# Image-Based Empirical Information Acquisition, Scientific Reliability, and Long-Term Digital Preservation for the Natural Sciences and Cultural Heritage

Mark Mudge, Tom Malzbender, Alan Chalmers, Roberto Scopigno, James Davis, Oliver Wang, Prabath Gunawardane,
Michael Ashley, Martin Doerr, Alberto Proenca, João Barbosa

## Abstract

*The tools and standards of best practice adopted by natural science (NS) and cultural heritage (CH) professionals will determine the digital future of NS and CH digital imaging work. This tutorial discusses emerging digital technologies and explores issues influencing widespread adoption of digital practices for NS and CH. The tutorial explores a possible digital future for NS and CH through key concepts; adoption of digital surrogates, empirical (scientific) provenance, perpetual digital conservation, and 'born archival' semantic knowledge management.*

*The tutorial discusses multiple image based technologies along with current research including; Reflectance Transformation Imaging (RTI), Photometric Stereo, and new research in the next generation of multi-view RTI. This research involves extending stereo correspondence methods. These technologies permit generation of digital surrogates that can serve as trusted representations of 'real world' content. The tutorial explores how empirical provenance contributes to the reliability of digital surrogates, and how perpetual digital conservation can ensure that digital surrogates will be archived and available for future generations.*

*The tutorial investigates the role of semantically based knowledge management strategies and their use in simplifying ease of use by natural science and CH professionals as well as long term preservation activities. The tutorial also investigates these emerging technologies' potential to democratize digital technology, making digital tools and methods easy to adopt and make NS and CH materials widely available to diverse audiences. The tutorial concludes with hands-on demonstrations of image-based capture and processing methods and a practical problem solving Q&A with the audience.*

**Keywords**: Reflectance transformation imaging, polynomial texture mapping, empirical provenance, photometric stereo, stereo correspondence, photogrammetry, structured light, digital preservation, archiving, cultural heritage

## 1. Introduction

The tools and standards of best practice adopted by natural science (NS) and cultural heritage (CH) professionals will determine the scope and nature of future digital scholarship. We will explore issues that influence these adoption decisions and showcase examples of emerging digital technologies designed to remove the existing obstacles to widespread adoption of digital practices.

### 1.1 Sequence of Presentations

Mark Mudge will begin by presenting an overview of the themes uniting the tutorial's presentations. These themes will explore issues that influence technology adoption decisions made by NS and CH professionals. He will explore the advantages that can be realized when image-based empirical information acquisition is organized in conformance with the fundamental principles of the scientific method. Reflectance Transformation Imaging (RTI) will be featured as an example of an image-based technique that can be structured in this advantageous manner.

Tom Malzbender will discuss the PTM representation and RTIs, including the advantages and limitations of the representation. He will review tools for building and viewing PTMs and basic approaches to their capture. He will offer several brief case studies including the Antikythera Mechanism and applications in paleontology, forensics, and art conservation. He will also present work using reflectance transformation techniques in combination with photometric stereo and a high speed video and lighting array to generate real time views of enhanced object surfaces.

Alan Chalmers will discuss the use of RTI and spectrally measured historic light sources, such as oil and beeswax, to recreate authentic Byzantine environments and their impact on architectural mosaics, painted icons, and frescos.

Roberto Scopigno will discuss large object RTI acquisition and present a practical, simple and robust method to acquire the spatially-varying illumination of a real-world scene. He will present an assessment of factors including the effects of light number and position influencing polynomial Texture mapping (PTM) normal accuracy.

James Davis will discuss photometric stereo, structured light and related image-based techniques for capturing information about the ‘real world’.

Oliver Wang, and Prabath Gunawardane will discuss new research into techniques used to visualize image-based, empirically captured objects. The research goal is to interpolate both lighting and viewing directions while using a small amount of data that can be easily transferable over the web. The work examines various alternative representations of the lighting and spatial information that can be used to compactly model this information. The research decomposes the measured reflectance function into view dependent and view independent components. From these results, it is possible to include not only color information, but any view independent components of the reflectance function, improving the robustness of 3D surface shape extraction.

Michael Ashley will discuss the concept of 'born archival' digital surrogates and the perpetual conservation of our digital knowledge through 'smart' media and 'dumb' archives. He will advocate for both individual professional responsibility and multi-institutional, multi-disciplinary curatorial management of digital heritage content for the foreseeable future. He offers a practical approach to enticing technology adoption by repositories and institutions of cultural memory through digital surrogates that adapt to their environment, resist 'bit rot' and improve in terms of stability, semantic meaningfulness and archival potential through time.

Martin Doerr will discuss the techniques and tools of empirical acquisition knowledge management. He will explore the concept that scientific data cannot be understood without knowledge of the meaning of the data and the means and circumstances of its creation. He will examine how this ‘metadata’ can be managed from generation to use, permanent storage and reuse. He will discuss: knowledge deployment; automatic translation of acquisition knowledge into widely used archiving formats for export and as finding aids; management and inheritance of provenance information for image-based derivatives; and determination of knowledge dependencies for digital preservation.

Alberto Proenca and João Barbosa will discuss their work developing processing tools to automate the generation process of the PTM data representation of an object. They will demonstrate how their tools both simplify and mostly automate the capture and processing of PTMs, while recording the empirical provenance generated along the processing pipeline.

During the final session of the tutorial the participants will demonstrate practical image-based empirical information capture, workflow, and processing techniques using commonly available photographic equipment. Questions and dialog with tutorial attendees will be encouraged during the demonstrations.

### 1.2 Replacing the ‘R’ in ‘RTI’

Mark Mudge and Tom Malzbender would like to replace their previous use of the term ‘**reflection**’ with the term ‘**reflectance**’ in their current and future work with RTI. In turn, this former usage has led to the use of ‘**reflection**’ by others. They suggest that those currently using RTI to consider incorporating this change of terminology in their future work. Mark and Tom’s contributions to the course notes reflect this suggestion.

********************************************

## 2. Natural Science, Cultural Heritage, and Digital Knowledge

Tutorial Presenter: Mark Mudge

Additional Authors: Carla Schroer, Marlin Lum

Cultural Heritage Imaging, USA

Email: `mark@c-h-i.org`

Humanity's legacy can be unlocked and shared between people through digital representations. Digital representations can communicate knowledge in a variety of ways. For clarity, we can define three types that distinguish different uses for these representations; art and entertainment, visualization, and digital surrogates of the world we experience.

### 2.1 Art, Visualization, and Digital Surrogates

Digital content can be fine art in its own right. It can also entertain. This content can also be used to visualize concepts, and illustrate hypotheses. In this case, we use the term ‘visualization’ in its broadest sense to include hearing, smell, taste and touch. For example, a computer animation of a large asteroid impacting the Yucatan Peninsula 65 million years ago is helpful to visualize the cause for worldwide dinosaur extinction. These images are useful not because they faithfully show the shape and color of the actual asteroid moments before impact but because they effectively communicate an idea. Visualizations are speculative in nature to varying degrees. Current research is exploring ways to explicitly describe the extent of this speculation. [HNP06]

Digital surrogates serve a different purpose. Their goal is to reliably represent ‘real world’ content in a digital form. Their purpose is to enable scientific study and personal enjoyment without the need for direct physical experience of the object or place. Their essential scientific nature distinguishes them from speculative digital representations. They are built from inter-subjectively verifiable empirical information. Digital surrogates are the focus of this discussion.

Digital surrogates of our 'real world' can robustly communicate the empirical features of NS and CH materials. When digital surrogates are built transparently, according to established scientific principles, authentic, reliable scientific representations can result. These representations allow re-purposing of previously collected information 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 concatenation of information across many collections and demystify complex semantic query of vast amounts of information to efficiently find relevant material. Digital surrogate archives remove physical barriers to scholarly and public access and foster widespread knowledge and enjoyment of nature and our ancestors' achievements.

The advantages presented by adoption of digital surrogates are great, but can only be attained if well recognized obstacles are overcome and the related incentives realized. As discussed below, the fundamental means to enable adoption of digital surrogates are understood. The necessity to achieve widespread adoption is driving the ongoing development of new tools, methods, and standards. The following four sections examine these efforts to aid digital surrogate adoption.

### 2.2 Empirical Provenance

A fundamental problem of the digital age is the qualitative assessment of digital surrogate reliability during scientific inquiry. A solution to this problem is necessary for digital surrogates to find widespread use in NS and CH scholarship.

Widespread adoption of digital surrogates by science in all fields, including the multi-disciplinary study of our cultural heritage, requires confidence that the data they represent is reliable. For a scholar to use a digital surrogate, built by someone else, in their own work, they need to know that what's represented in the digital surrogate is what's observed on the physical original. If archaeologists are relying on virtual 3D models to study Paleolithic stone tools, they must be able to judge the likelihood that a feature on the model will also be on the original and vice versa. If they can't trust that it's an authentic representation, they won't use the digital surrogate in their work.

We suggest that the concept of 'empirical provenance' offers to advance our understanding of the role of digital surrogates in scientific inquiry, enhance the development of techniques to digitally represent our world, and increase the adoption of digital surrogates as source material both for scientific research in general and the study of our collective cultural heritage in particular.

An essential element of traditional scientific inquiry is the systematic gathering of observations about the world through the senses. In the very, very old and still vigorously pursued epistemological discussion about the nature of human knowledge, the observations of the senses are labeled 'empirical'

Within scientific discourse the methodology employed in the process of generating scientific information has been traditionally called the inquiry's 'provenance'. This provenance is carefully recorded in lab notebooks or similar records during the inquiry and then becomes an integral element of the published results. This provenance explains where the information came from and permits replication experiments, central to scientific practice, to confirm the information's quality. Such provenance may include descriptions of equipment employed, mathematical and logical operations applied, controls, oversight operations, and any other process elements necessary to make both the inquiry and its results clear and transparent to scientific colleagues and the interested public.

Widespread adoption of digital surrogates requires that they be able to pass this traditional lab notebook test. Empirical provenance is for digital surrogates the equivalent of what a lab notebook is for non-digital representations. Empirical provenance is the extension of classic scientific method into the digital documentary practices used to build digital surrogates.

Empirical provenance records the journey of original, unaltered empirical evidence from its initial data capture all the way through the image generation process pipeline to its final form as a digital surrogate. Just as 'real-world' cultural material requires a provenance identifying what it is, establishing its ownership history, and proving its authenticity, digital surrogates require an empirical provenance, to document the imaging practices employed to create them. Empirical provenance ensures access to both original empirical data, original photographs for example, and the complete process history enabling the user to generate a confirmatory representation to evaluate the quality and authenticity of the data. That way, the user can decide for themselves whether to rely on the digital surrogate, or not.

Empirical provenance permits the assessment of digital surrogate accuracy. The experience of those engaged in distributed, Internet-based scientific inquiry confirms the necessity of documenting how digitally represented information is generated. These collaborations, frequently found in the biological sciences, rely heavily on process accounts of digital data creation to assess the quality of information contributed by the cooperating partners and make their own work valuable to others. [ZGWS03]

The attributes of empirical provenance information for a given digital surrogate are dependent on the tools and methods employed to build it. For a digital photograph, the empirical provenance information would include XMP data such as: the camera make and model, firmware version, shutter speed, and aperture; parameters used to convert the raw sensor data into an image like color temperature; and all editing operations performed in tools like Photoshop such as cropping, re-sizing, distortion correction, sharpening, etc. These editing operations can have a profound impact on image reliability and are examined in greater detail below.

For a 3D geometric model displaying photo-realistic surface texture and reflective material properties, the empirical provenance is complex. For these digital surrogates, complete process history accounts are required for the alignment of shape data acquired from different viewpoints, the registration of textural image data to geometry, the correction of geometric acquisition errors such as voids, smoothing in low signal to noise ratio situations, the effects of compressive data reduction, and other issues raised by the selected imaging method. In each case, whether digital photo or 3D model, the attributes including quantity of records, and ease, difficulty, or even possibility of empirical provenance collection result from the practices used to build the digital surrogate.

Only practices able to provide a complete empirical provenance can be used to construct reliable digital surrogates. Practices unable to produce a complete empirical provenance cannot be used to create reliable digital surrogates since their digital artifacts cannot be subjected to rigorous qualitative evaluation.

The requirement for empirical provenance information informs digital technology development and adoption. Tools and methods used to build digital surrogates that feature simplification and trivially configured automation of empirical data post processing, including empirical provenance generation, present significant benefits over those that call for significant amounts of subjective judgments by a skilled operator, since every operator action that transforms empirical content must be documented in a digital log for future scientific evaluation.

The importance of automation in the construction of reliable digital surrogates is highlighted by a recent major study. [BFRS05] This study examined the digital imaging practices in leading US museums and libraries. The study states:

> “Most museums included some visual editing and other forms of image processing in their workflow…When investigated closely, it was found that visual editing decreased color accuracy in all cases… In addition to visual editing, many images also incurred retouching and sharpening steps. The fact that many of the participants sharpened the images either at capture or before the digital master was saved raised the question of whether the implications of the choices made were well understood. Most of the image processing carried out was not automated; automation represents a possibility for improvement in setting up consistent, reproducible workflow.”

While an artist’s touch can increase the sales of a print in a museum gift shop or create a stunning cinematic effect, it has little direct role in the scientific construction of digital surrogates. The development of many of today’s digital imaging tools was driven by the entertainment industry’s desire to create special effects for movies and television, computer animations, video games, and multimedia products. Unlike the entertainment business where a good-looking image is the goal, scientific documentation requires that the material be represented reliably. If the empirical provenance, enabling assessment of reliability, is lacking, the digital representation may be enjoyed for visualization or entertainment purposes but not used as a digital surrogate.

As well as reliability, the synergistic combination of empirical provenance and automated digital processing, requiring trivial operator configuration, offer advantages for the organization, communication and preservation of digital knowledge.

Once the process used to construct a digital surrogate is automated, an empirical provenance log describing the process can be automatically produced. Knowledge management tools can map these process history actions to semantically robust information architectures. An example of a semantic knowledge management architecture is the International Council of Museums’ (ICOM’s) Committee on Documentation (CIDOC) Conceptual Reference Model (CRM), ISO standard 21127. [CCRMweb] The CIDOC/CRM working group has recommended amendments to the standard to include the terms ‘digital object’ and ‘digitization process’ which can be used to describe a digital surrogate’s empirical provenance. Martin Doerr’s following presentation will explore these tools and methods of semantic knowledge management in greater depth.

Digital processing can then automatically record empirical provenance information into these semantic architectures enabling the digital surrogates to be ‘born archival’. The concept of ‘born archival’ and related issues dealing with perpetual digital conservation will be examined in greater depth in the following presentation by Michael Ashley.

## 2.3 Perpetual Digital Conservation

**Figure 1:** *RTI Image, with specular enhancement, showing detail of a trackway of species Coltoni of the Early Triassic Period. From the collection of the University of California Museum of Paleontology.*

Access to archival services is an essential element of the digital workflow for people who acquire and use digital surrogates. Archival conservation strategies are also essential to guarantee that this digital information is available for both use and reuse by future generations. In turn, the work of archival conservators is simplified and their ability to plan ongoing conservation activities is greatly enhanced if this digital information possesses ‘born archival’ attributes. The essential attributes of ‘born archival’ information are defined by an empirical acquisition and digital surrogate generation processes that provides managed knowledge of the information’s methods of creation (empirical provenance) along with the digital surrogate’s ‘real world’ semantic context.

A collaboration between CHI, the University of California Museum of Paleontology (UCMP), and the University of California Media Vault program (MVP) [MVPweb] demonstrated an example of the value a digital surrogate’s empirical provenance information can have in archival conservation. Among the single-view RTIs CHI captured in the UCMP collection was a 220 million year old dinosaur trackway of species Coltoni in the Genus C heirotherium. PTMs were produced in 4 resolutions from full resolution to a dimension of 500 pixels along the image’s long aspect. Empirical provenance information from the PTM generation process permitted the analysis of data dependencies created during PTM processing. This dependency analysis enables the determination of which files were essential to the scientific record and which files could be regenerated from the originally acquired empirical data along with the empirical provenance information. Files that could be regenerated were discarded. CHI, in cooperation with the MVP staff, analyzed the data dependencies and reduced the number of files requiring archival storage from 516 to 63, a significant advantage in a preservation context.

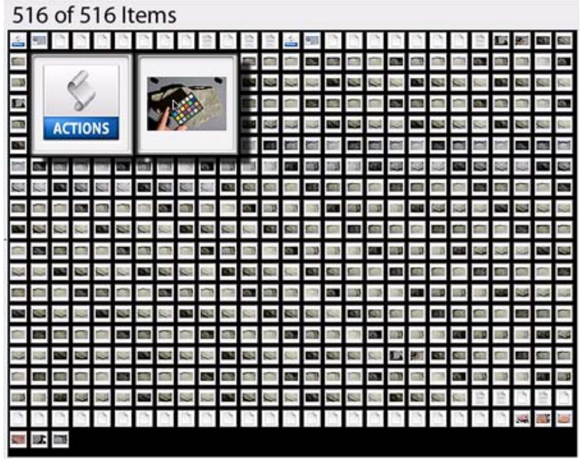


**Figure 2:** *Before dependency determination - 516 digital files were used to build four resolutions of RTI images. This includes process and log files.*

**Figure 3:** *After dependency determination, 63 files are saved in the UC Media Vault.*

### 2.4 Democratization of Technology

For widespread adoption of digital surrogates to occur, the NS and CH workers who build and use digital surrogates must be able to employ these new tools themselves. The means by which robust digital information is captured and synthesized into digital surrogates requires great simplification, cost reduction, increased ease of use, and improved compatibility with existing working cultures.

The emergence of the new family of robust image-based empirical acquisition tools offering automatic post-acquisition processing overcomes an important barrier to the adoption of digital workflow. As was previously discussed, automation requiring trivial configuration offers enhanced reliability and greatly reduces the computer technology expertise necessary to manage a digital workflow. These methods leverage new knowledge to enable NS and CH professionals to build digital surrogates with a minimum of additional training. In turn, this automation frees these workers to concentrate on the ‘real’ NS and CH tasks before them.

Digital photography skills are already widespread and disseminating rapidly. Employing digital photography to provide the empirical data for digital surrogates also lowers financial barriers to digital adoption. As will be seen below, rich 2D and 3D information can be captured with the equipment commonly found in a modern photographer’s kit.

Recent work has shown that computational extraction of information from digital photographs can create digital surrogates that reliably describe the 2D and 3D shape, location, material, and reflection properties of our world. Among these new technologies are single view RTI, multi-view RTI and associated enhanced stereo correspondence methods, as well as photogrammetric breakthroughs that permit automatically calibrated and post-processed textured 3D geometric digital surrogates of objects and sites. Some of these developments will be briefly reviewed here and will be explored in greater depth in following presentations by Tom Malzbender, Alan Chalmers, Roberto Scopigno, James Davis, Oliver Wang, Prabath Gunawardane, Alberto Proenca, and João Barbosa.

#### 2.4.1 RTI’s Role in Knowledge Management Research

RTI using PTMs was invented by Tom Malzbender of Hewlett-Packard Laboratories. It is an example of computational extraction of 3D information from a sequence of digital photographs. RTI is an image-based technology where operator post-processing can be reduced to trivial levels. The RTI process has been used as a model to explore the development of empirical provenance and semantic knowledge management tools. As will be seen later in the presentation by Alberto Proenca and João Barbosa and the technology demonstration section of the tutorial, both CHI and the University of Minho have developed tools and methods to record the empirical provenance information generated during RTI capture and processing. These tools create a log file of all operations performed during RTI processing. Combined with information stored in Adobe software .XMP files generated during original RAW digital image conversion, all empirical provenance for the RTIs can be recorded. In cooperation with CHI and the MVP, Steven Stead and Martin Doerr of the CIDOC/CRM special interest group modeled RTI processes as instances of the CRM. This was the first application of CIDOC/CRM semantic knowledge management concepts to image-based empirical acquisition processes and associated empirical provenance information. Prior to this work, CRM applications focused on uses within and among museums, libraries, and archives. This work also laid the foundation for the development of new, archive friendly, semantic knowledge management tools that promise to increase digital technology's ease-of-use for NS and CH professionals, enhance digital surrogate reliability, and lower barriers to digital technology adoption.

### 2.4.2 Recent developments in dense photogrammetry

Recent developments in dense photogrammetric technologies can generate 3D textured geometric digital surrogates of objects and sites from automatically calibrated and post-processed sequences of digital photographs. The European Project for Open Cultural Heritage (EPOCH), a seven year European Union sponsored initiative to develop digital tools for CH, fostered a major advance in photogrammetry-based 3D imaging using uncalibrated digital photos. The EPOCH 3D Webservice, developed by the computer vision group at Catholic University Leuven allows archaeologists and engineers to upload digital images to servers where they perform an automatic 3D reconstruction of the scene and return the textured 3D geometry back to the user [EWweb].

Commercial software, initially developed for the aerial mapping and mining industries by Adamtech, an Australian company, can automatically calibrate digital photo sequences from one or more cameras, automatically generate dense textured 3D polygonal geometry from one or more image pairs, and automatically align this 3D content using photogrammetric bundle adjustment [ATweb]. These tools have been used by U.S. Bureau of Land Management researchers Neffra Matthews and Tom Noble to document Native American petroglyphs at Legend Rock Wyoming State Park in collaboration with the Wyoming State Parks, Wyoming State University, and CHI. Photogrammetry digital image sequences were captured in tandem with CHI's RTI photo sequences. The integrated photo sequences demonstrate the synergies between automated photogrammetric capture of image-based geometry and reflection-based capture of normal data. These synergies, presented at the Computer Applications in Archaeology conference in Berlin, April 2007 include co-registered RTI images free of optical distortions, and dense, PTM textured 3D geometry. CHI used an identical photogrammetry image sequence of a sculpted architectural feature to test the 3D geometry produced by Adamtech software against that returned from the EPOCH 3D Webservice. The results showed that both methods generated dense 3D geometrical information of equivalent quality.

**Figure 4:** *Distortion corrected RTI image of petroglyphs at Legend Rock State Park, Wyoming.*

### 2.5 Tolerance of diversity

Given the powerful dynamic of change attached to all things digital and the history of human nature's resistance to conformity, adoption of digital surrogate-based workflow will be encouraged by tolerance of decentralized digital information architectures. Tolerance encourages optimizations to fit local conditions or the requirements of a given field of study. Within such a tolerant environment, scholarly, discipline-based, evolving standards of best practice will continue to guide local practice as it always has. Worldwide access to, evaluation, and oversight of these practices, aided by semantic query enabled access to the empirical provenance of digital surrogates and by use of perpetual digital conservation practices for digital surrogates along with their source data, can assist the proven, self-corrective mechanisms of the scientific method to do their work.

### 2.6 Conclusion

Empirical provenance, perpetual digital conservation, democratization of technology, and tolerance of diversity provide a a road-map for future digital scholarship, and enjoyment of humanity's legacy. Informed by these concepts, emerging tools and methods will enable NS and CH professionals to build reliable, reusable, archive friendly, digital surrogates by themselves. Archives of digital surrogates can enable distributed scholarship and public access. The aesthetic quality, usefulness to convey ideas, and completeness of empirical provenance information can guide decisions regarding which digital representations are perpetually conserved.

## References

[ATweb] ADAM Technology website (accessed January 2008). http://www.adamtech.com.au

[BFRS05] Berns, R.S., Frey, F.S., Rosen, M.R., Smoyer, E.P.M., Taplin, L.A. 2005. Direct Digital Capture of Cultural Heritage Benchmarking American Museum Practices and Defining Future Needs - Project Report, *MCSL Technical Report.*

[CCRMweb] CIDOC Conceptual Referenc Model (accessed January 2008). http://cidoc.ics.forth.gr

[EWweb] EPOCH Webservice (accessed January 2008) http://homes.esat.kuleuven.be/~visit3d/webservice/html

[HNP06] Hermon, S. Nikodem, J., Perlingieri, C., 2006 Deconstructing theVR – Data Transparency, Quantified Uncertainty and Reliability of 3D Models, *Proceedings of the7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage* (VAST2006), pg 123-129

[MVPweb] Media Vault Program (accessed January 2008). http://mvp.berkeley.edu

[ZGWS03] Zhao J., Goble C., Greenwood M., Wroe C., Stevens R., 2003. Annotating, linking, and browsing provenance logs for e-science. *Proceedings of the Workshop on Semantic Web Technologies for Searching and Retrieving Scientific Data*, October 2003.

**********************************************

## 3. PTM Tools for Relighting and Enhancement

Tutorial Presenter: Tom Malzbender
Hewlett Packard Labs, USA
`email: tom.malzbender@hp.com`

Polynomial texture maps (PTMs) [MGW01] are an extension to conventional texture maps that allow increased control of rendered appearance. Although PTMs were developed to be used as texture maps in the context of rendering 3D objects, they have found more use as ‘adjustable images’ in a 2D context. As opposed to storing a color per pixel, as in a conventional image or texture map, PTMs store the coefficients of a second-order bi-quadratic polynomial per pixel. This polynomial is used to model the changes that appear to a pixel’s color based on user defined parameters, typically a parameterization of light source direction. For example, if $L_u$,$L_v$ are parameterized light source directions *L* and $a_{0\text{-}5}$ the scaled and biased polynomial coefficients, a color channel intensity $C_i$ are arrived at via:

$$C_i = a_0 L_u^{2} + a_1 L_v^{2} + a_2 L_u L_v + a_3 L_u + a_4 L_v + a_5$$

Parameterized lighting directions are arrived at by projecting the normalized light vector into the 2 dimensional texture space (u,v) to yield Lu,Lv. For use as ‘adjustable images’, this just amounts to using the first two coordinates of a normalized vector that points towards the light source. Advantages of PTMs are:

- Ease of Capture – Several methods for capturing PTMs have been developed, all of which are fairly simple. For example, none of the methods require any camera calibration and several can be performed by laypersons without any technical training. Capture can be performed with low end digital cameras with minimal supporting hardware, such as a handheld flash or table lamp as light source (Figure 8). The procedure is to acquire a set of images under varying lighting directions. Methods are available for both the cases of when lighting direction is known or when it is not.
- Available Tools – Tools for making and viewing PTMs are freely available via http://www.hpl.hp.com/research/ptm/ and related pages. Several tools are available for displaying PTMs, the PTMviewer having the most functionality. Additionally Java-based viewers are available that don’t require any explicit download. Once a set of images of a static scene under different and known lighting directions are acquired the PTMfitter can be used to produce a PTM. Alternatively, one can use a reflective sphere (snooker ball) to capture images with unknown lighting direction and the PTMbuilder application can be used to produce a PTM. More detail can be found later in this document and at http://www.hpl.hp.com/research/ptm/MakingPtmNew.htm.
- Fast Rendering – PTMs were specifically developed to enable fast color evaluation from lighting direction. Since equation (1) consists solely of multiplies and adds, Micro-SIMD techniques [FFY04] (parallel subword instructions) can be used to compute color from lighting direction in real-time on any modern CPU without relying on any specific graphic hardware.
- Compact File Size – PTMs support JPEG compression resulting in compact files, so can be shared on the web efficiently. Examples of PTMs on the web are at:

http://c-h-i.org/examples/ptm/ptm.html

http://www.hpl.hp.com/research/ptm/relightdemo/index1.html

http://www.hpl.hpcom/research/ptm/antikythera_mechanism/index.html

- Surface Detail Enhancement – PTMs represent a reflection function from a specific viewpoint, and as such allow interactive control of lighting direction. This greatly assists in the perception of surface shape and detail. Additionally, it is possible to transform the reflectance

**Figure 5:** *Original and two specular enhancements of a cuneiform tablet.*

properties represented by a PTM and this allows one to change the material properties of the object that was imaged. For certain materials this allows perception of surface detail not directly visible when inspecting the original object with the unaided eye. These methods are elaborated in the next section.

### 3.1 Reflectance Transformation

The interactive control of appearance as a function of lighting direction allows PTMs to be used to help perceive surface shape. However, the reflectance function represented by a PTM can also be used to extract an estimate for the surface normal at each pixel. Once this normal is known, several transformations of these reflectance functions can be performed within the *PTMviewer* that keep the geometric information (the normal) fixed, but modify the photometric properties of the surface. This is often helpful in assisting the perception of 3D shape, and sometimes allows the perception of surface detail not readily apparent when inspecting the object directly. We have found 3 simple transformations of the reflectance function particularly useful [MGW01]:

1) Specular Enhancement – Adding synthetic specular highlights to the reflectance function of a mostly diffuse object can be quite effective. The *PTMviewer* implements this using simple Phong/Blinn shading and is accessed by right clicking, as are the remaining transformations.

2) Diffuse Gain – The reflectance functions of diffuse objects are slowly varying. Diffuse gain is an analytic transformation that keeps the normal estimate per pixel fixed, but increases the curvature (second derivative) of luminance of the reflectance function by an arbitrary gain constant under user control. As such, it has not physical analog, but is nonetheless useful.

3) Light Direction Extrapolation – Parameterizations of physical light directions specified in equation (1) by Lu,Lv are limited to the range of (-1, 1) for each coordinate. However with a parametric description of the reflectance function we are free to specify lighting directions outside of this range. These again have no physical analog, and can be thought of as yield lighting directions more oblique than physically possible.

**Figure 6:** *Original and 2 enhancements using diffuse gain.*

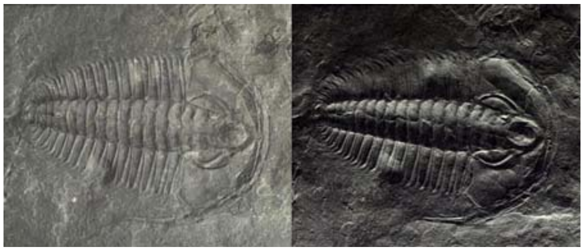


**Figure 7:** *Original and an extrapolation of lighting direction.*

### 3.2 Capturing and Building PTMs

PTMs are typically made from multiple images of a static scene or object illuminated from separate lighting directions for each image. These sorts of images are easily collected by a variety of methods, some of which are demonstrated at http://www.hpl.hp.com/research/ptm/MakingPtmNew.htm. The techniques can be broken down into two classes, each with its own set of tools to support constructing PTMs from the tools.

.

**PTM Formats currently supported by the PTMviewer**

| Format Name | Bytes per pixel | Description |
|---|---|---|
| PTM_FORMAT_LRGB | 6 + 3 | Luminance as a polynomial multiplied by unscaled RGB |
| PTM_FORMAT_RGB | 3 x 6 | Polynomial coefficients for each color channel |
| PTM_FORMAT_LUM | 1 or 2 | $YC_rC_b$ color space, only Y as a polynomial |
| PTM_FORMAT_PTM_LUT | 3 + 1 | Index to a lookup table that contains RGB values plus polynomial coefficients |
| PTM_FORMAT_PTM_C_LUT | Variable | RGB values plus an index to a lookup table that contains only polynomial coefficients |
| PTM_FORMAT_JPEG_RGB | Variable | JPEG compression of an RGB PTM |
| PTM_FORMAT_JPEG_LRGB | Variable | JPEG compression of an LRGB PTM |
| PTM_FORMAT_JPEGLS_RGB | Variable | JPEGLS compression of an RGB PTM |
| PTM_FORMAT_JPEGLS_LRGB | Variable | JPEGLS compression of an LRGB PTM |

In the first class, light source direction is known and specified in a file format called a.lp file. The.lp file is typically constructed with a text editor such as WordPad, a simple example is shown below:

```
  50
 C:\Leaves512\91-001.jpg -0.015760 0.196076 0.980462
 C:\Leaves512\91-002.jpg 0.181637 0.075514 0.980462
 C:\Leaves512\91-003.jpg 0.127865 -0.149482 0.980462
 C:\Leaves512\91-004.jpg -0.102547 -0.167864 0.980462
 C:\Leaves512\91-005.jpg -0.191321 0.045724 0.980462
 C:\Leaves512\91-006.jpg -0.269702 0.314284 0.910212
 .
.
.
 C:\Leaves512\91-049.jpg -0.950980 -0.309253 -0.000204
 C:\Leaves512\91-050.jpg -0.587692 0.809084 -0.000204
```

The first line contains the number of images in the set. For each image, the image filename is given (either.jpg,.tga or.ppm), then the x, y and z coordinates of a normalized vector pointing at the light for that image are specified. As one is looking at the object to be imaged through the camera, the x axis is off to the right, the y axis is towards the top, and the z axis points at the camera from the center of the image. For example, a light positioned directly overhead, where the camera is, would have direction vector (0,0,1). Once such a.lp file is constructed, the PTMfitter is run to convert these images and.lp file to a PTM. The PTMfitter is freely available at http://www.hpl.hp.com/research/ptm/. Suggested answers for questions the PTMfitter prompts that may not be clear are:

```
Enter desired fitting format: 1
Enter basis: 0
```

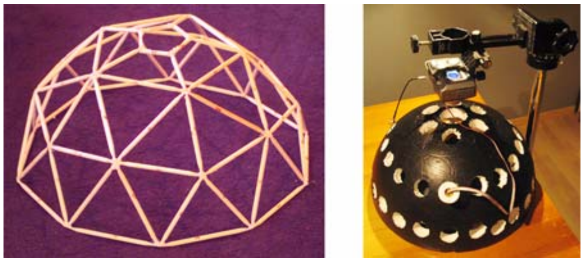


**Figure 8:** *Two inexpensive domes useful for specifying lighting direction. In both cases a digital camera is placed above and the object to be imaged placed on the floor below. Right image courtesy of Wouter Verhesen.*

A second approach to constructing PTMs will be covered in detail in section 9. In this approach, one uses a handheld flash to trigger the camera, so light directions or positions are not known. In this approach, one places one or two black or red snooker balls next to the object being photographed. The flash will leave a specular highlight in the balls, which can be used to infer the position or direction of the light. The PTMbuilder (also available at http://www.hpl.hp.com/research/ptm/) is then used to automatically detect the location of the balls in the image, recover highlights, infer light direction or position and produce a PTM. This typically does not require any user interaction besides the specification of a directory the images reside in.

### 3.3 PTM formats

Several different varieties of PTMs are available summarized in the table above. More detail is available from the PTM format document downloadable from

**Figure 9:** *Photograph and RTI enhancement of a footprint in dirt.*

http://www.hpl.hp.com/research/ptm/. The most commonly used formats by far are the first two, LRGB and RGB.

### 3.4 Real-Time RTI

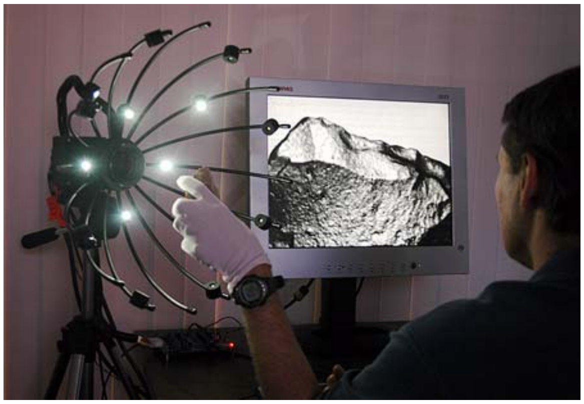


**Figure 10:** *Real-time surface detail enhancement is possible using high brightness L.E.D.s coupled to a high speed camera and GPU.*

The Reflectance Transformation Imaging (RTI) methods described above are useful for a number of applications including seeing more detail on object surfaces. Such objects must first be captured under varying lighting conditions, then these images are processed into a PTM, and finally the PTM is viewed under varying reflectance transformations. For many applications such as criminal forensics, this workflow is still more elaborate than desired. It is possible to achieve this same functionality in real-time using a combination of high speed cameras and fast GPUs as described in [MVGA06]. In this system, 8 high brightness LEDs are flashed sequentially as a 500 f/sec camera captures images of the object which are transferred to a graphics card. Every 1/60th of a second, surface normals are estimated using photometric stereo from a collection of 8 images at spaced lighting directions. Normal perturbations can be amplified, either in a local or global manner, to accentuate surface detail. Additionally, synthetic specular highlights can be added, as in the specular enhancement method mentioned earlier. Quantitative measures of surface roughness can be produced at frame rates as well. The resultant system allows untrained users to simple present object surfaces to the system while viewing enhanced results on a nearby display.

### 3.5 Case Studies

Reflectance Transformation has been used successfully in a variety of disciplines by researchers outside of the fields of computer graphics and vision, using the PTM tools. Some examples are highlighted below.

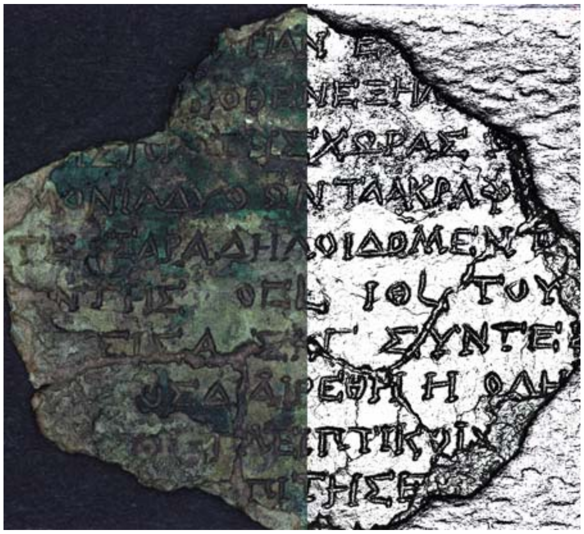


**Figure 11:** *Photograph and RTI enhancement of fragment 19 of the Antikythera Mechanism.*

Cultural Heritage – Many examples of the deployment of Reflectance Transform Imaging (R.T.I.) in the contact of cultural artifacts can be found on the Cultural Heritage Imaging (CHI) web pages and elsewhere, specifically: http://c-h-i.org/examples/ptm/ptm.html. A recent application of the method was in the study of the Antikythera Mechanism [FBM*06], by an international research team consisting of scholars and researchers from Greece, the UK and the United States, http://www.antikythera-mechanism.gr/. The

**Figure 12:** *The painting "Jean de la Chambre at the Age of 33", by Frans Hals, dates from between 1580-1666. Note the variation in brush strokes visible under varying lighting direction, from the left, center and above respectively. Images courtesy of the National Gallery in London. (http://cima.ng-london.org.uk/ptm/ng_examples.htm)*

Antikythera Mechanism is a mechanical astronomical calculator that was built by the ancient Greeks around 120 BCE and resides in the National Archeological Museum in Athens. It was uncovered by sponge divers in 1900 after being underwater for approximately 2 millennium. In conjunction with microfocus CT studies, reflectance imaging was applied to the device to uncover a total of over 2000 characters from a starting point of 800. In particular reflectance imaging was helpful in decoding lunar and solar eclipse glyphs indicating the Saros cycle.

Criminal Forensics – The enhancement capabilities of RTI are useful in a number of criminal forensics contexts. In the United States, the FBI has used the method for looking at faint indented writing. The California Department of Justice has used it for studying footprints on soft substrates and the San Mateo Police Department has employed it for looking at faint fingerprints. Several more criminal investigations using the method are underway.

Art Conservation – The capture and display of paintings under varying lighting direction is a more thorough characterization than any single image of the same painting. For this reason, both the National Gallery and Tate Galleries in London have explored the use of PTMs on several of the paintings in their collection [PSM05]. In particular, impasto, cracks, canvas weave, wood grain, pentimenti and point surface deformations can often be easily rendered visible and documented.

Paleontology – The reflectance transformation techniques in particular have proved useful to paleontologist gleaming information from fossils, specifically those specimens with low color contrast and low but definite relief [HBMG02]. One such example is shown in Figure 7. These methods have been successfully employed on a large number of fossils with different types of preservation, including Cambrian fossils from the Burgess Shale and Chengjiang conservation lagerstätten, Cambrian fossils with 3D relief from dark shales of Norway, Carboniferous plant fossil impressions from England, Cambrian trace fossils in sandstone from Sweden, and Neoproterozoic impression fossils from the Ediacara lagerstätten of south Australia.

## References

[FFY04] Fisher, J., Faraboschi, P., Young, C., *Embedded Computing: A VLIW Approach to Architecture, Compilers and Tools*, Elsevier Press, 2004, ISBN 978-1-55860-776-8.

[FBM*06] Freeth, T., Bitsakis, X., Moussas, J., Seiradakis, A., Tselikas, A., Mangou, H., Zafeiropoulou, M., Hadland, R., Bate, D., Ramsey, A., Allen, M., Crawley, A., Hockley, P., Malzbender, T., Gelb, D., Abrisco, W., Edmunds, M., "Decoding the Ancient Greek Astronomical Calculator known as the Antikythera Mechanism", *Nature*, Vol. 444, Nov. 30th, 2006, pp.587-591.

[HBMG02] Hammer, O., Bengtson, S., Malzbender, T., Gelb, D., "Imaging Fossils Using Reflectance Transformation and Interactive Manipulation of Virtual Light Sources", Palaeontologia Electronica, August 23, 2002. Appears at http://palaeo-electronica.org/2002_1/fossils/issue1_02.htm

[PSM05] Padfield, J., Saunders, D., Malzbender, T., "Polynomial Texture Mapping: A New Tool for Examining the Surface of Paintings", *ICOM Committee for Conservation, 2005, Vol. 1*, pp. 504 – 510.

[MGW01] Malzbender, T., Gelb, D., Wolters, H., Polynomial Texture Maps, *Proceedings of ACM Siggraph 2001*, pp. 519-528.

[MWGA06] Malzbender, T., Wilburn, B., Gelb, D., Ambrisco, B., "Surface Enhancement Using Real-Time Photometric Stereo and Reflectance Transformation", *Eurographics Symposium on Rendering 2006*, Nicosia, Cyprus, June 26-28, 2006.

**Figure 13:** *Wireframe of Angeloktistis Church, Kiti.*

## 4. Recreating Authentic Virtual Byzantine Environments

Tutorial Presenter: Alan Chalmers

Additional authors: Eva Z´anyi, Jassim Happa

Warwick Digital Laboratory University of Warwick, UK

Email: `alan.chalmers@warwick.ac.uk`

Computer reconstructions of heritage sites provide us with a means of visualizing past environments, allowing us a glimpse of the past that might otherwise be difficult to appreciate. To date there have been many computer models developed to recreate a multitude of past environments. These reconstructions vary vastly in quality. Furthermore there are in fact very few that attempt to authentically represent how a site may have been appeared in the past. To achieve such a high-fidelity result, it is crucial that these models are physically-based and incorporate all known evidence that may have affected the perception of a site. Failure to do so runs the real danger of the virtual reconstruction providing a false impression of the past.

A key feature when reconstructing past environments is authentic illumination [DC01, RC03]. Today the interior of our buildings are lit by bright and steady light, but past societies relied on daylight and flame for illumination. Our perception of an environment is affected by the amount and nature of light reaching the eye. A key component in creating the authentic and engaging virtual environments is the accurate modeling of the visual appearance of the past environment illuminated by daylight and flame.

In this section the high-fidelity computer reconstruction of Byzantine art, that is the rare visible remains of the long lasting Byzantine Empire. We show that there is a major difference in the way in which people view Byzantine art today, and as it may have appeared in the past when displayed in its original context and illuminated by candle light, oil lamps and day light.

### 4.1 Byzantine environments

The Byzantine empire grew out of the Eastern Roman Empire and comprised a large number of different cultures. Scholars do not agree when the empire began, but in 324 AD Emperor Constantine I (reigned 306-337) moved his capital to Byzantium, which was renamed Constantinople. The Byzantine Empire lasted for more than 1100 years until 1453 when the Turks occupied Constantinople. Despite large number of different cultures within the empire, a common architecture and sacred art style developed. During Byzantine times, Cyprus followed closely the art and cultural trends of the capital, Constantinople, with especially high-quality art. Today it is in Cyprus, a former rich and peaceful province of the Byzantine Empire that many of the most precious surviving relics of Byzantine art are to be found. This is due to the fact that Byzantine master painters visited Cyprus to paint and teach their art with much painting of church interiors and icons. Another reason is that Cyprus achieved a state of neutrality in the 7th century strife between Byzantium and Islam and therefore remained unaffected by the Iconoclastic edicts of the Byzantine Emperors, which resulted in many pieces of art elsewhere being destroyed.

The outside of Byzantine churches were unimposing, with little decoration or use of paint or precious materials. The interiors were, however, very different, being highly decorated including substantial amounts of gold and other precious materials. Manuals, known as typicons, regulated the positioning of the lighting within the environment in great detail. This was deliberately used to underline the difference between divine light and profane darkness. Care was thus taken to ensure the architecture used light and shadow to symbolically represent different sacral hierarchies and direct the attention of the viewer. The upper parts of the churches, which represented heaven, were better lit than the lower parts. In early Byzantium this was achieved with the help of daylight through small openings in the upper parts of the walls. From middle Byzantium on, the buildings had less openings letting in natural light and these were replaced by oil lamps and candles [The01]. In addition, the flickering light from different directions would have significantly affected the precious materials such as the gold and silver of the icons, mosaics and frescoes, making them sparkle. The whole purpose was to draw the visitor in the church into contemplation [Bel90, Pee04].

### 4.2 Artifacts visualized

**Figure 14:** *The 6th century mosaic depicting the Virgin Maria between Archangels at Angeloktistis Church, Kiti.*

The Byzantines were much preoccupied with the use of gold and favored it extensively in their churches. In the icons, massive wall and ceiling mosaics and frescoes, the use of gold was not only symbolizing immortality and the supernatural but was meant to illuminate the pictures from within. This lighting effect in combination with certain architectural elements of the churches was used to create certain illusions, including the holy people on the cupola mosaics seeming to step out of the golden background, approaching the viewer [HJK96]. Gold was not only used for the pictures, but also for candlesticks: with churches having masses of candles, both in ornate floor candle holders and in hanging candelabra. Byzantine architects in fact paid careful attention to the use of direct and indirect lighting in certain parts of the church building, depending on the firmly defined religious value of the respective space [The01]. This religious value was also symbolized by the architectural form and the use of pictures. For example, the cupola, being the most characteristic architectural element of the Byzantine churches, should be a direct representation of heaven, therefore it had to be illuminated by as much light as possible, including the generous use of reflecting gold [HJK96].

We investigated the high-fidelity reconstruction of three artifacts, all of which contain gold.

- The 6th century mosaic depicting the Virgin Maria between Archangels at Angeloktistis Church, Kiti, near Larnaca, Figure 14. Gold was used for the background and the halos. The mosaic stones were glass tesserae, which allowed light to reflect and refract within the glass.
- The Icon of Christ Arakiotis, from the Church of Pantocrator of Arakas from Lagoudera. The icon is currently displayed in the Byzantine Museum & Art Gallery, Bishops Palace in Nicosia. The icon is dated from the end of the 12th century and is painted with tempera and gold leaf on a wood panel, which was typical for artifacts primarily intended for ritual or ecclesiastical use during the Byzantine period.
- The fresco of St. George on horseback, 15-16th century in the chapel of Sts Cosmas and Damian, also at the Angeloktistis Church, Kiti.

### 4.3 Capturing the data

Detailed measurements were taken at the two environments, Figures 15, 16, 17. The geometry was measured using a Leica Disto A6 laser measure meter. This has an accuracy of ±1.5mm over a range of 200m. Light level measurements were taken at numerous points using a Minolta T10 illuminance meter with a measuring range of 0.01 to 299,000 lx. Finally several hundred digital photographs were taken, with and without the inclusion of a Mac- Beth color checker chart. A number of images were also stitched together to create panoramas of each of the environments. In addition HDR images were created of each of the environments using a series of photographs at different exposure levels [DM97].

To capture a single-viewpoint PTM image each artifact needed to be photographed from a fixed camera position. Multiple photographs were taken, each illuminated from a different light position. If the positions of the lights are known, the photo sequence can be mathematically synthesized into a single PTM image. The images are captured using a process termed the ‘Egyptian Method’ in which a string is used to measure the illumination radius distance based on the diameter of the subject. One end of the string is tied to the light source and the other end is held near to but not touching the subject at the location corresponding to the center of the composed image. For each light position photographed, the subject end of the string is positioned and the light distance is determined. The subject end of the string is then moved out of the camera’s field of view and the photo taken. This process is repeated until a representative hemispheric sample of light directions is acquired around the subject.

**Figure 15:** *Capturing the Icon of Christ Arakiotis, Byzantine Museum & Art Gallery.*

Capturing PTMs of the artifacts using this technique posed a number of challenging problems for the project. The presence of light sensitive objects, including tempura on the wood icon and the nature of the fresco, mandated a low photonic damage lighting system. While, in an isolated environment, the mosaic tesserae themselves are very resistant to photonic damage, and standard flashes or other photographic lights could have been used to document them responsibly. However, in its apse location, the proximity of light sensitive materials meant that responsible cultural heritage practice required another approach. The solution was to use a 250 watt xenon arc lamp light source designed to power a fibre optic swimming pool illumination system. Xenon sources emit visible light as well as large amounts of photonically damaging ultraviolet (UV) and infrared (IR) light wavelengths. While a variety of light transmitting fibers and guides are available to carry this light, the least expensive and most widely used material is PMMA acrylic cable. PMMA acrylic acts as a band pass filter, excluding both UV and IR light and passing only visible wavelengths between 400 and 750 nm. We used a bundle of this fiber to filter our light source. A Cypriot lighting contractor, Andreas Demetriou, loaned the equipment at no charge to the project.

**Figure 16:** *Capturing the fresco of St. George on horseback, Chapel of Sts Cosmas and Damian, Angeloktistis Church, Kiti.*

The apse is five meters off the floor at the top and over three meters at its base which caused some major difficulties when trying to capture the images of the mosaic. Although a four meter ladder was available at the church and kindly loaned to us for this part of the work, the enclosure of the sanctuary directly below the apse is separated from the rest of the church by a high, ornate grating which both segregated the sacred space from the main part of the church and constrained our working area. This limited area contained the alter, freestanding crucifixes, ritual objects, furnishings for practical support of ritual activities such as multiple daily masses, and in addition, all the necessary project equipment for the image capture, including cameras, lights, color checker charts, and reflection capturing black balls. The problem was overcome by attaching the subject end of the string for the Egyptian Method to a long pole, a broom handle loaned to us by the church. This subject end of the pole was cushioned with bubble wrap in case it accidentally touched the mosaic. This end was held close to, but fortunately never touching, the mosaic by a member of the team, and then another person on the ladder used the string to position the light correctly, Figure 17. The broom handle and string were then moved out of the way and the image taken. Despite all these difficulties, 79 light positions were correctly captured and this was enough to build the desired high quality RTI images.

**Figure 17:** *Capturing the 6th century mosaic depicting the Virgin Maria between Archangels at Angeloktistis Church, Kiti.*

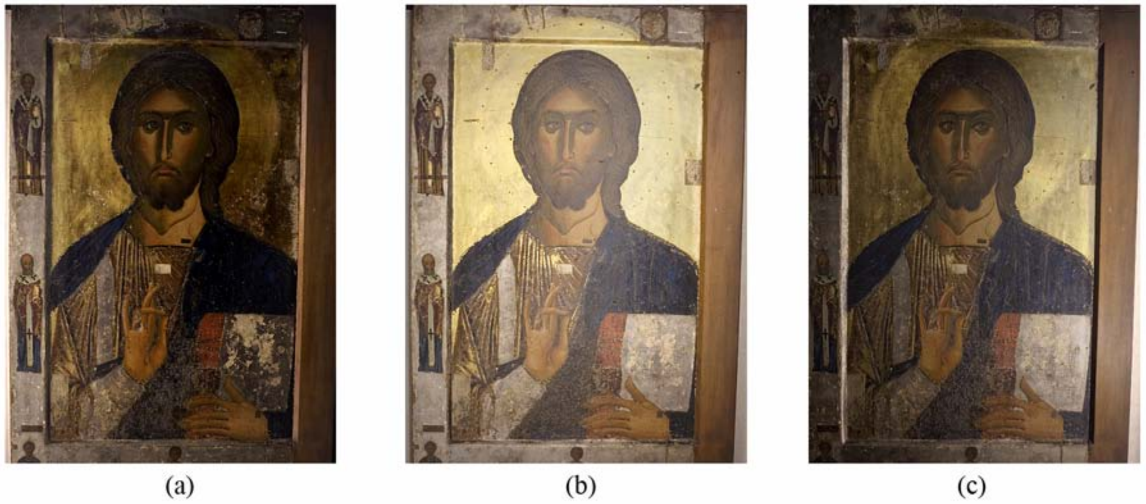


**Figure 18:** *Icon of Christ Arakiotis lit from the (a) left, (b) middle, and (c) right.*

Creating the context Using the detailed measurements, accurate models of the Angeloktistis Church at Kiti and the Byzantine museum were created using the 3D modeling software, Maya, Figures 13 and 19. Experimental archaeological techniques were used to build replica candles and oil for the lamps using authentic materials, in particular beeswax. These candles and oils were then set on fire and the detailed spectral data of each flame type measured using a spectroradiometer, which is able to measure the emission spectrum of a light source from 380nm to 760nm, in 5nm wavelength increments. These spectral results were then converted into a form so they could be incorporated in the physically based lighting simulation system, Radiance[WS98].

### 4.4 Results

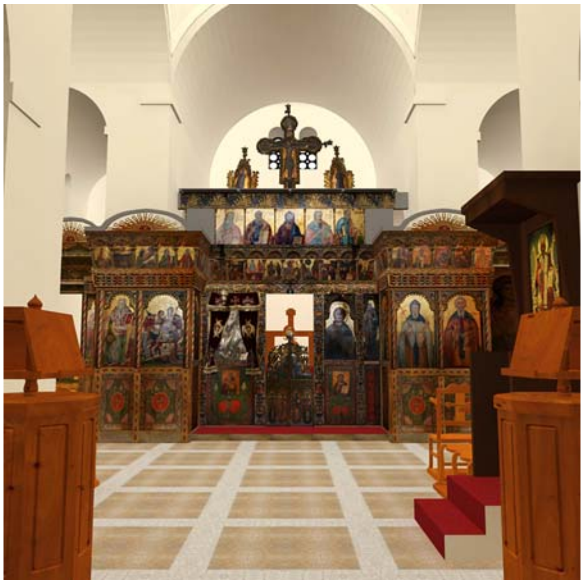


**Figure 19:** *Model of Angeloktistis Church, Kiti.*

Figures 18 and 19 show results from the PTM for the icon and the mosaic which clearly show how the position of the lighting may have affected the appearance of the artifacts. This affect is especially pronounced with the mosaic which is of particular interest as many of the Byzantine mosaics were on the curved walls and ceilings, which included gold and silver glass tesserae. As the viewer or the light moved within the church, these tesserae sparkled. Our study showed that the appearance of the mosaics is indeed significantly different when lit from various directions[ECMA07].

**Figure 20:** *Appearance of baby Jesus from the mosaic lit from different directions.*

Figure 21 shows the Icon of Christ Arakiotis lit by simulated modern lighting, as it appears in the Museum today, and Figure 22 with simulated beeswax candlelight as it may have appeared in the past [EYTA07, EYJ*08].

**Figure 21:** *Icon lit by simulated modern lighting.*

### 4.5 Summary

This section has shown has two novel technologies being applied to the computer reconstruction of ancient Byzantine artifacts and environments: high fidelity physically-based computer graphics techniques and PTMs. The results clearly show that there is indeed a major difference in the way in which the artifacts are perceived when lit from different directions, and with the candle light, oil lamps and day light. These new insights into how Byzantine art may have been viewed in the past will form the foundation for future high-fidelity computer reconstructions of cultural heritage sites and artifacts.

### References

[Bel90] H. Belting. Bild und Kult: eine Geschichte des Bildes vor dem Zeitalter der Kunst. CH Beck, 1990.

[DC01] K. Devlin and A. Chalmers. Realistic visualisation of the Pompeii frescoes. *Proceedings of the 1st international conference on Computer graphics, virtual reality and visualisation,* pages 43– 48, 2001.

[DM97] P. Debevec and J. Malik. Recovering high dynamic range radiance maps from photographs. *ACMSIGGRAPH 1997,* pages 369–378, 1997.

**Figure 22:** *Icon lit by simulated beeswax candle.*

[ECMA07] Zanyi E., Schroer C., Mudge M., and Chalmers A. Lighting and Byzantine Glass Tesserae. *EVA 2007: Electronic Information, the Visual Arts and Beyond*, 2007.

[EYJ*08] Zanyi E., Chrysanthou Y., Happa J., Hulusic V., Horton M., and Chalmers A. The High-Fidelity Computer Reconstruction of Byzantine Art in Cyprus. IV *International Congress of Cypriot Studies*, 2008.

[EYTA07] Zanyi E., Chrysanthou Y., Bashford-Rogers T., and Chalmers A. High Dynamic Range Display of Authentically Illuminated Byzantine Art from Cyprus. *VAST 2007: 8th International Symposium on Virtual Reality, Archaeology and Cultural Heritage*, 2007.

[HJK96] E. Hein, A. Jakovljevic, and B. Kleidt. *Zypern. Byzantische Kirchen und Kluster. Mosaiken und Fresken*. Melina-Verlag, Ratingen, 1996.

[Pee04] G. Peers. *Sacred Shock: Framing Visual Experience in Byzantium.* Penn State Press, 2004.

[RC03] I. Roussos and A. Chalmers. High fidelity lighting of knossos. *Proceedings of VAST2003*, pages 47–56, 2003.

[The01] L. Theis. Lampen, leuchten, licht. In J.J.K. Degenhaart, editor, *Byzans - Das Licht aus dem Osten*. Verlag Philipp von Zabern, 2001.

[WS98] G. Ward and R. Shakespeare. *Rendering with radiance: the art and science of lighting visualization*. Morgan Kaufmann Publishers Inc. San Francisco, CA, USA, 1998.

*********************************************

## 5. Reflection Transformation Imaging for Large Objects and Quality Assessment of PTMs

Tutorial Presenter: Roberto Scopigno,

Additional author: M. Corsini

Visual Computing Lab, ISTI - CNR, Italy

Email:`{corsini, r.scopigno}@isti.cnr.it`

Reflection Transformation Imaging has proved to be a powerful method to acquire and represent the 3D reflectance properties of an object, displaying them as a 2D image. One of the most popular techniques for reflection transformation imaging is Polynomial Texture Mapping (PTM), where for each pixel, the reflectance function is approximated by a biquadratic polynomial.

This tutorial section presents some practical issues about the creation of high-quality PTMs of large size objects. The aim is to analyze the acquisition pipeline, resolving all the issues related to the size of the object, from a practical point of view. Moreover, we presents some results about quality assessment of PTMs, showing the importance of lighting placement. The present methodology is particularly interesting for the acquisition of certain class of Cultural Heritage objects, like bas-relieves.

### 5.1 Methodology

As just stated, typically PTMs are acquired by positioning the object of interest inside a fixed illumination dome. This permits to automatically change the light direction during photos acquisition, but limits the flexibility of the overall system. Since, in this case, the objective is to acquire large objects, we decided to deal with a "virtual" light dome as explained in the next sections. In particular, we divided the acquisition process in three steps: acquisition planning, acquisition and post-processing.

#### 5.1.1 Acquisition planning

Selecting the correct lights placement is an important step in the PTM acquisition of large objects since, in general, we do not have the possibility to use a physical dome to illuminate the object. Instead, we will have to manually place the light in different positions, forming a "virtual" illumination dome. The size of this illumination dome and its light distribution will depend on the size of the target object and on the number of light directions we want to use to sample the reflectance function. To simplify the light placements we developed a specific software tool that helps us to plan the positioning of the lights. The tool usage is quite simple; the scene setup is generated as the user inputs the size of the object to be acquired, its height from the ground and the distance of the camera. Objects in the scene are scaled according to user specifications; camera is pointed towards the center of the object. Next step is the definition of the acquisition pattern. The array of light can be generated by choosing the light distance and two angles (vertical and horizontal step). The tool can automatically exclude the light positions that are too near to the obstacles around the object of interest (if given in input) or that are aligned with the camera axis (light will be shadowed by camera or will occlude the camera). The points are generated using a parallel-meridian grid. This does not guarantee a uniform distribution over the sphere but, having a series of light position at the same height will result in a much faster acquisition due to the manual placement. Finally, given a complete dome, the program can perform a light pruning following the "distributed" scheme (described in Section 5.2). This scheme, by generating a more uniform distribution, greatly reduces the number of required light positions while not influencing excessively the PTM quality. When the light setup has been completed, the tool can save a written description of the lighting setup by providing step by- step instructions on light placement.

#### 5.1.2 Acquisition

**Figure 23:** *The acquisition setup.*

Several experimental devices has been created to acquire PTMs. Typically, this devices are suitable for sampling small objects (from a minimum of 2 cm to a maximum of 50 cm of size) and are characterized from a fixed dome.

Following the previous considerations, our solution is shown in Figure 23.

Our acquisition equipment was composed of an 8MPixel Canon Digital Camera, a 1000W halogen floodlight, a tripod and a boom stand. The fact that we used only one light explains also the parallel-meridian placement of lights: with these configuration we needed to set the height and direction of the light only once for each level of height. The time needed to position the light was minimized by the acquisition planning just described, and by some references placed on the floor. We fastened the acquisition using a printed scheme of the angle directions (it helped in placing the references on the floor very quickly), and a plumb line attached to the light in order to facilitate the positioning. The acquisition steps can be summarized as:

- Take the measures of the object, find the center of it and its height from the ground.
- Using these data, generate the "virtual dome" and put the reference marks following the output of the PTM planner.
- Position the digital camera on the tripod. Measure aperture and shutter speed under the illumination of the central light. Keep these values fixed for all the photos, in order to have a constant exposure.
- For each level of height, set the height and the direction of the light, then put it on each reference mark related to the level, and take the photo.

Other advantages of this equipment are that it is quite cheap (nearly 1000 Euros in total) and easily transportable.

### 5.1.3 Data processing

In order to calculate a precise illumination function, a critical factor is that the digital camera must remain fixed from one photo to the other. Even a misalignment of a few pixel can produce a bad result, with visible aliasing. In our experimental acquisition set it could happen to have small movements of the camera. This led to the necessity of aligning the set of photos before building the PTM. To do so we performed the alignment automatically using a freeware tool for panoramic images. This is the only data processing we need before to generate the PTM.

### 5.1.4 About manual light placement

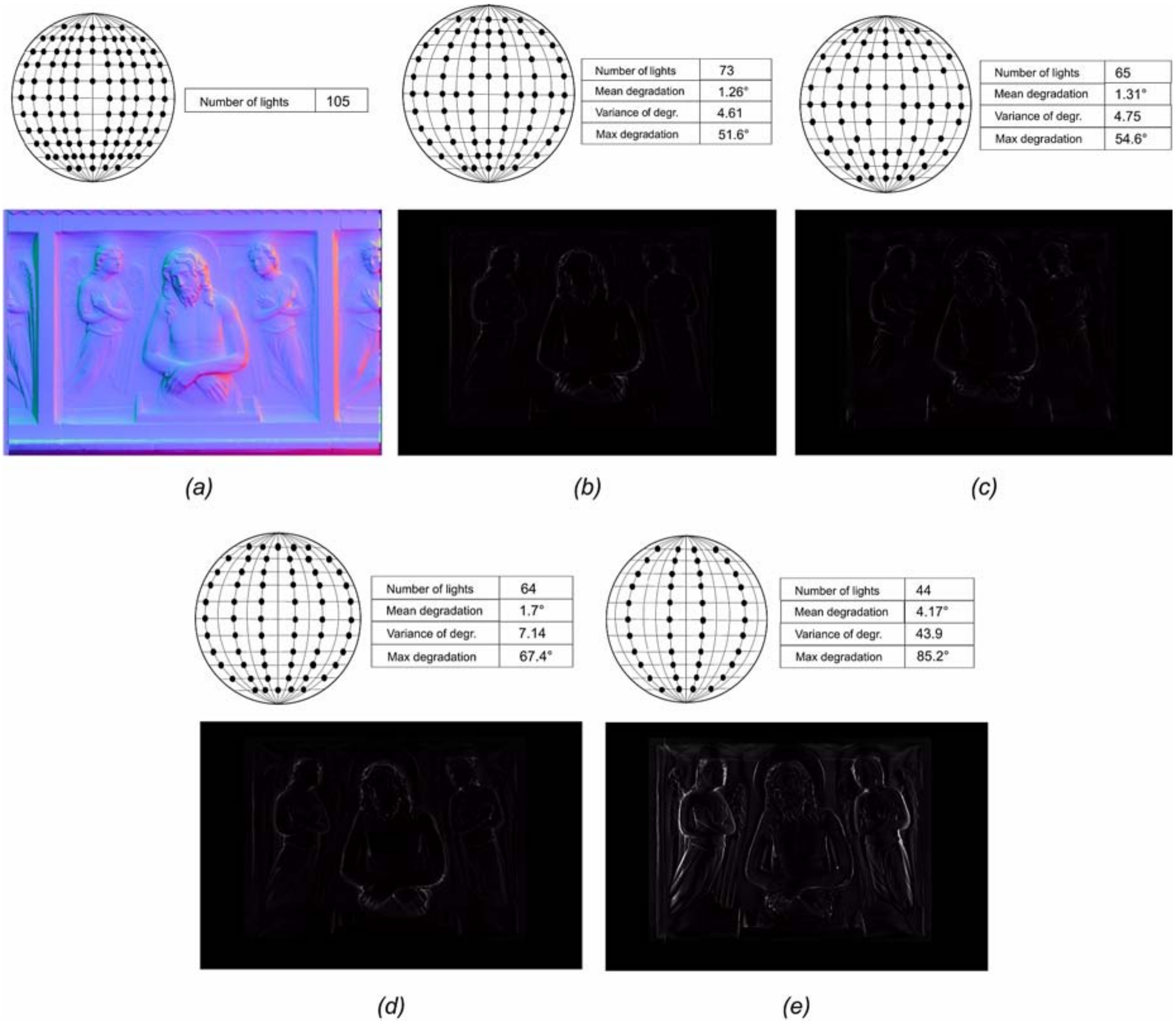
As just stated, the light in our acquisition device is placed manually for each direction sample. The acquisition planning and other solutions like the reference marks help us to optimize this time. Nevertheless, nothing prevent us to further reduce the acquisition time by employing solutions to eliminate the needed for manual placement of light positions. In fact, useful tool that use a mirror ball to estimate lighting direction without the necessity to measure it has just been used with success in PTM acquisition [MMSL06]. Even in this case, the acquisition planning continue to be helpful (e.g. obstacle avoidance). A completely image-based automatic estimation (with a certain degree of approximation) of the light direction is also possible (Winnemöeller et al., [WMTG05]) making the light positioning a easy and very fast task.

## 5.2 Quality assessment

In this part of the tutorial we consider some issues regarding quality assessment of PTMs. More specifically, we performed our quality evaluation with respect to the number and position of lights used during the acquisition. In order to perform this quality evaluation, we considered a 70 by 80 cm section of the XIVth Century Tomb of Archbishop Giovanni Masotti as a case study. We performed a very accurate PTM acquisition, using a large number of lights position (105 light positions, 11 angles and 11 height levels) and we acquired the same object also with a triangulation Scanner (Minolta 910i). We consider the 3D scanned model as a "ground truth" since for large objects 3D scanning is a very reliable technique in terms of accuracy. Following the steps just described, we created a PTM using all the 105 photos. We also generate an high-precision 3D model (nearly 2.4 millions of faces, 1/3 of millimeter of sampling resolution) from a set of 68 range maps.

**Figure 24:** *Comparison between the normal maps of the 3D scanning and the PTM: full model and particular.*

Our first comparison was between these two representations; as a measure of quality we compare the normals calculated from the PTM data with the surface normals of the 3D model. To do so we aligned the 3D scan model to the PTM image using a tool for image registration [FDG_05]. In Figure 24 a comparison of the normal maps is shown. The variation of the normals in the PTM is smoother than in the corresponding 3D scan, but their values are coherent. This test demonstrates that, even though PTM provides an approximation of the objects' geometry, the obtained data are reliable. It also demonstrates that our setup does not introduce significative errors. The other analysis was related to the degradation of PTM quality respect to the number and position of lights. For this purpose, we created four PTMs starting from subsets of the original lights. Then we made a comparison between the normal maps of the "best" PTM (the one with 105 lights) and the "sub-sampled" ones. The comparison was made calculating the difference



(a)

| | |
|---|---|
| Number of lights | 105 |

(b)

| | |
|---|---|
| Number of lights | 73 |
| Mean degradation | 1.26° |
| Variance of degr. | 4.61 |
| Max degradation | 51.6° |

(c)

| | |
|---|---|
| Number of lights | 65 |
| Mean degradation | 1.31° |
| Variance of degr. | 4.75 |
| Max degradation | 54.6° |

(d)

| | |
|---|---|
| Number of lights | 64 |
| Mean degradation | 1.7° |
| Variance of degr. | 7.14 |
| Max degradation | 67.4° |

(e)

| | |
|---|---|
| Number of lights | 44 |
| Mean degradation | 4.17° |
| Variance of degr. | 43.9 |
| Max degradation | 85.2° |

**Figure 25:** *Quality degradation: (a) Best quality PTM (normal map) (b-e) Maps of the differences in dihedral angle of normals. The sphere shows the lights placement*.

of the dihedral angles between the normals of each pixel. In Figure 3 we show the analysis of the difference between the best PTM and four possible subsets. In terms of number of lights, we can observe that we can considerably reduce the number of lights without having an excessive degradation of quality. For example, we can reduce the number of photos up to 65 (see Figure 25(c) and 25(d)) and we will have a PTM where mean value and variance (nearly 1.5 and 6 respectively) of, the overall degradation are still satisfying. As regards the different placement of lights, we can observe the case of Figure 25(c) and 25(d). Even though we have almost the same number of lights, a more uniform distribution of the lights brings to lower mean degradation and peak error. Considering these facts, we can conclude that a pattern of 60-70 properly distributed photos can produce a high-quality PTM.

### 5.3 Results

Several objects have been acquired with the developed system in order to show the reliability of the acquisition results. We will show in the tutorial the results obtained on three artifacts: a capitol, a bas-relief and a sarcophagus. Snapshots of the acquired PTMs will be shown in the presentation. The PTMs themselves are available for download with the additional course material from the course's website.

This testbeds produced satisfying results, and showed us that PTM can be an alternative method for documenting and communicating Cultural Heritage information also for large size objects. Moreover, they also gave useful suggestions on how to perform the acquisition more quickly, without compromising the quality of the final results. A final consideration regards the improvements of the proposed methodology using an automatic system to estimate the light direction.This permits to obtain more accurate results and reduce considerably the time needed by the light placement.

## References

[FDG_05] Franken T., Dellepiane M., Ganovelli F., Cignoni P., Montani C., Scopigno R.: Minimizing user intervention in registering 2d images to 3d models. *The Visual Computer* 21, 8-10 (sep 2005), 619–628. Special Issues for Pacific Graphics 2005.

[MMSL06] Mudge M., Malzbender T., Schroer C., Lum M.: New reflection transformation imaging methods for rock art and multiple-viewpoint display. In *VAST: International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage* (Nicosia, Cyprus, 2006), Ioannides M., Arnold D., Niccolucci F., Mania K., (Eds.), Eurographics Association, pp. 195–202.

[WMTG05] Winnemöeller H., Mohan A., Tumblin J., Gooch B.: Light waving: Estimating light positions from photographs alone. *Computer Graphics Forum 24*, 3 (2005), 433–438.

*********************************************

## 6. Photometric Stereo, Structured Light and Related Image Based Techniques for Real World Capture

Tutorial Presenters: James Davis, Oliver Wang, and Prabath Gunawardance

University of California, Santa Cruz, USA

Email:`{davis, owang, prabath}@cs.ucsc.edu`

This section of the tutorial will provide some overview of different real world sensing methods. The most commonly used methods in the context of cultural artifacts are triangulation methods. 3D Depth from triangulation has traditionally been treated in a number of separate threads in the computer vision literature, with methods like stereo, laser scanning, and coded structured light considered separately. In this overview, we attempt to unify many of these previous methods. Viewing specific techniques as special cases leads to insights regarding the solutions to many of the traditional problems of individual techniques.

In addition to 3D measurements, it is possible to directly measure the orientation of the objects surface using methods like photometric stereo. True 3D and direct orientation measurements each have advantages. Combining both methods can lead to surface reconstruction superior to using either method alone.

### 6.1 New Research

New research into techniques used to visualize image-based, empirically captured objects. The research goal is to interpolate both lighting and viewing directions while using a small amount of data that can be easily transferable over the web. The work examines various alternative representations of the lighting and spatial information that can be used to compactly model this information.

**Figure 26:** *An overlaid comparison (using horizontal stripes) of PTMs vs. hemispherical harmonics, showing that the hemispherical harmonic representation better preserves contrast from the original images.*

One of the key questions to answer is which low dimensional representation of lighting and viewpoints will most faithfully represent actual objects, especially given the interpolation and other processing which will be necessitated. As one example, Figure 26 shows a coin encoded using both PTMs and spherical harmonics. PTMs are the current standard in museum RTI imaging. The academic community has primarily been using spherical harmonics during the last few years. Both representations are efficient to compute and store. The PTM encoded stripes have substantially lower contrast and fail to capture important specular components. Even this simple change to lighting interpolation affects the ability of researchers to interpret the archival images. View interpolation requires some notion of pixel or light ray correspondence to smoothly blend from one view to another. Lightfields essentially assume planar objects and apply standard signal processing to reconstruct in-between views. An alternate approach would be to have fully 3D geometry and simply render in-between views. We have been investigating to what extent optical flow (or equivalently stereo correspondence) can be used to provide approximate geometry and thus aid in the task of view interpolation. In particular, multiple lighting conditions provides access to a larger portion of the objects reflectance function than does just a single image. By fitting a low dimensional model such as a Ward lighting model, or spherical harmonics to the lighting conditions in each view and performing stereo matching on the coefficients of this model, rather than raw image intensities, better stereo matching is possible. Below is an example of stereo reconstruction using (left) standard passive stereo and (right) reconstruction using a low order reflectance field to enhance the matching. The quality is clearly improved.

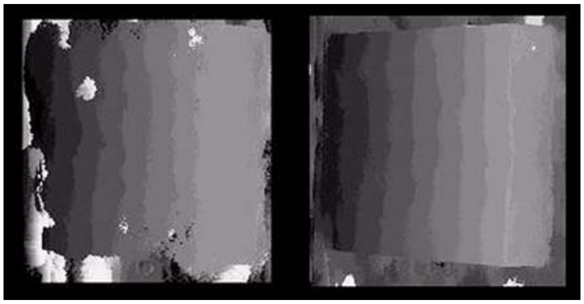


**Figure 27:** *A comparison of the disparity maps generates using standard passive stereo matching (left) and reflectance function coefficient matching (right). Darker colors indicate further distance from the camera.*

## References

[NRDR05] Diego Nehab, Szymon Rusinkiewicz, James Davis, Ravi Ramamoothi, Efficiently Combining Positions and Normals for Precise 3D Geometry, *ACM Transactions on Graphics* (SIGGRAPH), 24(3), 2005.

[DNRR05] James Davis, Diego Nehab, Ravi Ramamoothi, Szymon Rusinkiewicz Spacetime Stereo: A Unifying Framework for Depth from Triangulation, *IEEE Trans. on Pattern Analysis and Machine Intelligence* (PAMI), vol. 27, no. 2, 2005.

*******************************************

## 7. Not All Content is 'Born-Archival': Digital Surrogates and the Perpetual Conservation of Digital Knowledge

Tutorial Presenter: Michael Ashley

University of California, Berkeley, USA

Email: `mashley@berkeley.edu`

"Thousands of years ago we recorded important matters on clay and stone that lasted thousands of years. Hundreds of years ago we used parchment that lasted hundreds of years. Today, we have masses of data in formats that we know will not last as long as our life times. Digital storage is easy; digital preservation is not." - Danny Hillis

This is a tutorial about digital archives and end-user expectations, and how the practices and technologies of our collective tutorial can fundamentally revolutionize the way producers and consumers of digital content engage with media. We have focused thus far on state-of-the-art media production. Here we will look at the state-of-the-field in digital archiving and preservation to see if the world is ready for such innovation.

Within the past 48 hours (today is 1 February 02008), the world has seen two continents lose Internet access, and Microsoft offer to acquire Yahoo! for over 46 billion dollars. The internet, and digital technology, remains volatile, friable and at high risk from the perspective of long-term human history. Flickr, the huge photo sharing site owned by Yahoo!, is a digital repository for millions of users internationally, with over 2,000 images uploaded every minute. What would happen if the Internet 'died' or Microsoft decided to pull the plug on Flickr? Should we be asking, what will happen 'when'?

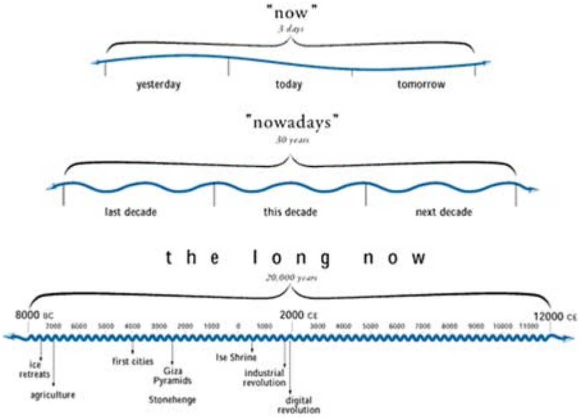


**Figure 28:** *The Long Now from:* http://www.longnow.org/about/

The Long Now Foundation, established in "01996" seeks to "become the seed of a very long term cultural institution," meaning adopting a counterpoint to today's 'faster/cheaper' mind set and promote 'slower/better' thinking [LNF08]. Archaeologists as well as archivists don't think that a decade is a long time, even a century, a millennium, when we take a look at time from the perspective of the human record.

Digital technology is changing all of this, not necessarily for the better. The tech industry measures time in financial quarters and product lifecycles. Those of us who care about the future of human knowledge need to step up and figure out how to make digital content persistent, insulated from the sea changes of innovation and stock prices. This is, as Stewart Brand says, a "civilizational issue." [Bra03]

### 7.1 The 'Digital Dark Ages'

Hillis describes the here and now as a "Digital Dark Age" because information is devalued by the ubiquity of digital content that cannot outlast our lifetimes. While we have more than enough storage media to hold the cultural memory of the planet, the half-life of data is currently about five years. This is due to the fact that digital preservation is not a corporate priority, nor a consumer priority at present. It must, therefore, be a producer priority. [Bra03]

Digital archivists resist new file formats, new metadata standards, new lifecycles and practices for all the right reasons. Consider the fiduciary responsibility of institutional repositories who are charged with keeping content safe, archival, accessible, for as long as possible. Minimizing file formats and standardizing metadata minimizes risk (and presumably, costs) as formats become obsolete. The problem is that by limiting the formats archives are willing to accept, we are actually putting the great majority of digital knowledge at risk. Jpeg and mp3 are just two examples of 'lossy' file formats that are ubiquitous and also not acceptable by most 'trusted' repositories. Is the information within these files meaningless?

If we wish to avoid a Digital Dark Age, we need to incite consumers into action. In this case, the consumers are the archives. To do so, there are several strategies we can apply. We suggest that we need to design digital media to be 'self-archiving', adaptable to virtually any digital environment, so that they have no need to rely on 'institutional' repositories to exist, at least not in the monolithic sense. We need file formats that are too clever to ignore, that minimize risk while maximizing semantic meaningfulness, and can transmogrify themselves without degrading as they move 'across the cloud'.

We need institutional repositories to exist, for as Clifford Lynch says, they are "most essentially an organizational commitment to the stewardship of these digital materials, including long-term preservation where appropriate, as well as organization and access or distribution." [Bai08] Until we can invent the digital equivalent of cuneiform tablets, that is, a substance that can preserve the medium and the message equally, we will need stewards of the human record. Our short-term proposition (for the next few decades, say), is to provide digital archives a revolutionary way forward in sustainability.

### 7.2 'Born-Archival' vs. 'Born-Digital'

Ideally, all of us can be carriers of the digital human genome, digital archivists in our own right, and the technologies and workflows we have been discussing and practicing in this tutorial program go a long way toward this aim. When digital file formats can provide consumers, and here we mean end-users, with digital content that is self-archival, we will have achieved the paradigm shift needed to end the reliance on digital libraries and institutions of cultural memory.

John Kunze, preservation specialist for the California Digital Library, calls for 'born-archival' media that is fully accessible and preservable at every stage, throughout the lifecycle of this data, from birth through pre-release to publication to revision to relative dis-use and later resurgence. Data that is born-archival can remain long-term viable at significantly reduced preservation cost [Kun08].

We advocate for both individual professional responsibility and multi-institutional, multi-disciplinary curatorial management of digital heritage content for the foreseeable future. Unlike the physical archives of the Library of Alexandria, lost forever to humanity, digital heritage can be in more than one place at a time and in more than one form, potentially assuring its longevity despite the ephemeral nature of the media. This multiplicity of location and form is both the promise and the peril of digital heritage.

With increasingly diverse data formats, larger file sizes, changing media types, distributed databases, networked information and transitive metadata standards, how are today's heritage specialists to plan for such an uncertain virtual future? It is increasingly difficult for individual scholars and researchers to do the right thing when it comes to digital heritage conservation. The accountability for the conservation of digital heritage falls to all in the natural science (NS) and cultural heritage (CH) fields. But what is a reasonable course of action in the face of such adversity?

### 7.3 Digital Heritage Conservation

The importance of developing sensible plans to preserve our digital heritage cannot be minimized. Responsible preservation of our most valued digital data requires answers to key questions: Which data should we keep and how should we keep it? By digital heritage conservation, we mean the decision-making criteria to discern what *must* be saved from what *can* be lost. Everything can't be saved nor is it desirable to do so. How is this data to be saved to ensure access in five years, 100 years or 1,000 years? In the next 100 years, we will go through dozens of generations of computers and storage media, and our digital data will need to be transferred from one generation to the next, by someone we trust to do it. Finally, who will pay for all this?

We produce more content now than it is humanly possible to preserve. Current estimates are that in 2006, 161 billion trillion bytes -- 161 exabytes, or 161 billion gigabytes -- of digital data were generated in the world -- equivalent to 12 stacks of books reaching from the Earth to the sun. In just 15 minutes, the world produces an amount of data equal to all the information held at the Library of Congress [BB07].

We can think of digital heritage in terms of what the value is of what is being saved, its viability, how available it is to stakeholders, and how long it will last. In other words, an ideal digital heritage repository would conserve archival quality digital surrogate files in an openly accessible way, forever. This is the simplest definition of a trusted repository.

The Library of Congress devised a set of sustainability factors for digital content that are as pragmatic as they are difficult to maintain over time. The core principles we advocate in this tutorial strongly adhere to these sustainability factors [CLIR02].

**Adoption**: Wide adoption of a given digital format makes it less likely to become obsolete while reducing investment by archival institutions for its migration or emulation.

**Transparency**: Open to direct analysis without interpretation, transparency is characterized by self-evidence and substantive metadata. Those who use digital surrogates benefit from complete and accessible empirical provenance.

**Self-documentation**: XMP (Extended Metadata Platform) and other key forms of self-evidence, such as automatically generated empirical provenance data, dramatically increase the chances for a digital object to be sustainable over time.

**External dependencies**: The less a media form is dependent on proprietary software/hardware, the better. If two documentation methodologies can yield similar results in terms of accuracy and productivity, the more open / less externally dependent method is recommended.

**Impact of patents and copyrights**: Intellectual property limitations bound to content can inhibit its archival capabilities in profound ways. Whenever possible, unambiguous, open licensing for content is recommended.

**Technical protection mechanisms**: "No digital format that is inextricably bound to a particular physical carrier is suitable as a format for long-term preservation; nor is an implementation of a digital format that constrains use to a particular device or prevents the establishment of backup procedures and disaster recovery operations expected of a trusted repository." Additionally, limitations imposed by digital rights management (DRM) or archaic security protocols severely limit the long-term viability of digital content.

Furthermore, the Archaeology Data Service (ADS) in the UK defines the most critical factor for digital heritage sustainability is to "plan for its re-use" [ADS07]. Indeed, the design of decision making principles for digital heritage conservation should above all aim to the perpetual use and re-use of this content by striving to assure its reliability, authenticity and usability throughout the archival lifecycle.

Digital technology and the creation of 'born digital' content are indispensable aspects of NS and CH management today. From low-tech documentation like Microsoft Office, html websites, PDF, and photography, to more complex technologies such as panoramas, object movies, laser/lidar scanning, scanning electron microscopy (SEM), x-ray fluorescence (XRF), Global Positioning System (GPS), 3D modelling, and distributed databases, to cutting edge techniques including Web 2.0, reflection transformation imaging (RTI), algorithmic generation of drawings from surface normals, and the family of photogrammetry influenced texture and 3D geometry acquisition tools, these new media types form a spectrum of opportunities and challenges to the preservation field that did not exist even 30 years ago.

### 7.4 A Role for All of Us

We are at a unique point in history, where NS and CH professionals must work to care for the physical past while assuring that there will be a digital record for the future. Peter Brantley, Executive Director of the Digital Library Foundation, thinks, "The problem of digital preservation is not one for future librarians, but for future archaeologists." If one imagines that the well-intentioned efforts of researchers and scholars in the modern era could be unreadable only fifty years from now, there is tremendous responsibility on individual NS and CH professionals to insure a future for their digital work.

In the mid 1990's, a critical gap between those who provide information for conservation (providers) through construction of digital heritage documentation and those who use it (consumers) was identified by the International Council of Monuments and Sites (ICOMOS), the Getty Conservation Institute (GCI) and the International Committee for Architectural Photogrammetry (CIPA), who together formed RecorDIM (for Heritage Recording, Documentation and Information Management) Initiative Partnership [GCI06]

A 2006, GCI-led literature review demonstrates that most of the key needs identified in RecorDIM are evidently still with us. After reviewing the last 20 years of cultural heritage documentation, the authors concluded, "only 1/6th of the reviewed literature is strongly relevant to conservation." [EC06] Their suggested remedy is to correlate the needs of conservation with the potential documentation technologies by involving more diverse audiences and by creating active partnerships between heritage conservationists, heritage users, and documentation specialists.

We are focusing on another gap, between cultural heritage and digital heritage, that has been created as we have shifted away from paper in favor of pixels throughout all of our communication and analytic processes globally. In 2000, the Library of Congress recognized that "never has access to information that is authentic, reliable and complete been more important, and never has the capacity of libraries and other heritage institutions to guarantee that access been in greater jeopardy." [CLIR02]

We see the crisis not between producers and consumers of digital data, but in the capacities of NS and CH specialists to produce the content for themselves in ways that can adhere to the principles defined by the LOC and other key international standards bodies. There is a desperate need for methodologies for digital heritage conservation that are manageable and reasonable, and most importantly, can be enacted by NS and CH professionals as essential elements of their daily work. The collaboration between NS and CH professionals and digital specialists should lead to the democratization of technology through its widespread adoption, not the continued mystification of technology that is still being defined by the persistence of a producer/consumer model [TA01]

## References

[ADS07] Archaeology Data Service: Digital Preservation FAQ (York, 2007), Archaeology Data Service, http://ads.ahds.ac.uk/project/faq.html

[Bai08] Bailey, C. W.: Institutional Repositories, Tout de Suite. (2008), Digital Scholarship, http://www.digital-scholarship.org/

[BB07] Barksale, J., Berman, F.: Saving Our Digital Heritage

[BBC08] BBC: Microsoft wants to purchase Yahoo! (London, 2008), BBC, http://news.bbc.co.uk/2/hi/business/7222114.stm

[Bra03] Brand, S.: Escaping the Digital Dark Age: Library Journal (2003), http://www.rense.com/general38/escap.htm

[CLIR02] Council on Library and Information Resources (CLIR) and the Library of Congress: Preserving Our Digital Heritage (Washington, D.C., 2002), Plan for the National Digital Information Infrastructure and Preservation Program. http://www.digitalpreservation.gov/formats/intro/intro.shtml

CNN08] CNN.: Third undersea Internet cable cut in Mideast (2008), CNN.com, http://www.cnn.com/2008/WORLD/meast/02/01/internet.outage/index.html

[EC06] Eppich, R., Chabbi, A.: How Does Hi-tech Touch the Past? Does It Meet Conservation Needs? Results from a Literature Review of Documentation for Cultural Heritage. In *VAST'06: Proc.7th Int. Symp. Virtual Reality, Archaeology and Cultural Heritage* (Cyprus, 2006) The European Research Network of Excellence in Open Cultural Heritage (EPOCH)

[GCI06] Getty Conservation Institute: About RecorDIM (Los Angeles, 2006), http://extranet.getty.edu/gci/recordim/about.html

[Kun08] Kunze, J.: New Knowledge and Data Preservation Initiative. California Digital Library (2008)

[LNF08] About the Long Now Foundation: The Long Now Foundation (2008), http://www.longnow.org/about

[LoC02] Library of Congress:

[LV03] Lyman, P., Varian, H.: How Much Information?. School of Information Management, UC Berkeley (Berkeley, 2003), http://www.sims.berkeley.edu/how-much-info-2003

[NSF03] The National Science Foundation and the Library of Congress: It's About Time (Washington, D.C., 2002), Research Challenges in Digital Archiving and Long-Term Preservation.

[Smi06] Smith, A.: Distributed Preservation in a National Context. D-Lib Magazine (2006)

[TA01] Tringham, R., Ashley, M.: The Democratization of Technology. (Berkeley, 2001), *Virtual Systems and Multimedia Proceedings 7th International Conference.*

[UNE05] UNESCO: Charter on the Preservation of Digital Heritage (Paris, 2005), http://portal.unesco.org/ci/en/ev.php-URL_ID=13366&URL_DO=DO_TOPIC&URL_SECTION=201.html

*********************************************

## 8. Techniques and Tools of Empirical Acquisition Knowledge Management

Tutorial Presenter: Martin Doerr

Information Systems Laboratory, Centre for Cultural Informatics of the Institute of Computer Science, FORTH

Email: `martin@ics.forth.gr`

As outlined in the previous section, scientific data cannot be understood without knowledge about the meaning of the data and the ways and circumstances of their creation. Such knowledge is generally called “metadata”, i.e., data about data.

In this section we deal with the problem to automate scientific image capturing and processing methods to the degree possible and to manage the metadata of these processes (“empirical provenance data”) from the generation to use, permanent storage and reuse.

We describe in the following requirements for tools, interface specifications, the design of the metadata lifecycle and the core data structure to enable the wide use of the respective imaging technology, in particular as low-cost and easy to apply method for low-budget customers and out-of-lab applications.

### 8.1 Function

Ultimately, the metadata should be sufficient to support the scientific interpretation of the resulting data of an imaging process. Frequently the evolution of technology, understanding of shortcomings in the execution of a particular process, or new requirements for the quality of the results may require recalibration or reevaluation of the empirical (primary) source data. Alternatively, parts of the source data may be replaced by better ones and the process be reevaluated. In wider scenarios, any part of the source data may be reused for other processes in the future. Also integration or reuse of resulting data may require recalibration of the results. The value of imaging data as information source and for reuse may deserve long-term

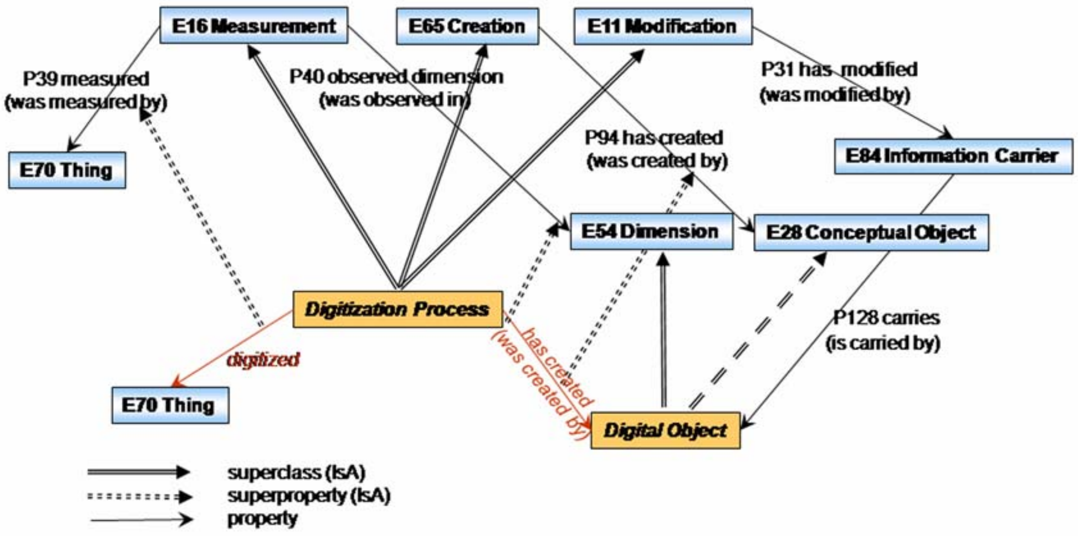


**Figure 29:** Digitization Process as specialization of the CIDOC CRM.

accessibility and preservation. This means storage in central repositories, search capability and preservation of knowledge needed to view, run or migrate imaging results to new platforms.

### 8.2 Environment and processes

Characteristic for cultural heritage is the field observation. Immobile objects, but also rare or valuable objects are not easily moved from their permanent location, or belong to a social context such as a church or temple. Therefore the capture of primary source data may occur in the limitations of the object location with mobile equipment. Under these conditions, reliable registration of the process and context conditions must be possible:

- The identity of the measured or depicted object
- The experimental setup (geometry, light sources, tools, obstacles, sources of noise)
- capture parameters

It must be possible to import all metadata that already exist in other sources, such as object descriptions, tool descriptions, processing parameters (such as EXIF), without retyping. All data common to a serious of captures should be entered only once. Automatic plausibility control of manually entered data is feasible to a certain degree.

The capture is carried out by a team, which may itinerate through various sites or stay at a home lab. Actual processing may occur (for trial purposes!) on field, or in a home lab, or by another team. Source and processed data may be transferred to other locations for use, reuse, reevaluation or permanent storage. So at various sites, supersets, subsets and derivatives of the same data emerge. The derivation graph is directed, but neither linear nor a tree. These sites may have different platform requirements. It must be possible to export and import parts and wholes of source and processed data in different formats and to preserve the identity of all the referred items, i.e. such as objects depicted, involved actors, individual captures, resulting data and complete, integrated data sets.

Metadata should be created with minimal manual input, consistent, avoiding any transcription errors. They must be interoperable with multiple platforms, easy to adapt to new processes, easy to migrate, decompose and integrate in different ways. A notion of identity for all partial products and their authenticity should be preserved despite decomposition and reintegration.

### 8.3 Approach

Only a workflow management system can sufficiently monitor and control the imaging processes in order to capture and import metadata and sufficiently correlate input data, intermediate steps and common processing parameters with final results, such as device description data, device parameters (e.g., EXIF), experimental setup, calibration data, identification of software used, time of capture etc.

Primary source data together with (preliminary) end results of an imaging process form a complex, coherent whole. The metadata of this whole form a “metadata masterfile”, which should contain all data scientists would regard as necessary for later interpretation and reuse – to the degree such foresight is possible and correct. Respective components, such as a single source image or scan, form self-contained subunits within the whole. In order to avoid data redundancy, the data structure will rely on suitable URI generators and a system of rich cross-linking.

Processing metadata and parameters may exhibit an incredible diversity. The only chance to create generic tools is a rigorous abstraction and generalization towards the above described functions, and to employ an extensible schema. Therefore we adopt the CIDOC Conceptual Reference Model (ISO21127) [Doe03], with the notion that scientific observations and processes can be seen as a network of real life historical events that connect things (data and physical objects) with actors, time and space. It has been originally designed for schema integration of museum documentation about the historical context and observational data on museum objects.

The CRM allows for the seamless connection of technical data with the description of the reality under investigation, and for describing all dependencies of results on other data and of source data on contextual parameters via generalization of an open number of specialized relationships. Generic functions can thus be implemented as navigation along data paths in a semantic network formed by the metadata. Only an RDF or equivalent representation will allow for the necessary data manipulations, in particular decomposition and merging. Thus implemented, data structures of the master metadata can be specialized without compromising the generic functionality. Figure 29 shows, how a digitization process can be characterized as a specialization of the generic CRM notions of Measurement, Creation, and Modification.

### 8.4 Derived Metadata

From the master metadata, other, more restricted metadata can be generated at any time by suitable portable software on demand for respective environments, such as Dublin Core or METS representations, in particular for to satisfy access capabilities of various repositories the data may be stored in. The master metadata themselves may not be separated from the data they describe. It is not possible to preserve in one self-contained unit all data a result set depends on. Some information, such as a JPG compression algorithm, must be regarded as common knowledge. In a controlled environment it may be uneconomic to duplicate data in cases where too many derivatives are produced from the same sources. Components kept in one environment internally may be linked to in another or vice-versa. The proposed metadata management will allow for implementing as generic repository technology the management functions to trace the availability of dependent components.

If suitable URIs are generated from the beginning and preserved through all processing steps, it will always be possible to recognize duplicates of existing data sets and their components. The impact of deleting or moving data results depend on, or of the obsoletion of the technology necessary to interpret the data, may thus be effectively controlled and suitable measures be taken. More complex is the situation with identifiers for *a priori* external data, such as museum objects, software components etc. Here both, political conventions and richer methods to register multiple identifiers in use and other data to assist identification must be employed.

The here described approach to manage metadata for the complete information lifecycle of complex scientific datasets in open, distributed environments is innovative. To our knowledge, no other work has addressed to abstract and generalize metadata structures and management function as described here. We regard it as a basis for new and powerful repository technology in e-science.

### References

[Doe03] DOERR, M. 2003. The CIDOC CRM - An Ontological Approach to Semantic Interoperability of Metadata. *AI Magazine*, 24(3).

*********************************************

## 9. Tools to Automate a PTM Generation

Tutorial Presenters: Alberto Proenca, João Barbosa
University of Minho, Portugal
`Email:{aproenca, jbarbosa}@di.uminho.pt`

Digital photography has become a convenient and affordable method to document artifacts. Polynomial Texture Maps (PTM) use digital photography to provide a textured representation of a 3D artifact. The generation of a PTM relies also on the light source positions, which are fed to a polynomial fitter. For small objects a homemade rigid dome with the lighting positions can be built, which helps to get the light source coordinates required by the PTM fitter. When documenting medium to large size objects, domes may become hard to use due to location constraint or dome size requirements.

To overcome the constraints of a physical dome, techniques were developed to help the photographers to place the light sources [DCCS06]. These techniques require careful measurements and hand annotation of the light source position during a shooting session. Methods were presented to estimate the light sources directions, either from highlights on a glossy sphere [MMSL06] [BSP07] [TSE_04], or by shadow casts by small sticks [CDMR03]. The former methods are the basis for Highlight-based Reflectance. However, the generation of HRTI representation requires considerable human intervention, becoming time consuming and error prone.

A software tool was developed, the LPtracker, to remove the burden to estimate the light sources positions, by automatically tracking these positions from the highlights on a glossy sphere. Images are captured with a glossy sphere next to the object, and the LPtracker applies image processing techniques coupled with special geometry to estimate the light source positions. From the set of captured images, the LPtracker guides the user through a set of pipelined operations: to find the glossy ball in the images, to compute its radius and center location, to track the highlights at each image, to geometrically estimate the lights positions, to record empirical provenance data in files, to feed the required data to a PTM fitter and to open a PTM viewer to present the final result, the PTM representation of an artifact.

A HRTI representation can be automatically generated by the PTMbuilder, a software bundle with 3 modules: the LPtracker is the user interface for the pipelined operations and acts as a frontend to the other two revised modules, the PTMfitter and the PTMviewer, both from HP Labs [HPL]. The PTMbuilder package, currently available at HP Labs web site (free under specific conditions), runs under Windows, Linux and MacOs X.

The guided tour to the PTMbuilder package that follows presents the main user interfaces and dialogues of the software tool, leaving relevant technical details for later

### 9.1 Guided Tour to Build a PTM

To build a HRTI file representation, images of the artifact must be captured with a glossy ball nearby and light sources should be positioned evenly scattered on a virtual dome over the artifact. Figure 30 illustrates a capture session with a superimposed partial 3-times subdivided icosahedron virtual dome over a petroglyph, while Figure 31 shows some resulting images from that session.

The PTMbuilder package contains 3 interconnected modules: the LPtracker, the PTMfitter and the PTMviewer. Once the artifact images are captured and the application is set to run, the user interface at the LPtracker guides the user into a processing pipeline

- selection of the image set and ball region of interest (Figure 33(a));
- detection, visualization and tuning of the center and sphere radius (Figure 33(b) and (c));
- detection, visualization and tuning of the center of the highlight (Figure 33(d));
- generation and visualization of text files for the light position (LP and HLT file) (Figure 33(e)).

Some features can be configured by the user: selection of red/black ball, detection algorithms, empirical provenance logging and process pipeline control (Figure 33(f)). The first three have a common user interface layout: the right side of the screen presents selectable image thumbnails while the left side displays the selected image for visualization and tuning. When analyzing the first image to load in memory it checks for its size and if it is above a pre-defined threshold it requests the user to select a region containing the ball (Figure 33(a))

When the detection of the ball is complete, the user can manually adjust the computed center and radius, using any of the images in the set, or some of the images produced during the detection stage (Sobel filter gradient, median filter image, blended red channel image). Once the user agrees with these computations, he/she can signal the software to proceed (Figure 33(b) and (c)).

When the highlights are detected the user can browse through the image set and, if necessary, perform further adjustments on each of the detected highlight centers (Figure 33(d)). During the highlight detection phase, two files are generated with the light positions for each image in the set: a Light Position file (LP) and a HighLighT file (HLT). The first contains the list of processed images, each followed by the normalized vector with the light source direction, while the latter contains the coordinates of the highlight center. These allow the output of LPtracker to be used by other software modules for the polynomial fitting.

These files may be recorded if the user configured the PTMbuilder to do so, and may also be edited (Figure 33(e)). By default, the PTMbuilder is configured to process and generate the PTM file using the PTMfitter, and later to visualize the resulting PTM with the PTMviewer (both from HP Labs).

### 9.2 Technical Background

The PTM generation process requires a set of captured images of the artifact and the light sources positions for each one. In HRTI the light source position is recorded in each captured image as an highlight on the surface of a glossy ball next to the artifact, as shown in Figure 31. Applying geometry and some assumptions (e.g. viewpoint and light source in the infinity), the light source position can be estimated from the highlight [MMSL06] and computer vision techniques can provide automation [BSP07].

The technical background required to grasp the techniques used in the processing tools to generate HRTI images are described below: how the ball and highlights are detected, and how the light source positions are estimated.

**Figure 30:** *Piscos Man, UNESCO Rock Art at Vale do Coa, Portugal: the shooting session with a virtual dome.*

#### 9.2.1 Ball Detection

The software uses two approaches to detect the ball in the image: search for a region with a given color (when red balls are used) or try to fit a circle into the image by using a Hough transform (HT, computational intensive). When black balls are used, the software only resorts to Hough transform, but when red balls are present in the image, the user can configure the software to use one out of three approaches: as a "black ball" (HT), as a "red region" or as a "red ball" (HT).

There is a strong reason to work with a "red ball": snooker balls are available almost everywhere and are sold in packages with 15 red balls. Besides, an image of this red snooker ball produce high intensity values in the R channel (behaving as white balls) while having almost null intensity in G and B channels (behaving as a black ball). Note that all the other colored balls in the snooker package (including the green and blue balls) have a strong mix of the RGB channels.

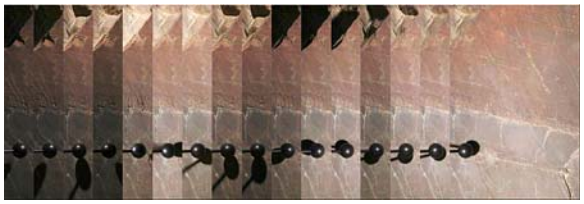


**Figure 31:** *Piscos Man, UNESCO Rock Art at Vale do Coa, Portugal: Set of captured images.*

Since the PTM representation assumes that the images were taken with a fixed single viewpoint, all objects must be represented by the same set of pixels [BSP07]. This assumption simplifies the detection process and the elimination of some problems related with light conditions (e.g. a shadow cast by the ball can be confused with the ball itself).

The software tool will follow one of two paths, depending on the selected approach to detect the ball. If the "black ball" approach is chosen, the software softens shadows cast by the ball using a median filter of all images, then applies a Sobel filter for edge detection and a modified Hough transform algorithm based on the gradient values to detect the ball contour and geometric center.

The two "red" approaches follow a similar path, but using only the information in the R channel. Red balls produce high intensity values in the R channel and allow the elimination of some problems, such as shadow casting, with a simple red filter. Both approaches, "red region" and "red ball", have a common path: they apply red filter to all images and blend resulting images into a single one, using the maximum values. The "red region" approach uses the resulting image to compute the ball center and radius using a labeling algorithm and a region center of mass computation, while the "red ball" approach applies a Sobel filter for edge detection and HT to find the contour and its geometric center and radius.

### 9.2.2 Highlight Detection

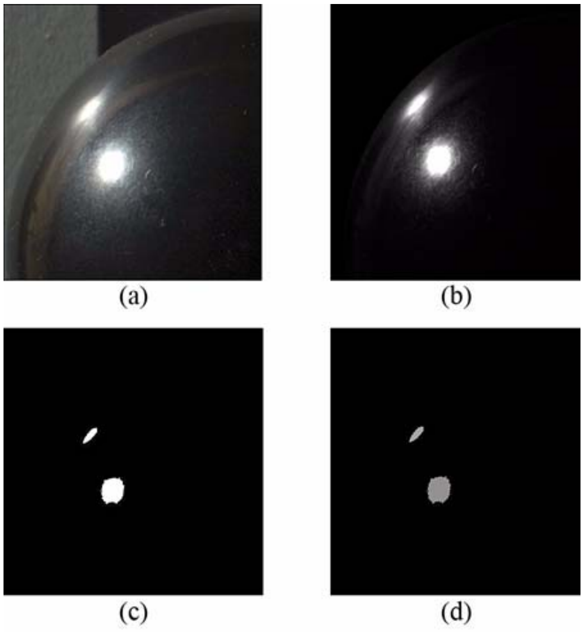
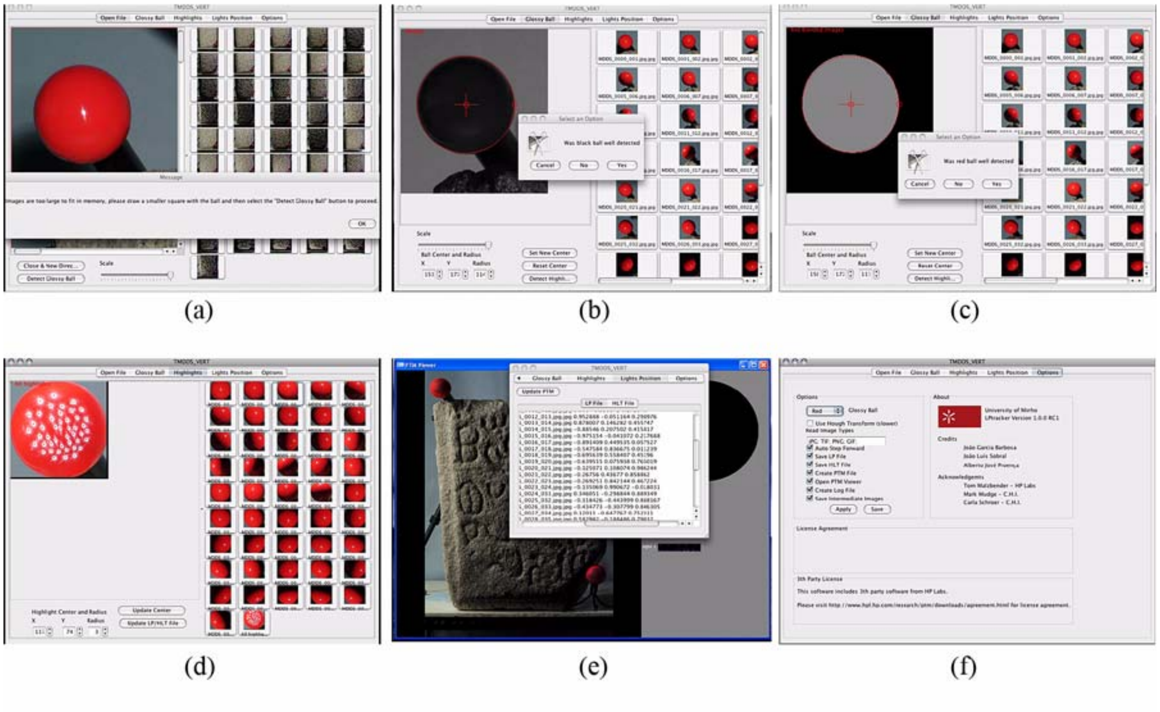


**Figure 32:** *Phases in the highlight detection, with a fake highlight.*

The software tool searches for the highlights center within the region defined by the center and radius, as computed earlier. It uses a region labeling technique and computes the center of mass per region. To remove interferences from the artifact, the highlight detection stage cleans the region outside the ball contour. This process uses a labeling algorithm to identify highlight candidates for light direction extraction (Figure 32). These highlight candidates can be due to inter-reflection of some nearby specular surface and if so, they must be discarded. This is done by analyzing the size of the highlight and its distance to the center of the ball: due to reflection laws on a sphere, the closest highlight to the center will be chosen. The final result of the highlight detection stage is an image combining all the highlights, which lets the user assess the quality of the lighting.

### 9.2.3 Light Source Position

The light source direction can be estimated from the highlight position, according to Figure 34. If the viewpoint and the light source position are assumed to be at infinity, then the view point direction V is parallel to the Z axis, and the light direction L is the same for any ball placement in the image and for any image pixel. With these assumptions, the software tool only needs to compute the light source direction values (x; y; z) and feed these data into the PTM fitter, since it normalizes this vector before computing the polynomial coefficients for the curve fitting.



mages are too large to fit in memory, please draw a smaller square with the ball and then select the "Detect Glossy Ball" button to proceed.

Was black ball well detected

Was red ball well detected

Red Glossy Ball
☐ Use Hough Transform (slower)
Read Image Types
JPG; TIF; PNG; GIF
☑ Auto Step Forward
☑ Save LP File
☑ Save HLT File
☑ Create PTM File
☑ Open PTM Viewer
☑ Create Log File
☑ Save Intermediate Images

University of Minho
LPtracker Version 1.0.0 RC1

João Garcia Barbosa
João Luis Sobral
Alberto José Proença

Tom Malzbender – HP Labs
Mark Mudge – C.H.I.
Carla Schroer – C.H.I.

This software includes 3th party software from HP Labs.

Please visit http://www.hpl.hp.com/research/ptm/downloads/agreement.html for license agreement.

(a) (b) (c)

(d) (e) (f)

**Figure 33:** User interfaces of the PTMbuilder at Museum D. Diogo de Sousa: (a) attempt to locate the ball, (b) black ball detection and tuning, (c) red ball detection and tuning, (d) highlight detection and tuning, (e) HLT/LP file edit over PTMviewer, and (f) User options interface.

To compute the light source direction under these assumptions, the software computes the normal at the highlight (N) from the coordinates of the highlight center and the ball center, and assumes the light source direction at 2F away from the Z axis. More details in [MMSL06] and adjusted in [BSP07].

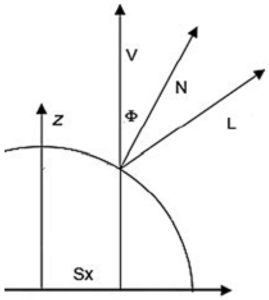


**Figure 34:** *Model for estimating the light source direction from highlight.*

### 9.2.4 Tracking Empirical Provenance

One of the major features of HRTI is the empirical data recorded in the raw format image set. Each image records not only a representation of the artifact lighted with a specific light source direction but also the direction of the light. If two balls are used instead of one, the precise light source position in the artifact space can be triangulated.

The LPtracker adds features to the richness of the original images set, namely it generates 3 new files: the LP, the HLT and the Log. Contents of LP and HLT files were presented earlier. The Log file records all actions performed by the software, and all adjustments made by the user. These 3 files, together with the original image set, complete all the necessary information to retrace the generation process of a specific PTM file, which supports the scientific validation of the whole process and establishes its empirical provenance.

### 9.2.5 Next Steps

The presented tools address some of the constraints posed by the HRTI method through the automation of the generation process of a PTM data representation. The LPtracker, with a user friendly interface, frees the end user from the most tedious stages of methods guiding him/her through the necessary steps to generate a valid PTM representation of large scale objects: ball detection, highlight detection, LP/HTL file generation, empirical provenance logging and PTM fitting. The empirical provenance data, intrinsic to the HRTI approach allows the scientific validation of PTM representation of the artifact, and its affordable cost accounts for the increasing number of supporters among scholars and institutions.

When the size of the object is large compared to the dome radius, however, the assumption used for light direction estimation may introduce critical inaccuracies, both at the estimated direction of each light source and at its distance.

Inaccuracies to the light source may be due to the ball placement (it may be far away from the image center) and pixels at opposite edges of the image have considerable different light source directions. If the lighting is not placed at a fixed distance from all pixels at all the images, fitting inaccuracies may also occur, requiring pixel intensity adjustments at each image. To overcome these limitations, critical for large objects, two glossy balls can be used as suggested in [BSP07]. Through geometric triangulation the precise light position can be computed and light intensities adjusted for each pixel at the images. Next PTMbuilder version will be available soon with these improvements.

### 9.3 Acknowledgements

This work was supported by a scholarship from Computer Science and Technology Center (CCTC), University of Minho. The authors acknowledge and thank the access to artifacts at the Parque Arqueologico do Vale do Coa (PAVC), and at Museu D. Diogo de Sousa, Braga, both in Portugal.

### References

[BSP07] BARBOSA J., SOBRAL J. L., PROENÇA A. J.: Imaging techniques to simplify the ptm generation of a bas-relief. In VAST'07: *Proc. 8th Int. Symp. Virtual Reality, Archaeology and Cultural Heritage* (UK, 2007), pp. 28–31.

[CDMR03] CULA O. G., DANA K. J., MURPHY F. P., RAO B. K.: Bidirectional imaging and modeling of skin texture. In *Texture 2003: Proc. 3rd Int. Workshop on Texture Analysis and Synthesis* (France, 2003), pp. 12–18.

[DCCS06] DELLEPIANE M., CORSINI M., CALLIERI M., SCOPIGNO R.: High quality ptm acquisition: Reflection transformation imaging for large objects. In *VAST'06: Proc.7th Int. Symp. Virtual Reality, Archaeology and Cultural Heritage* (Cyprus, 2006), pp. 179–186.

[HPL] HPLABS: Research hplr. hp labs site highlight based ptms. http://www.hpl.hp.com/research/ptm/HighlightBasedPtms/index.html

[MMSL06] MUDGE M., MALZBENDER T., SCHROER C., LUM M.: New reflection transformation imaging methods for rock art and multiple viewpoint display. In *VAST'06: Proc. 7th Int. Symp. Virtual Reality, Archaeology and Cultural Heritage* (Cyprus, 2006), pp. 195–202.

[TSE_04] TCHOU C., STUMPFEL J., EINARSSON P., FAJARDO M., DEBEVEC P.: Unlighting the parthenon. In *SIGGRAPH'04: ACM SIGGRAPH 2004 Sketches* (USA, 2004), ACM Press, p. 80.