Data Sustainability and Advanced Metadata Management for Scientific Imaging

WHITE PAPER

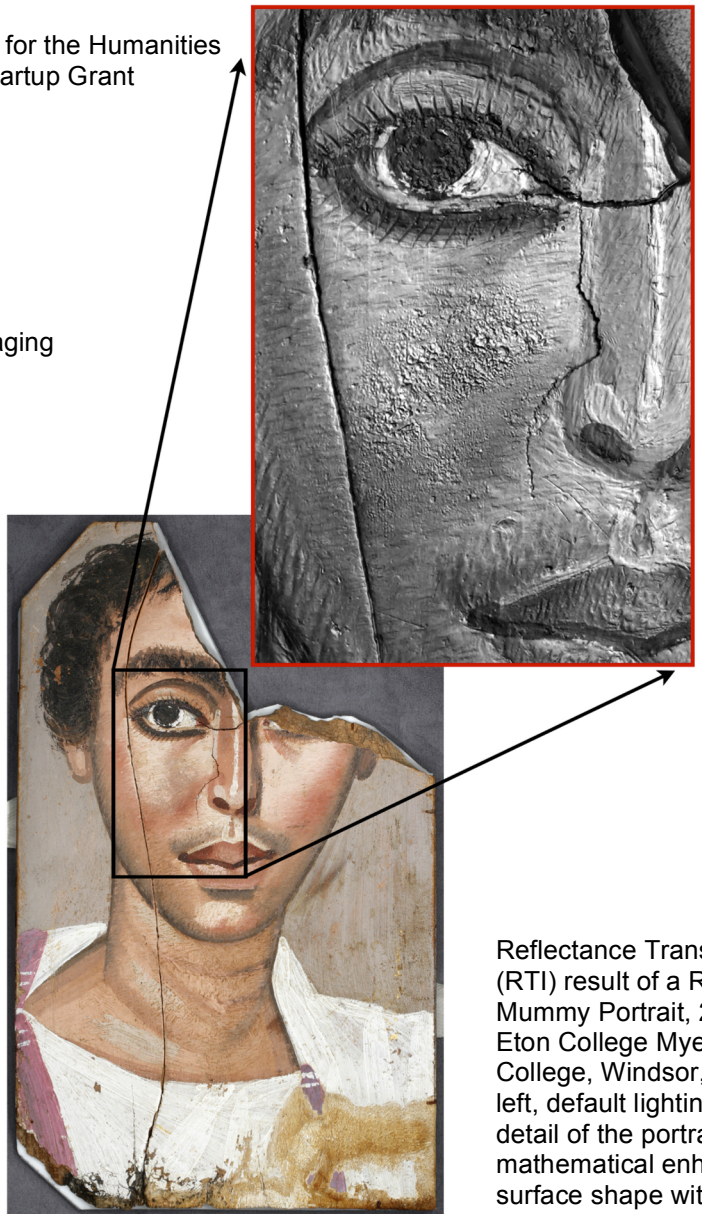
Grant Sponsor
National Endowment for the Humanities
Digital Humanities Startup Grant

Grant Number
HD-51978-14

Project Director
Mark Mudge

Grantee Institution
Cultural Heritage Imaging

Date of Submission
April 15, 2016



Reflectance Transformation Imaging (RTI) result of a Roman Egyptian Mummy Portrait, 2nd century CE, Eton College Myers Collection, Eton College, Windsor, England. Lower left, default lighting view. Upper right, detail of the portrait using mathematical enhancement to show surface shape with no color.

Introduction

Humanity's legacy can be unlocked and shared between people through digital representations. One form of digital representation, the digital surrogate, offers great potential for the advancement and sharing of knowledge. The production of digital surrogates is the goal of museum, library, and other scholarly digitization campaigns.

The purpose of digital surrogates is to reliably represent “real world” subjects in a digital form. Their objective is to enable scholarly and scientific study as well as personal enjoyment without the need for direct physical experience of the subject or place. Their essential scientific nature distinguishes them from art and entertainment. They are built from verifiable empirical data and, like all scientifically acquired information, they require a provenance account of the means and circumstances of their creation.

Today, digital provenance information, essential for science and scholarship, is the least likely type of information to be collected during digitization activities. While widespread generation of digital representations of cultural heritage materials is well underway, little work has been done to ensure the preservation of this data’s digital provenance. Such information is absolutely crucial for current and future reuse of both the original data and the advanced digital representations derived from them. The absence of such contextual knowledge critically threatens the value of these digital representations for scholarly and scientific purposes. This means that much of the new data being generated through advanced digital imaging may already be of very limited use for scientifically grounded scholarship. The current lack of support for managing the context of data acquisition and subsequent history of software operations upon it means that the practitioners of applied disciplines in the humanities cannot effectively exploit these technologies.

Background

The digital photography revolution fostered the adoption of computational photography techniques by many domains in the humanities and natural sciences. Computational photography uses sequences of images to extract information about the imaging subject that is not present in any one of the constituent images. The field encompasses many areas of dynamic research activity based on the convergence of computer graphics, machine vision, and camera/illumination system design. Computational photography overcomes the limitations of traditional photography by using computational techniques to produce a more robust, information-rich representation of our world.

Neuroscientists tell us that what we see is much more the product of the brain than the eye. Perceptual science shows that our brains do not simply “see" a photon pattern passively collected by our retinas. Instead, our brains see a world constituted through multiple neural processing operations on multiple patterns extracted from our normally dual-retinal experience. This is how we live our lives in

a 3D world. Similarly, computational photography allows us to take the photon patterns collected by the sensors of digital cameras and computationally process them into rich representations of the captured subjects.

Examples of computational photography tools include Reflectance Transformation Imaging (RTI), Photogrammetry Structure From Motion (SfM), High Dynamic Range (HDR) imaging, photo-stitching, and multispectral / hyperspectral imaging. The common element in these technologies is the presence of an automatic algorithmic process that generates the resulting digital representation. The algorithmic nature of computational photography promotes the creation of scientific imaging data.

The objective of this project was to create and evaluate a modest but critical part of the worldwide, emerging 21st Century digital ecosystem, designed to preserve and share digital cultural and scientific knowledge. The project's toolset uses the latest documentary science and is an extension of the enormous, worldwide efforts of the last two decades to build a new way to discover and manage knowledge in the digital age. The near-automatic nature of computational photography has advantages for the creation of digital representations for science and scholarship. These advantages, in combination with this project's new metadata and knowledge management methodology, offer greatly enhanced digital data and knowledge use, reuse, and sustainability.

Our Project

The project introduces greatly simplified methods to build a "Digital Lab Notebook" (DLN), which is an essential component of digital scientific imaging. This project has produced a user-friendly software toolkit in the form of two software modules, DLN:Capture Context and DLN:Inspector. The Digital Lab Notebook, built with this software, records the means and circumstances of the digital data's acquisition. This includes the resulting photographic data, the processes by which the data are transformed into digital surrogates of "real world" materials, and the maintenance of this information's archival integrity. All of this organized data and metadata is necessary to evaluate a digital surrogate's quality and reliability. The metadata and knowledge management methodology, the focus of this project, is designed to provide just such digital provenance information to the digital surrogate's potential users and conservators. This makes it possible to document not only the algorithmic transformation of photographic data, but also the context in which the photographs were created. This methodology supports digital representations that are intended for use in interdisciplinary science and humanities scholarship.

The "Data Sustainability and Advanced Metadata Management for Scientific Imaging" project is a continuing collaboration between the project participants, Cultural Heritage Imaging (CHI), Martin Doerr, and Steven Stead, and was begun in 2007. This collaboration continues to work towards the completion of both the Digital Lab Notebook and the knowledge ecosystem in which it will thrive. CHI is an institutional member of United Nations Education, Scientific and Cultural Organization's (UNESCO) International Council of Museums (ICOM). All three

collaborators are current members of ICOM's Conceptual Reference Model working group, with Martin Doerr serving as Chairman. This collaboration was responsible for developing the digital provenance recording extension of the CRM, CRM Digital (CRMdig). People who are designing software to collect Digital Lab Notebook information, which maintains the existing meaningful relationships within the metadata, use CRMdig architectures. Without these tools, building the DLN and all the advantages that flow from it would be impossible.

Many of the scientifically relevant aspects of any computational photography data capture operation are not electronically harvested today. The Digital Lab Notebook's DLN:Capture Context application enables the collection of this metadata. The Capture Context tool goes well beyond the information that is automatically collected by the camera, such as its settings, its make and model, and possibly lens information. The tool collects information describing the entire photographic equipment configuration, the people involved, the project associated with the imaging, the location, the subject itself, and related information. The collected configuration information can include lenses and filters, camera aiming and supporting equipment, equipment used to illuminate the subject, and the description of the illumination's characteristics. When documenting original data capture, these tools expand the range of relevant metadata capture while simplifying this task for the user.

The DLN:Capture Context software simplifies user management of the large volume of metadata through a user-friendly interface. This interface expedites user metadata input with a template process. For example, following a one-time entry of the user's photo equipment and associated metadata, the user creates templates and saves commonly used equipment configurations. At the time of the capture session, these templates can be selected with a mouse click. The software follows a similar process to help the user record and group metadata regarding the locations, institutions, imaging subjects, and people associated with the photographic data acquisition session. An associated document can be saved, either as a linked reference or incorporated into the DLN "in whole" as a saved file. Relevant metadata can be entered to an extent determined by the user, grouped as desired, selected with a mouse click at the time of the capture session, and added to the DLN for a specific set of images.

The software then automatically transforms this semantically structured metadata into both human-readable Extensible Markup Language (XML) and the machine-readable Resource Description Framework (RDF) formats. RDF statements are simple subject-predicate-object statements, such as "Francesca is Spanish," sometimes called *triplets*. RDF is emerging as a key standard for encoding metadata and other knowledge on the Internet. Available, easy-to-use tools can access RDF representations and display them as graphs, which can be intelligently queried. RDF statements can also be represented as Linked Open Data (LOD) containing Internet Universal Resource Locators URLs and/or Universal Resource Identifiers, URIs. The DLN software automatically encodes the RDF statements and associated URLs as

Linked Open Data, which communicates the relationships between entries in the Digital Lab Notebook and simplifies access to its information.

Linked Open Data uses a standard model for data interchange on the Web. This Linked Open Data will be represented as RDF in the Digital Lab Notebook. It will be machine-readable and can be accessible to search engines. This "lab notebook" will enable qualitative evaluation of its associated scientific images, improving access to its information in the worldwide storage and archiving environment. Its data will also be accessible via advanced, semantically organized querying of the stored information." In short, this approach can lead to a breakthrough for people looking for answers: the integration and interrogation of large amounts of separately stored, but related, information. The DLN will be far easier to query and access, making scientific evaluation of digital representations easy and practical.

All the RDF/LOD information can be represented in a graphical form that displays all of the possible relationships between the individual statements. This lays the groundwork to enable the metadata in the Digital Lab Notebook to be concatenated with other relevant information available to it. Such connections would not only enable the serendipitous discovery of new knowledge about a digital surrogate, but also increase the prominence of the digital surrogate in search engines, thus increasing its visibility to those in the humanities and the interested public. This real-time knowledge management framework enables the widespread qualitative evaluation of digital surrogates, today and in the future.

Reflectance Transformation Imaging (RTI), and most other computational photography techniques, involve a chain of tools and processes that are applied to a series of photographic images. Identifying all of the steps and processes and options that users have when creating the RTI data is a necessary part of this endeavor. Appendix A is a flow chart of the RTI processes and the DLN tools that were created and evaluated as part of this project. It includes both a flow diagram and detailed notes about the diagram. Appendix B is a list of all the RTI tools and file formats and their inputs and outputs and current status.

The DLN:Capture Context tool includes a software installer, which installs the open source Postgres database and configures the Capture Context tool for use on both Windows and Mac OS X operating systems.

The main goal of the DLN:Inspector software is straightforward: to automatically check the metadata for the image sets collected and preprocessed for RTI against documented rules and recommendations for camera settings, archival workflow, and preparation of images for future processing. However, the automatically produced metadata created by the camera, added during preprocessing by additional imaging tools, contains some poorly documented metadata. This data also varies among different camera manufacturers and image processing tools (and even within versions of these tools). Significantly more effort than expected was needed to resolve the "in-camera" Exchangeable image file format (EXIF) data ambiguities. Additionally, the subsequent Adobe Camera Raw software's preprocess-generated Extensible Metadata Platform (XMP) metadata issues also needed significantly more

attention than anticipated. The DLN:Inspector tool is intended to work with JPEG and Digital Negative (DNG) files, regardless of which processing tool was used to produce those files.

The 21st Century Knowledge Environment

Museums, libraries, and other archives are challenged by today's deluge of digital information, including advanced digital representations. Over two decades of work by many of the world's top library and museum informatics and knowledge management professionals have created a new, broadly integrated, and *semantically* organized system for knowledge representation. A semantic system documents the *meaningful relationships* existing between pieces of data. It does so by mapping the information to a semantic *ontology.* An ontology is simply a way to describe the things that exist or happen in our world, as well as the relationships between them, in an abstracted and generic way.

The ontology structure used in this project is not just the imaginative product of a committee, but rather is based on years of bottom-up analysis of the different organizational methods used by thousands of museums and libraries. It employs object-oriented, event-based modeling that can harmonize knowledge and different levels of detail from different data repositories, where each local repository uses incompatibly structured ways of organizing data.

The ontology used by the Digital Lab Notebook is the Conceptual Reference Model (CRM) of the UNESCO chartered International Council of Museum's Documentation Committee (CIDOC). The CRM, ISO standard 21127:2014, is an ontology that can represent most of human knowledge and has been empirically designed to support science and humanities discourse.

Similarly, the ontology recommended by the International Federation of Library Associations and Institutions (IFLA) is the Functional Requirements of Bibliographic References, object oriented (FRBRoo). FRBRoo is a subset of the CRM. The partnership of museums and libraries, sharing common knowledge management practices is the foundation of the 21st Century knowledge environment.

The CRM family now includes:

- CRM: Conceptual Reference Model
- FRBRoo: Bibliographic References
- PRESSoo: Periodicals and Serial Publications
- CRMinf: Logical Argumentation Inference Model
- CRMsci: Scientific Observation Model
- CRMdig: Digital Provenance Model
- CRMgeo: Spatio-temporal Refinement

For more than a decade, many of this project's collaborators have striven together to build tools for this 21st Century knowledge environment. The CHI team and their collaborators in this project previously developed the CRM's Digital Provenance Model, CRMdig. CRMdig is an essential part of the DLN.

The CRM is designed to have an inherently harmonizing approach, permitting the integration of knowledge housed in different, incompatibly organized collections and across dissimilar archiving systems, forming a machine-readable "common language." This enables their integration despite possible semantic and structural incompatibilities. In this way, cultural heritage information can be exchanged and retrieved, and museums, libraries and archives can make their information systems interoperable without having to compromise their specific needs or the current level of precision of their data. This mapping structure permits individual collections to retain the advantages of their decentralized information structures, while remaining part of the world's integrated knowledge base.

Next Steps

Additional features for the DLN:Capture Context and DLN:Inspector

Through the process of using and refining the tools and presenting them to others, a number of features have been identified that would improve the usability of the software. These additions could not be implemented within the timeframe and budget of the project. The list includes several minor features, but the most needed one for the DLN:Capture Context tool is a way for users to see and access the resulting metadata outside of the RDF and XML files. This would aid those who are using RTI but are not yet adopting a CRM or LOD approach to metadata. There are several possible visualization solutions, and additional funding would allow their development. The DLN:Inspector tool works well for those who have followed the workflow recommended by CHI. It does provide a human-readable report in addition to the produced RDF. Several reviewers requested that the Inspector tool be modified to support a wider variety of file and folder organizations and workflows that do not use the Digital Negative (DNG) file format.

Enhanced RTIBuilder software

To complete the full DLN tool chain for RTI technology requires an extension to the open source RTIBuilder software. RTIBuilder, jointly developed by PhD candidate Joao Barbosa and CHI, generates an XML log file. This log describes the user-selected processing parameters and other relevant information employed during the computational photography processing phase of the digital surrogate's creation. The proposed software extension will take this XML log, map it to the CRM, and export it to the Digital Lab Notebook as RDF Linked Open Data.

Extension to other computational photography technologies

While this project specifically dealt with the computational photography technology Reflectance Transformation Imaging (RTI), much of the digital photographic capture and image preprocessing is essentially the same across computational photography technologies.

This project provides a blueprint for future work to extend this methodology broadly throughout the computational photography field. This would enhance the

long-term sustainability and reusability of the digital surrogates produced by these technologies. Possible future extensions of the work to additional computational photography technologies could include, but are not limited to: 3D photogrammetry, the capture and measurement of textured, 3D geometry of "real world" subjects; multispectral/hyperspectral imaging, the capture and analysis of photographs illuminated by different wavelengths of visible and invisible light; and high-dynamic-range imaging, the extension of photographic tonal range to contrast levels far beyond those of standard low-dynamic-range cameras.

The use of this metadata approach was explicitly discussed for photogrammetry by the collaborators in this project, and some of the similarities and differences have been identified by the project team and the case study participants at the University of Texas, Austin.

Automated archival submission

Prior to beginning this NEH Start-up Grant, the project collaborators did the foundational work to map the features of the ubiquitous archival submission and distribution carrier, the Metadata Encoding and Transmission Standard (METS), to the CRM. This is the archival standard used by the Library of Congress, the California Digital Library, and the University of California system, as well as many other leading archives. Project member Martin Doerr mapped the CRM-based knowledge management structures to the knowledge management structures of METS.

This mapping enabled the production of software that can automatically package the original archival photographs, the completed digital surrogates, the DLN, and links to any relevant open source software into a widely recognized METS Submission Information Package (SIP). This work also identified which files are important to keep, and which files are “intermediate,” i.e., produced during processing but need not be saved. The resulting SIP package can then be submitted to the selected archival location. A similar process of mapping the CRM-based DLN knowledge management structures to other archival format submission structures could yield similar results.

Evaluation and Case Studies

Evaluation, discussion, and feedback were essential parts of the project. Many discussions took place with people adopting RTI and with others working in the knowledge management space. The DLN:Capture Context and DLN:Inspector tools were presented and discussed as part of many lectures, workshops, and training sessions. (See “Dissemination” below.) In addition to these formal presentations, discussions took place with an international group of museum professionals and nonprofit organizations. Towards the end of the project, six focus group sessions of approximately two hours each took place.

Extensive discussions with adopters of the CRM at the Getty Conservation Institute and the British Museum ResearchSpace project also took place. These discussions

allowed an extensive examination of the metadata approach and the specific usage of the CRM ontology.

In all cases, the work and its significance were very well received. Both the British Museum and the Getty Foundation have adopted the CRM as their knowledge management architecture with a focus on the core subject metadata. Both organizations see the potential for this work to complement and expand their existing projects by providing digital provenance metadata for their digital surrogates.

Case study meetings

Towards the end of the project, a more formal evaluation of the tools was done using a case study methodology. A series of meetings were set up with small groups of people with similar experience or interest in RTI or data management and archiving. The sessions started with demonstrations of the tools and allowed for discussion time. In some cases participants tried out the tools for themselves. A follow-up online questionnaire was provided to collect their input.

The primary case study sessions took place at the University of Texas, Austin, hosted by Professor Adam Rabinowitz of the Classics Department. Dr. Rabinowitz is a long-time user of RTI and more recently of photogrammetry. He is also involved in various metadata projects, and he cares deeply about longevity of data and data reuse. Adam set up five two-hour focus group sessions over three days. Each focus group included three to five participants. Two of the groups were not users of RTI: a group of museum staff and one of library staff. Both of these groups are potential users of RTI, and, in the case of the library staff, they are very interested in data access and reuse. By structuring the sessions in this way, the demonstrations and discussions could address the needs of the participants and their interests.

A sixth case study session took place with Dale Kronkright, head of conservation at the Georgia O'Keeffe Museum. Mr. Kronkright has been using RTI technology with the museum collection for many years, and he provided advice and feedback throughout the project.

Feedback received

The overall feedback was extremely positive. The case study participants felt that both DLN tools were easy to use and performed useful functions. The DLN:Capture Context tool has a more complex interface and requires greater user engagement and interaction. The participants noted consistency in how the software worked and how items could be added and edited. People appreciated the ability to smoothly duplicate existing information and edit it to easily create new items. Another common reaction was that people were very pleased with the ability to record a lot or only a little detail, and the fact that whatever they recorded could be easily reused.

A few sample quotes, from the evaluations:

> *I think that the clean and consistently organized UI and the resulting automation for the creation of capture image metadata are the GIANT LEAPS here. Consistent metadata creation with fielded organization of fundamental capture context is THE KEY to image-based analytical data being searchable, usable and meaningful in the future. Without it, imaged based scientific measurements and observations can not be comparatively used in the future.*
>
> *The tool is well-designed and its biggest strength is the ability to capture a very rich and properly structured set of metadata. It allows the user to input as much or as little as they have available.*
>
> *Powerful data management and data documentation tool for generating CIDOC-CRM records under the hood.*
>
> *I'd like to see it applicable to a wider range of complex data sets, including photogrammetry.*
>
> *I think that some work will need to be done to adapt the metadata wrapper to the simpler needs of many institutional repositories.*

Participants requested several additional features during the discussions. The most common request was for the ability to map the data to other metadata systems so that it could be used immediately with existing projects. The metadata files are in a text format and are quite small. These additional mappings, or intermediate ways of looking at the results, would be in addition to the fully organized RDF and XML metadata that is currently produced. While the participants saw value in the approach, they also wanted a "bridge" between their current practices and those they might adopt in the future.

Dissemination

CHI has widely disseminated news of this grant project and the upcoming software tools via the following talks and participation in conferences during the 20-month project period:

- *Fostering Transatlantic Dialogue on Digital Heritage and EU Research Infrastructures: Initiatives and Solutions in Italy and in the USA:* Meeting hosted by the Library of Congress, December 2014, Washington, DC. Mark Mudge presented the DLN:Capture Context tool to the leaders of the following European organizations: the Integrated Platform for the European Research Infrastructure ON Culture Heritage (IPERION-CH), Digital Research Infrastructure for the Arts and Humanities (DARIAH – IT), Advanced Research Infrastructure for Archaeological Dataset Networking in Europe (ARIADNE), and the Collaborative European Digital Archive Infrastructure (CENDARI). The unanimous response was that the DLN:Capture Context software will be a welcome addition to their ongoing projects and will be compatible with other ongoing EU-sponsored programs.
- *Advances in Computational Photography Techniques for Art Conservation and Digital Documentation*: Talk presented at the Metropolitan Museum of Art, December 2014, New York, NY

- *Advances in Reflectance Transformation Imaging (RTI) for Digital Archaeology*: Talk presented in the program "Science for Parks, Parks for Science" at UC Berkeley in association with the National Park Service and National Geographic,March 2015, Berkeley, CA
- *Computational Photography Techniques for Scientific Recording and Analysis: RTI, Algorithmic Rendering, and Photogrammetry*: Workshop presented at the Society for American Archaeology (SAA) Annual Meeting, April 2015, San Francisco, CA
- *Photogrammetry and Reflectance Transformation Imaging (RTI):* Half-day workshop presented at the Cultural Heritage Imaging Professionals Conference (an invitation-only event) held at Stanford University Libraries, July 2015
- *Reflectance Transformation Imaging: Generating Digital Representations of Cultural Heritage Objects:* 4-day RTI training course delivered at CHI studios, October 2015, San Francisco, CA; and at Johns Hopkins Archaeological Museum, October 2015, Baltimore, MD
- *Computational Photography Techniques for Cultural Heritage: Photogrammetry and Reflectance Transformation Imaging (RTI);* Half-day workshop presented at the Museum Computer Network Conference, Minneapolis, MN, November 2015.

Lessons Learned

This project included software design and development, analysis of the workflow and usage patterns of imaging practitioners, and an opportunity to present the newly developed tools and get feedback. Overall, the project was a success, and two new and valuable tools will be made available as open source software in mid-2016.

Successes

The National Science Foundation supported the early problem description, major feature requirements, use cases, initial specifications, and an early version of the software for the Capture Context tool. During this NEH-funded project, the Inspector tool was designed and built from the ground up, and the Capture Context tool was refined and features were added and tested. We found that it was critical to have good requirements documents completed before the developers laid out the specifics of what would be coded. The requirements documents described who the users are, what they need to do, what features are important for their success, and how the users would interact with the tools. Having detailed documents and specifications was also critical in deciding how to resolve issues and problems that came up along the way. This was especially so because we were both a physically distributed team and from different backgrounds. For example, the CHI team has extensive experience in using the RTI technique in a variety of settings and projects. The developers knew how to write the applications, but didn't have first-hand knowledge of the situations faced by users. Recognition of these different backgrounds aided the team in developing useful software.

We found the advice and feedback from the case study participants invaluable. This was true both in the tool-building stage and in the case study tests where the nearly complete tools were used.

Challenges

It is hard to predict the necessary time and budget for software development, especially when the type of software under development has never been written before. Building on existing tools is much more predictable. A corollary to this is that software that has dependencies on other software applications and specifications that are not directly part of the project can create delays.

Even though the team developing these tools was comprised of seasoned software developers and project managers with decades of experience, the tool building operation encountered complexities not identified in the initial requirements and specification process. There are many examples.

DLN:Inspector The concept of the Inspector tool is quite straightforward, and the team did not think it would take much time to code and test it. However, the amount of metadata to inspect within the Extensible Metadata Platform (XMP) image metadata carrier is enormous. Although it is an international standard with an ongoing Metadata Working Group, the XMP specification does not always describe the fields thoroughly. Additionally, different camera vendors and software creators do not always use the same fields in the same way. There are also optional fields and fields that have been updated and have two versions; for example, "Tone Curve 2012" and "Tone Curve." These variations required significant time to manage, determine the correct requirements, and test. We could have chosen to check only a handful of the most critical metadata items, but we decided it was important to be thorough in our approach. Even so, there will likely be some tweaks needed in how we handle all this metadata in future versions, as more users have a chance to try out the tools.

DLN:Capture Context The team understood from the beginning that this tool had some difficult challenges to solve. As expected, the core functionality supporting metadata acquisition of photographic equipment setups, people, places, subjects, and projects required work, discussions, and compromises.

Some of the unexpected challenges of developing software that has never been done before emerged when working within the existing systems for Linked Open Data and the CRM. The project raised a number of practical implementation issues within the CRM environment that had not been previously addressed or required more conceptual development. Martin Doerr and Erich Leisch worked knowledge management magic to make these successful tools possible.

The DLN:Capture Context tool, while ultimately designed with an eye toward all computational photography-based digital surrogates, is solving a specific problem set for digital provenance information for RTI data and results. A primary goal of the tool is producing metadata that can work with data being generated by people all over the world working in disparate organizations, institutions, and collections.

Adoption of a software tool in such diverse contexts requires great simplification, intuitive ease of use, and compatibility with the skills of existing working cultures. The team put great effort into refining the user interface design to meet these design criteria. Also, finding a balance between letting people enter extensive information, but not requiring it, and still providing an intuitive user experience, was a challenge.

This project also contains a lesson in patience, as the tools to examine and combine the output metadata are not yet fully implemented. In a project with the narrow scope of digital surrogate DLN capture, there remain dependencies on tools under construction by other collaborators in the worldwide development effort. The completion of this additional work is necessary for the broader 21st Century vision of the semantically connected world of linked data to reach its full potential.

Conclusion

Digital surrogates of our "real world" cultural heritage can robustly communicate the empirical features of their subjects. When digital surrogates are built transparently, according to established scientific principles, authentic, reliable scientific representations can result. These representations allow repurposing of previously collected information for novel purposes and enable collaborative distributed scholarship. Information about the digital surrogates stored in a semantically rich "common language," accessible to and from locally determined archiving architectures, permit the interlinking of information across many collections. Digital surrogates organized within the 21st Century knowledge environment demystify the investigation of vast amounts of information to efficiently find relevant material. Open digital surrogate archives remove physical barriers to scholarly and public access and foster widespread knowledge and enjoyment of nature and our ancestors' achievements.

For more information about the project, and to download the software and example data, please visit the project webpage at CulturalHeritageImaging.org.

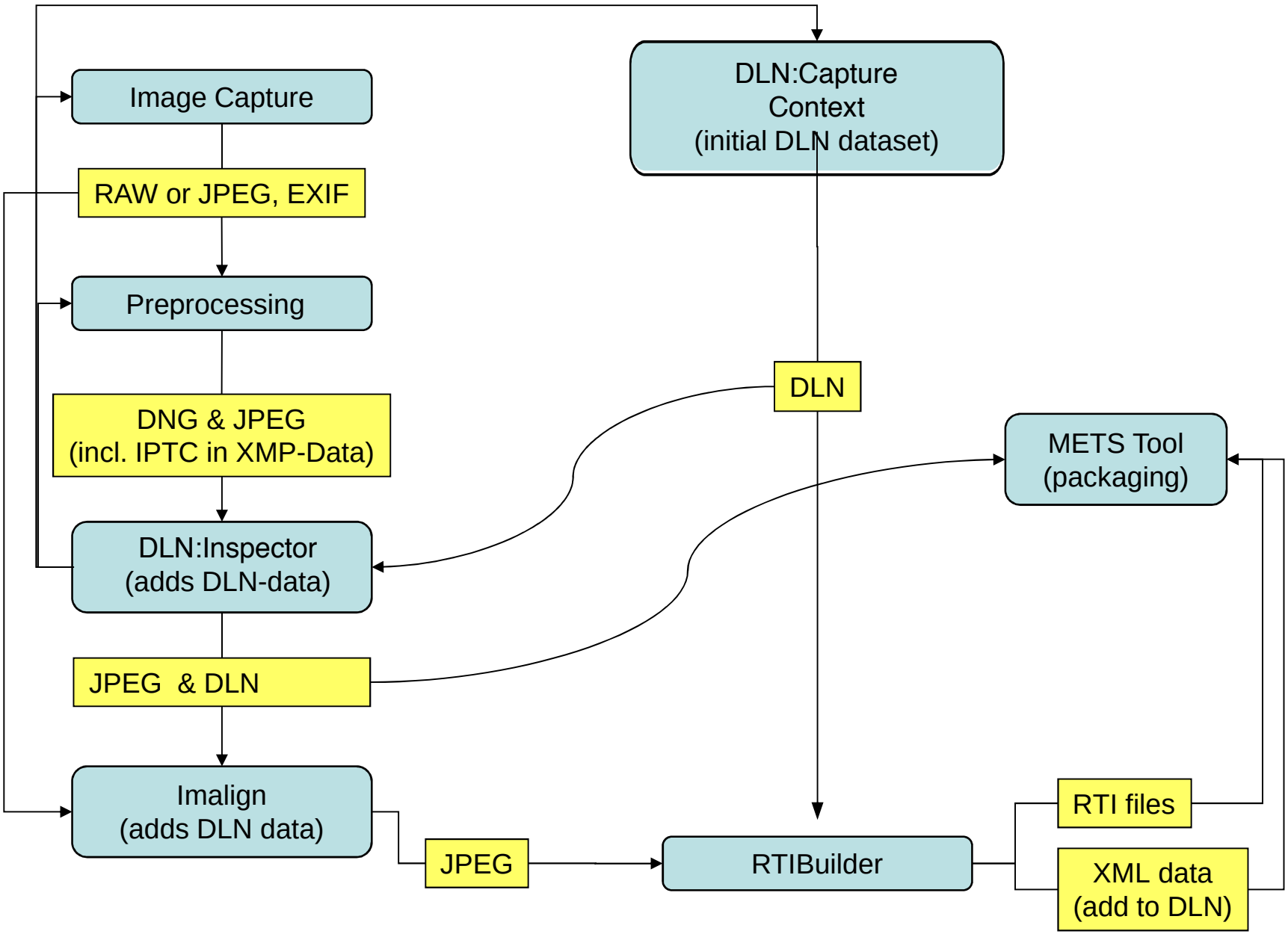
Please note: Any views, findings, conclusions, or recommendations expressed in this website do not necessarily reflect those of the National Endowment for the Humanities.

© 2016 Cultural Heritage Imaging. All rights reserved.

This work is licensed under the Creative Commons Attribution-Noncommercial-No Derivative Works 3.0 United States License. To view a copy of this license, visit http://creativecommons.org/licenses/by-nc-nd/3.0/us/

or send a letter to Creative Commons, 171 Second Street, Suite 300, San Francisco California 94105 USA. Attribution should be made to Cultural Heritage Imaging, http://CulturalHeritageImaging.org.

RTI and Digital Lab Notebook (DLN) Process Flow Chart



chi

culturalheritageimaging.org

Cultural Heritage Imaging
a nonprofit corporation

Notes for RTI and DLN Process Flow Chart

The creation of a Reflectance Transformation Imaging (RTI) result requires several steps and the use of multiple software tools. It begins with capturing a set of photographic images with light in different positions relative to the subject. This set of images then goes through a series of processing steps, and the user has various choices along the way. Multiple results may be created from a single set of images. The process flow chart shows the software processes and the creation and flow of data, including the Digital Lab Notebook (DLN) creation and how it is updated at each process step.

General Information

- Blue boxes represent processes. These are software tools, except in the case of "Image Capture" which is the process of capturing photographic image sets. (See the Image Capture section below for more details.)
- Yellow boxes represent data.
- Arrows show possible paths through the tools.
- Note that some processes may be performed more than one time during the lifecycle of an RTI image set.

Image Capture

There are several ways that image sets for RTI and AR can be captured and downloaded to a computer. This process flow diagram does not attempt to describe them. It assumes that the result is a set of images in either camera RAW or JPEG format. It also assumes that there is EXIF data stored in those images.

Software Tools

- DLN:Capture Context – Creates the initial Digital Lab Notebook (DLN) data stored as RDFs. Supports creating templates for equipment, locations, institutions, and people. At the time of image capture, this tool can create detailed metadata about all aspects of the capture setup, who is involved, and why the images are being taken. It simplifies collection of imaging subject metadata. It is flexible to allow users to create as much or as little of this data as meets their needs.
- Preprocessing – We recommend that users capture images in a camera RAW format. These must be converted to an archival format with the conversion metadata present and intact. We recommend the DNG format. In addition, JPEG images are created as intermediate files used by the RTI software. There are a variety of tools that can be used for this initial preprocessing, including software from Adobe Systems and free tools.
- DLN:Inspector – The software validates that images meet RTI criteria for a valid image set. For example, it checks that all images in the set were taken with the same camera settings. The tool also verifies that preprocessing steps meet the requirements. For example, all images in the capture set must have the same processing steps applied to them, such as white balance or exposure compensation. Certain processing options can make the resulting file unreliable, such as applying sharpening or contrast curves. If these have been applied, the Inspector flags it as an error.

Additionally, the software checks that the metadata in DNG files matches the metadata in JPEG files. The Inspector produces an HTML report and also creates an RDF file. Some errors can be fixed by the user, such as those made in the image preprocessing steps. If errors were made in the camera settings, this requires that the image sequence be recaptured.

- Imalign – An optional tool that checks images for pixel alignment and makes adjustments to individual images in the set to precisely align images, using a variety of algorithms. While this step is not required, aligned images produce much more accurate results.
- RTIBuilder – This tool reads in a set of validated and aligned JPEGs. It produces RTIs using a choice of algorithms. The tool manages the overall process of creating RTIs and can build multiple results from a single capture set, such as different cropped areas, different algorithms for calculating the RTI, and different options for each algorithm. It stores processing history in the DLN.
- RTIViewer – This tool allows users to view and dynamically relight RTI files. It also can apply mathematical enhancements (see Appendix C, Illustrations and Figures). It offers the option to create 2D images of specific views within the RTIViewer environment.
- METS tool – This is a planned tool for creating a METS wrapper for the original images, DLN data, and finished products from a single capture set. Note that other archiving packages are also possible additions to the tools. Also note that part of preparing the data for archiving includes throwing away intermediate files that can be recreated and are not needed. The DLN helps make this possible.

See also Appendix B, RTI Software Tool Chain, for more details on the available RTI tools and file formats.

Definitions

- DLN – Digital Lab Notebook – This term refers to the managed data produced by the tools and saved as RDFs for each image capture set. The DLN: Capture Context tool produces the original DLN with information that cannot be collected automatically, such as equipment details, location, institutions, and people. This can be read in and added to by the subsequent tools.
- DNG – Digital Negative Format – This is the recommended archive format for original photographic images in the RTI and AR workflow. DNG is an extension of the TIFF format. The conversion process converts the proprietary camera RAW image data to a 16-bit TIFF and adds an XMP data structure. The philosophy of a DNG is that the image data is never modified. Instead all changes to the image are stored as metadata in the XMP file and applied when the file is opened. (These include functions like cropping, while balance, brightening, etc.) This enables tracking of all transformations and also the ability to get back to the original image data with no processing applied.
- EXIF – Exchangeable Image File Format – Most cameras collect data about the camera settings and store that data in the image files produced by the camera. This includes camera make and model, date, and camera settings such as shutter speed and ISO.
- XMP – Extensible Metadata Platform – This is a data structure standard for image files. It includes standard data such as EXIF and IPTC. It also contains data conversion information for images converted from a camera RAW format to the DNG format. An XMP data structure is included within DNG files and may be included in JPEG and TIFF files, depending on how they are created. Additional information may be available in the XMP data structure. XMP can be exported as a separate file.

chi

culturalheritageimaging.org

Cultural Heritage Imaging
a nonprofit corporation

RTI Software Tool Chain

Component	Description	Author/ Language	Input	Output	Dependencies	Status	Notes
Image Capture							
EOS Utility (Optional) Highlight Method	Drives the camera from a computer - available for Windows and Mac	Canon/ binary only	User specified camera settings, folder locations, filenames	Images that can be numbered, named and saved to specified folder	Comes with Canon cameras - can be updated online	Consumer tool from Canon - does not create log file, but images contain EXIF metadata	Can use a Nikon alternative with Nikon cameras Used for highlight method and for general testing of a camera setup
DSLR Remote Pro (Optional) Highlight Method	Third-party software for driving Canon or Nikon cameras when tethered to a computer	Breeze Systems commercial software	User specified camera settings, folder locations, filenames	Images that can be numbered, named and saved to specified folder	Separate purchase – runs on Mac and Windows	Consumer grade tool from Breeze Systems	Used for highlight method and for general testing of a camera setup
Capture to card on camera Highlight Method – no software used	Users may shoot RTI images directly to the card on the camera using a remote trigger for the camera, without tethering to a laptop	Requires a remote trigger that could be a cable or wireless	N/A	Image files saved on flash card in camera	User must keep track of when sequence starts and ends to separate test images from the true capture sequence.		User must handle file naming and add a sequence number to the images

Component	Description	Author/ Language	Input	Output	Dependencies	Status	Notes
CHI capture client Dome Method	Drives CHI-designed lighting domes. Fires lights and Canon SLR cameras - Windows only	Tim Lindholm, Prabath Gunawardane C++	User-specified data for number of lights and location and naming of captured images. Supports a turntable for use with a multi-view unit	A named, numbered image sequence saved to a specified directory on the computer. A log file of images taken and all the settings	Works with only 2 types of CTI controllers. Has been tested in 32, 40, and 48 light configurations. Has a version for Arduino controllers. Uses Canon SDK Windows only	Sometimes needs to be recompiled against updated Canon SDK to support new cameras	Low volume of users, just those with a CHI-built light array
* Shooting log template	An Excel spreadsheet template for information about the capture session. It includes some equipment and setup information, who was present, and basic object information	Carla Schroer Excel document	Filled out by user at time of capture. Can support multiple capture sets as part of a larger session, possibly over multiple days	An Excel spreadsheet (can be output as comma delimited text)	Is a manual process and therefore error prone and likely for people to use different terms and/or spellings for the same thing	In use during CHI training sessions and given to training participants. Used at all training sessions beginning in March 2011 at NYU (includes all 21MP training sessions)	This will be obsolete when the DLN:Capture Context is in place

© Cultural Heritage Imaging, 2012-2016

Component	Description	Author/ Language	Input	Output	Dependencies	Status	Notes
* DLN:Capture Context	A tool to build and use templates for gathering information about equipment, location, basic object data, and who was present, etc. for a capture session	CHI, Erich Leisch, Martin Doerr C++	User created records of equipment, people, institutions, locations, subjects, and projects	Template files, RDF and XML as Linked Open Data mapped to CRMdig for a specific capture set		Close to 1.0 release	Some additional features for a future release have already been identified
Image Preprocessing							
Photoshop or Lightroom / Adobe Camera RAW	Convert RAW files to DNG and perform needed corrections	Adobe binary commercial product	RAW files from any camera make or model	DNG files with transforms such as white balance and exposure saved in XMP data. Also includes EXIF data from camera capture	Relatively expensive. Many institutions already use these tools,, but they are a barrier to smaller institutions and those with fewer resources	Looking for a replacement that is cheaper or free. Can get free DNG converter from Adobe. Need some other tool for the other corrections	Most of the free tools like Gimp, RAW Therapee, and Dark table do not fully support DNG file
* DLN:Inspector	Check RTI image sets after preprocessing to ensure the camera settings and	Ron Bourret C++	Folders that contain image sets for RTI (can do batch processing)	An HTML report of what was checked and any errors or warnings found. Also can create RDF	Requires that the use followed the recommended workflow and folder structure when creating RTI data	1.0 will ship in May, 2016	If more funding is obtained, will allow a broader set of folder names and structures. Can also be modified to support photogrammetry data sets

© Cultural Heritage Imaging, 2012-2016

Component	Description	Author/ Language	Input	Output	Dependencies	Status	Notes
Imalign	A tool to correct minor movement in capture sets intended for RTI. Assumes all images in the set are intended to be aligned with each other	Sema Berkiten / Szymon Rusinkiewicz Princeton C++	A capture set intended for RTI. Supports multiple file formats including RAW, TIF, and JPEG	An aligned set of images along with a text "sidecar" file showing the transformations applied	Cannot currently write out to DNG format. If DNG is desired archive format for original captures, must use alternate tool for that process	Close to 1.0 release. Working on documentation and final bug fixing	Likely most common use will be to produce JPEGs for input to RTIBuilder
RTI Processing							
* RTIBuilder	Manage the process of creating RTIs from capture sets. For highlight RTI, has features to determine light positions using reflective spheres contained in the images. Also can be used with dome-captured data	U. Minho/ Java	Image set in JPEG format. Images should be aligned and preprocessed as shown in preprocessing steps	Can create both PTMs and RTIs using the PTM fitter or HSH fitter (user choice), highlight file (.hlt), light position file, (.lp), and log file	Uses fitter programs that are outside of the RTIBuilder. HSH fitter is packaged with the software, PTM fitter is a separate download to due to licensing incompatibilities	Version 2.0.2 released in Fall 2011 on CHI website. 3.0 release will not ship. A complete rewrite to C++ in version 4.0 is underway .	Allows reprocessing capture sets to create multiple RTIs in either format and with different options, crops, sizes, etc. In other words, multiple finished RTIs are often the output from this tool, including reprocessing a data set at a later time.
ptmfitter	Processes an image set and light positions into a PTM	HP Labs/ binary only	Image sequence in JPEG format and .lp file; command line interface	Polynomial Texture Map - PTM			Contains HP IP. Available free for non-commercial use
* hshfitter	Processes an image set and light positions into URTI	UCSC/ C++	Image sequence and .lp file; command line interface	RTI format	.lp file		Originally written with MATLAB - still needs some performance tuning

© Cultural Heritage Imaging, 2012-2016

Component	Description	Author/ Language	Input	Output	Dependencies	Status	Notes
RTI Viewers							
* RTIViewer	Views RTI and PTM files, dynamic relighting, and mathematical enhancements	CNR Pisa/ C++	PTM or RTI file	Can create images of specific lighting views saved as JPEG or PNG	Standalone application	Version 1.1.0 is in current use	More user-friendly than PTM Viewer, also includes detailed user guide
ptmviewer	Original research viewer from HP Labs for relighting and enhancement of PTM files	HP Labs Binary only	PTM file	Can create images of specific lighting views saved as TARGA files (.tga)	Standalone application	Has not changed in many years. Has some features not in other viewers (fill lights, extrapolating normal space)	Free for non-commercial use. Limited interface and documentation – research tool. Very robust
Applet Viewer	Views PTM file, dynamic relighting, and mathematical enhancements - runs over the web	Cliff Lyon/ Java	PTM file	None	Works only in a browser context from an HTML page - no standalone version	Has missing features, but no one is working on it. Streaming approach for web is being developed separately.	A little clunky but works reasonably well with small files (< 8MB) over the web – source code is available under GPL 2 license
WebRTIViewer	Supports large RTI files over the web. Has pan, zoom and relighting. No mathematical enhancements	CNR Pisa/ HTML 5 and WebGL	PTM or RTI file prepared for the web through a utility	None	Requires that you run your RTI file through a utility that prepares it for streaming on the web. Requires the user to write some HTML code	Available now as open source.	Does not support mathematical enhancements, snapshots, and various other desired features. Is the basis for a proposed updated viewer (not yet funded)

© Cultural Heritage Imaging, 2012-2016

Component	Description	Author/ Language	Input	Output	Dependencies	Status	Notes
RTI File Formats							
.ptm	File format for Polynomial Texture Maps	HP Labs / Published in 2001 as an open format	N/A	N/A		Finished file format published in 2001 - will be replaced by RTI	This file format has a number of limitations, prompting the development of the new RTI format in 2007-2009
.rti	RTI format. Designed to support PTMs, files produced by the HSH fitter, and additional future algorithms	UCSC, Tom Malzbender, CNR Pisa, Martin Doerr, CHI	N/A	N/A	Specification is available via the CHIForums and by request.	Draft spec available. Need to finalize metadata structure (XMP is contemplated in current draft). Not funded to complete	In use now, produced by HSH fitter, and read by the RTIViewer
.lp	Light position file - used with an image set as input to the fitter algorithms.	Tom Malzbender, HP Labs	N/A	N/A	Prone to breakage if spaces are used in file pathnames	Finished file format used by both PTM fitter and HSH fitter	Very simple file: number of images in the sequence, full path to each image, and x,y,z coordinates for light position
.hlt	Highlight file - used to show the x,y co-ordinates of highlight on a sphere for calculating the 3D light position	HP Labs	N/A	N/A		Finished for single sphere calculations	Likely need a different version for calculating the LP from 2 or more spheres (which is more precise)

Notes:

- = Asterisked items are those for which the source code is available in the CHI source code repository.
- PTM = Polynomial Texture Maps
- RTI = Reflectance Transformation Imaging
- DLN – Digital Lab Notebook

© Cultural Heritage Imaging, 2012-2016

Illustrations and Figures

Reflectance Transformation Imaging (RTI) and Photogrammetry

Figure 1: Three images from the same Reflectance Transformation Image (RTI) with the light source coming from three different directions.

Figure 2: Two images of a coin commemorating Julius Caesar's Funeral Games. A comet is circled in its full context and then magnified. Due to heavy wear, there is significant abrasion of the coin's surface features. On the left, the coin is seen unenhanced. On the right, the coin is seen in specular enhancement mode, which demonstrates superior clarity. Easily discernible are the four rays of light surrounding the comet along with the triangular comet's tail extending behind it at approximately the "five o'clock" position.

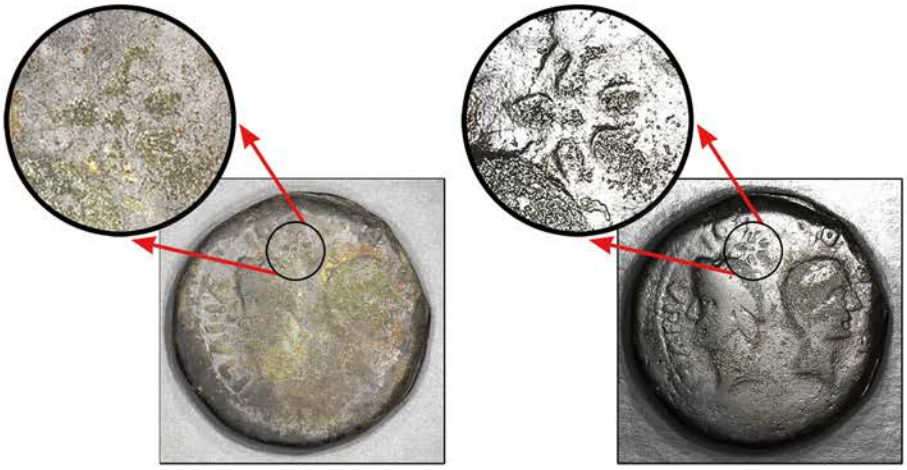
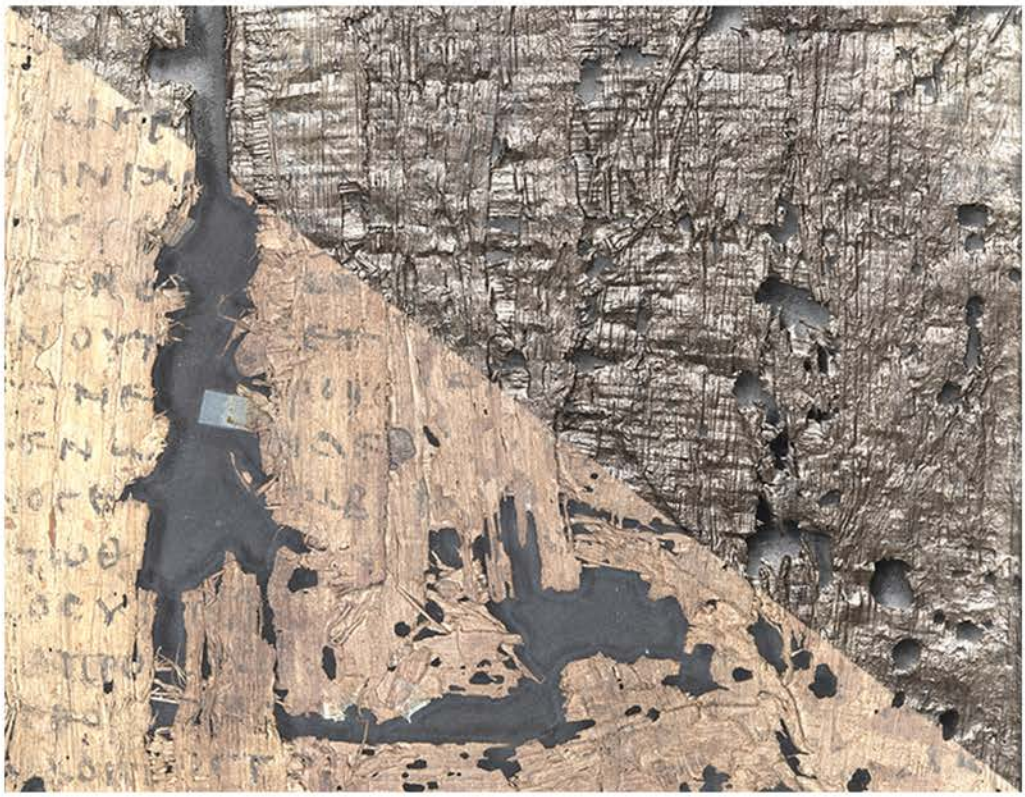


Figure 3: Two images of the obverse of a Merovingian Triens. The image on the left is one of the input images for the RTI. It clearly shows two areas, indicated with arrows, where specular reflections have caused data loss. The image on the right is from the resultant RTI and shows complete surface information for the areas in question.

Reflectance Transformation Imaging

Figure 4:
Bronze Etruscan mirror from the 3rd century BCE, 26.4cm X 13.2cm, from the collection of the Worcester Art Museum. An engraved decorative scene depicts four figures thought to represent Castor and Pollux, a female figure, perhaps Helen, and an unknown male figure wearing a crown. A compact layer of stable corrosion diminishes the readability of the image and tool marks. The lower left shows the RTI in "default" lighting; the upper right of the figure shows the incised design under specular mathematical enhancement.

Figure 5:
Image detail of the papyrus fragment from the Ephemeris Belli Troiani, authored by Dictys Cretensis, from 200 – 225 BCE, 33cm X 26cm, from the collection of the University of California, Berkeley's Bancroft Library. The lower left shows the RTI in default lighting; the upper right of the figure shows the incised design under specular mathematical enhancement.



Reflectance Transformation Imaging

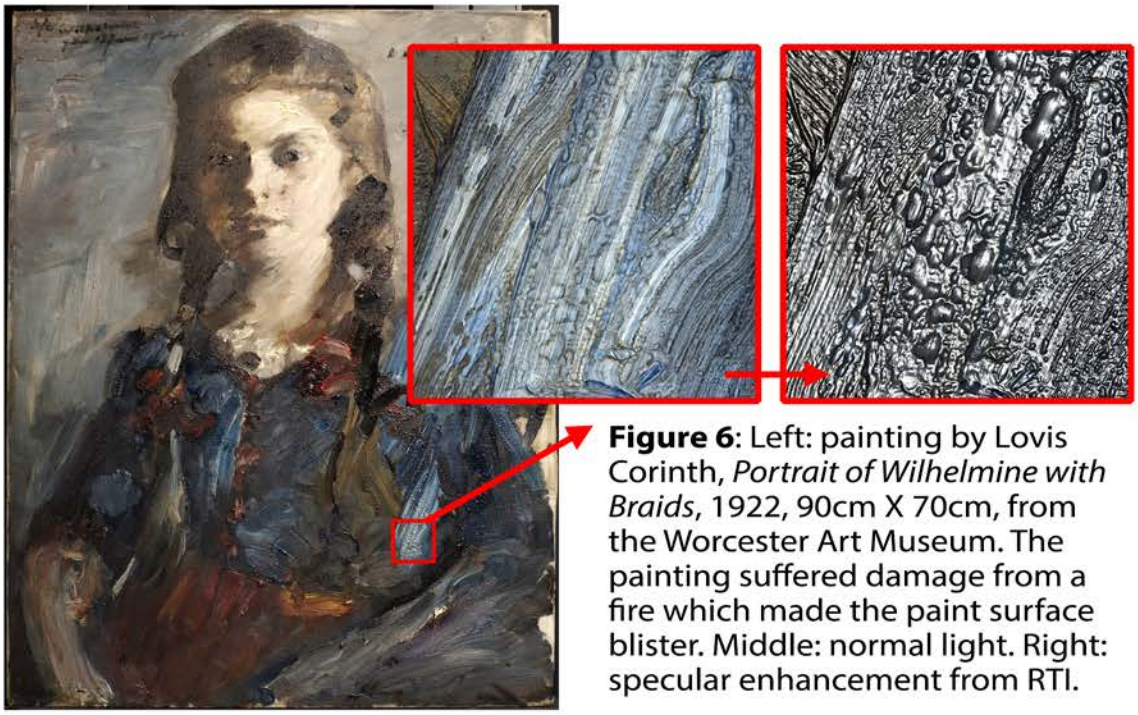


Figure 6: Left: painting by Lovis Corinth, *Portrait of Wilhelmine with Braids*, 1922, 90cm X 70cm, from the Worcester Art Museum. The painting suffered damage from a fire which made the paint surface blister. Middle: normal light. Right: specular enhancement from RTI.

Figure 7: Reflective spheres are placed in images captured for RTI. The positions of the highlights are used to infer the location of the light source.

Figure 8: Setup for shooting an RTI of a small object.

Photogrammetry

Figure 9: Neolithic point from Sweden mounted on turntable for 360º capture.

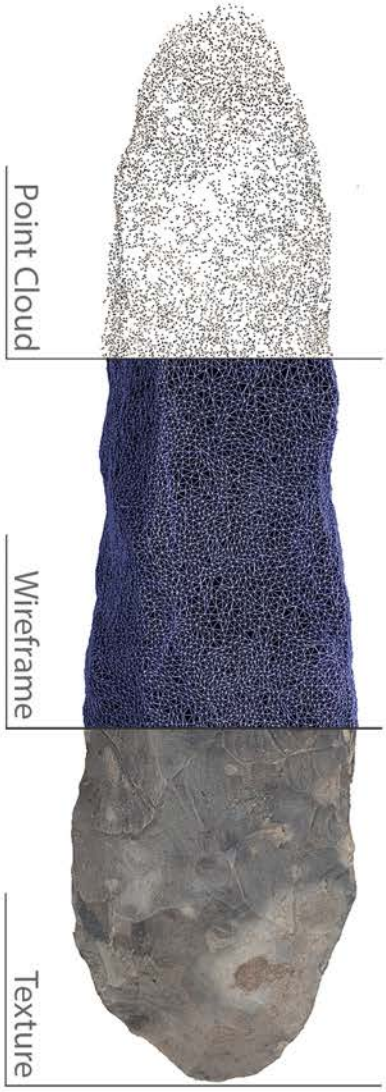


Figure 10: Neolithic Swedish Point from ~2200 BCE, 19.8cm long, showing three different forms of processed 3D information: **Point Cloud** shows points reprenting positions on the surface of the subject. The **Wireframe** is a polygonal mesh constructed from the point information. The **Texture** view shows the surface material taken from the original photos mapped to the 3D representation. The mapping is exact since the 3D info came from these photos. The density of the Point Cloud and Wireframe were reduced by 95% for this illustration.

Figure 11: Wireframe view of the full 19.8cm long stone tool.

Photogrammetry

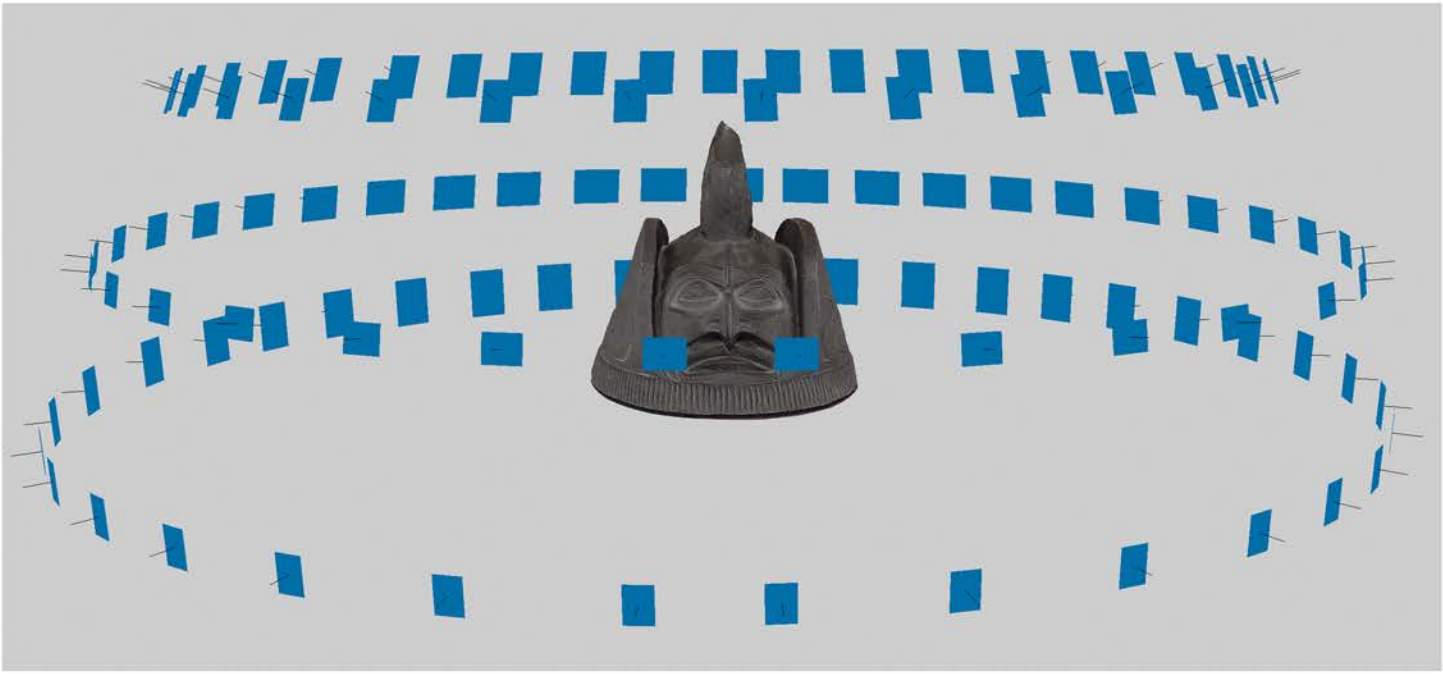


Figure 12:
This is a Tlingit helmet made of carved wood by artist Richard Beasley, 1998. The blue rectangles represent the camera positions for the photogrammetry project. The helmet was placed on a turntable and three rows of 36 images were captured.

Figure 13:
Three views of the 3D model created from the above project. The image combines three views of the model, illustrating wireframe, solid, and texture views

Photogrammetry

Figure 15a

Figure 14:
Illustrations of the processed 3D model of a rock art panel from the Owens Valley, CA. Figure (15a) shows the rock art panel in its context. Figure (15b) shows a textured 3D model of the rock art panel. Figure (15c) shows a detailed view of the textured model, which has also been rotated. Figure (15d) shows a detail area with only the geometrical shape and no color. Figure (15e) shows a dense point cloud of 12 million points. Note: The individual points and the spaces between them are not visible unless the model is zoomed in significantly.

Figure 15b

Figure 15c

Figure 15d

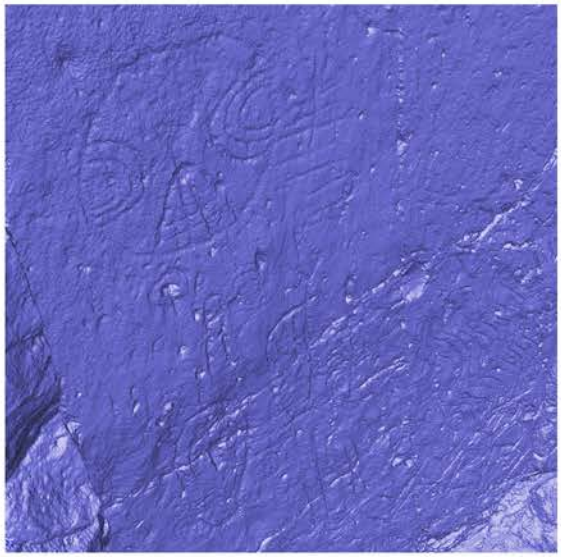


Figure 15e

chi

culturalheritageimaging.org

Cultural Heritage Imaging
a nonprofit corporation

Online Reference Materials

Digital Lab Notebook and Linked Open Data

Cultural Heritage Imaging (CHI) Digital Lab Notebook page
http://culturalheritageimaging.org/Technologies/Digital_Lab_Notebook/index.html

Cultural Heritage Imaging (CHI) NEH Digital Humanities Start-Up Grant page
http://culturalheritageimaging.org/What_We_Do/Projects/neh-startup/index.html

Research Space Semantic Processing Page
http://www.researchspace.org/home/rs-semantic-processing

CIDOC Conceptual Reference Model page
http://83.212.168.219/CIDOC-CRM/

Realizing Lessons of the Last 20 Years: A Manifesto for Data Provisioning & Aggregation Services for the Digital Humanities (A Position Paper)
http://www.dlib.org/dlib/july14/oldman/07oldman.html

Linked Data – Connect Distributed Data across the Web.
http://linkeddata.org/home

Reflectance Transformation Imaging (RTI)

Cultural Heritage Imaging (CHI) RTI Page
http://culturalheritageimaging.org/Technologies/RTI/

RTI Software, User Guides, and Practice Files

- **RTIBuilder**: An interface to a set of tools that process a set of captured images and produce the final RTI files. Page includes links to user guide and example files.
http://culturalheritageimaging.org/What_We_Offer/Downloads/Process/index.html
- **RTIViewer**: A tool that enables viewing and exploring RTI files at a very high resolution. Page includes links to user guide and example files.
http://culturalheritageimaging.org/What_We_Offer/Downloads/View/index.html
- **WebRTIViewer:** A tool for presenting RTIs on the web. Supports pan, zoom and relighting, but no rendering modes. http://vcg.isti.cnr.it/rti/webviewer.php
- **RTI: Guide To Highlight Image Capture (PDF):** A how-to guide that describes the camera, lighting, software, setup, and capture sequence process.
http://culturalheritageimaging.org/What_We_Offer/Downloads/RTI_Hlt_Capture_Guide_v2_0.pdf

- **Light Positioning for Horizontal RTI Data Capture (Instructional Video):** Explains the basic factors governing light positioning for a horizontal RTI data capture. http://vimeo.com/67164689
- **Light Positioning for Vertical RTI Data Capture (Instructional Video):** Explains the basic factors governing light positioning for a vertical RTI data capture. http://vimeo.com/68811240

Glossary of Photographic and Technical Terms for RTI
A master list explaining terms related to the setup, capture, and processing of RTI images. http://culturalheritageimaging.org/What_We_Offer/Downloads/Capture/CHI-RTI-Glossary_v1.pdf

RTI-Related Publications
There are many RTI articles in this collection of CHI publications: http://culturalheritageimaging.org/What_We_Do/Publications/

RTI Examples

- **RTI in Art Conservation:** CHI's page with examples of RTI in the field of conservation: http://culturalheritageimaging.org/What_We_Do/Fields/conservation/index.html
- **Video Examples:** Three CHI videos embedded on this page show different examples of how RTI can be applied in the study of cultural heritage objects: http://culturalheritageimaging.org/Technologies/RTI/index.html#examples_RTI
- **More RTI Examples:** CHI's page lists several independent projects that demonstrate the application and efficacy of RTI: http://culturalheritageimaging.org/Technologies/RTI/more_rti_examples.html
- **Smithsonian Museum Conservation Institute (MCI) Imaging Studio re RTI:** MCI's page with examples of RTI, including videos: http://www.si.edu/MCIImagingStudio/RTI
- **Hewlett-Packard Labs' Project on Polynomial Texture Mapping (PTM):** Malzbender and Gelb, research scientists at HP Labs, invented PTM, a forerunner of RTI. http://www.hpl.hp.com/research/ptm/index.html
- **Hewlett-Packard Labs' Project on Imaging the Antikythera Mechanism:** http://www.hpl.hp.com/research/ptm/antikythera_mechanism/index.html
- **English Heritage's Publication "Multi-light Imaging for Heritage Applications":** http://www.english-heritage.org.uk/publications/multi-light-imaging-heritage-applications/
- **Georgia O'Keeffe Museum's Imaging Project Blog:** A collection of postings by the museum project team about their 2012 application of RTI and photogrammetry to objects and buildings at the museum: http://www.gokmconservation.org/resources/blog/

CHI User Forums
A free discussion site where the user community can share information. (Posting requires a free account to prevent spam)

- http://forums.culturalheritageimaging.org

RTI Highlight Capture Starter Kit
Get details and order the starter kit. http://culturalheritageimaging.org/rti-kit