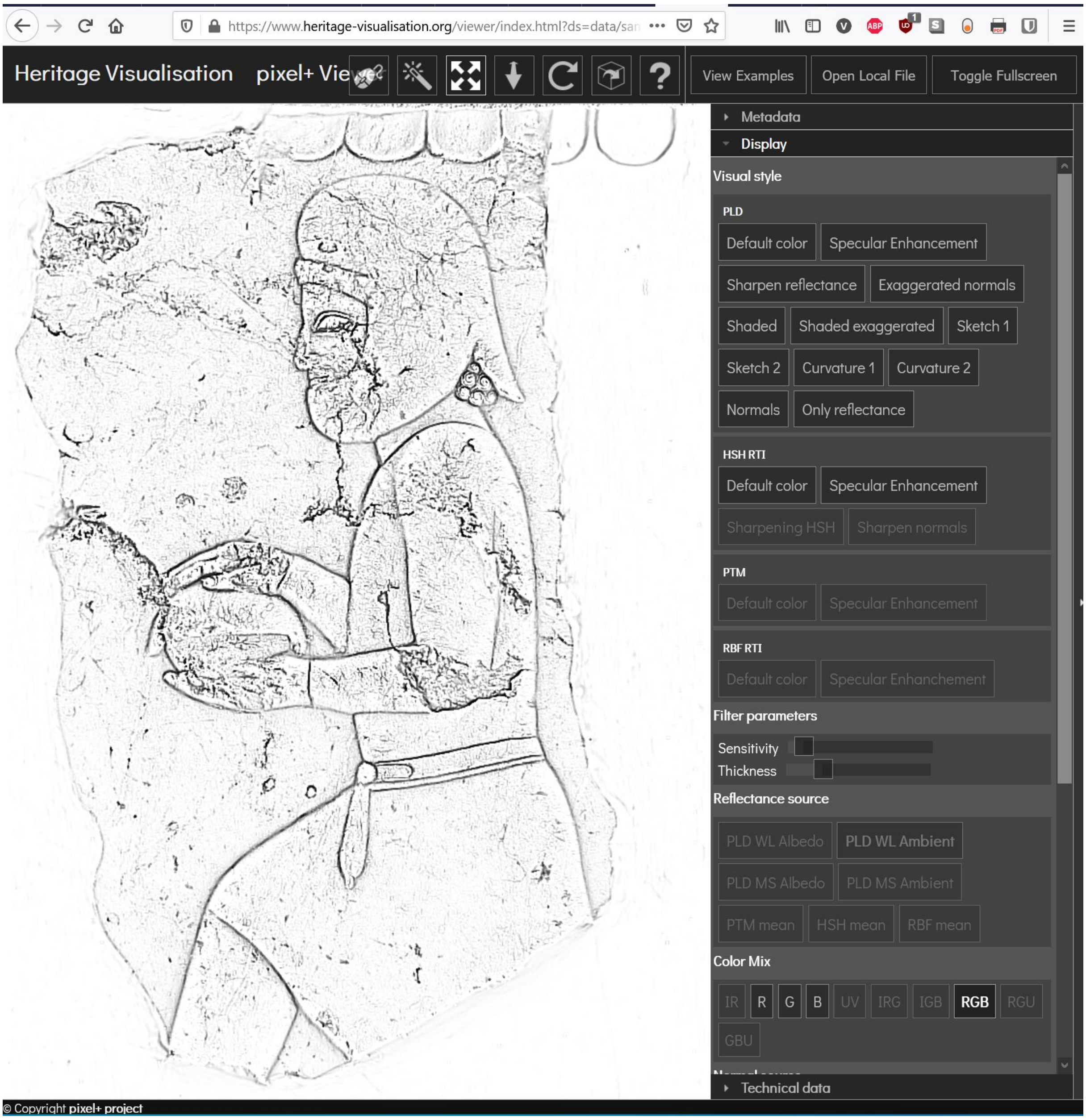

Fig. 7 - Detail of a stone Persian relief (© IAP: Greater Mesopotamia project Art and History Museum: IR.1034) as visualised in the pixel+ viewer. The source image set using RTIbuilder was processed into a HSH RTI file. This HSH RTI file is opened in the pixel+ viewer and displayed with PLD's sketch 1 visual style to accentuate the areas where the surface orientation abruptly changes. This is achieved by calculating the surface normals from the hemispherical harmonics coefficients in the file, which is performed in a separate javascript web worker to avoid deteriorating the responsiveness of the browser tab. Example can be consulted via https://www.heritage-visualisation.org/viewer/?ds=data/samples/KMKG_relief/IR1034_cropped_2042.rti.

The pixel+ viewer allows to directly compare the outcome of SCML methods on one and the same specific dataset, as can be seen in the following figure. This provides the potential to support a variation of both studies on the qualitative aspects of the different SCML technologies as well as content driven research questions on the imaged objects. PLD's surface orientation estimation tends to be more robust, therefore generally resulting in better normals. Another general observation is that the specular behaviour of the object is best captured in RBF RTI. Providing the end-user to apply all these varying view modes in one viewing environment, gives them insight into the technicality of these technologies: with one dataset, imaged features can be analyzed from multiple perspectives.

Fig. 8 - PLD SCML source image set in pixel+ viewer (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 with PLD's shaded viewing style, bottom: false color surface orientation (normal map), see also Vanweddingen et al. 2020.

By 2D integration of the surface normals, a depth map can be reconstructed. This allows other viewing methods, like moving the virtual camera. It also permits the end-user to interact with the imaged object in a more familiar manner; it makes it easier to understand the object's true dimensions and volume. The following figure shows the outcome of such integration with various SCML normal maps, as integrated in the pixel+ viewer. This depth information can be calculated during processing/conversion into the novel SCML file format.

Fig. 9 - 3D mesh based on the same SCML source image set, 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. In this case, the comparison with the help of the depth information reveals the PLD normals have estimated the global curvature of the tablet's surface best (see also Vanweddingen et al. 2020).

SCML: the novel file format

Overview of the various existing (Summer 2021) Single Camera Multi-Light file formats and types of output during and after processing.

- After acquisition: Typically a folder of images (=source image set), whether or not including technical and other metadata stored in (a) seperate file(s) or in the image headers.
- During/after processing: Intermediate results (e.g. the light positions obtained from the reflective spheres).
- Final exports: These custom file types contain the processed results and can be opened in a custom viewer (that included the pixel+ viewer).
    - CUN: PLD's default format containing metadata and losslessly compressed Albedo maps, Ambient maps, and Normal maps. CUN can save up to 6 sides of a recording (Top, Bottom, Left, Right, Front, and Back) that are displayed as a net. Recordings with white light LEDs have RGB Albedo and Ambient maps and a single Normal map. Multispectral recordings have 5 (NIR, R, G, B, NUV) greyscale Albedo and Ambient maps and 5 Normal maps.
    - ZUN: Web optimized version of CUN, resulting in bigger files, but much faster decoding times in the browser.
    - PTM: See www.loc.gov see Sustainability of Digital Formats 2018a.
    - RTI: See www.log.gov see Sustainability of Digital Formats 2018b.

NEED FOR AN OPEN, WEB OPTIMIZED FORMAT

All final Single Camera Multi-Light file types (CUN, ZUN, PTM, RTI) contain (technical) metadata and per pixel rastered texture data (PTM coefficients, HSH coefficients, Albedo values, normals…). Efforts have been made to decrease the transfer time (compression) and time to open these files on desktop viewing applications.

Most browsers support WebGL, that can leverage the power of a GPU to efficiently render 3D scenes including the various visual styles of SCML files. Whereas a CPU implementation has to sequentially loop over all pixels, a GPU implementation can calculate the color value of each texel (texture pixel) in parallel.

Depending on the resolution of the capture device (light sensor or camera) the file sizes are in the order of magnitude of 10-300MB. Before the GPU can be put to work however, the files have to be parsed and decoded, followed by a preparation and transfer of (texture) data from CPU memory to GPU memory. Both steps can take quite some time - as can be seen when loading legacy .cun, .rti and .ptm files in the pixel+ viewer.

To partially address this, several speed optimizations have already been implemented: After having parsed the first side (out of 6 possible) of a .cun or .zun file, the WebGL scene is initialized already to visualize that first side. In the background - by another web worker - the other sides are being calculated. Dynamically they become visible when their data is ready. Similar for HSH RTI and PTM: after parsing the coefficients, the WebGL scene is initialized, rendering the RTI using the default viewing mode. The calculation of intermediate maps, needed for some viewing modes, is done in the background. When this texture data is ready, the viewing modes that depend on them become available. But none of these solutions truly solves fast/fluent web based viewing of this type of complex, and sometimes high definition SCML file formats.

SCML ARCHITECTURE

glTF (Graphics Language Transmission Format) is a specification that tackles this problem of slow in-Browser runtime decoding and preparing of the data before it can be sent to the GPU of assets needed for a webGL program. It consists of a JSON formatted file that describes the scene. Textures and meshes can be stored base64 encoded in data URIs or as separate files. GLB combines all needed files into one binary file.

The in the pixel+ project elaborated SCML file format is similar to glTF, and consists of open standard file formats.

The extension .scml is a single file format for web based consultation of SCML imagery. The single file is an uncompressed zip (thus, to be unzipped with any program that supports this standard). The general structure of a ZIP file (and thus an SCML file) is seen in the figure below. It consists of one or more entries (i.e. files or directories) and a central directory placed at the end of the file. Each entry has a local header containing per entry information such as file name, (un)compressed size, a CRC check, etc. At the end of the SCML file, a central directory contains information about each of the entries and where to find them (relative byte offsets). For more information, see the https://en.wikipedia.org/wiki/ZIP_(file_format))

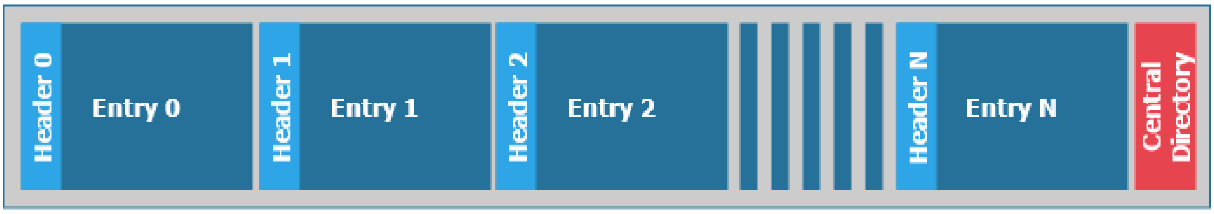

Fig. 10 - The general architecture of an SCML file is an uncompressed ZIP of a folder containing all the assets (textures, json data). Note that the central directory, the last chunk of bytes at the end of the SCML file contains information about what entries are included, and where to find them (byte ranges).

Each .scml file contains an info.scml, i.e. a JSON parsable file containing the general data structure. An example can be seen in the code block below. Besides metadata, it contains information about the textures that are present in the file and general (not pixel dependent) data. Viewer specific settings (such as image rotation, default visual style when opening) are optional.

```
{
  "SCML Version": "1.0",
  "SCML Generator": "SCML Converter 1.0",
  "metadata": {
     "mm per pixel": 0.02445876970887184,
     "notes": "SS 500\nF/8\nWB 111 210\nIS 40.89\n",
     "description": "",
     "creator": "",
     "creation date": "14/03/2013",
     "copyright": "",
     "collection number": "SABBE_MS1_003V_1",
     "database number": "",
     "publication number": "",
     "relative date": "",
     "publication info": "SABBE_MS1_003V_1"
  },
  "pld": {
     "side_0": {
        "metadata": {
           "width": 6576,
           "height": 4384,
           "mm per pixel": 0.02445876970887184
        },
        "wl_nor": {
           "bias": [
              0.499967485666275,
              0.499967485666275,
              0.499967485666275
           ],
           "scale": [
              1.9998699426651,
              1.9998699426651,
              1.9998699426651
           ],
           "file": "pld_side_0_wl_nor.dzi"
        },
        "wl_alb": {
           "bias": [
              -0.0,
              -0.0,
              -0.0
           ],
           "scale": [
              2.144477605819702,
              2.67781925201416,
```

```
          2.81115460395813
        ],
        "file": "pld_side_0_wl_alb.dzi"
      },
      "wl_amb": {
        "bias": [
          0.0,
          0.0,
          0.0
        ],
        "scale": [
          2.0436041355133057,
          2.6091296672821045,
          3.226066827774048
        ],
        "file": "pld_side_0_wl_amb.dzi"
      }
    }
  },
  "viewersettings": {
    "zrotation": 90.0
  },
  "layout": "deepzoom"
}
```


PLD, PTM, HSH RTI, RBF RTI all output per pixel data that can be easily stored in texture files. Together with viewing styles (i.e. vertex and fragment shaders of WebGL) and global parameters, various relighting modes can be performed. Currently, browsers can very easily parse PNG and JPG image types, so these 2 are currently supported. Texture data is grouped per 3 and normalized per channel by applying a scaling and bias correction, to minimize quality loss.

Depending on what the user has selected during SCML conversion, the image files can be stored as a single (downsampled) file, or in the Deep Zoom Image format. For higher resolutions, DZI is preferred, as it will decrease loading time, and allow for viewing the SCML files on more modest hardware (GPUs with less RAM)

Texture sizes depend on the resolution of the camera that was used to record the SCML sequence and vary between a few megapixels up to tens of megapixels. An ultra high resolution composite PLD SCML file of 442MP has been used to successfully test both the SCML converter (which slices and rescales the original 25230 x 17546 texture files) as well as the web viewer.

A DZI consists of a .dzi file (XML) containing metadata (code block below), and several folders containing several image slices at a specific resolution (next figures). It follows a quadtree data structure, in which the highest level contains image tiles at the full resolution. Each image tile has a width and height of e.g. 254 px or less (for outer tiles). The highest but one level contains image tiles that are half the resolution of the highest level, the highest but 2 contains image tiles of 1/4th the resolution, etc, until level zero, which only contains 1 tile representing the entire image.

```
<?xml version="1.0" encoding="UTF-8"?>
<Image xmlns="http://schemas.microsoft.com/deepzoom/2008"
 Format="jpg"
 Overlap="1"
 TileSize="254"
 >
 <Size
  Height="4384"
  Width="6576"
 />
</Image>
```

```
.
├── [ 4.0K]  0/
│   └── [  33K]  0_0.jpg*
├── [ 4.0K]  1/
│   ├── [  74K]  0_0.jpg*
│   ├── [ 7.4K]  0_1.jpg*
│   ├── [  44K]  1_0.jpg*
│   └── [ 5.1K]  1_1.jpg*
├── [ 4.0K]  2/
│   ├── [  69K]  0_0.jpg*
│   ├── [  70K]  0_1.jpg*
│   ├── [  10K]  0_2.jpg*
│   ├── [  70K]  1_0.jpg*
│   ├── [  72K]  1_1.jpg*
│   ├── [  12K]  1_2.jpg*
│   ├── [  66K]  2_0.jpg*
│   ├── [  65K]  2_1.jpg*
│   ├── [  12K]  2_2.jpg*
│   ├── [  18K]  3_0.jpg*
│   ├── [  18K]  3_1.jpg*
│   └── [ 3.4K]  3_2.jpg*
```

Fig. 11 - Folder structure of a multi tiled texture, in the Deep Zoom Image format

Fig. 12 - Level 0 mosaic of a multi tiled texture. Notice the limited resolution.

Fig. 13 - Level 1 mosaic of a multi tiled texture. Notice the increase of resolution w.r.t. level 0.

Fig. 14 - Level 2 mosaic of a multi tiled texture. Notice the increase of resolution w.r.t. level 1.

IIIF IMAGE SERVER CAPABILITIES

By placing all assets of an SCML dataset into a single container file, data management on the content serving databases can be straightforward. The following are the required steps for content providers to set up their system:

1. SCML files are placed on a html server. Note that the viewer is served through http over TLS/SSL (i.e. https only, no http) for extra security. Most browser policies don't allow mixed active content, meaning that the SCML file also has to be served over https.

2. Links following a specified, so called query format, are included in the online catalog in the info that is displayed about the object. The query string starts with a ? followed by one or more parameters. ds=http://museum.org/pathToFile.zun passes along the url where the dataset is placed. Currently, other options include type=[ptm/rti/zun/cun/scml], which is mandatory when the dataset url doesn't end with a file extension. Finally, several viewing options can be passed along to the web viewer. zrotation=180 (or 90, 270) can be passed along to rotate objects when opening, as some might have been recorded and processed upside down or under 90 degrees.
These viewing options can also be encapsulated directly into the SCML file, during conversion. This keeps this information in the file, whereas otherwise it would be in the URL to the file, and thus harder to keep this information together. As such, we recommend to use the query string method to pass along viewing settings only for legacy formats, that don't support storing viewing settings.

3. Cross origin resource sharing is to be enabled for https://www.heritagevisualisation.org.

4. Optional HTTP 206 Partial Content should be enabled and the content-length header exposed. When loading a newly web optimized SCML file, the web viewer can use HTTP 206 Partial Content to only those bytes that it currently needs. The benefits are: Dramatic decrease in loading time, decrease in CPU memory usage, no wastage of HTTP traffic between the server and the client. HTTP 206 Partial Content allows the web viewer to ask the server for a specific byte range in the big scml file (e.g. the byte range consisting of a requested texture file). A fallback is implemented for web servers that are not configured properly or older browsers that don't support this. This fallback mechanism, after having tried to download partially, downloads the entire SCML file, after which the rest of the functionality stays the same. The CPU memory usage will increase, but the quadtree data structure of the texture files still makes sure that the GPU memory is not affected, and therefore still allows viewing high resolution data on modest hardware. As the central directory that holds the information about where to find each asset in the SCML file is placed at the end, the web viewer needs to know the total file size of the file.

SCML Converter

To convert existing SCML (PLD and RTI) datasets, a format Converter tool was written in standard c++ + QT. It is available via the dissemination website of the pixel+ project. This tool will be actively updated with novel functionalities, depending on changing end user requirements as well as upgrades to the PLD and RTI pipelines. Currently (version 1.0), it supports conversions to .scml from:

- mono or multi sided regular or multispectral legacy .cun or .zun (i.e. PLD processed) files.
- legacy .ptm and HSH .rti files (i.e. the most common processed RTI files)
- PLD source image sets (necessary are: the .cfd metadata file + folder with the original raw recordings)
- RTI source image sets (necessary are: the already computed light positions (.lp) file + together in the folder of the original recordings)

The newly obtained .scml files can include a variation of processed content. This can be determined by the operator of the converter. Consequently, depending on choices made, the file size of the .scml container file will in/decrease. The converter can determine and include the following:

- pyramidal image tiles, i.e. applied to all visual styles [recommended]
- pld data, i.e. the legacy visual styles [recommended]
- ptm data, i.e. the legacy visual styles
- HSH RTI data, the legacy visual styles
- RBF RTI data the legacy visual styles
- Depth data
- Downsampling of the original input data
- Orientation of the original input data
- Adding metadata

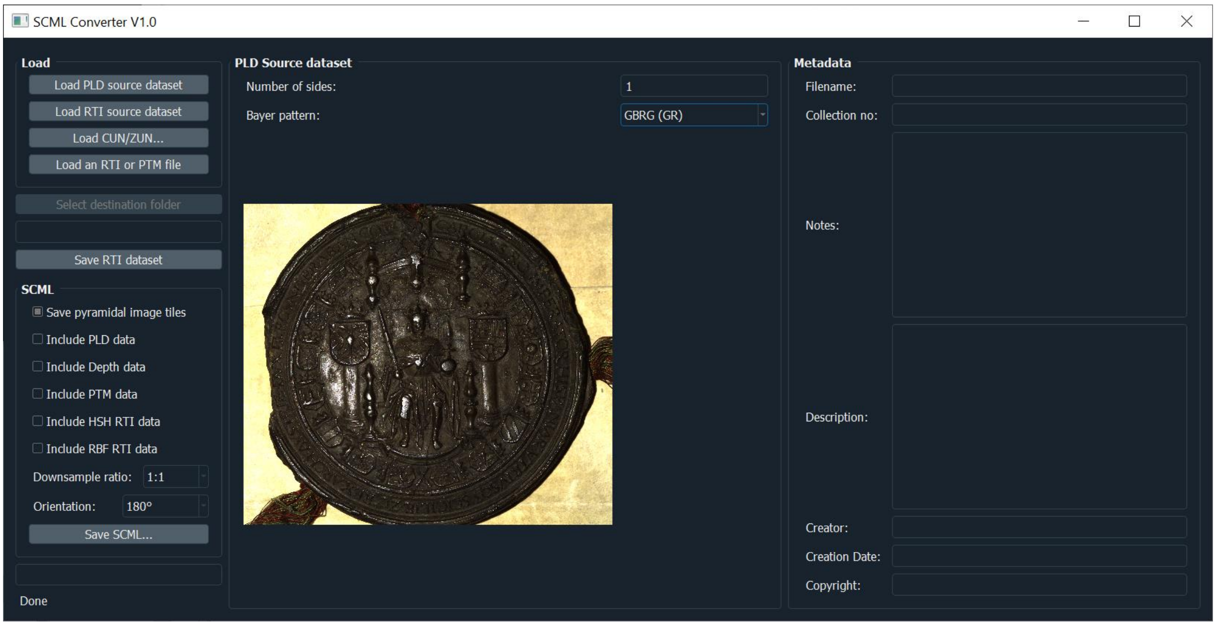

Fig. 15 - Screenshot of the SCML Converter 1.0

Use Case: St. Galler Klosterplan

A project of the Photogrammetry and Remote Sensing group of ETH Zurich of Prof. Dr. Konrad Schindler required the medieval map of the monastery of St. Gallen to be scanned with a SCML technique at submillimeter resolution. For the job it was opted to use the Portable Light Dome system for which both the Multispectral and the White Light Minidomes (version 2) were selected. The central challenge in this project, to obtain this qualitative SCML high resolution, was to make a high number of scans with the recording devices and then to stitch the interim results together. For this, it was crucial to be able to (re)position the recording device safely and perfectly horizontally above the plan throughout the entire recording sequence. To meet this, a specially designed custom-made frame at the monastery was set up for this task.
The plan is approx. 113 cm x 78 cm and was scanned resulting in a stitched mosaic of 25230 px by 17546 px; that was achieved with an overlap grid of 6 by 10, with a total of 141 recordings. The 443 MP texture data was saved into pyramidal image tiles and can as such be viewed at full resolution in the pixel+ web viewer, even on standard PC or laptop. The results of the project will be published in the near future.

Fig 16. - P. Konijn operating the adapted PLD acquisition setup

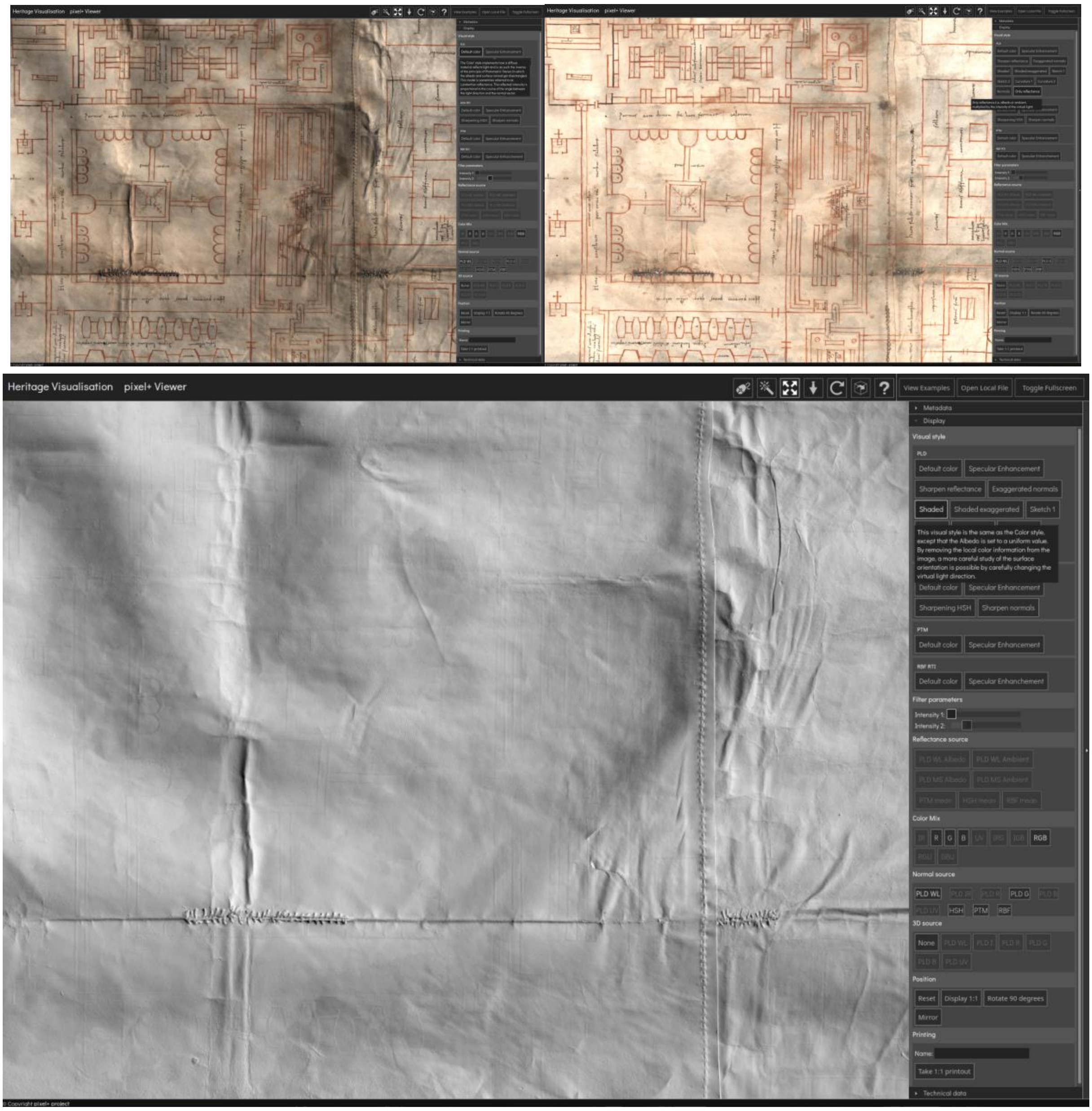

Fig. 17 - Detail of St. Galler Klosterplan (© Stiftsbibliothek St.Gallen), as viewed in the pixel+ viewer. Left top: default Lambertian shading mode, right top: reflectance mode, bottom: shaded mode to visualize the surface orientation.

3. DISSEMINATION AND VALORISATION

As a project introducing technology with a potential for a very large and widespread audience and aiming to attract an Open Source technology community, communication of the aims and results of the project is of utmost importance. The Covid-19 situation unfortunately reduced the opportunities for live contacts and presentations. However, in the starting years of the project a number of live presentations were possible. Since early 2020 presentations and dissemination opportunities were reduced and limited to online events.

The end users and developers of SCML technologies are very heterogeneous and scattered. To make sure other voices in the community were also heard, we paid attention to disseminating the progress and outcomes of this project to the community, both to the end users, as well as the ones who have been developing the RTI and PLD frameworks. At Digital Heritage Benelux 2018 in Amsterdam, the Scanning for Syria expo 2018 in Leiden, Euromed 2018 in Cyprus and RAI 2019 we actively promoted our project to researchers and stakeholders of the heritage communities. At Digital Heritage 2018 in San Francisco we organised in collaboration with Cultural Heritage Imaging a technical workshop and had many interesting and warm discussions with the users and developers of the RTI technologies. Among others, those include Mark Mudge, Carla Schroer and Marlin Lum of Cultural Heritage Imaging (CHI), Taylor Bennet (University of Oxford), Graeme Earl (professor of digital humanities at the University of Southampton and King's College London), and E. Keats Webb (Imaging scientist at the Smithsonian Museum Conservation Institute).

Due to the Covid-19 situation, 2020 had little to offer in terms of live events and encounters with colleagues and end-users. 2020 was the year in which the project intended to do most of the communication, as the products would be ready for testing and demonstration was foreseen. Our presentation about a technical paper for SPIE Optics, Photonics and Digital Technologies for Imaging Applications VI 2020 was, due to the Covid-19 situation, given online. In a number of online international presentations (2020-2021) by members of the project the new pixel+ viewer has been presented, equally in several publications its use has been advocated.

All project partners highly value the outcomes of the pixel+ project. Therefore dissemination and valorisation efforts will continue after the completion of this project.

Conferences and events

Event	Date	Location	Format	Representative
DH Benelux 2018	06/06 - 08/06	Amsterdam	Poster / Demo	C. Vastenhoud V. Vanweddingen
Scanning For Syria	07/06/2018	Leiden	Presentation / Demo	C. Vastenhoud V. Vanweddingen
Digital Heritage 2018	26/10 - 30/10/2018	San Francisco, US	Workshop / Demo	H. Hameeuw V. Vanweddingen
Euromed 2018	29/10 - 3/11/2018	Nicosia, Cyprus	Poster	C. Vastenhoud
Project St. Galler Klosterplan	04/03 - 06/03/2019	St. Gallen	Demo	P. Konijn V. Vanweddingen
The Illuminated Dante Project	21/05 - 22/05/2019	Napels	Presentation / Demo	L. Watteeuw H. Hameeuw

RAI 2019	12/07/2019	Paris	Presentation	H. Hameeuw
SPIE Optics Europe, Photonics and Digital Technologies for Imaging Applications 2020	06/04 - 10/04	Strasbourg (online)	Paper / Presentation	V. Vanweddingen
Tecnologia informatica applicata alle scienze filologiche e librarie	13/05/2020	Napels (online)	Presentation	L. Watteeuw H. Hameeuw
MEMS 2020	04/12/2020	Harvard University (online)	Presentation	H. Hameeuw
The Woodblock Webinar	06/12/2020	Antwerp (online)	Presentation	H. Hameeuw B. Vandermeulen

Fig. 18 - Dr. M. Ionnanides presents Best Poster Award to C. Vastenhoud, Euromed 2018 Nicosia, Oct. 30 2018

Fig. 19 - Dr. H. Hameeuw presents the workshop “Portable light domes in Pixel+, acquisition, viewing and analyses” at Digital Heritage2018, San Francisco, Oct. 26 2018

Website

The main channel for dissemination and valorisation of the pixel+ project’s results is https://www.heritagevisualisation.org. It both introduces the technologies and proposes best practices. The website is hosted by KU Leuven and will be supported in the long term.

From the start of the project KMKG as acting coordinator of pixel+ had a project-webpage online: http://www.kmkg-mrah.be/pixel. Idem for the project partners at KU Leuven: https://www.esat.kuleuven.be/psi/projects/current/PIXELPLUS, https://bib.kuleuven.be/BD/digitalisering-en-document-delivery/digitalisering/pixelplus. Via the communication platform of project partner KBR the press release on the launch of the pixel+ viewer was published: https://kbr.prezly.com/nieuwe-dimensies-werpen-verdiepende-blik-op-erfgoed

Twitter

Via the project partner Twitter accounts of @ArtHistoryBRU, @imagingkuleuven, @kbrbe and @LabHeritage targeted announcements were made when presentations were given, papers were published and the pixel+ viewer was launched.

Blogs

Posts on project events and the launch of the pixel+ viewer have been published on:

- https://portablelightdome.wordpress.com/2018/11/08/pixel-project-first-results/
- https://portablelightdome.wordpress.com/2020/05/18/new-dimensions-take-a-deeper-look-at-heritage/
- https://enrichingheritage.wordpress.com/2020/05/16/new-dimensions-take-a-deeper-look-at-heritage/

Open Data

Source code of the pixel+ viewer: https://github.com/vvanwedd/pixelplusviewer
Source code of the companion site: https://github.com/vvanwedd/heritagevisualisation

Scientific publications

see section 5

4. PERSPECTIVES

The pixel+ project has leveraged several novel web technologies to create a sustainable framework for visualizing and disseminating Single Camera Multi-Light (SCML) results. Data providers (e.g. musea, libraries, ...) have no various options to facilitate the dissemination of their SCML datasets. Firstly, they can view their already existing legacy PLD and RTI datasets in one single web based viewing environment, which automatically enables well documented extra viewing styles (e.g. PLD's visual styles on RTI files). Secondly, they can convert their legacy processed formats to the novel .scml format, again, to be viewed in the same environment. The latter option decreases parsing time to a minimum thanks to a clever way of leveraging new web technologies. Even though a IIIF image server specification for SCML (or even 3D) datasets is not for the near future, the combination of the webviewer and novel web optimized SCML file format offers IIIF image server capabilities without having to install software on the data servers of the data providers, and is, as such, the recommended option. Finally, data content providers have the option to reprocess their existing source image sets (i.e. original SCML data) using new RTI and PLD processing techniques. As the SCML format can hold more than one SCML type at the same time, researchers can quickly compare PTM, HSH, RBF and PLD processing methods on one specific dataset. The pixel+ project hopes that these forms of integration will help in a better understanding of the advantages and disadvantages of various SCML methods.

Still too often, engineers and computer vision researchers tend to focus on the technical aspects and algorithms, and lose sight of other important aspects like metadata. As the project's steering committee consisted of both developers as well as experienced end users, the focus of the project has been to maximize the outcome for the heritage community. Many contacts with stakeholders in the heritage imaging communities were strengthened. Together with ISTI/CNR, the path towards the novel way of disseminating SCML collections is paved. However, working out extensive metadata schemas was not part of the original pixel+ proposal, and was therefore only partially covered. Nonetheless, the new .scml file format was developed with this challenge in mind and is ready to be elaborated on that path.

Centralization and documentation of SCML techniques on the dissemination website, in terms of acquiring, processing, and viewing, will help heritage scholars in better using this fascinating set of scanning technology. Even though the scanning principles and visual outcomes of SCML techniques are relatively straightforward, a real understanding of the various steps involved, will further valorize this technology in the heritage community. In fact, any scanning technology should supply ample documentation about the scanning procedure, the scanning equipment, the various processing steps involved, and what the processed outcome actually represents. When these steps are described as additional metadata, a heritage scholar should be able to more easily assess the quality of a particular interactive 2D and 3D datasets, which, for scientific research, is paramount.

The web viewer, dissemination website and the novel file format should be flexible enough to visualize, document and store future RTI/PLD processed outputs (such as more advanced interpolation techniques in the case of RTI and other material property data (such as Bidirectional Reflectance Distribution Functions) for PLD, as well as local annotation data.

With the pixel+ project, it was the aim to give the use of the SCML technology a renewed impuls. But this will continue to be a challenge. Technologies will keep evolving, institutions curating this type of complex datasets will always have to anticipate and adapt to it. RMAH, KU Leuven and KBR and any other institution interested in the outcomes of the pixel+ project have now made the step to face this and to arm themselves for the near future.

The development of the novel .scml file format and the format converter has demonstrated the importance of decent, well balanced DMPs (Data Management Plan) when complex datasets, such as originating from SCML methods, are used for the imaging and documenting of heritage objects. These relatively young technologies are still in full development, and thus, new ways of processing are still being worked out at a reasonable pace. In such situations, pixel+ shows digital preservation strategies should incorporate solutions for 1. the original capture data, 2. the intermediate processing files, and 3. the final processed files.

Cuneiform tablets, ancient papyri and old manuscripts have preserved the information that is written on them for several millennia. In fact, all cultural artifacts conceal information, hundreds, sometimes many thousands of years old.
Long term preservation of data and the digital age hasn't always been a good marriage. Digital information has been lost, because the medium on which it was stored deteriorated beyond repair, could not be opened on modern computers or couldn't be interpreted any more. Even though the scope of this project was not on long term preservation of SCML data, attention to this problem has been given. A thorough documentation, a restriction of using only widely available, open formats for the websites (which remain accessible after the projects have finished) and SCML file format should tackle some of these problems of what some call the digital dark age.

5. PUBLICATIONS & PRESENTATIONS

- Vanweddingen, V., Vastenhoud, C., Proesmans, M., Hameeuw, H., Vandermeulen, B., Van der Perre, A., Lemmers, F., Watteeuw, L., Van Gool, L. “A Status Quaestionis and Future Solutions for Using Multi-Light Reflectance Imaging Approaches for Preserving Cultural Heritage Artifacts.” Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection. EuroMed 2018. Lecture Notes in Computer Science, vol. 11197, 2018, pp. 204–211. **(including Best Poster Award)** (doi: 10.1007/978-3-030-01765-1_23) (open access)
- Hameeuw, H., Vanweddingen, V., Proesmans, M., Vastenhoud, C., Vandermeulen, B., Van der Perre, A., Watteeuw, L., Lemmers, F., Van Gool, L., Schroer, C., Mudge, M., Earl, G. “Portable Light Domes in pixel+: Acquisition, Viewing, and Analysis.” Digital Heritage 2018 3rd International Congress & Expo (San Francisco). [presentation]
- Vincent V., Vastenhoud C. 2018: Pixel+: Towards integration of 2.5D technologies at Scanning For Syria - Archaeology of the Future Symposium [demo/presentation]
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- Vanweddingen, V., Hameeuw, H., Vandermeulen, B., Vastenhoud, C., Watteeuw, L., Lemmers, F., Van der Perre, A., Konijn, P., Van Gool, L., Proesmans, M. 2020: “pixel+: integrating and standardizing of various interactive single-camera, multi-light imagery” SPIE Optics, Photonics and Digital Technologies for Imaging Applications VI 2020. (doi: 10.1117/12.2555685)
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- Hameeuw, H. 2020: Digital Solutions vs. Endangered Heritage: Reflections on the use of interactive imaging methods, at Methodologies in Egyptology and Mesopotamian Studies (MEMS) - Department of Near Eastern Languages and Civilizations at Harvard University [presentation]
- Watteeuw, L., Hameeuw, H. 2020: MLR applications to artefacts and rare books, digital imaging, viewing, research. The Integrated Portable Light Dome system for Book Heritage Studies. Invited by Scuola di Alta Formazione A. Varvaro, Girolamini

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- Janssens P., Messens F. 2021: How to visualize the surface structure of a 16th century copper plate? A CORS-use case of the Pixel+ Online Viewer and SCML-imaging, at National Libraries Now 2021 Conference. [presentation]
- Hameeuw H. 2021: Producing interactive relightable cuneiform tablets for study and online publishing with MLR methods, at ASOR: ArtiBites workshop. [presentations]

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ANNEXES

Source code of the pixel+ viewer: https://github.com/vvanwedd/pixelplusviewer
Source code of the companion site: https://github.com/vvanwedd/heritagevisualisation