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3D and semantic web: new tools to document artifacts and to explore cultural heritage collections

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L'UNIVERSITÉ PIERRE ET MARIE CURIE**

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Denis Pitzalis

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**3D et Sémantique: nouveaux outils pour la documentation et
l'exploration du patrimoine culturel**

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3D and Semantic Web: new tools to document artefacts and to explore cultural heritage collections

Abstract:

Keywords: documentation, 3D, 3D modelling, post-processing, 3D data acquisition, computer graphics, data analysis, data visualization, integrated models, interactive visualization, large data sets, model rendering, object representation, real-time analysis, transformation tools, data analysis, data visualisation.

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Chapter 1

Introduction

1.1 Context

The role of museums and libraries is shifting from that of an institution which mainly collects and stores artefacts and works of art towards a more accessible place where visitors can experience heritage and find cultural knowledge in more engaging and interactive ways. Due to this shift, information and communication technologies have an important role to play not only in assisting in the documentation and preservation of information, such as with images or 3D models about historical artefacts and works of art, but also in creating interactive ways to communicate to the population at large beyond those working in cultural fields the significance that these objects have for humanity.

The possibilities inherent in technology as a medium for representing heritage extends to domains of museums including audiovisual guides, interactive multimedia screens, and 3D interactive virtual environments. These mediums add the possibility to provide a better understanding of the represented objects by contextualising artefacts outside the aseptic environment of the museum in a different time and space. Such technologies complement other forms of more traditional media such as books, artistic reconstructions, or photography that deal with representations of the past.

In particular, 3D models are a unique medium for representing heritage as they are able to provide a semi-realistic representation of 3 dimensional objects and spaces. This makes them a particularly suitable mechanism for providing context to otherwise isolated pieces of information or physical objects which are often only displayed in glass cabinets or on museum walls.

Hence, 3D models enable visitors to interact virtually with historical objects that would otherwise be inaccessible due to their nature and fragility; in Figure 1.1 former President of the Republic of Cyprus observes a copy of a fragile item, the “Kazafani” boat, exhibited at the Smithsonian museum in Washington. Due particularly to the fact that “printing on demand” is a common practice with 3D models, the creation of physical replicas of cultural heritage objects (i.e. rare and fragile items), archaeological artefacts (i.e. carvings) or human remains and its application in museum contexts is attracting increasing interest.

Moreover, 3D surrogates (copy of real objects) offer a real interactive experience since they can be observed and manipulated from different viewpoints even via web interfaces. This capacity and the fact that 3D technologies are more and more sophisticated and easy to use is why interest in 3D data acquisition for purposes of documentation, research, virtual reconstruction and presentation is growing.

Despite this fact, it must be recognised, however, that the creation of Virtual Museums based on three-dimensional digital databases is more viable for larger cultural heritage institutions who have more resources for the digitisation process, digital databases creation, and the types of installation that virtual environments require.

Nevertheless, it is expected that as the price of digitisation drops, and the cost of acquisition and maintenance of hardware and software becomes more accessible, more cultural heritage institutions will increasingly be able to experiment with this type of environment.

In museums particularly, we have seen an increasing trend in the use of 3D models as surrogates for distant, fragile or complex objects not only for study, but also exhibition and virtual tourism. As a tool for historical research, 3D is gaining more and more credit for its value in supporting developments in and use to validate hypotheses about, for example, the possible form, function, and use of historical objects. Furthermore the democratisation of the 3D television, the easy set-up of 3D cinemas, and the use of 3D in cinema production has vastly increased and the technologies are quickly evolving. The success of cultural heritage reconstructions in 3D and further dissemination via television programs not only demonstrate how the technology is engaging and perfectly fits the needs of the consumer, but also highlights the wide range of requirements a 3D model, and the technology beyond it, must respond to.

The process of building a 3D collection draws on many different technologies and digital sources. From the perspective of the Computer Graphics and Computer Vision professional, technologies such as photogrammetry, scanning, modelling, visualisation, user interfaces, run-time engines, and interaction techniques need to all work together. Furthermore, data exchange formats become essential to ensure that the digital sources are seamlessly integrated.



Figure 1.1: 3D reproduction of a chalcolithic Cypriot boat “Kazafani” dating from 1200 BC exhibited at the Smithsonian museum in Washington for the temporary exhibition “Cyprus crossroad of civilizations” in 2010.

1.2 Background and Ongoing Initiatives

Over the past decade, the impact of 3D content in the field of cultural heritage was demonstrated to be high for both the research and general interest communities. Today, we can assert that digital 3D assets are an important tool for interacting with cultural heritage for the simple reason that humans perceive reality in 3D. Three-dimensional representation is as natural an evolution in cultural heritage documentation as digital photography has been in legacy photography techniques. Such technology allows the presentation of museum artefacts as well as very large objects (i.e. virtually reconstructed archaeological sites, cities, façades, excavations and buildings) in a very realistic way. These representations have an intrinsic interest in scientific documentation.

The EPOCH Research Agenda [Arnold and Geser, 2007] explored the reasons behind the low participation of cultural heritage institutions in the European Digital Library initiative concluding that, at that time, the lack of guidelines, tools, and best practices was the root cause. Since then, the situation has improved and it is almost normal for a museum interested in creating a digital collection to participate in initiatives like [Europeana, 2009] and its satellite projects or other national

or international digital initiatives. Initially, the concept of a mass digitisation effort, driven by the need for long term preservation and commercial market considerations, was encouraged primarily through national libraries and archives. This fact was largely due to the availability in the market of solid technologies for the digital acquisition of “two-dimensional” material such as books and photography.

Following the lead of this small group of digital acquisition pioneers, the museum sector became engaged mainly in 3 areas:

1. Collection organization (i.e. [Minerva, 2006] and [Michael Culture, 2007] projects);
2. Acquisition objects in both 2D and 3D (i.e. [ACOHIR, 2000], [EPOCH, 2004], [SCULPTEUR, 2002] and [3D-COFORM, 2009])
3. Data provenance and long-term preservation (i.e. [Europeana, 2009] and [ATHENA, 2008] projects).

During 3D-COFORM a significant step forward was made that extended a focus from the sole acquisition of objects to include digitisation of all tangible heritage, widening the scope from mass digitisation of museum collections to environment acquisition (monuments, sites, excavations and even historic cities).

The 3D-COFORM project started in December 2008 and finished in November 2012. The project’s objective was to advance the state-of-the-art in 3D digitisation and make 3D documentation an everyday practical choice for digital documentation of artefacts, places, and campaigns in the cultural heritage sector.

This ambitious but successful project addressed, like this thesis, all aspects of 3D data capture, 3D data processing, material properties acquisition, metadata and data provenance, and integration with other media sources while taking into account search, research, and dissemination to the general public and cultural heritage professional alike. Furthermore, the technical aspects have been complemented by research into practical business aspects including business models for exploitation of 3D assets, work-flow planning and execution for mass digitisation, and socio-economic impact assessment.

In addition to the 3D-COFORM project, the cultural heritage community is very active and therefore research in the field of three-dimensional documentation and semantic data organization is continuously expanding and opening new frontiers. In each of the chapters in this thesis, we will discuss the state-of-the-art in the specific field.

1.3 Contributions

This PhD thesis aims to address the documentation of works of art by proposing a methodology for the acquisition, processing, and documentation of heritage objects and archaeological sites using three-dimensional information. The main challenge in this thesis is to convey to stakeholders the importance that a 3D model must be ‘fit for purpose’ for a very wide set of situations and must be created with a specific function in mind; from very high definition and accurate models for academic studies, monitoring of the conservation conditions over time and preliminary study for restoration, medium resolution for on-line web catalogues, public illustrations, sculptures and reproduction, to low definition for television stages or computer games.

As a demonstration we see how a multi-source data capture work-flow, with the right modelling tools, can produce the right results both from an aesthetic point of view for exploitation in communication as well as from a scientific point of view with high precision of data and correct capture of meta and provenance data information.

Hence, this PhD thesis study the integration of technologies for 3D capture, processing, integration between different sources, semantic organization of meta-data, and preservation of data provenance.

In Chapter 2 I describe the work-flow for the scientific documentation of artefacts [Pitzalis et al., 2008a] and try to highlight methods and good practices that would enable the systematic production of 3D models of objects in the same way digital cameras enabled the mass production of 2D digital material [Pitzalis et al., 2011a].

Capture and processing are presented in Chapter 3. In particular in 3.2 I will discuss the various 3D technologies available and more frequently used for acquisition in the field of cultural heritage [Pitzalis et al., 2007], assessing their pros and cons in order to articulate why certain methodologies are better than others under certain environments.

In Chapter 4, using case studies, I show why multi source data acquisition often better covers the needs of museum and archaeological documentation. These case studies have been conducted during my professional experience at the C2RMF and at the Science and Technology for Archaeology Research Centre (the Cyprus Institute). They are presented to support the discussion on the integration of technologies for digitising and creating three-dimensional models, which takes advantage of the 3D documentation of works of art undertaken in these frameworks [Pitzalis et al., 2008b].

Semantic data organizations for preservation and provenance will be discussed in Chapter 5. After an introduction on semantic techniques and methodologies used in cultural heritage [Pitzalis et al., 2006], especially in relation with the Europeana project, a real case of a data provenance mechanism will be presented based on the LIDO metadata standard and validated against the CRMdig CIDOC-CRM extension [Pitzalis et al., 2011b] described more in detail in Chapter 5.3.2.

Because of their versatility and the relatively cost-effective technology, 3D models are gaining increasing recognition as a tool to support research, conservation, education [Pitzalis et al., 2012], exhibition and planning not only in the field of cultural heritage, but also in other domains such as architecture, urban planning, entertainment, manufacturing and, increasingly, artistic creation.

Chapter 2

Scientific Documentation Work-flow

In this chapter I introduce the scientific documentation work-flow for cultural heritage artefacts. Due to the heterogeneity of the cultural heritage area of application I first introduce a common definition suitable to contextualize the research (Section 2.2). Then, I identify the communities involved in the field (Section 2.3) to focus on setting the user requirements.

Once the environment has been contextualized, I will discuss the technical analysis work-flow used to document artworks at the C2RMF, among others, identifying where the 3D and the semantic web technologies can enhance the quality of the work. At the end of the chapter, a case study, presenting a comparative study on a large collection of 3D statuettes, is presented in order to show how physical and chemical analysis can naturally be supported by the techniques at the centre of this thesis.

Bourdeu, A., Pitzalis, D., 2010. *Geometric morphometrics for provenance determination of Gallo-Roman white clay figurines*. In: VAST10: The 11th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage. pp. 25–31.

Pitzalis, D., Cassan, I., Thomas, L., Gianoncelli, A., 2008. *Non-Destructive Analyses for Modern Paintings: The Russian Avant-Garde Case*. In: 9th International Conference on NDT of Art.

Pillay, R., Aitken, G., Pitzalis, D., Lahanier, C., 2007. *Archive Visualization and Exploitation at the C2RMF*. In: ICHIM 2007. Toronto, Ontario, Canada.

2.1 From “Acquisition” to “Digital Preservation”

It is now a common practice, in the field of cultural heritage, to support the documentation of works of art not only with visual material, including high definition photographs, but also with more complex analysis of optical techniques, non-destructive and non-invasive by definition, such as macro-photography, infra-red reflectography (IRR), and ultraviolet fluorescence (UVF), among others. The results of these image analyses provide enormous added value to the standard “naked eye” observation but often, unfortunately, do not sufficiently establish with a high level of accuracy the painting or carving techniques and materials used in the work of art. Introducing 3D acquisition and modelling as a standard practice for artefacts, we can significantly improve the quality of such results.

Chemical analysis can be used to support findings, including, for example, the nature of pigments used. In the past, chemical analyses were conducted using destructive techniques such as cross-section or micro sample to *Scanning Electron Microscope* (SEM) analyses. Relatively new non-destructive analyses like *X-Ray Fluorescence* and *Raman Spectroscopy* are currently used in order to analyse works of art and provide chemical results.

The results of these tests on works of art are very important for conservationists, art-historians and keepers of private or public museum collections as these investigations reveal information which is of historical interest including, for example, materials that were used and that can be compared with other materials that were available at a certain period in a particular region.

Nowadays new methods such as three dimensional digital acquisition and semantic web technologies, inherited from computer graphics, vision and web semantics, can be used to enhance, improve, and facilitate the exploitation of the results collected.

In this chapter I show how 3D acquisition and modelling could integrate in a natural and practical way the process of documenting tangible cultural heritage. To better understand the complexity of the scope of the issue, a clear definition of the nature of the heritage to be documented and the extent of what is meant by documentation must be elaborated.

2.2 Definition of Cultural Heritage

Culture Culture has been defined in many different ways. The Welsh academic and critic Dr. Raymond Williams, in his book “Culture and Society” [Williams, 1958], claims that “Culture is a way of life” and supports the cause of culture for the masses stating that “culture is ordinary. Every human society has its own shape, purposes and meanings. Every society expresses these in institutions and in arts and learning”. The World Tourism Organization defines culture in [UNESCO, 2001] by saying that “other people’s lifestyles are expressed through their religion; festivals; costumes; cuisine; arts and crafts; architecture; music and dance; folklore; and literature. These cultural manifestations differentiate one group of people from another. They make life colourful and interesting”.

To date not a single definition has been accepted that encompasses every meaning of the term Culture without it becoming too general. Again Dr. Williams in [Williams, 1976] identifies three ways in which the term Culture can be defined: a process of intellectual, spiritual and aesthetic development; an indicative of a way of life and as works and practices of intellectual and artistic activity. Furthermore Greg Richards, in [Richards, 1996] believes that the usage has shifted away from the first category, towards the other categories. Therefore, Culture can be viewed as a process which includes codes of conduct within a social group, or a product of individual or group activities to which meanings are attached. For example “High culture” could refer to fine art while “Low culture” could be referring to “soap operas”.

Viewing Culture as a product has been criticised by some as a commodification of Culture. Tourism is identified by industry observers as a significant factor in the commodification of Culture. From these alternate views of Culture, it appears that a central theme is the differentiation in forms of expression, whether that is in terms of art, music, dance, etc.

Cultural Heritage The term “cultural heritage” has evolved over time and has not always meant the same thing. The last decades have seen the concept of heritage undergoing a profound change; from having, at one time, referred exclusively to the monumental remains of ancient cultures, to today being seen as a concept that has gradually come to include new categories like intangible heritage [Ahmad, 2006].

The Venice Charter made reference to “monuments and sites” and dealt with architectural heritage. The question rapidly expanded to cover groups of buildings, vernacular architecture, and industrial and 20th century built heritage. Over and above the study of historic gardens, the concept of “cultural landscape” highlighted the interpenetration of culture and nature.

A noteworthy effort was subsequently made to extend the conceptualization and description of the intangible heritage. This is due to the fact that closer attention is now being paid to humankind, the dramatic arts, languages and traditional music, as well as to the informational, spiritual and philosophical systems upon which creations are based. The concept of heritage in our time accordingly is an open one, reflecting living culture every bit as much as that of the past. According to the Convention for the Safeguarding of the Intangible Cultural Heritage [UNESCO, 2003], UNESCO proposes five broad domains in which intangible Cultural Heritage is manifested: Oral traditions and expressions, including language as a vehicle of the intangible Cultural Heritage; performing arts; social practices, rituals and festive events; knowledge and practices concerning nature and the universe and traditional craftsmanship. Instances of intangible Cultural Heritage are not limited to a single manifestation and many include elements from multiple domains.

The Convention on the Protection and Promotion of the Diversity of Cultural Expressions [UNESCO, 2005] sets up a legally-binding international agreement that ensures artists, cultural professionals, practitioners and citizens worldwide can create, produce, disseminate and enjoy a broad range of cultural goods, services and activities, including their own. It was adopted because the international community signalled the urgency for the implementation of international law that would recognise the distinctive nature of cultural goods, services and activities as vehicles of identity, values and meaning while underlining that while cultural goods, services and activities have important economic value, they are not mere commodities or consumer goods that can only be regarded as objects of trade.

Recognizing that culture is no longer just a by-product of development, but rather central to sustainable development, UNESCO has pushed for the elaboration of an integrated international framework for the governance and management of culture by encouraging the introduction of cultural policies and measures that nurture creativity, provide access for creators to participate in domestic and international marketplaces where their artistic works/expressions can be recognized and compensated, and ensuring these expressions are accessible to the public at large. This framework has promoted the recognition and optimization of the overall contribution of cultural industries to economic and social development, particularly in developing countries, the integration of culture into sustainable development strategies and national development policies, and the promotion of international cooperation to facilitate the mobility of artists as well as the flow of cultural goods and services.

Nowadays Cultural Heritage, as defined by international organizations such as UNESCO, is commonly accepted to cover everything from monuments to objects in museums and sites. UNESCO has tried to summarize and has listed the main types of Cultural Heritage. It includes: Heritage Sites, Historic Cities, Cultural Landscapes, Natural Sacred Sites, Underwater Heritage, Museums, Moveable Heritage,

Handicrafts, Documentary and Digital Heritage, Cinematographic Heritage, Oral Traditions, Languages, Festive Events, Rites and Beliefs, Music and Song, The Performing Arts, Traditional Medicine, Literature, Culinary Traditions, Traditional sports and games.

2.3 Identification of Users Communities

It is very important when defining the scope of such complex research, to clearly identify the different communities that are involved, in both active and passive way, in the process. For the purposes of this document, user communities can be defined, in a wide sense, as all professionals and non professionals, specialists and non specialists, who, for either personal or professional motives, create, acquire, use or maintain Cultural Heritage IT tools or applications. This definition target the professional photographer as well as the public of an exhibition interacting with a computed device.

It is very important when defining the scope of such complex research to clearly identify the different communities that are involved, in both active and passive ways, in the process of cultural heritage preservation. For the purposes of this document, user communities can be defined, in a wide sense, as all professionals and non professionals, specialists and non specialists, who, for either personal or professional motives, create, acquire, use or maintain cultural heritage IT tools or applications (see Figure 2.1. This definition targets the professional photographer as well as the public of an exhibition interacting with a computer device. The heterogeneity of the Cultural Heritage sector prevents the clear identification of user communities, making it a difficult task to catalogue them; however, the following main categories can be identified:

- Cultural Heritage professionals (i.e. Curators, Historians, Archaeologists, Archivists)
- Technical users
- Commissioners (Profit/non-profit)
- Public Users
- Communities drawn together by shared interests.

Among each of these main user communities, several sub-categories with specific needs can be identified.

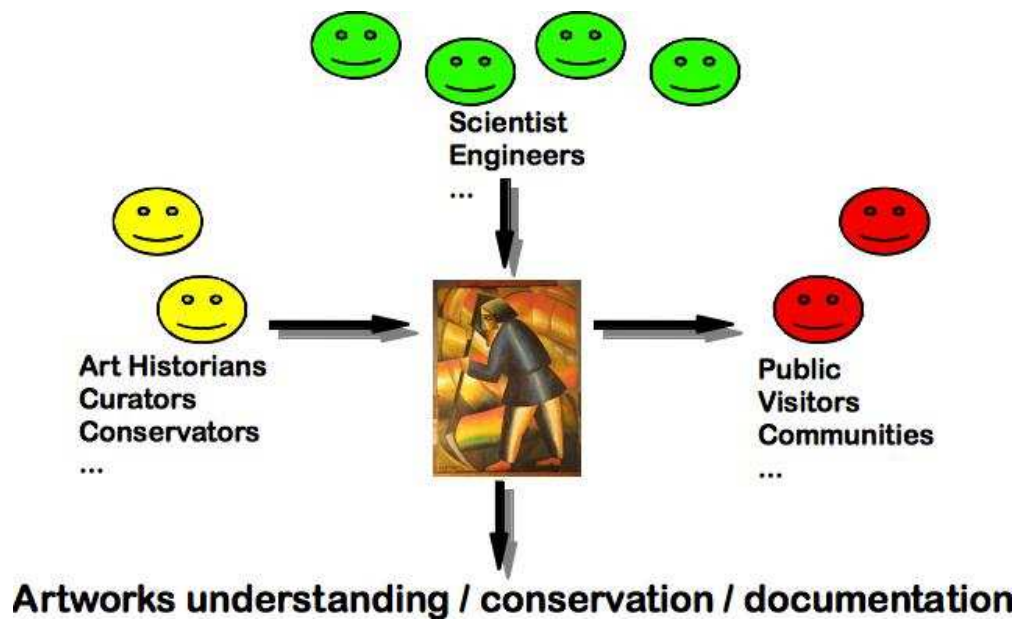


Figure 2.1: Different communities of experts have to cooperate to preserve and decipher artefacts for the public

Cultural Heritage Professionals Usually cultural heritage professionals have a background related to art history, archaeology, archival science, conservation, museology, librarianship, etc. and a deep knowledge of some area or areas of cultural heritage and the associated objects and their environments. Cultural heritage professionals usually need to access very accurate information about the individual objects, the collection of objects, and the related contextual information. This means the necessity to create a complete catalogue containing or referencing all the information about a collection's history, the provenance of the individual object, and its metadata.

Typically the members of this community have good knowledge of the legislation for the use and the respect of copyright and Intellectual Property Rights at the local and international level. Furthermore, they not only need to have access to a detailed set of specific metadata, but the quality of the images / models they use to better appreciate the smallest detail is particularly important to them. They understand the need to work close to the artefact when working with the physical artefacts, and would not be surprised if they had to access the highest quality digital assets via a system / repository in, for example, a Local Area Network (LAN).

For this group of users, which is the most demanding of the user communities, there are three important criteria for a documentation process based on 3D: the high quality of the model in both terms of geometry and texture, accurate enough

to be a scientific measure of the artefacts; the digital long term preservation and accessibility to the data, that means the adoption of opens standards for data and procedure; Copyright and Intellectual Property Rights protection in relation to their needs of 3D artefacts and collections.

Technical Users Technical Users are those that handle the tools to produce scientific data. They can be engineers, photographers, or 3D modellers, but also those who manage the system like the database or system administrators. These users do not always have an art background but frequently have knowledge of the field and work closely with cultural heritage professionals to produce scientific data.

Their requirements relate to technical needs to ease their ability to deliver the systems that the cultural heritage professionals need such as standardised data formats and systems with adequate documentation, support, and training materials.

Commissioners Commissioners can be for-profit or not for-profit. These users are entrepreneurs, Small/Medium Enterprises or the cultural heritage institutions themselves. They are usually interested in an overview of the whole system, practical information about the environment, thematic information and anything that can be exploited, for example, by the tourism industry. The commercial use of cultural content is quickly growing especially in creative industries, journal publishing etc.

These stakeholders are interested in high quality images / models, a quick / dynamic delivery system, and a clear solution for copyright issues of the content. Commissioners can be local authorities and other custodians of heritage. They require clear business models to support the investment in development of strategic resources. The return on this may be in terms of social returns (quality of life for citizens, etc.) or in terms of economic return either to a heritage site or other manager of the concerned assets.

Public Users Public users are the widest and most heterogeneous category. We can identify two main types: virtual visitors (multimedia, website, books, catalogues) and in-person visitors. The public is likely to need online access to existing materials, detailed information about the collections exhibited, and the option to follow a virtual tour of their choice (navigate). For this they need information on the institute including opening hours, current events, and current exhibitions. Furthermore, they must be provided with good quality images and information, contextualisation, and thematic and geographic information about the events or the objects.

Physical access to advanced information like catalogues, books, multimedia etc *in situ* will also be required unless and until digital access to the complete set of materials is available. Access to such digital surrogates is extremely unlikely to be satisfactory in all cases due to additional information such as annotations and alterations that would be difficult to capture completely. One form of public access will be from interested learners and student researchers who could be considered as pre-professional or hobbyist users. Such users may well benefit from digital access to assets that are in storage. However, since they are currently unlikely to have access to stored items this must be considered as a potential additional benefit of digitisation as opposed to a strict requirement.

More than other groups, public users also require connectedness in accessing and interrogating many sources of information in parallel in order to allow idle exploration and the browsing of content without obvious specific purpose which can allow unexpected linkages between different apparently unrelated areas.

Communities of Interest Such groups of users may include members of each of the other categories here, but they bring together their differing backgrounds and skill sets in the context of shared values and interests. The requirements they have in respect of the tools they use may be shared with those of similar background from other categories, but these requirements in terms of skill sets may be overlaid with particular needs for specialists, such as controlled thesauri.

2.4 Scientific Documentation

When documenting an artwork, an archaeological site, or an architectural element, we must ensure that our actions and measures can be reproduced and validated in the future. In order to do so we have to introduce a protocol, or a procedure, describing the adopted principles. In the case of cultural heritage artworks, a real “standard procedure” does not exist, therefore a series of “good practices” need to be defined in order to facilitate the identification of the procedure to use to document artworks and archaeological sites alike.

At the 9th International Conference on “Non-destructive investigations and micro-analysis for the diagnostics and conservation of cultural and environmental heritage” I presented a paper [Pitzalis et al., 2008a] in which I describe the process of documentation of paintings as a three step cycle:

1. Scientific imaging techniques;

2. Physical and Chemical analysis;
3. Data storage and analysis.

This work flow can be adapted to every object of art we want to analyse and go to the simple digital image, to the X-Ray acquisition passing through multi or hyper spectral imaging and terminating, if we decide to push the analysis, to physical and chemical analysis. Once all the information are collected from steps 1 and 2, the data are then given to the Cultural Heritage professionals for data storage and analysis.

For example when documenting an artwork the first important analysis is the naked eye observation. An experienced curator or art historian can attribute an artwork to an author by simply inspecting it and carefully looking at the details. To validate the hypothesis, the expert usually proceeds with scientific imaging techniques before to end with chemical-physical analysis. In the field of cultural heritage, optical imaging techniques are appreciated and preferred to others for the safety and the effectiveness that characterize these diagnostic methodologies.

Some of the most frequent physical and chemical analyses in use in the specialised laboratory, such as the C2RMF or ArtAnalysis, are described in the Appendix B. In the section I demonstrate how three dimensional acquisition techniques are the natural evolution of some of the analyses used in the scientific documentation process, and how modern semantic web techniques and methodologies can improve the data organization process, simplifying the way data is assembled, organized, studied and made available.

2.4.1 3D as an Acquisition Technique

Each one of the identified communities expresses different needs in terms of three-dimensional modelling from scientific documentation to use in serious games. The final scope of a 3D model has many implications on the choices of technologies to deliver the required functionality.

There are many motives for doing 3D reconstruction of cultural heritage artefacts or sites:

- documenting historic buildings and objects for reconstruction or restoration;
- creating educational resources for history and culture students and researchers;
- reconstructing historic monuments that no longer or only partially exist;

- visualizing scenes from viewpoints impossible in the real world due to size or accessibility issues;
- interacting with objects without risk of damage;
- providing virtual tourism and virtual museum exhibits.

To do so, of course, there are many tools and methodologies targeting just as many purposes, each of which includes functionalities for which there may be several potential routes to delivery making the choice of the right technology sometimes very difficult. But even at this stage, it is possible to predict which technologies currently in use have more potential than others by identifying how their capabilities address the demands and needs of the various user groups.

In recent years the development of the use of techniques for data capture about the surface of three-dimensional artefacts has allowed more geometrical and structural information to be recorded. Several approaches have been developed each of which addresses different circumstances and records different characteristics of the 3D artefact [Blais, 2004]. The capabilities of different technologies vary in terms of the resolution of the scanning devices, the operational requirements, the ability to operate in different environmental conditions, their requirement for trained personnel in their operations, and the cost of the equipment. Some technologies may enable internal micro structure as well as the general geometry of cultural objects to be studied, while some others focus more on one characteristic.

If the measure fits on a three-dimensional matrix, the technique is operating in “three dimensions”. Among these techniques we find the tomographic [Morigi et al., 2010] and [Targowski et al., 2004] and the shape measurement techniques [Levoy et al., 2000], more extensively described in the next chapter.

Such technologies can complement, or in some case even substitute, 2D digital techniques. The application of three-dimensional documentation has already been demonstrated to be successfully applied in cultural heritage in the framework of projects such as 3D-COFORM, and in other innovative works like the ones described in [Fontana et al., 2005] and [Barazzetti et al., 2010]. In the first publication, the authors apply quantitative morphological analysis of painting surfaces as a diagnostic tool; in particular they apply micro profilometry based on “holographic conoscopy” to retrieve three-dimensional information on the state of the painting surface. This information can be then used for several purposes, for example to measure the traces left in the engravings and the support deformations and the discrimination between real and fake “craquelures”. In the second paper the authors report an overview of the methods aimed to assess the conservation state of some analysed paintings and provide useful information for further diagnostic applications. Figure 2.2 represents an example of simulated raking light from a 3D model.

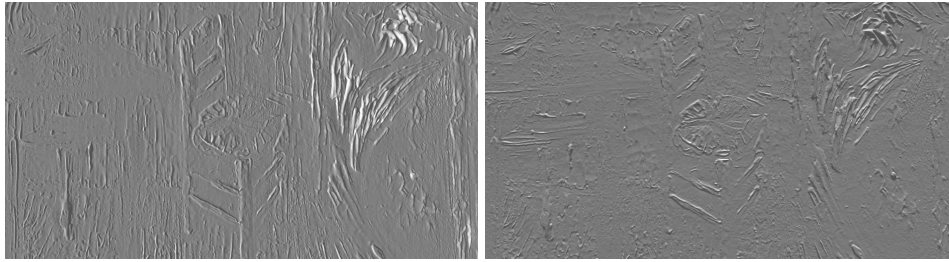


Figure 2.2: Example of raking light from 3D model of a painting. The image on top simulates a raking light with illumination source from left, the same detail in the bottom image with light source from top. La Chambre à Arles, Vincent Van Gogh, 1889 Musée d'Orsay ©C2RMF

In Appendix B we describe the most common imaging and physical-chemical techniques used at the C2RMF for artworks study and how these techniques can be combined with three-dimensional models to improve the quality of the data.

The scanning technologies we are going to describe works without coming into contact with the artefact and hence fulfil the curators' requirement that recording devices will not come into physical contact with the artefact at any moment. In addition their luminous intensity is limited to relatively small values and the produced light has controlled characteristics and thus does not cause material damage (e.g. bleaching pigments) due to overheat or ultraviolet exposure. These two properties make non-touch technologies particularly adapted for the applications in cultural heritage, where non-invasive and non-destructive analyses are crucial for their protection. The technical details are discussed more extensively in chapter 3 consecrated to three-dimensional models and cultural heritage.

2.4.2 Digital Repositories for Search and Research

The user communities and their needs, as outlined above, demonstrate the requirements for many different entry points in searching and possibly across multiple datasets. Applying the five W's method to an ideal repository of cultural heritage assets, the entry points for any search should reflect interests originating from, or relating to:

- WHERE place (i.e. planning a tourist's visit to museums);
- WHO people (i.e. tracing the production of an artist and the evidence in digital collections around the world);
- WHY communities (i.e.. highlight the cultural values of minorities through art);

- WHEN time (i.e. drawing all information and evidence together relating to Second World War);
- WHAT particular activities (i.e. gathering all the events related to a particular artist across Europe).

It is clear that the variety of entry points for the content search can be as big as the number of single users using the infrastructure. For example, an artefact is perceived with different significance by different communities; to satisfy this requirement it means that the research in the database should be supported by a rich ontological structure from which the repository can be efficiently navigated from many perspectives and would support the user requirements across multiple applications, i.e. if the type of search and research supported has to span from professional research in art history to touristic enquiry to general public interest.

To make use of the many entry points possible we must use a rich data interconnections net within the repository, often associated with the technologies of the Semantic Web. The ontological structures to support such rich semantics in standard systems are likely to be based on quite complex international standards such as CIDOC-CRM, rather than the essentially flat structures with metadata lists encoded in incompatible variants of the Dublin Core, better explained in Chapter 5.

Today Semantic Web technologies have evolved to be robust enough to step out of the field of pure academic research and can be used instead to access such rich repositories.

An issue linked to the aforementioned technologies produce very large and complex datasets that, before being exploited by cultural heritage experts, have to be post processed and stored. At this stage I must introduce two major problems: 1) the integrity of the data and its provenance and 2) long term preservation.

A critical user requirement is that any decision to adopt a specific technology now does not preclude the use of the produced data in future systems based on technical solutions yet to be implemented that could validate, invalidate, or complement current discoveries. To ensure so, the professional must make sure to keep all the original raw data and to correctly enhance them with the metadata related to the condition of acquisition, the object itself, and all other necessary information.

Doing so we assure the “data provenance” and I further demonstrate in chapter 5.3.2 how modern standard ontologies provide us with the correct framework to standardise our documentation. On the other hand “digital preservation” refers to the reliable preservation of the digital material over time. All the factors of data storage will be outdated including hardware, software, and file format, while the information must be preserved. Bit-level preservation is the lowest level of data

preservation and it is commonly referred to in the digital-preservation community. Given current technologies, it is quite simple to imagine that if we have a defined set of bits we will be able to preserve it over time using solutions such as storing redundant copies on different media and different geographic locations, auditing the copies regularly to assure that they are identical and periodically migrating and validating them from older to newer media. This is why when storing data information we always have to store with the correct metadata.

Techniques used to index and organize metadata are discussed more in detail in chapter 5 while a short analysis of indexing of 3D content-based models is done in the chapter 3.5.3.

2.5 Case Study

2.5.1 The Gallo-Roman White Clay Figurines

This case study, used to illustrate the documentation work-flow introduced in the previous sections, is based on the studies conducted at the Centre de Recherche et de Restauration des Musées de France (C2RMF) on “white clay figurines” that began in the 70’s with the idea in mind of finding a way of classifying these amazing objects using physical-chemical analysis to improve and confirm this classification in 2010 with complex morpho-metrical analysis done on 3D models.

2.5.2 The Documentation Work-flow

During the Gallo-Roman period (from 40 to 300 AD), numerous workshops in the Centre of Gaul produced white clay figurines made of kaolin. For a significant period of time, C2RMF has been involved in the study of the Gallo Roman white clay figurines discovered across the French territory. A few thousand samples have been discovered of both figurines and their moulds and then stored in a number of French museums. Using the same work-flow described before, several visualisation analysis and physical characterization methods have been used in the past [Bemont et al., 1993; Revel and Lahanier, 1991] in order to determine the origin of these objects. At that time revolutionary “micro dilatometry” and X-Ray radiography methods provided some information about the composition leading to the understanding of fabrication techniques, but only multi elemental analytical methods allowed a better determination of the clay origin after a complex mathematical data processing of the results. The results obtained by methods such as X-Ray fluorescence spectrometry, proton induced X-Ray or gamma emissions, and neutron

activation analysis demonstrated to be often complementary in providing decisive results. The scope of this analytic work-flow was to create a methodology to classify the statuettes based on their “atelier” rather than their finding place, based on the collected scientific data.

More than 30 years later a few hundred of the white clay figurines have been digitized by the C2RMF using three-dimensional surface scanner technologies. Shapes of the statuettes may differ according to many parameters including the sites of origin, the artist creating them, the furnace and even how many times the same mould has been used. Some interesting results on this dataset have been achieved with the French ANR funded project Eros3D [EROS3D, 2008] especially on the indexing and retrieval of three dimensional objects into the C2RMF EROS database.

Today, some 5800 figurines are registered in the EROS database at the C2RMF. The knowledge acquired on how these artefacts have been produced and the extension of their diffusion had a very interesting impact in French archaeology confirming the role of the ancient commercial routes of the Roman Empire and the religious influence between civilisation from the Northern and Southern countries.

In collaboration with the anthropologist Alexandre Bourdeu and in the framework of this research, we tried to reach the same conclusions made 30 years before using mathematical methods to quantify and compare the shapes of the figurines and interpret results obtained by using such methods on a set of three-dimensional virtual objects. The details of the implementation are available in the Appendix C.1

2.5.3 Discussion

Even if with encouraging results, three dimensional morpho-metric analysis should not be used alone, like all other analytical techniques, as it seems not to be sufficient to segregate the figurines by clusters according to their geographic origin. In a previous work, presented in [Gorisse et al., 2007] and discussed more in detail in Appendix 3.5.3, using three-dimensional features as Extended Gaussian Images or 3D Hough transform, the research group shows that self-learning methods can only classify up to 80% of the models correctly.

In the same perspective, morpho-metric methods can give indications for the classification of the statuettes, as other numerical methods can. It is indeed clear that a single method for pure automatic semantic classification is not yet available and only human archaeological expertise can assure, via supervision, that a semi-automatic classification system manages to achieve the most integrated classification of complex elements.

The results of the work have been published in [Bourdeu and Pitzalis, 2010]. The intent of this experience was to show how new technologies, such as 3D acquisition and further geometric studies, can integrate the normal documentation work-flow. Using geometric morpho-metrics, including essentially generalized Procrustes analysis, to measure and display the differences in shapes and characterize the provenance of the Gallo-Roman figurines, not only confirmed the results of the physical-chemical analyses carried out on the same models 30 years before to determine the provenance of the statuettes, but provided a basis for the discussion on the comparison of results and a clear evidence of how three dimensional technologies, with mathematical analysis, are a valuable asset in scientific documentation.

2.6 Conclusion

In the first part of this chapter, section 2.2 and 2.3, I introduced the concept of the inherent conflict between the requirements of the different user categories. The most obvious for cultural heritage institutions is the conflict between the most stringent interpretation of preservation and the requirement for public accessibility. Another potential conflict is between political pressures for economic sustainability, which tend to encourage cultural heritage managers to restrict and control aspects such as copyright and other politicians that believe that culture must be publicly owned and that the public should have access in some form for free, further promoting exchange and Open Access.

It should be apparent that where the requirements of different groups of users are in conflict they cannot all be met. In the case of 3D representation, for example, at a public dissemination level the accuracy of the displayed model will need to sustain display of features necessary to illustrate the messages to be conveyed.

Thus a very small artefact will need an absolute accuracy which reflects ability to view the detail of the artefact. The difficulty, of course, is to know what views may be expected to be used. For example, professionals are likely to want to be able to support different analyses of the digitised artefacts. These scientific applications usually require much greater detail in the digitisation and representation of the artefact than a model used for a virtual visit of a museum, depending upon the scope and the needed of detail needed by the analysis.

In section 2.4, I have illustrated what is the “scientific documentation work-flow” and how this apply to artworks. The case study show the integration and complementarity of the results obtained with the “classic” work-flow applied few years ago to the study of the statuettes provenance with the ones obtained with the intro-

duction of 3D geometry analysis. In Appendix B some of the technologies used for “scientific documentation” are described.

In the next chapter I describe the three dimensional acquisition and processing work-flow, including an overview of the 3D technologies I have used in my professional experience at the C2RMF and the Cyprus Institute for acquisition, modelling, processing and visualization of cultural heritage artefacts.

Chapter 3

3D and Cultural Heritage

The requirements highlighted in the previous chapter have many implications for the choices of technologies to deliver the required functionality. At one level there are many tools targeting as many purposes, each of which involves functionality for which there may be several potential routes to delivery. Even at this stage it is possible to predict current technologies that have more potential than others by identifying how their capabilities address the demands of representing the user groups' needs.

Similar to film photography and high resolution digital two dimensional photography, three-dimensional models are the result of a sequence of actions that we can summarize in Acquisition and Processing. The first is the physical process of acquisition, like the planning of the photo campaign and the shooting and can be done using different technologies; the latter, is like the development of the film and require the use of specific algorithm and tools developed for 3D. After examine the current technology trends in order to highlight the requirements they might meet in each area and further suggest promising lines of development, I discuss the problematic related to data storage, 3D model visualisation and indexing.

Niccolucci, F., Spearman, M., Pitzalis, D., 2012. *Documenting Abu Simbel: The 3D-COFORM Approach*. In: *Electronic Imaging and the Visual Arts: EVA 2012* Florence. Firenze University Press.

Pitzalis, D., Kaminski, J., Niccolucci, F., 2011. *3D-COFORM: Making 3D documentation an everyday choice for the cultural heritage sector*. In: *Virtual Archaeology Review*, 2(4), 145-146.

As mentioned in chapter 1 the aim of this PhD thesis is intended to prove that 3D documentation is a way to improve, in a more efficient way, the creation of documentation of cultural heritage items, from paintings to archaeological sites, through objects, architecture, monuments and even books. Historically such artefacts have been documented by textual description, including dimensions, and since the last century, augmented by film and now digital photography. However, individual photographs can only record appearance from one direction and the need for enhancing a single view has led to the use of multiple images to improve 2D documentation of 3D objects (like in [SCULPTEUR, 2002] and [ACOHIR, 2000] projects). As the number of 2D views increases, the effective documentation covers more of the underlying 3D object. As we have described in the previous chapter, to make the creation of a complete 3D surrogate of an object which can then be stored, analysed and viewed from any direction and from everywhere and to which all documentation can be attached will be a great achievement in conservation techniques.

Indeed objects with an internal structure such as the “Coronelli’s globes”, presented in the Chapter 4, or models incorporating kinematic properties, like a watch, can have a lot of added value from the documentation of 3D objects and assemblies. Unfortunately, data other than volumetric information is not achievable directly with the available scanning technologies and requires significant additional processing and modelling out of the scope of this work.

In chapter 3.1, I do an overview of the work-flow for the creation of a three-dimensional model, starting from the planning of the campaign, to the acquisition and the post-processing. Each phase of the work-flow are then discussed later in the chapter.

Then, in chapter 3.2, I describe the most used acquisition methods, laser triangulation, structured light, stereo photogrammetry, structure from motion, time-of-flight, to then summarize them in a table presenting pros and cons of each technique.

In the end of the chapter, we see what are the post-processing steps to achieve a final 3D model and how the problematics linked to the data storage and visualisation.

The case studies illustrating these techniques are all collected in the next chapter.

3.1 3D Acquisition Work-flow

Different families of scanning technologies have different properties and thus different results and should be chosen according to the nature of the artefacts to be recorded, the operational imperatives, and the environmental conditions. There is

already considerable experience in cultural heritage institutions about the use of such technologies in the field to undertake digitisation campaigns and create an inventory of cultural sites. However, there are significant variations between their capabilities which must be taken into account in formulating campaign strategies.

It should be taken into account that these limitations of specific technologies are not user requirements. To be practical, we can assume that the user measures his requirements as a combination of time and effort to dedicate to the task, level of accuracy of the obtained results, overall costs of the campaign, and any technology that can deliver this combination in the specific environment that would meet these requirements. However, for practical implementation in the current state of the art, a specific combination may limit the result that technologies can deliver.

Whatever technology we use the procedure to generate the data is always the same: the sensors deliver a set of views that give the depth from the sensor of each visible point on a surface. To document a complete surface we need several scans depending on the complexity of the surface, i.e. occlusions or transparencies, that need to be aligned and combined. The methods used to complete this process are an intrinsic part of the documentation technique and may be built into the package available from a particular scanning tool. In [Bernardini and Rushmeier, 2002] the authors define a model for the acquisition of objects starting from the assumption that there is a basic pipeline of operations for taking the acquired data and producing a usable digital three-dimensional models. To do so they take into account the fundamental technical problems of range image registration, line-of-sight errors, mesh integration, surface detail and colour, and texture mapping. More recently the group led by Prof. Scopigno confirmed the same basic work-flow in [Larue et al., 2012], adding to the process some modification to increase the level of automatism of the different tasks. The three-dimensional work-flow is independent from the acquisition technology used and can be resumed as in Figure 3.1.

With all the post processing included in the production of the final model, we challenge the definition of what might be considered the final data from the point of view of user requirements. The final result of reconstruction is still strongly dependent on the algorithms used in the merging, registration, and post-processing phases and this is why one of the recommendations pointed out from 3D-COFORM is that storing the “original” raw data for a potential later processing, as the combination techniques improve, must be a requirement.

In the case of the data provenance and preservation, the user requirement is probably best expressed as the long-term storage of the initial dataset produced as input to application level processes (the real raw data, i.e. in photogrammetry, the photographic set; in laser triangulation, the raw output and the sensor information). Part of the processing that leads to the creation of a complete 3D model involves the recognition and removal of any parts of a scan that do not record the artefact itself

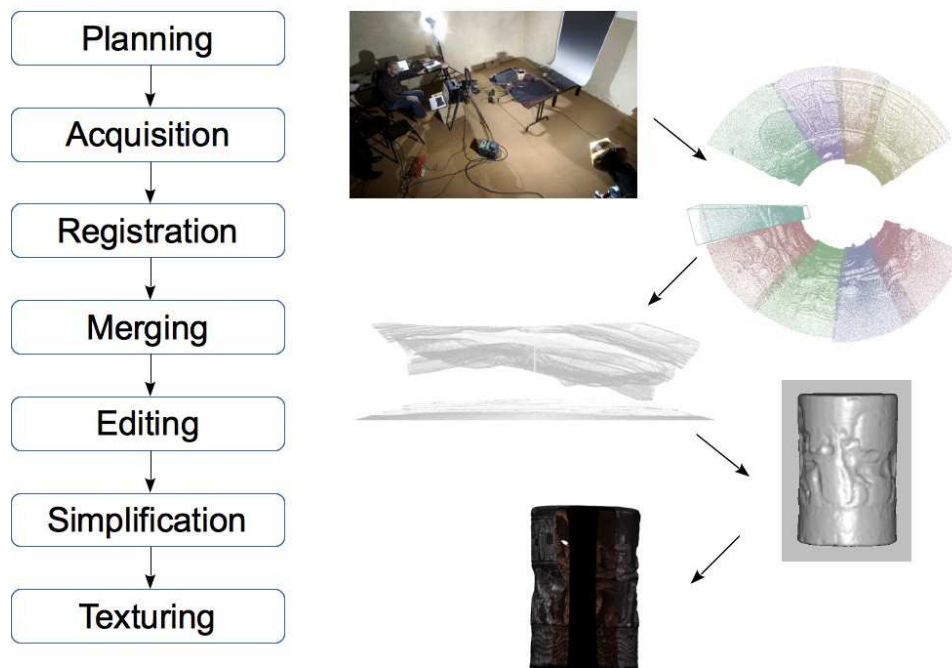


Figure 3.1: Three dimensional model production work-flow. The same workflow can be applied to whatever acquisition technology or acquisition protocol we choose.

but the background to it in the scanning location. This cleaning of the scan data is another aspect of the complete recording process and as such is a potential opportunity for errors to be introduced. User requirements are ensured for the background to be safely and easily identified and removed from the raw scans. This process also complicates the definition of “raw” data and the perceived requirement for its preservation.

There is a well-recognised need for the recording process to include information about the specific hardware and software used in the process and increasingly instruments are designed to include this data automatically. Some instruments also include environmental data automatically i.e. date, time, and GPS recording are becoming commonplace and the likelihood of recording of other items (i.e. temperature) is increasing and this trend is likely to continue.

3.2 Three-Dimensional Geometry Acquisition Methods

Currently, there exists a variety of 3D acquisition methodologies. These can be classified as contact and non-contact 3D scanners [Hernández Esteban, 2004] and [Sansoni et al., 2009]. Contact systems are not popular in the cultural heritage domain due to the fragile nature and rarity of the artefacts. In contrast, non-contact systems have been successfully used in many digitisation projects during the last decade. According to the bibliography, non-contact systems are divided into active and passive. Active scanners are based on the detection of emitted light or radiation while passive scanners rely on detecting reflected visible light [Pavlidis et al., 2007].

A complete taxonomy of Shape Acquisition techniques is represented in Figure 3.2 from the course [Curless, 1999]. In Figure 3.3 the optical methods are detailed.

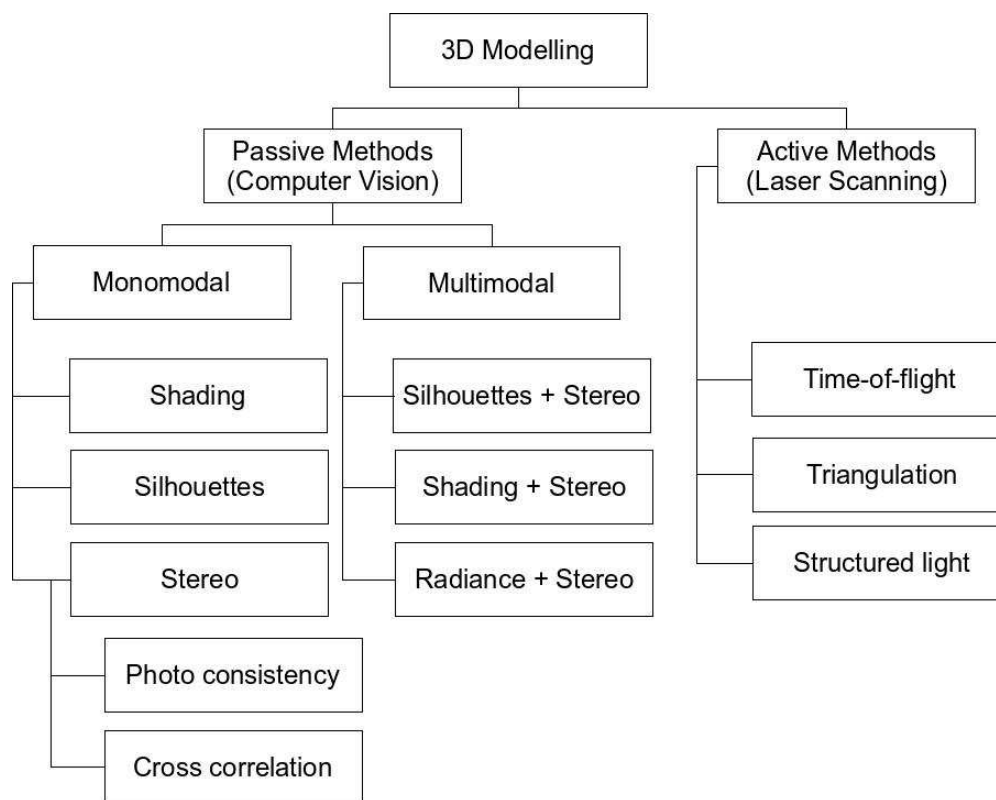


Figure 3.2: overview of three dimensional Shape Acquisition Techniques according to [Curless, 1999].

The most used techniques in three-dimensional object acquisition are laser scanning, structured light scanning, time-of-flight and photogrammetry, according to

the 3D acquisition taxonomy in Figure 16. For the reasons outlined above, methods of 3D acquisition which require physical contact are excluded here. All of these techniques have, as the end point of the documentation, a model of the surface, produced as a set of points in 3D, or a “mesh”, with alternative methods of constructing a surface on which all the points lie, and a colour texture which is attached to the surface at any point. However the different acquisition technologies affect the inherent characteristics and suitability of the resulting data.

For example, it was a common idea that triangulation techniques can produce greater accuracy than time-of-flight, but can only be used at relatively short range. Thus where great accuracy is a requirement it can normally only be provided with access to the object to be digitised from perhaps $< 1m$ and thus, if physical access to the artefact is difficult or requires the construction of special gantries, other constraints come to bear (i.e. using non-invasive techniques and limitations of cost in digitisation). Alternatively if on a specific site physical access is impractical without unacceptable levels of invasive methods, then sensing from a greater distance may require time of flight techniques and the results may be less accurate. This is no more the case today as we can get very interesting results with a time of flight device and some dedicated post-treatment as demonstrated in [Callieri et al., 2009] where the authors describe the acquisition of “The Fountain of Neptune”, a complex fountain in the centre of Florence situated on the *Piazza della Signoria* close to the *Palazzo Vecchio*. The central sculptures decorating the fountain are authored by Bartolomeo Ammannati (1511 – 1592) and were commissioned in 1565. The central piece of the fountain is a five meter tall Neptune statue, placed on a high decorated pedestal making the acquisition using a laser scanner very difficult without using a special infrastructure. The three small figures (mermen) are between the Neptune’s legs carrying shells that originally were water sprinklers.

Using a RIEGL® LMS-Z390i and few scans technicians have been able to acquire the complete model. Coupling the final model plus a set of 70 High Definition (HD) photos, the team reproduced the model with a precision of $2mm$ and the restoration campaign planned by the *Opificio delle Pietre Dure* could take place.

Furthermore as surface colour, reflectivity, and transparency are factors that affect the ability of an acquisition system to capture the shape of an object, current research is aimed at the development of methodologies that are able to capture challenging objects with metallic specular or transparent surfaces [Bajard et al., 2011] described as a method that works where classic laser triangulation approaches fail.

The ability to automate the digitisation procedure has also been an important research domain. Apart from high accuracy geometry capture, recent research efforts have been primarily directed towards the accurate acquisition of surface properties. The main scope is to determine the behaviour of a surface caused by the environment conditions such as the incident light, its illumination, and the positions of the

viewpoint. In [Müller et al., 2005] the authors describe a method that faithfully reconstructs the look-and-feel of an object’s surface by using Bidirectional Texture Functions (BTF) to encode material properties. Similar results can be achieved even with less complex techniques such as the one described in [Callieri, 2006].

As shown in Figure 3.3 optical techniques are commonly classified as passive systems (subsequently divided in monomodal or multimodal. Monomodal are, for example, the shape from silhouette and multimodal consist in the coupling of a monomodal technique plus stereo i.e. the method used at the C2RMF and described later more in detail) and active systems, which sample the surface by projecting some light on the object (i.e. a laser or a structured light pattern), and then measure the geometry of position of the point either by triangulation or by time of flight. The result of such acquisition is called “range map” and consists in a 2D matrix of points represented usually as XYZ or, like in the case of the A3D® systems for example, as $XYZRGB$, including not only the space coordinates but also the colour value for each point.

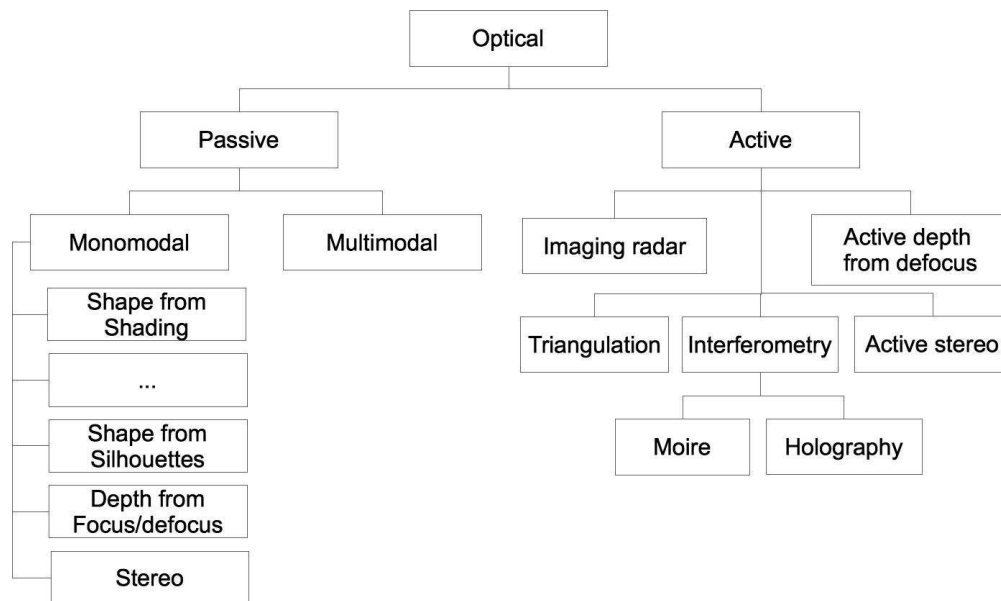


Figure 3.3: 3D Optical acquisition methods. Passive methods are the one based on Computer Vision techniques. Actives include laser, time-of-flight and structured light.

In the next subsections I present the most used 3D acquisition technologies discussing the pros and cons for each one and trying to provide comparison where possible.

3.2.1 Laser Triangulation

One of the most widely used active acquisition methods in cultural heritage, and perhaps in industry, is Laser Triangulation (LT).

A laser scanner acquisition system can be based on a single spot of light (1D), a stripe or profile (2D) or an area (2.5D). The usual setup is constituted by a camera and a sensor (i.e. laser or projector), and spaced by a certain, well known, distance called a baseline. The working range of these systems may vary from 0.1cm to 500cm and they provide a lateral spatial (X, Y) resolution of up to 50 μ m and a depth uncertainty starting from 10 μ m.

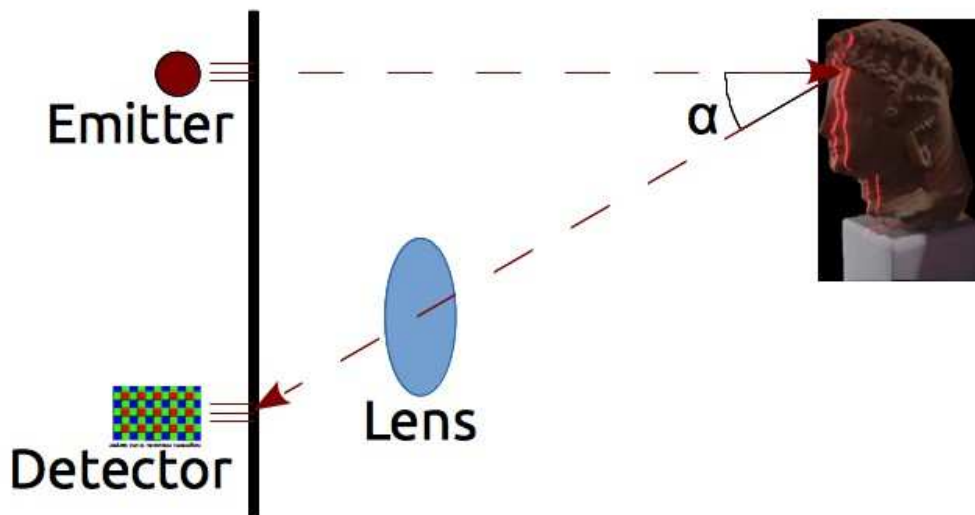


Figure 3.4: Principle of a laser triangulation sensor. The laser beam is projected onto the object. This laser beam is reflected from the surface and falls on the detector through the lens. Depending on the position of the beam and the detector, the angle(α) is calculated and hence the height from the sensor to the target surface is detected. As the height increases the angle decreases and as the height decreases the angle increases.

The method is based on a system with a laser source (generally a red laser diode, with a wavelength of about 650nm) and an optical detector as see in in the principle in Figure 3.4. The laser source emits light in the form of a spot, a line or a pattern on the surface of the object while the CDD camera captures the deformations that occur. Depth, and so 3D data, is calculated by using the triangulation principle: the light source illuminates an object and an image of this light spot is then formed, by means of a lens, on the surface of a linear light sensitive sensor. By measuring the deformation of the light spot image, the distance of the object from the instrument can be determined, provided the baseline and the angles are known.

Laser scanners are well known for their high accuracy in geometry measurements ($< 50\mu m$) and dense sampling ($< 100\mu m$) [Rioux, 1994]. Modern laser scanners systems are able to offer algorithmic registration between geometry and colour information, one of the most challenging needs in cultural heritage digitisation projects. Some of the most broadly used laser scanners based on laser triangulation are the Minolta® Laser Scanner v900 and v910 [Konika Minolta, 2013], for its ease of use and commercial support to cultural heritage initiatives, and the Nextengine® [NextEngine, 2013], mainly for its price. The latter offers a USB powered colour multi-laser solution the size of 2 A4 paper blocks, with an integrated lighting system and an easy to use software, able to automatically register the 3D scans when used with a turn-table.

During my stay at C2RMF we had the possibility to work with a laser scanner mounted on a CMM device: the A3D colour laser scanner, from the Arius3D company [Arius3D, 2013]. The device had been donated in the framework of a Franco - Canadian collaboration after the successful scanning of the Leonardo da Vinci painting “Mona Lisa” in 2004, with a laser scanner prototype based on the same technology. One of the moment of the acquisition can be seen in Figure 3.5. The results of these studies have been published in two books [Mohen et al., 2006] and [Lahanier, 2007], in which I participated in the elaboration.

The system needs to be installed in a dedicated room to ensure the possibility of working in a completely controlled environment. The device is composed of 3 main components: the CMM body, heavily weighted, the sensor, and the lasers. The scanner is well suited for repetitively scanning object of the same size and shape. In this way the operator can define the CMM movement and the integrated scanner will do the rest. However, if there is the need of scanning many different, complex objects (like vases for example) then the A3D scanner is not the best solution. A note about the 3 colour lasers; while this feature is quite interesting, and produces a colour-per-point point-cloud, the result is not always accurate and light and temperature in the room must be kept under strict control.

Principal characteristics of the system at C2RMF (you can see the installation in Figure 3.6) are a Scan Width and a Depth of Field of about $50mm$ and a range measurement resolution of $25\mu m$ X-axis with $6 - 10\mu m$ error. An important consideration is that the system has a colour resolution of 24 bits per point, 8 bits per channel in *RGB*, and the colour is acquired measuring the backscattering light of 3 lasers at different wavelengths: $473nm$ for blue, $532nm$ for green, and $638nm$ for red.

For the acquisition of the points, the scanner uses a linear scanning technique; position in the *Y* axe is known by the CMM system, the position in the *X* axe is calculated based on the position of the mirror connected to a galvanometer in the sensor and then the *Z* axe is calculated by the principle of triangulation. The huge

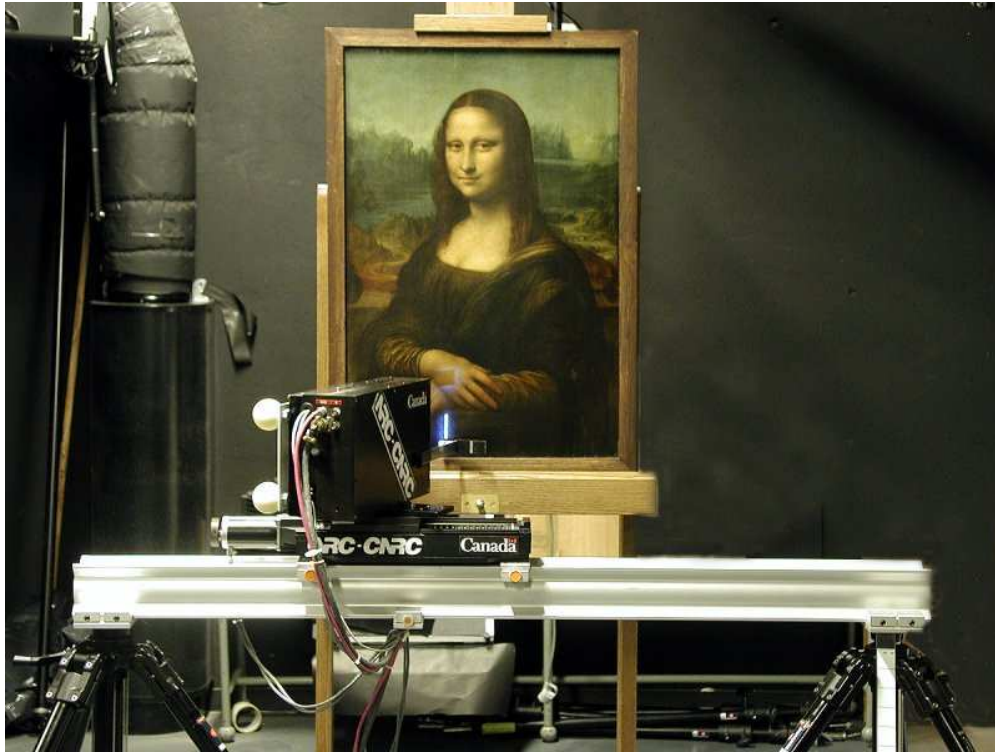


Figure 3.5: 3D acquisition of the “Mona Lisa” at the C2RMF using a prototype RGB laser technology provided by CRC-CNRC Canada. “Mona Lisa”, by Leonardo da Vinci, 1506, Louvre museum.

quantity of data produced by the system is then stored in a format saving the characteristics per point: *XYZrgb* plus the information on the colour calibration and a proprietary software, called PointCloud®, are capable of automatically putting together all the lines scanned in real time.

Expensive laser triangulation devices can be used for precise scientific measurement, keeping in account the limitation in precision and completeness of the final model if scanning materials with special features like, for example, translucency (i.e. glass, ivory or marble), transparency (i.e. glass, jewellery or gems), and reflections (i.e. metals, mirrors, varnish).

In these cases the level of accuracy of the produced model is well below the documented for “standard” material. A visual inspection of the model produced by laser scanning of items with materials presenting some of the aforementioned characteristics make clear that laser scanning is not the proper technology for such campaigns. Where a higher accuracy is needed, compared to the one offered by the Multi Laser Technology (MLT, such as NextEngine®) devices, a structured light approach may be better suited for the acquisition of reflective/transparent artworks;

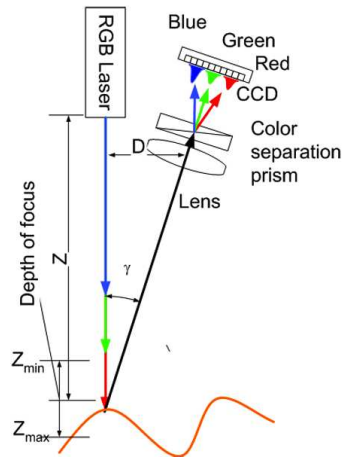


Figure 3.6: Arius3D setup at C2RMF. (left) schema representing the acquisition process. (right) the CMM and the laser head. The laser sources are hidden below the CMM for security reasons. On the right we can distinguish the dedicated unit for the CMM and laser real time acquisition, colour calibration and synchronization.

by using a light pattern instead of a single laser line, these scanners are less sensitive to specular reflections.

3.2.2 Structured-Light Scanning

Three-dimensional scanning using a particular pattern of white light is called “structured light scanning” or “fringe projection scanning”. This method does not require special light sources like its competitor, the laser scanner, does and consists in projecting a series of alternated dark and bright light stripes on an object to record the deformed patterns of light with a camera. The projector and the camera are usually fixed on a rigid column and form a known angle which makes it possible to measure all the parameters of the triangle formed by the camera, the projector, and a projected fringe.

The projection of structured light on an object can be observed from a different perspective as a deformed pattern according to the shape of the object. Structured light systems are therefore an alternative triangulation method. Triangulation methods can achieve the greatest accuracy of current technologies with accuracy below $1mm$

depending upon the instrument and the scanning set up. Where the object surface has inclusions, holes in the scans may result from some orientations of scanning. Similar to the other three dimensional techniques, these deformations are removed by aligning and combining scans from several orientations in the post-acquisition processing described later.



Figure 3.7: Acquisition of the “Mona Lisa” painting at the Louvre Museum with Breuckmann Optotop-VI. From left to right: Denis Pitzalis, Dr. Bernd Breuckmann, Dr. Christian Lahanier, Mme Cécile Scaillierez. “Mona Lisa”, by Leonardo da Vinci, 1506, Louvre museum.

Structured Light is a very popular active method among the cultural heritage community that is based on projecting a sequence of different density bi-dimensional patterns of non-coherent light on the surface of an object and extracting the 3D geometry by monitoring the deformations of each pattern. Thanks to the increasing computational power, current research can focus on developing structured light systems that are able to capture 3D surfaces in real-time. This is experimentally achieved by increasing the speed of projection patterns and improving the capturing algorithms.

The last generation of industrial structured light system is able to provide rapid acquisition times (up to 0.8 sec per scan) and the level of accuracy offered is of about $45\mu m$. Such precision is similar and in some circumstances surpasses laser triangulation systems, depending on condition and materials.

Structured light has been used to acquire high-resolution 3D models of paintings. In particular, at the C2RMF, I participated in the acquisition of the “Mona Lisa” painting from Leonardo da Vinci, Louvre, using a Breuckmann optoTOP-VI camera, visible in Figure 3.7. This device came with a 6.6 mega pixel camera and a Field of View of $170mm$ operating from approximately $300mm$. Because of the shininess of the surface of the painting due to the varnish, we were forced to acquire the same region twice, one with vertical and one with horizontal sensor position, and then register the two partial results to achieve a 100% coverage.

Considering ease of use, portability, user-friendliness, flexibility, and the lack of calibration procedures, structured light systems are often considered as optimal solutions in the field of cultural heritage especially where the projects include the digitisation and detailed analysis of marble-made sculptures, jewellery, paintings, etc.

3.2.3 Stereo Photogrammetry

Stereo Photogrammetry is the analysis of two-dimensional photographs of a scene to extract three-dimensional information. At least two images are necessary to reconstruct a three-dimensional model of the object, as for our eyes. Homologous points are set on the pairs of images, and subsequently the intersection of light rays going from an object point to a camera allows for the production of the three-dimensional coordinates of the points of interest as shown in Figure 3.8.

This technique operates on the same principle as the human vision system. The main advantage of such an approach is the simple instruments needed which include usually one or more digital cameras and the speed of acquisition (Figure 3.9). The accuracy of the digitised models, however, is somewhat poor, typically some millimetres. In general we can identify 3 limitations of the stereo photogrammetry reconstruction:

- The shape of the physical object. An object may have holes or obstructed parts that cannot be “seen” by the algorithm from any point of view. The algorithm will then be unable to build or reconstruct the correct topology;
- The limited number of camera positions. The more views of the object we acquire, the more close to reality the topology of the reconstructed 3D model

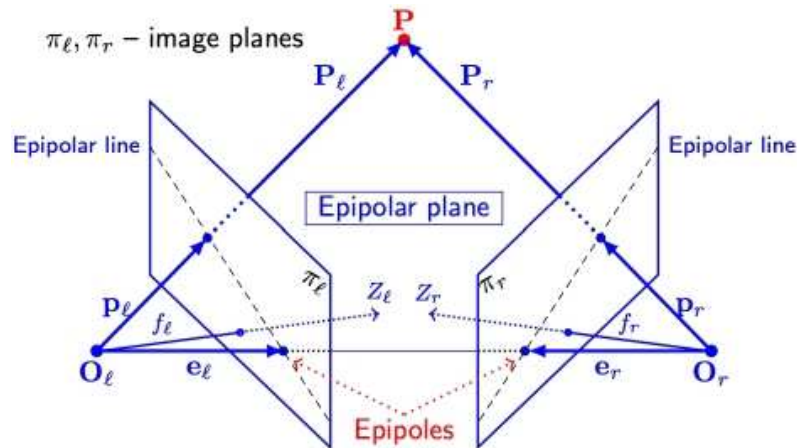


Figure 3.8: Epipolar geometry: the basic geometry of a stereo imaging system. The two cameras, with center O_l and O_r , observe point P on top of the image. The projection of the point P into the “Epipolar Planes” π_l and π_r is denoted p_l and p_r . e_l and e_r are epipoles.

will be;

- The reconstruction algorithm. Usually the reconstruction algorithms make some assumptions that will impact on the final representation of the 3D model. Starting from the same set of images, but using different reconstruction algorithms, we can obtain different topologies.

Different photogrammetry methods are described in literature and each one has its characteristics and limitations [Paparoditis et al., 2001]. Since 2004 at the C2RMF we have been using the method published in [Hernández Esteban and Schmitt, 2004].

Starting from a calibrated sequence of colour images, the algorithm is able to reconstruct both 3D geometry and the texture. The method is based on a deformable model, which defines the framework where texture and silhouette information will be fused. This is achieved by defining two forces; one driven by the texture and the second driven by the silhouettes. The image coherence force of the algorithm is based on the following projective geometry property; if two cameras see the same surface, then the two images are related by a geometric transformation that depends only on the 3D geometry of the object.

Different approaches exist in literature to measure the coherence of a set of images that can be classified into two main groups whether they make a punctual radiometric comparison (e.g. photo-consistency measures as in voxel coloring) or a spatial comparison of relative radiometric distributions (i.e. cross-correlation measures). The method used in Hernandez-Schmitt is based on the normalized



Figure 3.9: set up for “shape from silhouette” acquisition method at the C2RMF. In the centre of the photo the object and the camera are placed. The camera must not project any shadow in the acquisition area. The two light diffusers are covered with a polarized filter, to limit the backscattering from the object surface and the background is chosen to be of high contrast with the object itself. On the right side, the operator is handling the photographic and the 3D acquisition while using the turn table micro-controller.

cross-correlation which gives a particular robustness in the presence of highlights and changes of lighting conditions, a typical case in cultural heritage acquisitions. Using the schema in Figure 3.8 as reference, the normalized cross-correlation $C(P_l, P_r)$ between pixels P_l and P_r is defined as follows:

$$C(P_l, P_r) = \frac{\pi_j(N(p_j)) - \overline{\pi_j(N(p_j))}}{\|\pi_j(N(p_j)) - \overline{\pi_j(N(p_j))}\|}, j = l, r \quad (3.1)$$

where $N(p_j)$ is a neighbourhood around p_j in image π_j , and $\pi_j(N(p_j))$ is the vector of the image values in this neighbourhood. This measure compares the intensity distributions inside the two neighbourhoods and gives us the basis for the calculation of the 3D shape. A disadvantage of the Hernandez-Schmitt algorithm is the

very long time needed to extract precise silhouettes, a work that remains to be done manually.

With this method, and with stereo photogrammetry in general, the quality of the resulting texture is highly photorealistic. The equipment necessary for this kind of acquisition is not expensive i.e. smartphone's camera, compact camera or DSLR; as, in principle, stereo photogrammetry involves stereo calibration, feature extraction, feature correspondence analysis and depth computation. All post processing is computed algorithmically, without the support of any special device and thus it is considered a simple and low cost method. It is important to note that the user of this technique must have some basic training in how to acquire the original photo-set. During the "Campana Collection" campaign, aimed in acquiring by this methodology the vases from the Louvre's department of Greek and Roman antiquities, I established, by comparison, that to have a correct acquisition of a vase at least 36 acquisitions, one every 10 degrees, of the rotating object is required. The number can go down to 12 when acquiring, for example, floor tiles, and go up to 72 for complex objects such as the cylinder seal or a painting on wood.

Stereo photogrammetry in general has a medium/low topographic quality which makes the technique useful for web dissemination and archaeological site documentation, but it is merely acceptable for all scientific purposes that require precise measurement.

3.2.4 Structure From Motion

Another method of the same family of stereo vision is the Structure-From-Motion which can be considered as the extension of the latter. Instead of considering image pairs, this method attempts to reconstruct depth from a number of images that depict a static object from arbitrary viewpoints. Thus, apart from the feature extraction phase, the trajectories of features over time are also computed. As previously mentioned during the EU funded research project 3D-COFORM, a lot of effort has been focused on developing a system based on the Structure-From-Motion method, the publicly available Arc3D [Tingdahl and Gool, 2011].

Arc3D consists of an automated Web-service where the user uploads, after registration, a number of images that depict the object from different viewpoints. At that point, if the images are coherent, the system is able to identify the relative camera positions and the depth map of each image. In the Wikipedia page dedicated to stereo photogrammetry a list of online services similar to Arc3D is available [Wikipedia, 2013a].



Figure 3.10: reconstruction of an archaeological excavation acquired using Arc3D.



Figure 3.11: 3D model reconstruction of a statue of Abou Simbel, Egypt. The model has been done with Arc3D on a set of photos (right) from 1963 photogrammetric campaign, courtesy of IGN.

3.2.5 Time-of-flight

Time-of-flight scanners (also called ranging scanners or laser pulse-based scanners) operate through the use of a pulsed laser beam which is reflected by the surface of the object to be scanned. After the emission of the impulse, the time spent by the light to return to a laser receiver is measured to compute the distance of the point of reflection, using an assumed speed of light. This kind of scanner, usually very expensive, is able to measure much longer distances than instruments that work by triangulation. It is, however, less accurate compared to the previous techniques, especially at close range, due to the speed of light approximation. These devices use circuitry that is accurate to picoseconds to measure the time it takes for millions of pulses of the laser to return to the sensor, and calculates a distance. By rotating the laser and sensor (usually via a mirror), the scanner can scan up to a full 360 degrees around itself and in this way modern devices are able to measure ranges up to 6Km. The accuracy can vary between a few millimetres and two or three centimetres, depending mainly on the distance between the scanner and the object.

The Time-Of-Flight methods are commonly used, for example, to conduct a 3D survey of a portion of large urban areas, of entire archaeological sites, or of facades and buildings. As we have discussed previously, these devices can provide excellent results even working on short distances.

Laser Phase-Shift systems are another type of time-of-flight 3D scanner technology, and share a similar concept to pulse-based systems. In addition to pulsing the laser, these systems also modulate the power of the laser beam, and the scanner compares the phase of the laser being sent out and then returned to the sensor.

Systems based on the Phase-Shift method are usually preferred for medium range distance measurements because of the higher accuracy of the acquisition as described in [San José Alonso et al., 2011].

3.2.6 Other methods

3.2.6.1 Computed Tomography

The first radiography on a painting done at the C2RMF for documentation and restoration purposes was carried out in 1920. Nowadays non-destructive methods of diagnosis based on simple X-Ray digital radiography, like the one in Figure 3.12 and on computed tomography to record volumetric information are more and more used for the conservation, analysis, documentation and restoration in the cultural heritage field.

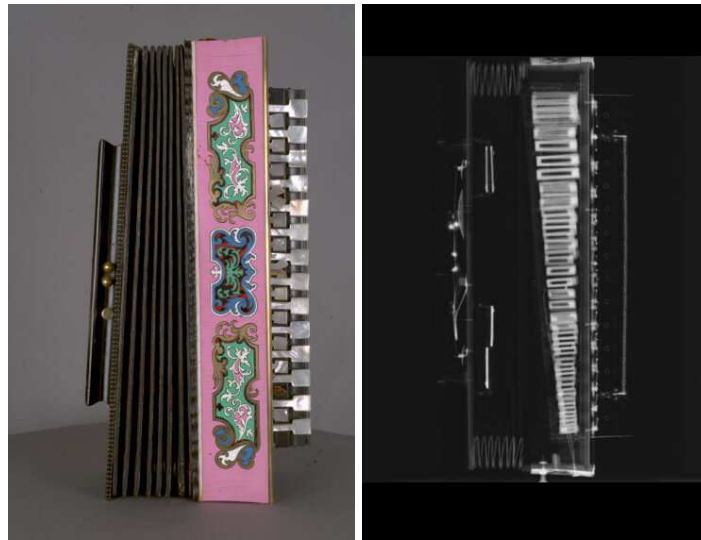


Figure 3.12: Colour and X-Ray images of an accordion (inventory E995.29.30) conserved at the museum of Music in Paris. Courtesy of C2RMF

In particular this kind of analysis can help not only to survey the state of the object but also to understand the construction techniques of the object under examination. We can also assess that the use of X-Ray tomography for the analysis of objects is a big step forward in the interpretation of data, compared to “basic” digital X-Ray systems. In [Morigi et al., 2007], for example, Computed Tomography has been used to inspect the Celestial Globe of the cartographer Vincenzo Maria Coronelli to acquire information about the manufacturing technique and the presence (and the position) of significant defects and damages in order to determine the most adequate maintenance and restoration procedure.

Computed Tomography system generally consists of:

- a X-Ray radiation source;
- a mechanical device to rotate the object, as for photogrammetry, micro-controlled;
- a X-Ray digital detector for image data collection;
- a dedicated machine to control all the overall acquisition process;
- a computer for image processing and rendering.

Disadvantages of the use of computed tomography technique is that it is difficult to use and expensive. In fact, to produce good tomography 3D models, several hundred digital radiographies are necessary and the equipment to achieve this is very

expensive. Furthermore, the obtained three dimensional model is unfortunately not exempt from noise and the final shape is slightly deformed depending on the position of the detector. In order to have useful results and avoid meaningless data the system and the acquisition conditions must be chosen carefully according to the information we want to collect.

3.2.6.2 μ Topography

This technique, also called optical roughness-meter, is based on a quasi-confocal, z-axis extended field. This axis field extension is obtained by stretching the axial chromaticism generally encountered in a confocal dioptric set up when working with a polychromatic point source. That means that we know the z axis of the point via the wavelength of the univocal colour back-scattered [Ezrati et al., 2007].

Using a CMM micro controlled translation table in the x and y axis in combination with this complex optic technique we are able to scan surface portions of objects and thus obtain a micro-topographic image of the surface to analyse. Although this technique is very time consuming it gives very good results and the geometry of the “scanned” surface is highly precise, up to $0.1\mu m$ in all 3 axes.

On the other hand, using this approach, we remain unable to extract colour information, the acquired data presents only local information, and there remains significant missing information from the non-acquired areas.

3.3 Three-Dimensional Acquisition Methods Comparison

As summarized in [El-Hakim et al., 2004] in general, most applications of three-dimensional acquisition specify eight requirements:

1. High geometric accuracy, to be able to study the object in detail;
2. Capture of all details, even the most difficult such as glass, or gold;
3. Photorealism, to give the best sense of reality in rendering;
4. High automation level, to ease the acquisition process;
5. Low cost, to be able to digitize thousands of collections;
6. Portability, to enable the manipulation of the device like a simple camera;

7. Application flexibility, that does not require the knowledge of the algorithms to apply to get simple effects; and
8. Model size efficiency, to enable easy data exchange and conservation.

The weight that the final user should associate to the importance of each of these requirements is directly dependent on the applications objective and whether the final result must be used for documentation purposes, restoration, or virtual tourism. If we want to use the final model for documentation, like in [Borgeat et al., 2007] then we want our model to be as precise as possible, in order to give the possibility to future curators to measure exactly every variation happening in the painting. In the case of restoration, the model must contain the information that is necessary to the curator or art historian including volumetric data, internal structure and so on. In the case of virtual tourism, we should prefer photorealism and model size efficiency if we are planning to operate over the web.

A single system that can satisfy all of these requirements does not exist yet. It is also not yet possible to accurately capture all details with a fully automated system, although some research is going in this direction. The European funded project [Presious, 2013] addresses this problem investigating an on-the-fly auto-completion algorithm for 3D digitization that exploits similarity between the acquired model and previously computed templates to allow gradual shape prediction from partially digitized objects. Such a system, even if not a perfect solution for automation, opens a windows of opportunity to decrease the acquisition time and simplify acquisition procedures that can lead to a reduction in both effort and cost.

When choosing a scanner device, depending on the technology, a scanner can be small or large, hand-held or standalone, portable or static, sensitive to colour contrast or brightness and transparency. Post processing of the intermediate results would vary from minimal, to semi-automated, to completely relying on final-user capabilities. Hence the selection of the appropriate device not only depends on the application needs, but also on the user skills. Although commercial devices are built to be relatively easy and simple enough to operate, the final result often require some human correction.

In addition, as we have seen in the previous section, all of these acquisition methods come with both advantages and disadvantages that I have summarized and quantified in the radar map diagrams based on my own experience. In Table 3.1 the reader can see the pros and cons of each technique.

It is not surprising then that a lot of research has been done in finding the best combination of multiple methods in order to improve the quality of the final model. Such methodology is nowadays very often used in both archaeological field acquisition, where the precision of time-of-flight for medium-long range is coupled

Table 3.1: Pros and Cons of scanning techniques

3D Scanner Types	Pros	Cons
Laser triangulation	Easily to very easily portable Resistant Less sensitive to ambient light Fast data acquisition Low to medium price Accuracy to $< 1mm$	Sensitive to material properties High noise Sensitive to colour contrast Limited FoV Operating distance $< 1m$
Pattern fringe triangulation	Easily portable Less sensitive to material properties Low noise Fast data acquisition Medium price Accuracy to $< 1mm$	Limited to area scanner type Requires specific lighting conditions Operating distance $< 1m$
Pulse-based	Operating distance: medium - long from approx $2m$ to $6Km$ Medium to high price	Less accurate than triangulation / fringe Slower data acquisition Very high noise Accuracy from approx $5mm$ to few cm
Phase-Shift	Faster data acquisition than Pulse-based More accurate than Pulse-based Less noise than Pulse-based	Accuracy from approx $5mm$ to few cm Medium range only High price
Stereo photogrammetry	3D reconstruction services available online High quality texture (Photorealism) Easy to use Algorithmic based Cheap	Quality dependent from lot of external parameters Accuracy from few mm to few cm

with GIS and photogrammetry to include accurate position data with the colour information, as well as in acquisition of special objects, as it was the case of the *Cylinder seal of Ibni-Sharrum*.

As described in [Pavlidis et al., 2007] we can resume the influential decision factors in three points:

- Complexity in size and shape (i.e. is the target movable or unmovable; is the target an artefact or an archaeological site; is it flat like a painting or is it cylindrical like a statue);
- Morphological complexity (i.e. level of detail we want to manage; is there a mechanical structure; are there concave or empty areas);

- Composition (i.e. raw materials: is it ceramic, ivory, glass, metal).

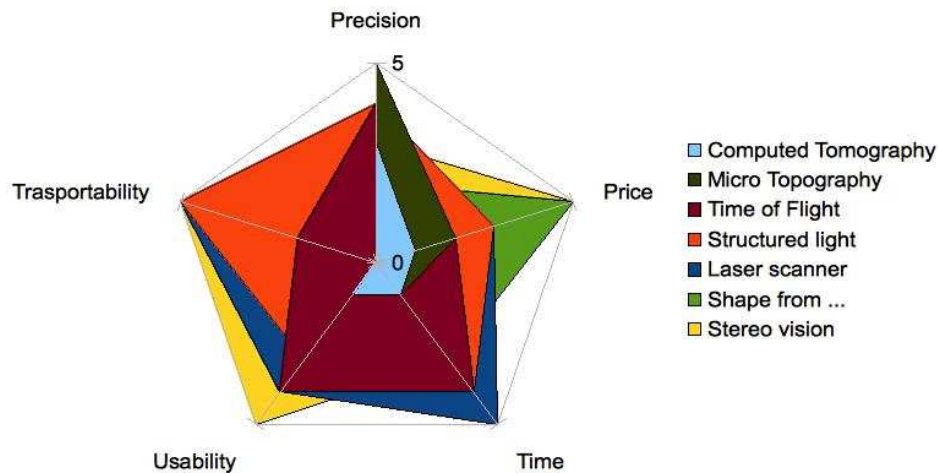


Figure 3.13: Stereo Vision, Structured Light, and Laser Scanner are the most “user friendly” methods and are also relatively cheap. On the opposite end of the spectrum is Computed Tomography and the Micro Topography, although a lot of research is going in to making these tools more accessible. Time-of-flight remains expensive, not easily transportable (in comparison to a camera or a Nextengine®) and it is difficult to handle.

In [Guidi et al., 2007] the authors compare the scanning result of the NextEngine® with the Minolta® Vivid 910 and a ShapeGrabber® SG100 provided with a mechanical linear rail against a reference panel and a museum object. The conclusions presented in the paper and reached with scientific measurements are the same dictated by the practice when comparing this low cost active sensor device based Multi Line Triangulation (MLT) with more expensive appliances.

Concerning the application in cultural heritage, both systems find their use in controlled indoor environment for the acquisition of collections. Minolta® devices are used also for acquisition in the fields because of their robustness. The main difference between the two devices is that Nextengine® use a MultiStripe Laser Triangulation (MLT) technology, based on a twin array of 4 solid state lasers (class 1M, 10mW) with $\lambda = 650nm$ (red laser) and two 3 Mpixel CMOS RGB array sensors used for the device “wide mode” and “macro mode” while Minolta® v900 and v910 use a single laser on a galvanometer – driven rotating mirror.

Although some metrological significant issues exists, the MLT scanner is a good instrument for three-dimensional general purpose data acquisition and the final measurements are not much different from the more expensive devices in terms of accuracy and precision. Indeed the MLT device is not ideal for scientific measurements

and when high-resolution, sometimes necessary in cultural heritage applications is needed (i.e. measure of variation of a panel in a painting's wood support due to the humidity).

Table 3.2: NextEngine® vs Minolta® v910

	NextEngine® (Macro - Wide)	Minolta®v910 (Tele - Wide)
Field of View	130x96mm 343x256mm	140x100mm 600x450mm
Resolution (point density on target surface)	200DPI 75DPI	N/A N/A
Texture density (on target surface)	400DPI 150DPI	N/A N/A
Accuracy	±13µm ±38µm	±10µm N/A
Input time	±2min N/A	±0.3sec ±2.5sec

It is also interesting to note that the NextEngine® scanner, because of its MLT technology and the correction applied by the acquisition software, seems less sensible to the errors caused by the object surface translucency, scattering, or contrast. However, the data acquired from a non-straight position is almost useless. Moreover, the fixed focusing distance and the length of time acquisition of the instrument makes it difficult to produce a complete model of very elaborated objects. In the case of the “Kazafani boat”, an archaeological artefact discovered in a Cypriot tomb in 1963 and representing a boat crafted from pottery in the 12th century BC, to assure the completeness of the model and the precision necessary for the creation of a 3D replica, we had to take 4 scans in “wide mode” and 20 scans in “macro mode”. The full process of creating the replica is described in the case studies section.

The Minolta® has a higher accuracy but presents more noise in areas with stronger translucency or colour contrast. Due to high sensibility to specular reflections, some editing is required in each range map in order to eliminate geometric spikes.

In conclusion, we can say that laser scanners, even the cheapest ones, are very good for generic cultural heritage use like prototyping, 3D web visualisation, serious games, virtual reconstruction, or even documentation.

3.4 Three-Dimensional Processing

In summarizing the previous sections, one can state confidently that none of the techniques illustrated and used can currently satisfy all the requirements of the acquisition of large-scale environments or artworks that form the everyday challenge in cultural heritage documentation. Although laser scanning responds to almost all the necessary characteristics and it can be a good compromise, it is usually not practical to only rely on one technique for every object and structure.

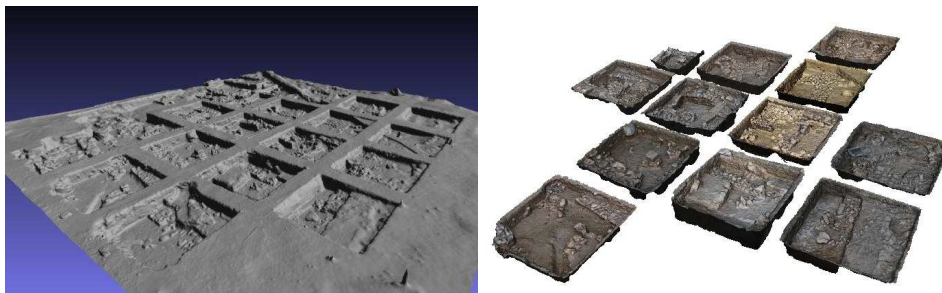


Figure 3.14: Archaeological site of PASYDY, Nicosia, Cyprus. Left: Phase-shift reconstruction Right: Arc3D reconstruction of the same area.

As mentioned before, the best results are obtained by using multiple technologies and then “fusing” the data all together. The most obvious fusion procedure is the image registration on a 3D model to obtain the texture. We will see this technique after in more detail. Another multiple data fusion approach is to fuse together all the data obtained by the different captures, keeping only the best information. Adopting this technique, we can compensate for the defect of a technology with the characteristics of another. This technique is very often used in archaeology, where models of archaeological sites, captured using time-of-flight devices, are usually enriched with dataset coming from photogrammetry (Figure 3.14).

As we have seen, a wide variety of three-dimensional acquisition setups are available in literature that employ a large number of different technologies and imaging techniques, even the most extravagant (like heating a metal surface and then scanning it using an infrared structured light source). However, they all produce the same result: a point cloud. The point cloud is then the discrete representation of the object shape in a 3D space. These points are characterized, among other information, by the sampling rate, which define the minimum distance between two sequential measures, and the sampling resolution which sets the minimum quantitative difference between the two measures.

The acquisition device is usually connected to a computer which corrects (cali-

brates) the raw data according to the physical characteristics of the sensor. For example acquired points that are closer to the centre of the sensor are in general kept over those near an edge. The sensor driver can also attenuate spikes in noise produced by i.e. reflectance, sharp transition between colour contrast, and transparency.

Although the point cloud is the common format of the raw data produced by any 3D acquisition system, it comes with some limitation, one of which is the limited visualisation capacity: the density of the model is determined, as we have seen, by the sampling rate and it can get very sparse on large models. A sparse model is very difficult to “imagine” and it can look more similar to a “connect the dots” game than a 3D model. A solution to this problem would be to increase the number of dots, for example, by interpolation, noting that this will affect the model management in terms of usability, performance, and interactive visualisation.

Usually, after the first preliminary work done by the acquisition software, a mesh is produced and, by doing so, other editing options become possible such as mesh regularization, hole filling, surface smoothing, mesh decimation, mesh subdivision, image registration and so on.

A real 3D data storage format does not exist, so when we have to operate multiple source fusion we face the problem of data format normalisation. Today, many 3D mesh processing software exist in the market: Rapidform®, Polyworks®, Geomagic®, OptoCat® and MeshLab. With the first 4 I had a positive experience, but they are very expensive, quite complex and they are not, usually, very flexible (i.e. import/export from one native format to another one is sometimes very time expensive if not impossible).

Because of the heterogeneous nature of the source of data, we need a versatile tool that is able to manipulate huge amounts of information in many different formats. MeshLab [Cignoni et al., 2008b] is the tool of choice, especially in cultural heritage, both for its fairly mature stability and for the open source characteristic of its code. The possibility to access the code has been very useful especially because, as already explained, the data issued from proprietary software is not always available in a format that is easier to manipulate.

3.4.1 Acquisition - the 3D Point Cloud

In the previous section we have seen some of the 3D acquisition methods I have been using during documentation campaigns of objects or archaeological sites. When a 3D acquisition device, or technique, acquires the raw data, they are going to form “partial points clouds”. The final model is the result of the cleaning

and fusion (or registration) of all those partial points clouds. The first step after the acquisition is then the cleaning of the “non desired data” that has to be done before doing the partial clouds registration. By “non desired data” I mean all those parts of the scan that are meaningless or misleading for the reconstruction, i.e. the areas that do not belong directly to the object, the outlying points, or any other area judged visually unsatisfactory.

Especially when an acquisition is made moving the scanner device around the object and the POV (Point Of View) changes we save lot of non-important information such as the background of the object or the base. Another case of “non desired data”, caused by internal measurements limitation is the areas poorly acquired because the points are located in the edge of the beam field of acquisition or that present a high deviation between the laser incidence and the surface’s normal.

3.4.2 Registration

Once the dataset is cleaned the next step is the alignment of the partial points clouds to form the point cloud that will become the final model. The quality of the alignment has a direct impact on the quality of the final model. The most used algorithm for alignment is the Iterative Closest Point (ICP) [[Rusinkiewicz and Levoy, 2001](#)].

Most of the software for 3D reconstruction offers semi-automatic registration: the user inputs three pairs of points in the partial scans that have similar positions for an initial guess and then the program computes an automatic refinement using ICP, trying to minimize the error metric.

3.4.3 Mesh Regularization

Once the model is complete, there is a complete point cloud, it is common practice to transform it into a mesh, which offers a more dense visualisation, allows easier manipulation, and provides other characteristics such as volumetric information and surface normals. Furthermore, noise reduction, hole filling, and data filtering is more efficient when applied to a mesh due to the additional information implicit in the new representation, for instance the surface topology and the surface normal vectors of the neighbouring triangles. A polygon mesh is a collection of vertices, edges and faces that defines the shape of a three-dimensional model. The faces are usually formed by three, four, or another number of points that can define a convex polygon. The most used mesh format is the triangular one.

The procedure to transform a point cloud into a triangular mesh is to group triples

of vertices to compose a triangle that respects some properties.

Once the mesh is obtained and the noise reduced we still have to optimize it, removing redundant points, filling holes, and decimating. All those algorithms are well known in literature. The hole filling is an automated procedure that fills the holes, within a certain size, based on the curvature trend of the hole boundaries and the topology of the neighbour's triangles.



Figure 3.15: Mesh example from the “Cylinder seal of Ibni-Sharrum” model.

As already mentioned, another advantage of the mesh representation is that we do not need lot of points to display a regular surface. We apply then what is known as “decimation”, or mesh simplification. The word *decimation* come from Latin, meaning “removal of a tenth” and was used in the Roman Army as a form of discipline.

Using this technique we are able to reduce considerably the quantity of data that is necessary to describe the complete surface of the model and it is easier to render the model.

3.4.4 High Resolution Image Registration

A common, understandable, requirement in cultural heritage for 3D models is the possibility to acquire not only the geometry, but also the colour information. For example the 3D model of an ancient vase without texture makes the model almost completely uninteresting and useless for web communication.

The direct acquisition of real colour, as shown by Arius3D example, is extremely complicated and involves lot of parameters and assumptions to be taken into account such as the materials absorption and reflectance properties, the light sources, the illuminant, etc.

A different approach is to make it simple, and “stitch” on the surface of the 3D model a series of pictures taken by a digital camera, trying to avoid reflections and shadows as much as possible.

This procedure is called “High Resolution Images Registration” and it is a common practice now that more and more mesh processing tools allow it to be done [Franken et al., 2005] thanks also to increasing computational power. Once the photos are registered onto the 3D model we can then merge, algorithmically, the colour information contained in the photographic data. The obtained colour information results in a colour per-vertex or colour per-triangle model.

3.4.5 Multiple Data Fusion

Once the meshes have been cleaned and the formats standardised, the next step is to create the final model. To do so we have to “fuse” all together the data obtained by the different captures improving in this way the weakness of some acquisition.

This means that by coupling techniques and/or different captors, we can compensate for the defects of one technology with the characteristics of another. A well known “multi-modal data fusion” technique is used to enhance the texture of a 3D model acquired via laser scanning with the texture resulting from a photogrammetry reconstruction of the same object. In both case studies of “The Cylinder Seal of Ibni-Sharrum” and “The Paphos Theatre” I describe the procedure I had to use to improve the quality of the texture of the final model using this technique. The procedure was slightly different in the two occasions; in the first case I registered the High Resolution images into the 3D model, while in the second, I transferred the colour information from one model to the other (from the aerial photogrammetry reconstructed 3D model to the phase-shift acquired model, more precise in measure, but with no texture at all).

Multiple Data Fusion is also used for multi layered object representation: a façade can be represented in an approximate way as a flat surface, but we can have ROI (Region Of Interest), like decorations, where we need more information.

3.5 Three-Dimensional Data Storage and Visualisation

3.5.1 Data Format Normalisation

The choice of the right format is very important in order to save a model. Some formats only allow meshes, some others only points, or vectors, or scenes, worlds, and animations. According to [Chen, 2009] the most used 3D formats are DFX, VRML, 3DS, MAX, RAW, LightWave, POV and NFF. It has to be noted that this list includes only formats that are able to save a scene. For personal experience, when handling import and export of 3D objects, the most used formats are RAW, OBJ, PLY, STL, COLLADA and X3D.

RAW With open specifications, this ASCII-only format is the simplest 3D format and usually is the format used by the scanning devices. We can have different format representations and usually each line contains 3 vertices, separated by spaces, to form a triangle, like so: *X1Y1Z1X2Y2Z2X3Y3Z3*, but also the format colour per vertex: *XYZRGB*.

OBJ This file format was first developed by Wavefront Technologies. It is open and widely adopted by 3D modelling tools. It is a universally accepted format for its simplicity and is represented in ASCII. The format represents 3D geometry alone and each polygon is defined as a list of vertices, and texture vertices. Vertices are stored in a precise order, making explicit declaration of normals unnecessary. OBJ files can contain information and comment line.

PLY The PoLYgon file format was first invented to store three-dimensional data from devices. It supports the association of properties, such as colour and transparency, surface normals, texture coordinates, and data confidence values to the description of polygons. It can be stored in both ASCII and BINARY format and allows the description of polygons per face.

STL The STereoLithography file format describes only the surface geometry of a three-dimensional model without any associated property. The STL format can be stored as both ASCII or BINARY format. As for PLY, binary files are more common, since they are more compact. For its characteristics, STL is commonly used as an exchange format for rapid prototyping and CAD/CADM.

COLLADA COLLADA file format, identified by the extension .dae, Digital Asset Exchange, is, as the extension says, an exchange file format recognized as standard in 2012 (ISO/PAS 17506). COLLADA is a very complex XML file format that defines a standard schema to make it easy to exchange 3D assets between applications. It also enables the creation of a production pipeline containing the information of 3D authoring and content processing tools. It can contain, for example, data on geometry, shaders and effects, physics, animation, kinematics, and multiple versions of the same asset. We will illustrate in the next chapter how the COLLADA format can be used along with semantic information to keep track of the entire creation process and documents, in this way, the data, and thus the model, provenance.

VRML and X3D VRML is a standard web format designed for use on internet as its primary use. X3D is the successor of VRML and, as the first, is based on scene-graph architecture. Both formats have been published by the ISO as standards: VRML in its last complete version VRML97 (ISO/IEC 14772-1) and X3D (ISO/IEC 19775-1). The first version of VRML appeared in 1994. X3D extended VRML by adding support for XML into the file, in order to better integrate with other WWW technologies such as DOM and XPath. This means that a scene containing 3D elements, such as shaders, textures, reflects, NURBS (Non-uniform rational basis splines), etc., could be manipulated at rendering time with a simple javascript, as it is represented with XML syntax. It is planned to include the native support of X3D scenes in future versions of HTML v5 as it has already been done with the Scalable Vector Graphics and the Mathematical Markup Language.

3.5.2 Three-Dimensional Models Visualisation

One of the biggest problems, for the moment, when working with 3D datasets, both mesh and point cloud, is the size. Datasets, especially those produced for large terrestrial surveys or painting assessment, can be extremely large, often composed by millions of points or triangles. The more dense a point cloud is, the more difficult is its rendering in real time.

As “3D” is becoming more and more an everyday technology many are the tools that enable the visualization of 3D models. Some of them are:

Polyworks IMView : a free viewer provided by Polyworks. It can read Polyworks projects which can include point cloud, mesh, or CAD datasets and even calculate basic measurements including distance, radii, angles, and cross-sections to generate inspection reports in PDF, Word, Excel or HTML formats. IMView can also

display OBJ, WRL, PLY and others with some limitations.

Rapidform Explorer : a free data viewer that supports 3D viewing and measurement capabilities for numerous point cloud, mesh, and CAD formats. It can read and manipulate ASCII, OBJ, and DXF and numerous scanner proprietary formats.

Geomagic Review : limited to Geomagic files.

Meshlab : as already discussed, is an open source software for processing and editing point cloud and mesh datasets. In addition to the visualization, Meshlab has mesh creation, editing, cleaning, healing, and more. Meshlab can import and export point cloud and mesh in many different data formats. Furthermore it offers basic distance measurement and is available as an application for mobile devices.

The work presented in [Foni et al., 2010] gives an interesting overview of the user perception of different kinds of 3D representation, discussing not the tools but the rendering techniques, i.e. comparing Augmented Reality to photo realistic rendering.

3.5.3 Indexing and Retrieval of Three-dimensional Objects

As the user has been used to searching in large databases with keywords first, and similar images after, it is the next logical step that we apply the same search paradigm to three-dimensional models.

However, even if the logic behind is the same, indexing three-dimensional models differs a lot from the process of indexing images [Tangelder and Veltkamp, 2008], [Benois-Pineau et al., 2012] and [Iyer et al., 2005]. 3D geometry represents an unambiguous description of the physical geometry of the artefacts we are searching for. It is easy to imagine how shape constitutes a semantic in its own right. This is particularly evident in fields like art and architecture where the descriptive language is “standardized”. In Appendix C.3 I present an implementation of a search by content framework we developed during the SCULPTEUR project, including the description of some of the developed methods.

3.6 Conclusion

We have seen that there is a variety of technologies that can achieve complete three-dimensional models. These technologies can be based on advanced, experimental devices, on commercial and very precise systems, or on algorithms that works out of the box. Some of these technologies complement each other, others are obtain more or less the same result but with a different methodology or a different technique. What should then be taken into consideration is the final goal of the digitisation campaign, as each methodology has its own working principles that can vary from project to project.

In a digitisation campaign the most delicate part is the design of the digitisation plan because all the variables of the project depend on the chosen methodology. I demonstrated that it is important, during the planning phase, to indeed take into account the physical properties of the object to scan, but also, at the same level of importance, the purpose of the 3D digitisation and the final scope of the use of the 3D model. Also the phase of post-processing should not be underestimated. If there are now systems that can do an acquisition in a semi-automatic way, that does not means that the model is ready for its final use without any manual improvement.

During my professional experience in the 3D-COFORM project, I have touched almost all the aspect of the use of three-dimensional technologies from acquisition to exploitation in cultural heritage. In the area of acquisition the project followed two major strands: the enhancement of the techniques for a more automatic and user friendly rapid digitisation (in-hand digitisation) of 3D-shape such as the web-based 3D reconstruction techniques for immovable objects as well as the 3D digitisation process of moveable regular objects based on available laser digitisation technology; and the development of a new approach for image-based reconstruction, the “3D-dome” [Weinmann et al., 2011], which has the ability to digitise shape, reflectance properties and, if necessary, spectral response of the colour of complex artefacts such as gems, jewellery, etc. for which standard techniques are not effective. In the area of visual and semantic browsing and inspection features, studies in how to overcome current 3D technological limitations (i.e. how to manage huge 3D models; how to improve visual presentation accuracy) and how to improve the ergonomics of complex tools (i.e. easy integration of 3D and other media, easy authoring, cooperative management, effective GUI, etc.) have been conducted, resulting in some notable achievements.

Some of the acquisition campaigns I carried out during 3D-COFORM are part of the case studies presented in the next chapter.

Chapter 4

Case Studies of 3D Acquisition of Cultural Heritage Artefacts

In this chapter I present a collection of three significant case studies I have been working on during my professional experience. The scope of this chapter is to show the difficulty of applying theory to real world in a complex and heterogeneous field such as cultural heritage. These examples cover almost all the digitisation technologies mentioned in chapter 3.2, as well as give a hint of the difference in materials, sizes, and shapes. Each case study is organised to present information about the artefact being digitised, the purpose of the campaign or of the specific acquisition, the details about the acquisition work-flow and the various processing phases, and a final assessment on the model exploitation and dissemination.

Imaging and 3D data acquisitions in the field of cultural heritage are not always an easy task. The heterogeneity of the collections is so big that there is not a fixed, well described approach, but people must take into account a series of circumstances and adapt each method depending on the object studied.

The digitisation used as case studies are the following:

- The Cylinder Seal of Ibni-Sharrum (Chapter 4.1);
- The Coronelli's Globes (Chapter 4.2);
- The Kazafari Boat (Chapter 4.3).

Other case studies, including one in acquisition of landscape and one in morphometric geometry analysis are illustrated in Appendix C.

Pitzalis, D., Cignoni, P., Menu, M., Aitken, G., 2008. *3D Enhanced Model from Multiple Data Sources for the Analysis of the Cylinder Seal of Ibni-Sharrum*. In: VAST 2008: The 9th International Symposium on Virtual Reality, Archaeology, and Cultural Heritage. Eurographics. Portugal.

4.1 The Cylinder Seal of Ibni-Sharrum

The cylinder seal of the scribe Ibni-Sharrum is one of the finest examples of carving in miniature [Amiet, 1976]. It was produced during the Agadé period, under the reign of Sharkali-Sharri and it can be dated around 2217-2193 BC. It is both ancient and beautiful; the two naked heroes are symmetrical and half-kneeling and they hold vases from which water is gushing and the two buffaloes drink from this water.



Figure 4.1: Cylinder Seal of Ibni-Sharrum and its development on clay, inv. n. AO22303, Oriental Arts dept., Louvre Museum

As we can see in Figure 4.1 the object surface is finely engraved, with delicate and accurate drawings organised in a symmetrical and elegant composition that make this seal a real masterpiece of glyptic art and a specimen of this style. It measures 3.9cm in height and has a diameter of 2.6cm . Small cylindrical seals such as this were quite common in ancient Near Eastern civilisations, but they are often eclipsed by more monumental works. A vertical perforation is present along the highest axes to help to “roll” the cylinder over the clay.

This masterpiece is conserved at the Louvre Museum, inv. AO22303. The central inscription says: “Shar-kali-sharri, king of Akkad, Ibni-Sharrum, the scribe, (is) his servant.” Seals of such high quality were prerogative of the royal family or high officials and probably come from a workshop that produced objects for the elite.

The object was brought to the C2RMF for analysis and an assessment of its conditions with the intent of creating a 3D surrogate for use in a contemporary exhibition of the artist Michel Paysant, called OnLAB [Paysant, 2010]. In this exhibition the artist wants to reinvent original works on a different scale, proposing cities planned in nano-structures and the “imprinting” of the cylinder seal, one of the smallest pieces of the Louvre museum, in a 4 meter long replica.

At the laboratory, the elementary chemical composition of the stone has been de-

terminated using the PIXE technology (Particle Induced X-Ray Emission) and the mineralogical composition has been identified using XRD (X-Ray Diffraction). The use of the small particles accelerator AGLAE (Accélérateur Grand Louvre d'Analyse élémentaire), combined with other technologies, gives us enough information to classify the stone as a black, shiny, *diorite*. Furthermore, from the physical analysis arose the presence of some *pyroxene* inclusion that would be useful to better locate the provenance of the artwork, or at least, of the stone used.

To document this incredible micro monument in three-dimensions we had to adopt an experimental protocol to support the multi-modal data fusion of different techniques and integrated the results in one complete, complex, rich model. This acquisition had very high experimental value as it was the first time at the C2RMF we tried to couple all the 3D data available. The final, enhanced 3D model contains information originating from X-Ray Computed Tomography, μ -topography, photogrammetry, and high resolution images. The data's spatial resolution varies from macro (photogrammetry and CT, precision in order of millimetres) to micro scale (μ -topography, precision up to 1μ).

This interdisciplinary experiment represented a new way to document objects and works of art in a cultural heritage environment such as the C2RMF and the Louvre Museum.

4.1.1 3D Acquisition Work-flow

The acquisition of the cylinder was very difficult because it is very dark with varying green/brown reflections and its surface is predominantly shiny. This means that the lasers cannot be used because the black colour absorbs almost all of the colour spectral information from the laser light and the reflectance produces a certain quantity of noise data. A valid alternative is to acquire the object via photogrammetry but we already know that the resolution would not be enough to do a satisfactory 3D model at such a scale as the one requested by the artist.

This is the main reason why I chose to use a multi-modal approach.

Computed Tomography As previously shown in Chapter 3.2.6.1, Computed tomography gives us the possibility to measure exactly structural details like, in our case, the variation of the diameter of the perforation in the centre of the object (Figure 4.2). The use of X-Ray CT for objects is a big step forward in the interpretation of data compared to digital X-Ray systems.

Disadvantages of the use of Computed Tomography technique include the fact that

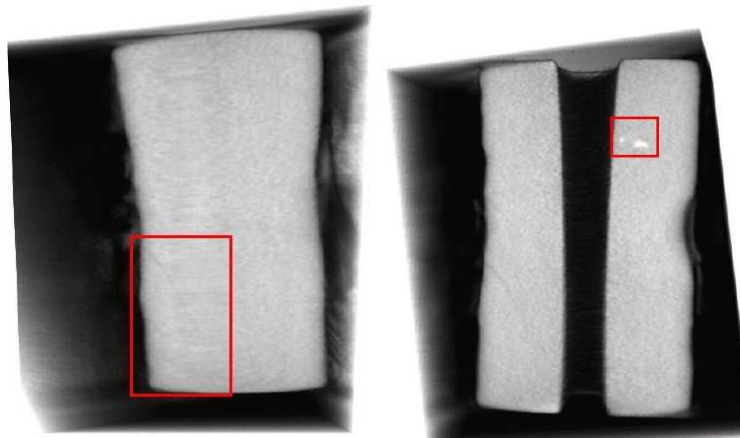


Figure 4.2: X-Ray Computed Tomography: (left) in evidence the crack inside the stone; (right) the small inclusion, with a higher density.

it is difficult to use and the equipment to achieve this is very expensive. In fact, to produce good tomography 3D models, several hundred digital radiographies are necessary of the object from different angles and each of these acquisition needs to be exactly calibrated.

The obtained model is unfortunately not exempt from noise (Figure 4.3) and the final shape is slightly deformed depending on the position of the detector. In order to have an exploitable result and to avoid having too much meaningless data, the system and the acquisition conditions must be chosen carefully.

Micro Topography This technique, also called optical roughness-meter, is based on a quasi-confocal, z-axis extended field. This axis field extension is obtained by stretching the axial chromatism generally encountered in a confocal dioptric setup when working with a polychromatic point source. That means that we know the z axis of the point via the wavelength of the univocal colour back-scattered [Ezrati, 2008]. The technology used at C2RMF is a special implementation of the method presented more generally in Chapter 3.2.6.2.

Coupling this complex optical technique with a translation table (a CMM) in x, y we are able to acquire surface portion and thus obtain a micro-topographic image of the surface to analyse (Figure 4.4). Indeed this technique is very time consuming, but it gives very good results and the geometry of the “scanned” surface is highly dense and precise, up to 1 micron. On the other hand with this approach, we do not collect colour information, there are lot of “blank”, un-acquired areas, and the data we have is just local information (Figure 4.5).

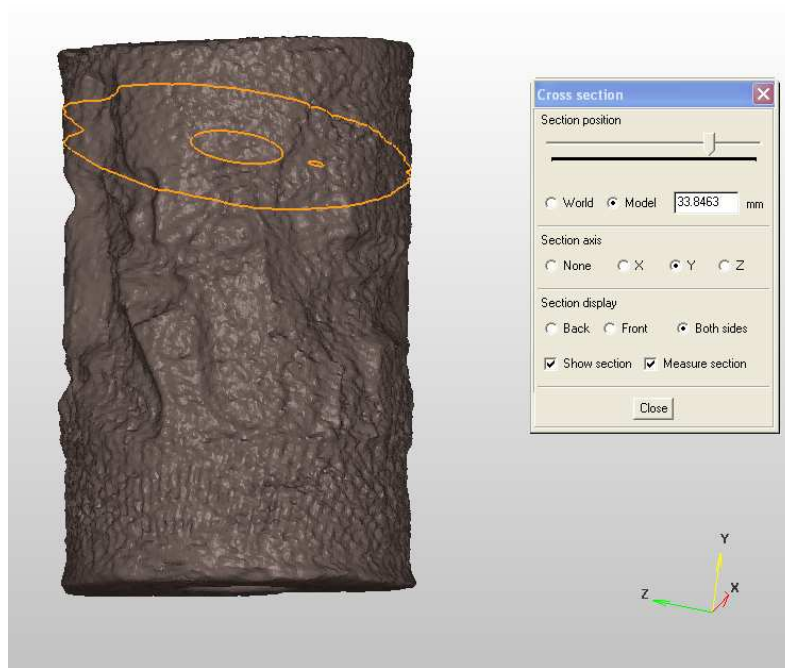


Figure 4.3: Rendered X-Ray Computed Tomography with cross-section plane contour.

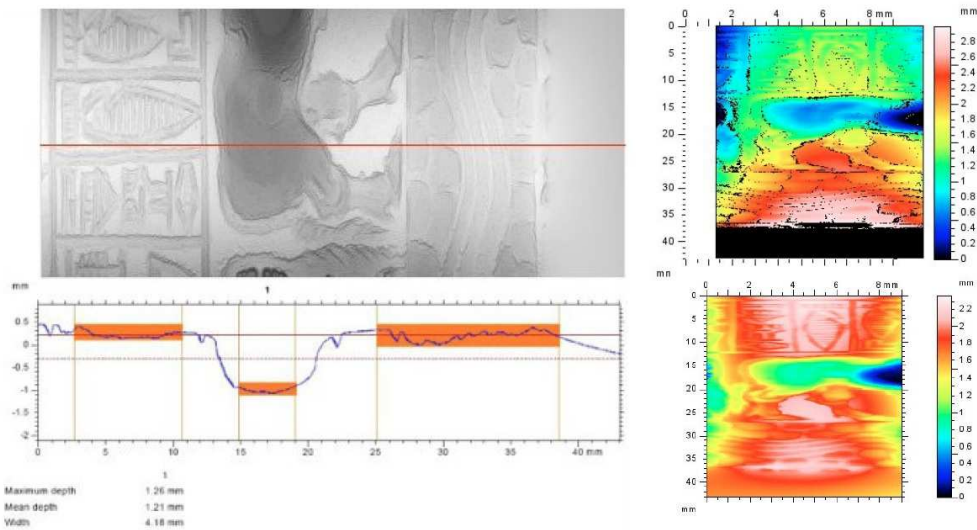


Figure 4.4: μ -topography: (left) line of measure and (right) its values.

Photogrammetry Since 2004 at the C2RMF the method presented in [Hernández Esteban and Schmitt, 2003] is used. Starting from a calibrated sequence of colour images, the algorithm is able to reconstruct both 3D geometry and its tex-

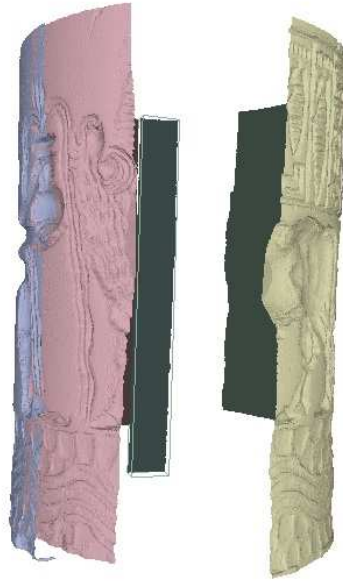


Figure 4.5: Partial reconstruction using few μ -topography scans. The information is strictly local and there is not enough overlapping for automatic matching.

ture. The method is based on a deformable model, which defines the framework where texture and silhouette information will be fused. This is achieved by defining two forces: one driven by the texture and the second driven by the silhouettes. The complete procedure is described in Chapter 3.2.3.

The quality of the resulting texture is very high, comparable to the original photos, the equipment is not expensive, and the topographic information is global to the object. A disadvantage is the very long time and manual work needed to extract precise silhouettes and the fact that the final model has a medium/low topographic quality (Figure 4.6 and Figure 4.7).

4.1.2 3D Processing

Apart from the software used to export the computed tomography model that saved the final result in STL format, both photogrammetry and μ -topography required the development of input plugins for MeshLab (thanks to the Meshlab team, always very responsive). The first method, the photogrammetry algorithm, saved its models in TRI, a binary format created to store information about the photogram-



Figure 4.6: Photogrammetry: the top and the bottom of the model are not visible.

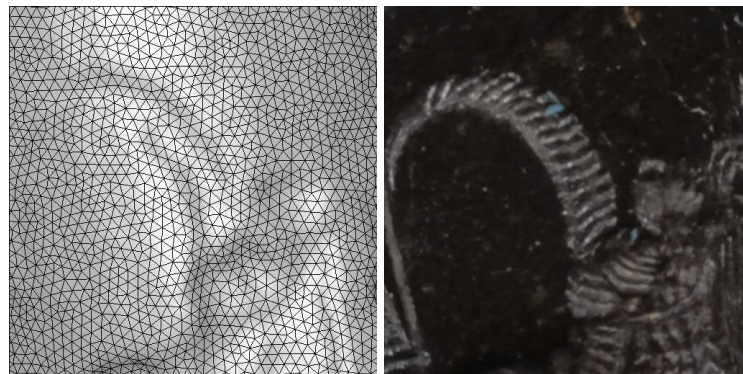


Figure 4.7: Photogrammetry: details of the resulting model.

metry parameters and variables in a compressed way. The second method was to export data in ASCII, a text format where the data is organised for a fixed step in x , y and printed out the z values. Once the data normalized, I moved on with the fusion of the different sources.

Multiple Data Fusion The original μ -topography data contained a lot of automatically filled portions corresponding to the area that the device was not able to acquire in Figure 4.8. These portions have been filled by a smooth interpolation approach that, while useful in most cases, is not the best option when applying multiple data sources technique because the calculations happens in the local geometry, without taking into account the whole surface information

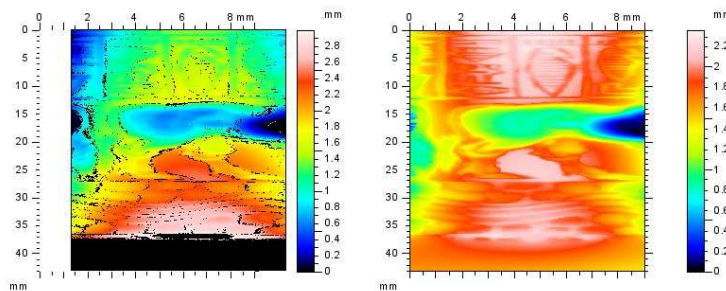


Figure 4.8: The result of the automatic area filler. On the left the raw acquisition data of a portion of the surface, on the right side, the interpolated result.

I then removed the reconstructed areas and substituted them with the corresponding 3D data from the photogrammetric reconstruction. The photogrammetric 3D data, even if at a resolution and precision much lower than the data acquired from the μ -topography, is more consistent and a much better guess than the interpolation algorithm used by the μ -topographer software.

The merging of the range maps obtained with the μ -topographer was done using the Poisson surface reconstruction tool [Kazhdan et al., 2006], which is available as a MeshLab plugin.

To align the Computed Tomography (Figure 4.9) data with the other two methods we relied on another MeshLab tool, the Alignment plugin. I aligned the exterior of the Computed Tomography reconstruction of the *Cylinder Seal* with the model resulting from the integration of μ -topographic and photogrammetric data. Once aligned I discarded the portion of the Computed Tomography geometry leaving only the internal hole surface and the inner *pyrite* inclusion. I applied again the Poisson surface reconstruction algorithm and merged all the 3D sources. With the help of the Meshlab team we weighted the input data with their accuracy so that more accurate data has been preferred when available.

By this mean we automatically selected Computed Tomography and photogrammetric 3D geometries only for these portions of the model not covered by the μ -topography data. In particular we used the Computed Tomography data only for the inner hole and for the inclusion because of the high level of noise on the surface.

High Resolution Image Registration For the alignment of the photographic data onto the surface geometry we used the approach proposed in [Franken et al., 2005] that allows to find, in a semi-automated way, the intrinsic and extrinsic calibration parameters for a given set of photos over an existing scanned 3D model.



Figure 4.9: Model obtained from Computed Tomography. We can barely recognize the two kneeling figure because of the high noise produced by this technique.

Once the photos have been registered onto the seal model we used the technique described in [Callieri et al., 2008] to merge in a seamless and coherent way the colour information contained in the photographic data. The obtained colour was stored following a colour per-vertex approach that avoids the need of a direct texture parametrisation of the surface of the seal. The achieved result is visible in Figure 4.10.

4.1.3 Results, Exploitations and Dissemination

Once the 3D acquisition finished and a complete 3D model is obtained from the fusion the partial point cloud resulting from the different techniques, we can exploit it in many different ways, without touch the artwork. This original exploitation of the images in a 3D space permits us to do an innovative reinterpretation of the work of art showing the traces of its creation and give us the basis for a new documentary tool based on 3D imaging. Once the enhanced model is finalised in Figure 4.11, it can be used in many different ways. For example, in the physic chemical research field, to focus the research on the precise point where the inclusion or the crack is; or to better document the object itself using more detailed images, models and

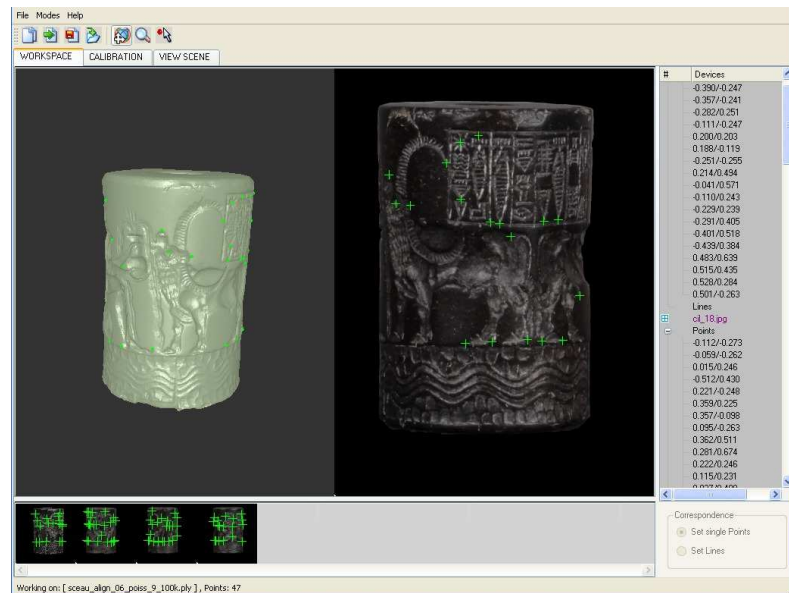


Figure 4.10: A snapshot of the TexAlign tool for registering photographic data over a 3D mesh. Some of the original photogrammetric images are used as a source for recovering the surface colour. The small green cross-hairs show correspondence points between images and the 3D surface.

information; or prototyping it for educational purposes as illustrated in Figure 4.12; or, as a contemporary artist proposed, to re-sample it in a bigger scale to better explain to the public how difficult it is to work in this medium and to attract the attention of the public to an art older than 4000 years.

An interesting achievement of this modelling has been the development, by the Meshlab team, of a simple, but efficient, module to unwrap the model along an axe as in Figure 4.13 right, that corresponds to get the inverse shape rolling the seal over a soft substance like clay or wax as it was done originally [Meshlab, 2009a]. This will help to prevent these cylinders from being printed again over time avoiding the possibility of accidents or deformation or simple pollution like in Figure 4.13 left.

The Cylinder Seal Stereoscopic Movie

During my time at the Cyprus Institute, I had the possibility to work with the NCSA Illinois Visualization group in the creation of 3D side-by-side movies. I set up a JVC 46-INCH 3D display monitor equipped with circular polarization that offered a 1920x1080 LCD panel with a glass filter and a horizontal interleaving polarization method that complements the side-by-side format and converts to line interlace



Figure 4.11: The final model (left) sliced by a x, y plane showing the inner hole and the inclusion detail. (right) X-Ray data rendering simulated using MeshLab. In red we can see the inclusion of different material discovered with the use of the particle accelerator.

(line-by-line).

Using Blender I was able to render the 3D model in side-by-side stereo as in Figure 4.14, so that the user, wearing inexpensive polarized glasses as in the cinema, was able to see the movie in 3D. The result has been a video of almost 2 minutes showing the unwrapping of the seal. The video has been played few thousand times on youtube and it has been used as “educational” multimedia during a thematic exhibition in Australia.

I created a python script for blender that implements an “off-axis” stereo camera. When creating 3D stereo movies there are 3 possible render methods (Figure 4.15): the “converge” or “Toe-in” method, that tend to generate a vertical parallax error, resulting in an annoying feeling of “too much 3D” for the user; the “parallel” cameras which always produce negative parallax, so that the objects always seems out of the screen (this error can be fixed in rendering mode adjusting manually the zero parallax); and the “off-axis” method similar to the previous one, but optimized for side-by-side rendering.

4.1.4 Conclusion

Having the possibility to study such great objects in such an interdisciplinary context gave us new ideas under the stimuli of art historians, conservation scientists, scientific researchers and photographers. The final 3D surrogate we provided is a good starting point from where professionals can work on the interpretation of



Figure 4.12: Two rapid prototyping reproductions, (left) done with the standard rapid prototyping technique; (right) with an automatic colour enhancement algorithm that put in evidence the small features of the seal using the technique proposed in [Cignoni et al., 2008a]; this recently proposed approach allows for the obtention of a better readability of the shape of the objects reconstructed using standard rapid prototyping techniques.



Figure 4.13: (left) Some plasticine (in blue) probably from a previous impression, (right) an unwrap simulation.

results from a new perspective.

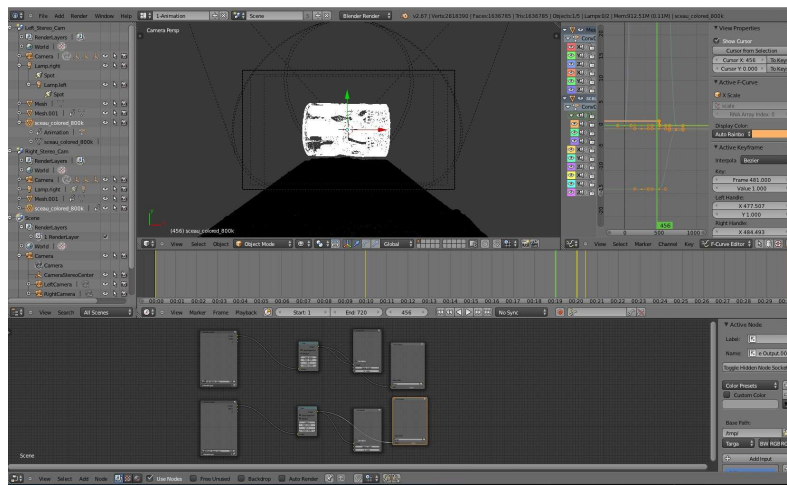


Figure 4.14: Blender interface showing the two cameras in off-axis mode.

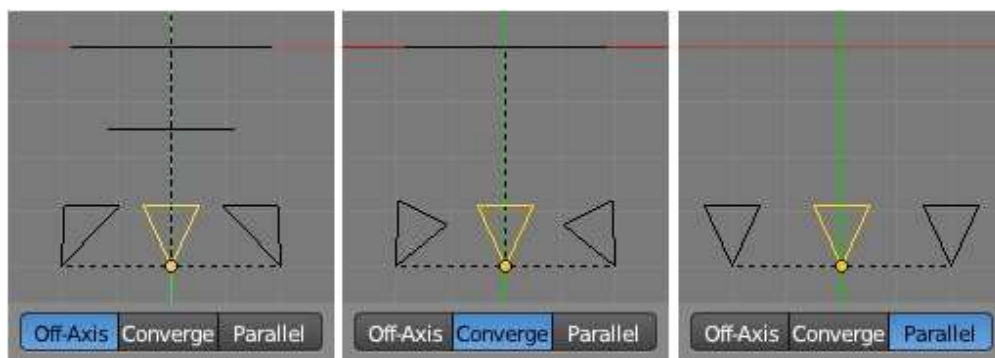


Figure 4.15: Camera methods that can be simulated using Blender.

4.2 The Coronelli's Globe

The famous globes made by Vincenzo Maria Coronelli, completed in Paris in 1683 to be given to Louis XIV by Cardinal d'Estrees, were intended to present the scientific knowledge of that time and, simultaneously, the glory of the King. It is said that the Cardinal, while ambassador to Rome, saw the Duke of Parma's globes and invited the artist to Paris in 1681 to construct a pair of globes for the King.

These globes, measuring 3.84 meters in diameter and weighing approximately 2 tons, are displayed, today, in the "Bibliothèque Nationale François Mitterrand" in Paris, after being exposed first at Marly, then in the Louvre and in the Royal Library. The globes depicted the latest information of French explorations in North America.

4.2.1 3D Acquisition Work-flow

Before their final destination, in 2006, an analytical work and an assessment of their conservation state was conducted at the C2RMF. During the analysis, a comprehensive photographic acquisition project had been carried out. This work, interesting “*di per se*” allows us to have a complete coverage of the globes surface. With the recent progress in camera self-calibration and Structure-From-Motion (SFM) systems for unordered image collections algorithms I thought that it would have been possible to build a 3D model from the acquired dataset.

Structure-From-Motion Starting from these photos, with the help of Carlos Hernandez, and from the assumption that the globes can be reduced to a sphere simple geometry, we built a 3D model for each of the two magnificent artworks. Image-based modelling, as already described in this chapter, is the process of creating three-dimensional models from a set of input images. In this case we are using algorithms that apply to the Structure-From-Motion, to recover the camera parameters, the pose in space estimated, and a sparse 3D scene geometry that will then be used to build the final model.

4.2.2 3D Processing

First, I computed the Scale Invariant Feature Point features (SIFT) using the [Lowe, 2004] algorithm. The more modern siftGPU software could not be used because I did not have compatible hardware. SIFT points are distinctive invariant features in images that will be then used to perform a reliable matching between the different planes (or photographs). A point of interest, or feature, to be selected must be proven to be invariant to image scale and rotation and so are proven to provide robust matching across different affine distortion, change of viewpoint in space, noise, or different illuminant settings. SIFT points are also often used in databases for image recognition. A high resolution image, such as the one used in this experiment, can have several thousands of SIFT points.

Once the Sift points extracted, for each pair of photographs, we matched the key point descriptors between the pair (if existant), using the local properties of the SIFT features. Then, we applied a RANSAC algorithm to robustly estimate a fundamental matrix for each pair and we removed the pairs too close to the edges of the matrix.

Bundler [Snavely et al., 2006] is a Structure from Motion (SFM) algorithm that I used to organize the images in clusters according to their keypoints and start the

reconstruction of the 3D sparse model. First it recovers the camera parameters and the 3D location for each of the clusters and makes sure that the camera parameters are consistent within each cluster (Figure 4.16).

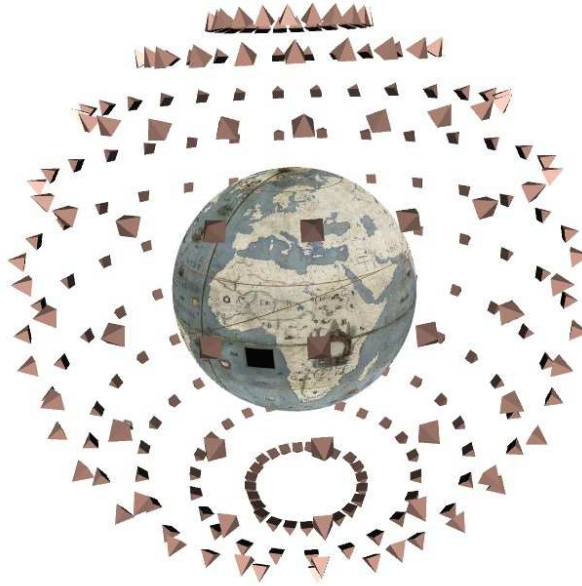


Figure 4.16: Position of cameras computed by Bundler. The dataset consist of 288 HD photos for a total of 16Gb per each Globe. The dataset is also available in infrared and ultraviolet

Once the 3D sparse model is produced I fit a sphere into the sparse point cloud to obtain a simplified mesh surface where I could retro-project to high resolution images. Fitting a sphere into a cloud of data points is known as finding the “Inscribed sphere” or “insphere”. An insphere of a convex polyhedron (in our case, our sparse cloud point) is a sphere that is contained within the polyhedron and is tangent to each of the polyhedron’s faces. It is the largest sphere that is contained wholly within the polyhedron and it enable us to fuse this simplified sphere with the obtained cloud point “patches” result of the SFM algorithm.

Given m random points of the sparse reconstruction $\{(x_i, y_i, z_i)\}_{i=1}^m$, $m \geq 4$ the problem is then to fit them with a sphere $(x - a)^2 + (y - b)^2 + (z - c)^2 = r^2$ where (a, b, c) is the sphere center and r is the sphere radius. An assumption is, obviously, that

the points are not coplanar. The energy function to be minimized is then:

$$E(a, b, c, r) = \sum_{i=1}^m (L_i - r)^2 \quad (4.1)$$

where $L_i = \sqrt{(x_i - a)^2 + (y_i - b)^2 + (z_i - c)^2}$. The implementation, in Octave, is available online.

Once the sphere fits into the structure, I ran a Poisson reconstruction to obtain a uniform, simplified mesh. A drawback of this approach is that fitting the sphere into the 3D structure simplifies the mesh, but increases the percentage of retro-projection error, generating artefacts in the texture map called “ghost artefacts” because they are visible only under certain viewpoints.

I then re-ran Bundler again to minimize the retro-projection error against the new geometry and I computed the multi resolution texture map. Once the model finished we had a closer look at the camera settings and we realized that the camera sensor had a systematic error at the level of 0.5 pixels, generating more “ghost” effects. The low resolution models are visible in Figure 4.17.

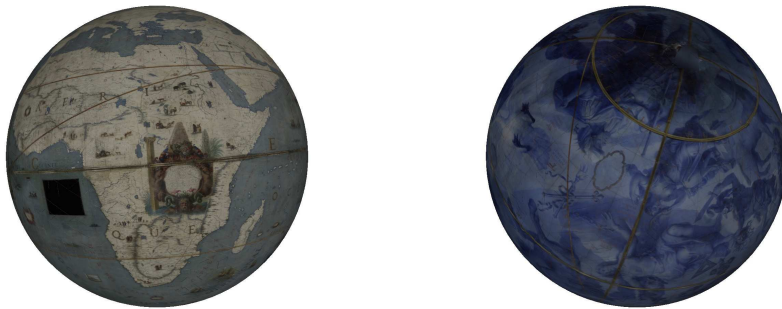


Figure 4.17: The two 3D models of the reconstructed globes: left the Earth, right the Sky.

4.2.3 Conclusion

The first version of the Globes’ reconstruction, based on Hernandez algorithms, is available online at [C2RMF, 2013].

The growth of computational power, especially the exploitation of GPU for parallel processing, and the improvement in the algorithms of Structure from Motion and photogrammetry in general, are the reasons to think that 3D can be made available for mass 3D models production. Projects like “Building Rome in a day” and

“Dubrovnick” [Agarwal et al., 2009], but also Google Street View, demonstrate that it is already possible.

Future development concerning these magnificent artworks are the reconstruction of the 3D surface using the infrared and ultraviolet datasets, an incredibly useful *exploration tool* for curators and art historians.

4.3 The Kazafani Boat

The Kazafani model boat, a unique, delicate, cyprriot artefact, was found in a tomb in Cyprus in 1963. It has been crafted from pottery approximatively during the 12th century BC, and it is now on display at the Cyprus Archaeological Museum in Nicosia. In 2010 the boat was requested to be lent to the Smithsonian museum in Washington for the temporary exhibition: “Cyprus: crossroad of civilizations”, but it was too fragile to be moved.



Figure 4.18: The Kazafani boat in the middle and the two replicas, left and right. It can be seen that there is no major difference between the original and the copies, if not for the colour patch, a limitation due to the printing technique used. As the scan has been done with the sensors in vertical position, the vertical details are hidden.

To give the possibility to this masterpiece to be displayed, at the STARC, with the Museum of Antiquity of Nicosia, we tried to propose an accurate 3D printed replica, visible in Figure 4.18, that is close enough to the real model to be made available in the exhibition for a wider public.

4.3.1 3D Acquisition Work-flow

The delicate boat was carefully scanned using the NextEngine ®laser scanner device, and then the model was created with Meshlab software. The object is

40x15x15cm in size, and therefore I asked for acquisitions with the wide objective to have an overview of the global geometry and then a set of 24 scans in macro mode to make sure that all the surface was captured in an accurate way (Figure 4.19).



Figure 4.19: Acquisition of the Kazafani boat using NextEngine®LaserScanner.

4.3.2 3D Processing

The reconstruction took more than 48 hours of work, using Meshlab, to make sure that the measures on the model were the same as the physical object, a specific request of the curators. In this case, unfortunately, the ICP was not precise enough to stick all the pieces together as the global geometry of the object was not accurate enough.

Once the digital three-dimensional replica was as accurate as possible in every detail (Figure 4.20), I saved the work in STL format, also because being terracotta, to object's texture was not important. Using rapid prototyping an external laboratory was able to produce two replicas of the artefact with exactly the same geometry. Size, shape, colours, surface markings and even evidence of past damage and previous restoration are visible, although some in an approximative way, in the 3D models.



Figure 4.20: Iso view of the final model, without texture, of the Kazafani boat. In this view we can see the internal side of the model.

4.3.3 Results, Exploitation and Conclusion

One of the limitations of the reconstruction was the absence of the vertical cracks in the final model. This is due to the fact that during the acquisition, the lasers were parallel to the crack so that the scanner did not record the change in shape. A crossed scan would have provided more accurate datasets.

The 3D printed replica gave art historians the possibility to physically analyse a copy of the boat in greater detail than would have been possible via simple images, without risking any damage to the original. The experiment was also intended to show how simple, fast, and cost effective this method is, producing obvious benefits for those in the field of curation, education, and marketing.

The final result has been exhibited at the Smithsonian Museum as part of the travelling exhibition: “Cyprus: crossroad of civilizations” (see Figure 1.1).

4.4 Conclusion

With these case studies, I demonstrated how different technologies can be used together to obtain three-dimensional models of cultural heritage artefacts. A collection of case studies like this can be of real help for others that want to start their own digitisation campaign, and is more effective than a simple comparative table.

In the first case study, about the “Cylinder Seal of Ibni-Sharrum” I presented a complex case of multi source data fusion. The “Coronelli’s globes” are a typical situation in the work environment, we start from a dataset acquired for other reasons and we try to adapt to a 3D model. Finally the “Kazafani boat” show how the 3D physical copy of an ancient artefact can become part of an exhibition, and doing so, satisfy the curiosity of the public and preserving the integrity of the delicate object. Other case studies are illustrated in Appendix C.

Once all the models are reconstructed, a new problems arise: how this huge quantity of data should be organized, when it is safe to delete a partial cloud, when the final model can be considered as an accurate copy of the original object. Some of these questions are part of the investigation described in the next chapter.

Chapter 5

The Semantic Web and Cultural Heritage

In the field of cultural heritage, the use of semantic web technologies have the potential to impact on several levels. We have seen in the previous chapter how three dimensional day by day operations and research projects in cultural heritage institutions generate a huge quantity of high quality digital data in many different forms. Interoperability between multimedia collections should be implemented based on these technologies, allowing users to exploit the knowledge spread across different, heterogeneous, collections.

In this chapter we discuss briefly the history of the semantic web and the technologies involved in the exposing of digital content to the web. After that I describe the building blocks of the semantic web and how they interact in chapter 5.1 to finally propose some use in the field of cultural heritage in chapter 5.2.

Digital collections must follow standards and good practices not only to grant usability to the final user, but also for the conservation of the data themselves. Problematics such as long term digital preservation and data provenance are important challenges to face if data must be conserved integrally. I demonstrate, through real case studies, the problematics I have encountered mapping a relational database into a semantic structure 5.3.1 and how a metadata schema can be used for data provenance documentation 5.3.2.

Pitzalis, D., Niccolucci, F. and Cord, M. 2011, *Using LIDO to handle 3D cultural heritage documentation data provenance*, in Content-Based Multimedia Indexing (CBMI), Madrid, 2011, pp. 37–42.

Pitzalis, D., Niccolucci, F., Theodoridou, M. and Doerr, M., 2010, *LIDO and CR-Mdig from a 3D cultural heritage documentation perspective*. in Proceedings of the 11th International Conference on Virtual Reality, Archaeology and Cultural Heritage, VAST'10. Eurographics Association, Paris, pp. 87–95.

The term “Semantics” defined as “the study of meaning”, often lead to the ambiguity in the definition of “Semantic Web” that means many things to many communities. The term “Semantic Web”, as intended by its creator, should be seen more as a vision, a way of thinking, rather than a real technology (i.e. the Internet), or the use of a protocol or development technique (i.e. HTTP, or ajax, or agile), or an established practice (i.e. the Web 2.0). The notion was formalized for the first time in [Shadbolt et al., 2006] as a set of ideas of what the web should be, and not a set of guidelines and implementations on how to do it. Due to the above, a single definition of “semantic web” does not exist as it varies depending on the communities of practice we are talking with. According to Wikipedia and W3C: “The Semantic Web provides a common framework that allows data to be shared and reused across application, enterprise, and community boundaries” [Wikipedia, 2013b].

In section 5.1 I expose a rapid overview over the Semantic Web history and evolution introducing the concept of the fundamental blocks of this technology: URI, RDF and ontologies, and their interaction role in the “web of data”.

I then describe, in 5.2, the specific problematics linked to the cultural heritage field and how the use of semantic web technologies could make an impact on several levels. Day by day operations and research projects in cultural heritage institutions generate a huge quantity of high quality digital data in many different forms. In the previous chapter we discussed the creation of 3D assets, but we have to take into account other media too. Interoperability between multimedia collections can be implemented based on these technologies, allowing users to search and retrieve related material across different, heterogeneous collections.

During my participation in 3D-COFORM, a lot of effort has been undertaken to underpin the development of tools capable of embodying metadata and integrated descriptions into the 3D model itself [Schröttner et al., 2012]. The approach investigated by the project has been to design the processing tools (following the successful experience of EPOCH’s MeshLab tool) together with the design of the libraries aimed to store the data representation schemes and algorithms, in order to follow a common path towards a complete integration. I investigate these aspects in chapter 5.2.2.

Furthermore, richer standardized semantics can improve the exchange of information between conservators, curators and historians by enhancing the retrieval and browsing facilities. A new way of finding relationships between artefacts by exploring collections can help to have a greater overview over history and their connection. Using semantic markup to search within metadata mapping between different formats enables richer presentation, as Wikipedia currently does. For example, it becomes possible to search for an artist as we would search for a person rather than simply search for a name so that the richness of the biographical data

about that artist can be revealed. In more detail, we can search for all the artists doing “Russian avant-garde” in the first half of the 20th century and living in France and obtain a list, instead of searching for a name that we already know. Finally, making the data available to others through modern semantic web services could allow the data to be exploited by third parties offering new ways of interpreting information.

In order to investigate the problematics linked to the use of those standards, I propose two case studies in chapter 5.3 describing the implementation of the Semantic Web technologies to the C2RMF dataset. In the first, 5.3.1, I present a methodology to expose the relational database using a specific work-flow; in the second one, 5.3.2, I present a way, with examples, to map the content of the C2RMF’s relational database into a modern metadata schema and validate this method for data provenance preservation.

5.1 The History of the Semantic Web

The paradigm shift in the daily use of web technologies started only recently with the advent of the semantic web. However the utopic concept of a “Web of Data”, in contrast to the idea of a “Web of Documents” has been around since a long time.

The concept of a Web of Data, in contrast to a Web of Documents, has been around as long as the Web itself. In [Berners-Lee, 1989], Sir Berners-Lee, in writing the first proposal for what will become, later, the www, included a section about the “Data Analysis” in which the first visionary representation of semantically linked data is articulated. In another document [Berners-Lee, 1998], he describes the Semantic Web as a “web of data, in some ways like a global database” implemented via “languages for expressing information in a machine processable form”.

The fact that machines can speak a common language, and therefore speak to each other, does not mean that the computer will propose new solutions for us. The human involvement is needed in the semantic schema at the beginning (entering the information) and at the end (interpreting the information) of the knowledge representation chain. Between those two points, different technology layers compose the Semantic Web “Layer Cake”. The “Layer Cake”, or the Semantic Web “Stack” first presented by Sir Berners-Lee in 2000 (Figure 5.1), evolved over time and the last version available is the one presented in 2007 (Figure 5.2).

To understand how the Semantic Web works, it is important to understand at least three of these blocks: URI, RDF and Ontologies (OWL):

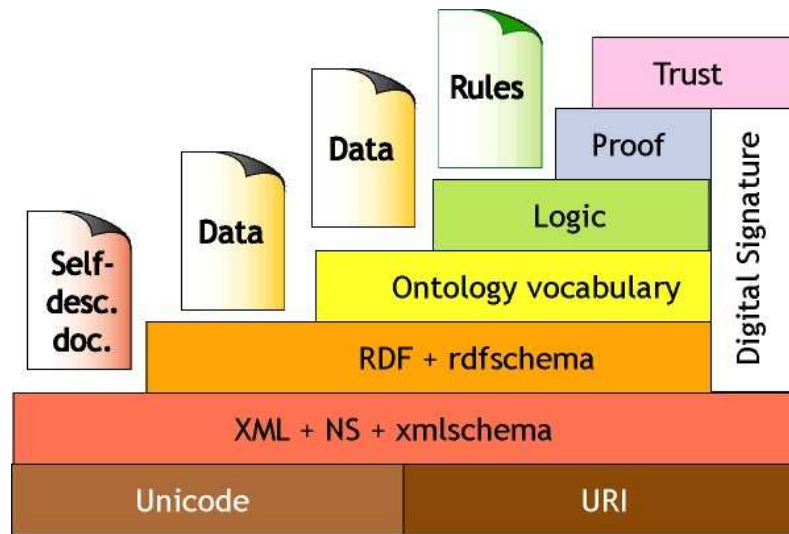


Figure 5.1: Semantic Web Stack in 2000. All definition are detailed in [Wikipedia, 2013c] ©Tim Berners-Lee

URI Uniform Resource Identifier is an alphanumeric string used to identify, in a unique way, any atomic concept, be it a digital document, a web page, or anything else that can be located on the web. A URI can be used as a resource locator (URL), as a name identifier (URN), or as both. The difference between the two formats is that the Uniform Resource Name (URN) is like a person’s name, while the Uniform Resource Locator (URL) is like that person’s street address. For example an ISBN number, a URN, gives us the unique identifier of a book, while a web address on *Amazon*, a URL, gives us the place where to find it. A Digital Object Identifier (DOI) works as both.

A URI is composed of two parts: the URI scheme name (such as http, https, doi) identifying the specifications to be applied for the interpretation for the scheme-specific part, and an alphanumeric string which syntax is governed by the scheme definition. It is common practice to use HTTP URI to dereference the terms over the Web.

RDF The Resource Description Framework is the “glue” of URI. The RDF framework is the way the knowledge resource is presented by means of “triples” formed by a Subject, a Predicate, and an Object. While the first two elements of the triplet must be URI, the third element can be either a URI or an alphanumeric string (i.e. a date, or a description). The most exciting added value of RDF is that putting together different RDFs coming from different databases, but using the same labels (URI), is easy and the result of the merge is a self completed graph.

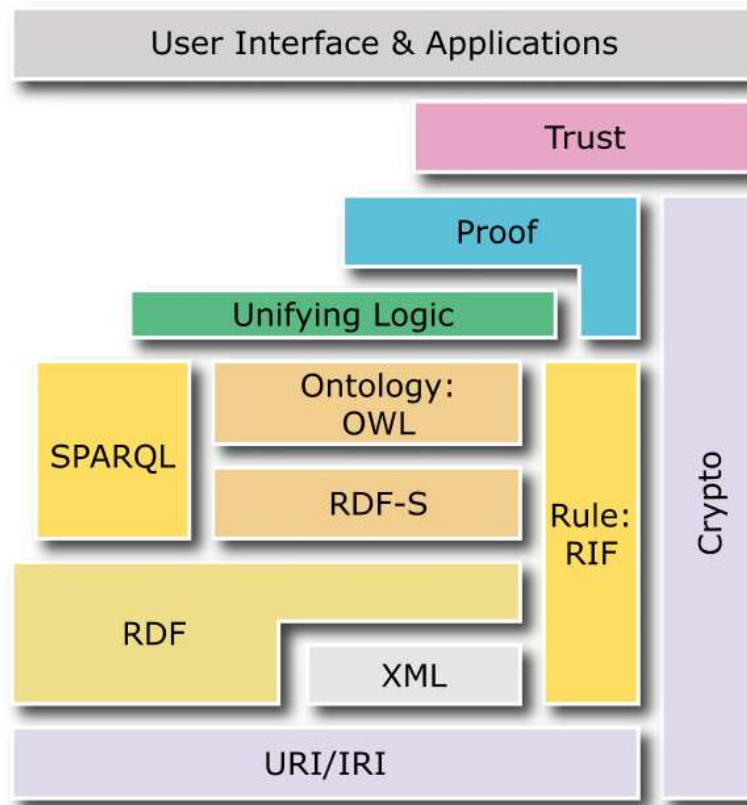


Figure 5.2: Semantic Web Stack in 2007. All definition are detailed in [Wikipedia, 2013c] ©Tim Berners-Lee

RDF is notation independent and can be represented in various format: diagrams (Figure 5.3), N-triple, Notation3 (N3) [Berners-Lee, 2005], RDF/XML [Beckett, 2004], Turtle [Beckett and Berners-Lee, 2011], RDFa [Adida et al., 2008]. In Appendix D I present examples of how the concept “Leonardo da Vinci is the author of Mona Lisa” can be expressed using the different notations.

Ontologies Ontologies in computer science are used to identify concepts within a defined domain. Such concepts are thus part of the knowledge representation. These systems for knowledge representation are the formalization of what it is possible to define using the RDF technologies in order to standardize according to a given model. Such models are available in the form of meta-ontologies and include the RDF Schema (RDFS) to define the context of the RDF structure, the Web Ontology Language (OWL) used to formalize ontologies and Simple Knowledge Organization System (SKOS) used for any kind of structured vocabulary.

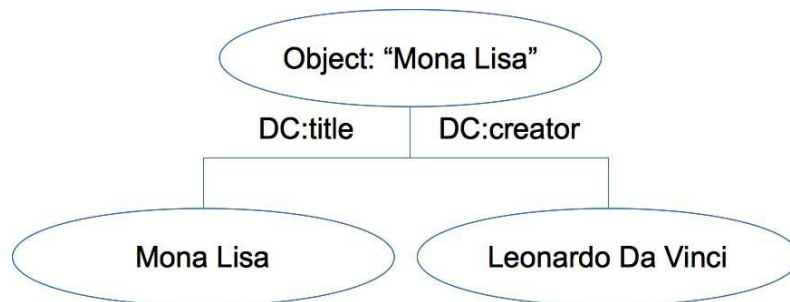


Figure 5.3: RDF representation of the “Mona Lisa” painting using Dublin Core metadata format.

These 3 building blocks, with SPARQL, a standardized query language for RDF, are the basis for the semantic web. The evolution of the specifications followed the exponential improvements of the computational power necessary to process the new amount of data. Semantic web, as the new concept of “enriched data” came along with a huge amount of data that makes the appreciation of the semantic web very low in the academic world, because of the added level of complexity in information management.

The real explosion in the use of Semantic Web technologies came with the involvement of the big firms. First Yahoo! then Google, Microsoft and Facebook, among others, started including semantic web tools and guidelines to achieve a true web of “linked data” that they could use and exploit to better reference the web, and know more about their users.

5.2 The Semantic Web in Cultural Heritage

Thanks to the effort of the European Commission pushing the research in the field of interoperability within “Memory Institution”, a large part of the European cultural heritage exists in digital collections. Initiatives such as the Europeana digital library are a good instrument to focus research and bring together researchers from different fields.

The huge quantity of information generated by these projects are more and more demanding in terms of infrastructure (both physical and logical), management, preservation, and delivery mechanisms. Nowadays, images are probably still the most common form of non-textual digital content stored in cultural repositories, but other media are becoming widely available in parallel with the improvement in the serving technologies; it is now easy to play a video, or add a music play-list

or a 3D model to a web page. In particular, three-dimensional content is expected to become more and more popular in cultural heritage repositories because of the availability of the tools to create and manipulate such digital representations.

5.2.1 Ontologies and Metadata Formats

The choice of the metadata schema to be adopted in a digital library depends on a number of different factors: the nature of data, their intended use, and the interests and research methodology of the relevant community. Simplicity pushes a preference for schemas as simple as possible, which may then be perceived as inappropriate when the scope of the repository extends to cover other domains or other research goals. This has been the case of metadata schemas based on Dublin Core [DCMI, 2006], suitable for managing web-sites but not capable to deliver all the richness of content required by tangible cultural heritage, for example museum content. On the other hand, overarching schemas such as CIDOC-CRM [Crofts et al., 2009] have been labelled, as you can see in Figure 5.4, too complex. The pacific, and fruitful, co-existence of digital objects pertaining to different culture domains is then assured by mapping the relevant metadata schemas to each other, the first step of interoperability.

So far, as already mentioned, metadata schemas used in digital libraries were considered by heritage professionals as not being rich enough to convey the information necessary for current heritage research and practice. Others were perceived as too complex for practical use. LIDO [ICOM, 2010] is simultaneously lightweight and rich enough.

Demonstrating the capability of managing provenance information and compliance to CIDOC-CRM through a mapping is therefore a significant step towards standardization. Moreover, a theoretical compliance and a formal mapping are not convincing enough. A practical example demonstrating how the mapping works is demonstrated in the case study 5.3.2.

The lack of good practices in knowledge management in cultural heritage institutes has caused an almost complete ignorance of the standardization procedures for digital assets. Before the European Commission effort in pushing the research in the semantic web for cultural heritage, almost every country, and often every big institution, created its own regulations for documenting cultural heritage.

Therefore, a real need and necessity for harmonization of standards and alignment of techniques was present and the easiest way to achieve it was to reduce the interoperable information to the simplest metadata format, applicable to every dataset: Dublin Core (DC). The obvious downside of this approach was the limitations im-

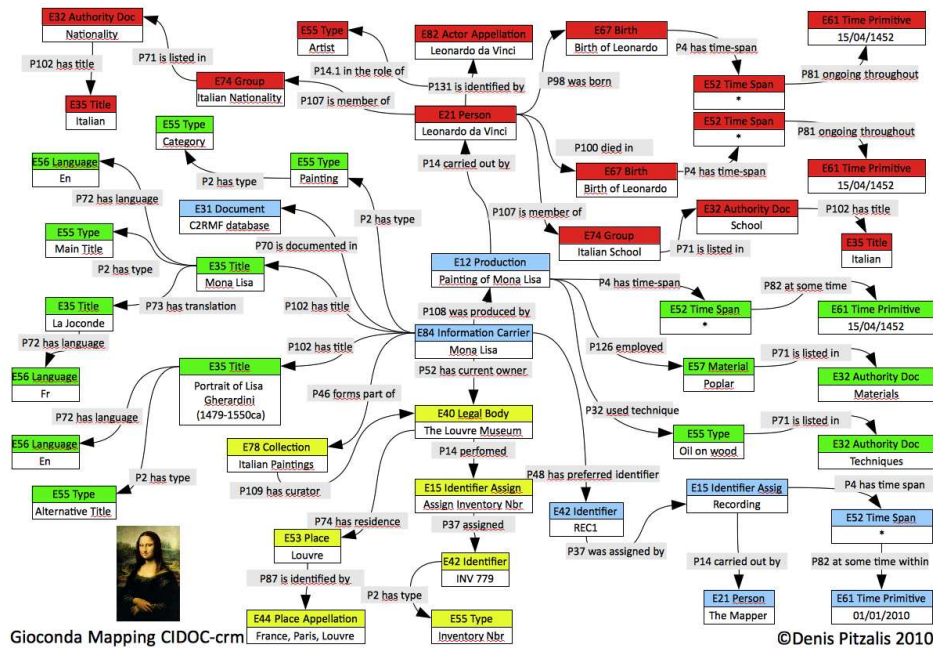


Figure 5.4: CIDOC-crm representation of the “Mona Lisa” painting. The different colours of the metadata labels means in blue: What, red: Who, green: How, Yellow: Where. The starting point is the “Information Carrier” representing the virtual object from where we then explicit our properties. The boxes are the Subjects / Objects, and the lines are the Predicates.

posed by the format, developed to support the indexing of web pages, when adopted for large and heterogeneous cultural heritage collections.

As shown in the case studies, it is clear that metadata is present at different levels in a digital collection. The use of metadata is no more limited to the description of the single object, covering information such as the creation date or the artist that made the object, but it become a way to document all the information associated to the digital representation of the object, for example the technique used for the creation of the digital object, the camera or the laser scanner, the algorithms used to improve the quality of the picture or to smooth the surface of the 3D model and the settings used for the device. All those information are at the base of the data provenance concept. Metadata is also used to describe the licence to be applied to the object, to the digital object and to the metadata themselves and to create the relationships between objects, artists, periods, material, and so on.

It is then clear that, in order to represent correctly the heterogeneity and the complexity of the cultural heritage collections we have to move behind the use of a

simple metadata schema, and start using ontologies and semantic web technologies. CIDOC-CRM ontology is an ISO standard (ISO 21127:2006) that establishes the guidelines for the exchange of information between cultural heritage institutions and it is supported by the ICOM CIDOC working group and adopted as a standard model by many European Projects, 3D-COFORM, SCULPTEUR and EPOCH-noe among others. CIDOC-CRM is well appreciated for its scalability and its extendibility, as demonstrated by the CRM_{dig} extension, and provides the mechanisms and the definitions necessary to describe the implicit and explicit concept and relations used in the field of cultural heritage documentation. The level of abstraction of the CIDOC-CRM is high enough to allow all cultural heritage collections to be mapped against it, thus it can be the “semantic glue” that Dublin Core could not provide.

Alternatives to CIDOC-CRM are VRA Core [Visual Resource Association, 2011], a data standard for the description of works of visual culture as well as the images that document them and MPEG-7 [Salembier and Sikora, 2002], another ISO standard more oriented to visual content description than to cultural heritage artefacts. To add a layer of complexity in this vast world, multiple ontologies can be used on the same model, i.e. an object being described with CIDOC-CRM can have its digital surrogates expressed in MPEG-7.

5.2.2 Data Exchange in Cultural Heritage

The most important characteristic of Digital Libraries is their flexibility in exposing content. Typically a Digital Library provides a search interface which allows resources to be found. These resources can be local or remote, depending on how the data are organised within the Digital Library and on how these data are made available for harvesting from/to other Digital Libraries.

This kind of communication is only possible because the structures of different Digital Libraries are expressed following a formal specification. In particular, especially in cultural heritage where we need to describe an extremely heterogeneous environment, some metadata standards are emerging and mappings are proposed to allow metadata exchange and enrichment. The CIDOC-CRM is an ontology designed to mediate contents in the area of tangible cultural heritage and it is ISO 21127 : 2006 standard.

As already introduced in the chapter 3.5.1 and as result of the discussion on ontologies and metadata, an interesting area of work is the one of data exchange of three-dimensional material. We do not want only a data format that is easy to manipulate and readable by most of the 3D authoring tools, but we also want such a format be able to carry metadata information on digital provenance. Digital prove-

nance authority is very important in cultural heritage because conservation of data is part of the mandate of “memory institutions” and because of the necessity of a guarantee on the credibility of the data over the years.

Of the 3D data format described in “Data Format Normalisation” only X3D (and VRML) and COLLADA support extensive use of metadata and thus are suggested for long term data conservation operations, but also for data exchange within 3D tools. Both X3D and COLLADA are XML based 3D scene descriptors and offer a very powerful framework for 3D scene representation, shadowing, basic shapes, simple dynamic effects and dynamic animations. While X3D is an ISO standard designed for the web as a content deployment format, COLLADA is a standard de facto adopted mainly by the gaming industry (initially developed by Sony) built as an interchange format.

Embedding metadata into 3D models is very important to preserve the information on data provenance. Multiple metadata format can be used but LIDO and CIDOC-CRM, with CRM_{dig}, best suited for this task, as I demonstrate in the next section.

5.3 Case Studies

The two case studies presented here are meant to show the difficulty encountered implementing a semantic framework to expose a legacy relational database and the work that needs to be done to correctly “map” two ontologies between them. In the first case study, after presenting the C2RMF large dataset, I describe the steps needed to convert the relational database into an rdf based triple dataset to then expose it with new web interfaces that are semantic aware and enable semantic data browsing. I also discuss why a certain approach demonstrate to be more performing under the imposed conditions. The second case study is intended to clarify the difference between a metadata format and a data transfer mechanism, how LIDO can be used as both and especially how LIDO can support the data provenance preservation. Also in this case we support our investigation using the C2RMF data set.

5.3.1 Semantically Exposing C2RMF Knowledge Repository

One of the scopes of the Sculpteur project [Addis et al., 2003] was to investigate how cultural heritage institutions, such as museums and photographic archives, could get benefit from Semantic web technologies. As already said these institution are rich in resources of heterogeneous multimedia content, containing information on people, objects, events, places and so on. We have also seen how this digital

material, along with all the metadata information, tends to be locked into internal closed systems, each one organized following its own metadata standard explicitly conceived to deal with the specific collection objects.

C2RMF database management system, called EROS (European Research Open System) was not in a different situation. EROS' strength lay on the complete multilingualism of the interfaces, vocabulary terms and their definitions, translated in 16 languages [Lahanier et al., 2002]. The data hosted in the relational database contained all the information on the objects that have been studied by the laboratory since 1931 and included:

- metadata related to the artworks themselves, images, reports, analysis, analytical reports, restoration reports, conservation surveys, chemical, structural, isotopic and molecular quantitative and qualitative analytical results and published papers;
- high definition digital images: photographic films taken with different techniques such as infra-red, X-ray, ultraviolet, cross-sections, electron microscopy, multispectral images, panoramic views, audio, video and 3D models;
- feature vectors for 2D and 3D image content recognition for retrieval and semi-automatic classification of images and 3D models.

This work permitted us to further explore the issues that can emerge when applying a complex semantic mapping such as CIDOC-CRM to a real world case multimedia collection.

5.3.1.1 Methodology

Semantic interoperability of cultural heritage digital libraries has been investigated at the C2RMF since the SCULPTEUR project by using a z39.50 search and retrieve web service (SRW) at the beginning and upgraded later to another protocol and by mapping legacy metadata schemas to the CIDOC-CRM. For the sake of simplicity the schema used for the mapping was a subset of the CIDOC-CRM, called CRM-CORE. Additional semantics are kept attached to the legacy database attributes in order to more fully define their meaning in the context of the Knowledge Management framework.

The mapped attributes were exposed through the SRW as a flat list that can be queried by using Common Query Language (CQL) expressions. The SRW was in charge of publishes the mapping information into RDF/XML format. It is in the

prerogatives of the SRW to dynamically map Common Query Language queries expressed in terms of the CRM CORE mappings to the relevant legacy database fields (in our case using SQL against a relational database) and return the results as XML structured according to the CRM CORE mappings (Figure 5.5).

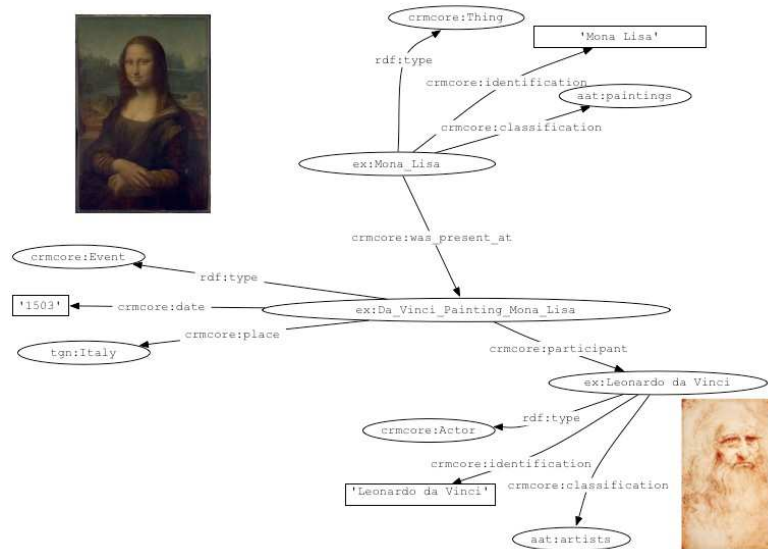


Figure 5.5: a graphic representation of the Mona Lisa mapping using CRM CORE ontology for the project Sculpteur.

Unfortunately, the approach of using SRW demonstrated serious limitations in terms of scalability when used with dataset as big as the one of the EROS database: to dynamically generate the triples, the system had to convert the CQL query to a MySQL query (the relation database supporting the EROS database), then the answer had to be converted into RDF/XML format. And this had to be done every time resulting in a huge overload of the servers. Thus a new, more pragmatic solution, was adopted. We decided to use the D2R server [d2r, 2012] to serve RDF triples to the browse interface. The D2RQ Platform is a framework for accessing relational databases as if they were virtual, read-only RDF graphs. It exposes RDF-based triples of the content of the relational databases dynamically, without having to replicate the data into an RDF store (Figure 5.6). With this implementation we had two main outcomes: first the triples are produced by a batch process and not in real time, so that the creation, being incremental, does not require constant stress on the server; second we serve the triples in a json format instead then RDF/XML. This format, although not standard, is more easy to manipulate client side from the navigation interface.



Figure 5.6: Screenshot of the mapped EROS resource served in HTML mode by the D2R server.

5.3.1.2 Results

Once all the triples generated and exposed through D2R, we need to provide the information to the final user using a semantic web aware visualisation interface (Figure 5.7) more user friendly and interactive. The choice ended on mSpace [m.c. schraefel et al., 2003], an experimental interaction model and software framework, to help web users to access and explore collections. mSpace is intended to help building new knowledge from exploring relationships between existing data.

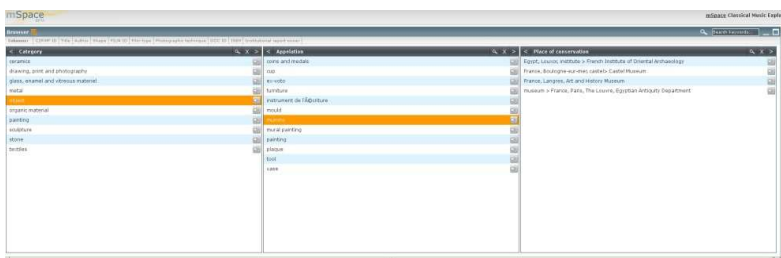


Figure 5.7: Subset of the EROS data set displayed through the mSpace interface.

Figure 5.7 shows a subset of the EROS dataset presented through the mSpace interface. Each category in the information space is displayed as a separate column, and the selection in each column narrows down the results presented in the next column.

5.3.1.3 Conclusion

Through this case study I have described how it is possible to semantically expose an existing cultural heritage multimedia repository, such as EROS, through the RDF/XML techniques. There are still barriers to the practical use of semantic web technologies in the cultural heritage domain, and this successful experiment can be a starting point for discussion on the benefits of those methodologies whilst still supporting the existing infrastructure [Pitzalis et al., 2006].

One of the indirect outputs of the project has been the investigation of the integration of the EROS system with the bibliographic records in the C2RMF library to take full advantage of the work carried on by the CIDOC-CRM working group on the alignment of the UNIMARC standard to the CIDOC-CRM. It should be considered also the use of LIDO instead of CRMCORE as metadata format as presented in [Pitzalis et al., 2010]

The goal of this implementation is to give to the user the possibility to provide real time, cross-collection searching and browsing of disparate multimedia sources in the cultural heritage domain should be investigated. This requires dealing with the alignment of the different data sources representations, ranging from time and date, places, identifying the people across collections, and categorization schemes such as controlled lists and thesauri.

Many of the issues encountered during this deployment were due to the scale of real world collections, such as the EROS system. As such, optimisation techniques have to be investigated, as well as how the underlying database schema could be optimised and improved to solve the data serve bottleneck.

5.3.2 Using LIDO to Handle Data Provenance

In chapter 3 the terms long term preservation and data provenance made their first appearance. The long term preservation, or digital preservation, is a collection of policies, guidelines and strategies that are necessary to, and have the goal to, ensure access to digital material for as long as necessary. Such activities include challenges of an interdisciplinary nature: technical, managerial, social, and organizational. On the other hand, the data provenance, one kind of metadata, pertains to the derivation history of a data product starting from its original sources [Simmhan et al., 2005].

The issue of provenance of digital artefacts is gaining increasing importance as digital technologies acquire an important role in cultural heritage research and prac-

tice. Provenance in science means experiment repeatability and verifiability.

How can one ensure that the 3D model, issue of the acquisition carried on a few years before is a valid 3D model and not an “improved” version of the original digital copy? It is because of questions like this one that researchers in the field developed the CRM_{dig}, an extension of CIDOC-CRM, that deal with the Data Provenance of digital surrogates. In this case study we investigate LIDO as a metadata schema, and how it can be used to keep Data Provenance track of the acquisition / processing of 3D models. After contextualizing the experiment and a brief introduction to the two metadata formats, LIDO and CRM_{dig}, I will provide an example of the mapping between LIDO and CRM_{dig}.

5.3.2.1 Methodology

The case-study scenario presented here is based on the “Cylinder Seal of Ibni-Sharrum” digital acquisition procedure. As seen before, in 2008 a 3D model has been acquired using a multi technique 3D acquisition. Based on a hypothetical database, I expose here the information stored at C2RMF where every artwork corresponds, in a relation 1 : 1, to a record “oeuvre” structured as such:

```

struct oeuvre
string oeuvre_recordId = REC1;
string oeuvre_title = (fr) Sceau Cylindre de Ibni-Sharrum, (en) Cylinder Seal of Ibni-Sharrum;
struct oeuvre_artist
string oeuvre_artist_name = (fr) Ibni-Sharrum, (en) Ibni-Sharrum;
string oeuvre_artist_nationality = (fr) Mesopotamia, (en) Mesopotamia;
string oeuvre_artist_school = (fr) Regne de Sharkali-Sharri , (en) Reign of Sharkali-Sharri;
struct oeuvre_owner
string oeuvre_owner_place = (fr) France, Paris, Musée du Louvre, (en) France, Paris,
The Louvre Museum;
string oeuvre_owner_inventoryId = AO 22303;
string oeuvre_owner_collection = (fr) Antiquités Orientales, (en) Near Eastern Antiquities;
string oeuvre_category = (fr) sculpture, (en) sculpture;
time oeuvre_date_creation_begin = 2217 BC;
time oeuvre_date_creation_end = 2193 BC;
string oeuvre_material = (fr) Serpentine, (en) Serpentine;
string oeuvre_technique = (fr) gravure, (en) engrave;
struct oeuvre_size
string oeuvre_size_diameter = 26 mm;
string oeuvre_size_height = 39 mm;
time oeuvre_dataEntry = 01/01/2010;
string oeuvre_ownerEntry = The Mapper;
url oeuvre_thumb = http://www.louvre.fr/...

```


For every artwork we can have multiple digital resources, with the relation $1 : N$ where 1 is the artwork and N the number of digital resources. In the special case of a 3D model we can have multiple digital sources.

```
struct film
string film_recordId = DIG2;
string film_oeuvreId = REC1;
string film_technique = photogrammetry;
string film_mime = dae;
string film_device = Nikon D2X;
time film_date = 29/07/2008;
string film_author = John Doe;
string film_right = C2RMF;
string film_view = whole;
string film_size = 500K vertex;
string film_path = /path/to/model.dae;
```

According to [Doerr, 2000], [Le Boeuf et al., 2005] and [Pitzalis et al., 2006] we can represent the “oeuvre” record in CIDOC-CRM as in [Pitzalis et al., 2010]. The complete mapping between the two metadata schema is available on the CIDOC-CRM website. In Figure 5.8 is the graphical representation of the RDF definition of the “Cylinder Seal of Ibni-Sharrum” data.

LIDO The LIDO (Light Information Describing Objects) rich metadata schema [ICOM, 2010], is a metadata format that has been proposed to handle museum-related content in the framework of Europeana. Besides being a self-sufficient schema to be possibly used in the museum framework, LIDO is proposed by the European project ATHENA as a standard for digital content aggregators. A two-step process is envisaged: mapping individual repository schemas to LIDO and mapping (once for all) the latter to the current Europeana Data Model schema (EDM) [Doerr et al., 2010].

LIDO is based on previous museum schemas: CDWALite [Baca, 1996], museums-dat [Museumdat, 2009] and SPECTRUM, and strongly relies on the CIDOC-CRM reference model. From the museum schemas, LIDO derives flexibility, ease of use for museum personnel and coverage of most of the needs arising in a museum environment. Being CIDOC-CRM compliant, LIDO adopts the event-oriented approach and guarantees a high level of interoperability. LIDO has not been conceived as another collection management system, but as a harvesting schema for the delivery of metadata. The current version of LIDO is 1.0, released in 2010 and endorsed by the ICOM committee.

A LIDO record is conceptually organised in 7 areas called Wrappers: **Object Iden-**

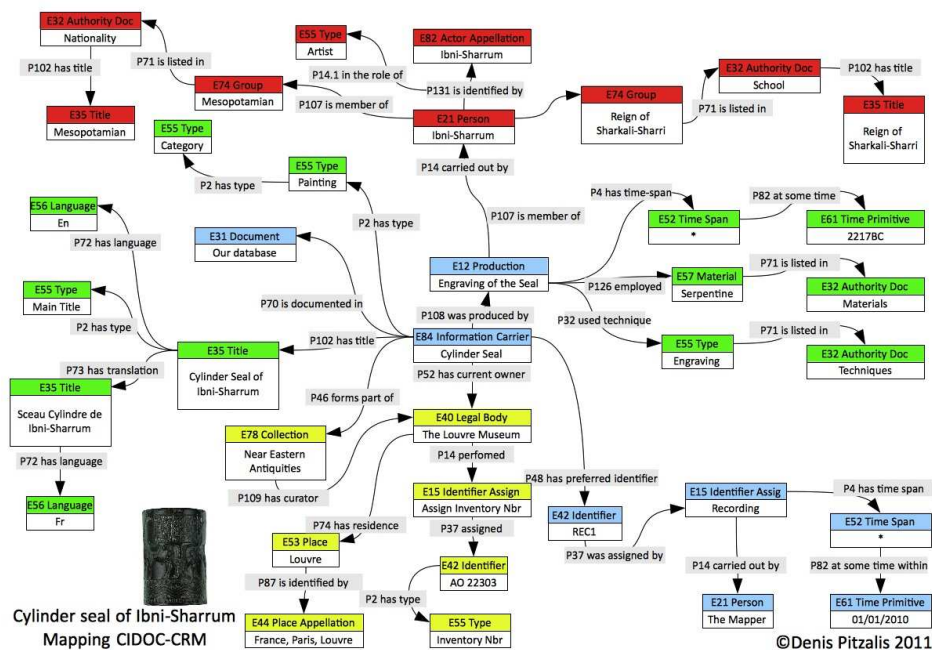


Figure 5.8: CIDOC-CRM mapping of the “Cylinder Seal of Ibni-Sharrum” record. The different colours of the metadata labels means in blue: What, red: Who, green: How, Yellow: Where. The starting point is the “Information Carrier” representing the virtual object from where we then explicit our properties. The boxes are the Subjects / Objects, and the lines are the Predicates.

tification, where the physical Object is identified; **Object Classification**, including information about its type; **Relation**, with the relations of the Object with other objects and its subject; **Events**, describing events in which the Object took part; **Rights**; **Record**, carrying the record information; and **Resource**, containing information about the Object’s digital representation. In order to deal with data provenance information of digital objects, an extension to CIDOC-CRM, named CRM_{dig} , has been developed in the framework of the CASPAR [CASPAR, 2009] first, and 3D-COFORM later, EU projects. As already said such information is paramount when dealing with digital replicas of artefacts or archaeological landscapes, in order to guarantee the transparency of the relation between the digital replica and the real physical original, therefore it is important to enable this feature for LIDO as well.

CRM_{dig} It is indeed not easy to keep track of all the changes that a digital object is submitted to during its acquisition and post-processing phases, for example the simple “clean” of a mesh or the decimation of a cloud point can be done in many

different ways using many different algorithms. For this reason an extension of CIDOC-CRM, called CRM_{dig}, has been developed to document provenance meta-data [Theodoridou et al., 2010]. To monitor all the relevant parameters of digital provenance it is necessary that an interactive Work-flow Monitoring Framework is available and that the machine action is determined and dependent on known variables such as the machine specification and its input parameters.

5.3.2.2 Data Mapping to CRM_{dig}

In this example, the digitisation process operates on a well-known physical object and produces digital output for each of them and ultimately generate a 3D model. The modelling approach is event centric and follows a hierarchical workflow structure. The main data acquisition process is an event referred to as the Data Acquisition Event, a super event comprised of sub-events that describe the details of the process. The Data Acquisition Event includes generic set-up information about the acquisition process that is valid for all sub-events unless it is overwritten. The Data Acquisition Event can exist on its own without sub-events and is identified either by a *UUID* or by a *URI* of the form: *http://“responsible organisations URI”:digitisation:“set of objects ID”:date*.

Each of the events used in our model has its own properties (links to other classes) according to the class it belongs to and also complies with the class hierarchy concepts which means that it inherits properties from its superclasses. Thus the common properties that could be inherited between super and sub events can be grouped with four main questions as it concerns who, where, when and what.

Digitisation Process

D2.Digitization_Process “3D Scanning of the Cylinder” → L11F.had_output → D9.Data_Object
“Cylinder Seal Model”

D2.Digitization_Process “3D Scanning of the Cylinder” → L1.digitized →
E84.Information_Carrier “Cylinder Seal”

Struct film

D13.Digital_Information_Carrier “3D of Cylinder Seal” → P70B.is_documented_in →
E31.Document “our database”

film_recordId DIG2

D13.Digital_Information_Carrier “3D of Cylinder Seal” → P48F.has_preferred_identifier →
E42.Identifier “DIG2”

film_oeuvreId RECI

D13.Digital_Information_Carrier “3D of Cylinder Seal” → L19F.stores → D9.Data_Object
“Cylinder Seal Model”

E84.Information_Carrier “Cylinder Seal” → P48F.has_preferred_identifier → E42.Identifier

“RECI” **film_technique** *photogrammetry*

D2.Digitization_Process “3D Scanning of the Cylinder” → P2F.has_type → E55.Type “photogrammetry”

film_mime *dae*

D9.Data_Object “Cylinder Seal Model” P2F.has_type → E55.Type “mimetype:dae”

film_device *Nikon D2X*

D2.Digitization_Process “3D Scanning of the Cylinder” → L12F.happened_on_device →

D8.Digital_Device “Nikon D2X” → P2F.has_type → E55.Type “photogrammetry”

film_date 29/07/2008

D2.Digitization_Process “3D Scanning of the Cylinder” → L31.has_starting_datetime →

E61.Time_Primitive “29/07/2008”

film_author *John Doe*

D2.Digitization_Process “3D Scanning of the Cylinder” → L30.has_operator → E21.Person “John Doe”

film_right *Centre de Recherche et de Restauration des Musées de France*

D9.Data_Object “Cylinder Seal Model” → P105F.right_held_by → E39.Actor “Centre de Recherche et de Restauration des Musées de France”

film_view *whole*

D9.Data_Object “Cylinder Seal Model” → P2F.has_type → E55.Type “whole”

film_size *500K vertex*

D9.Data_Object “Cylinder Seal Model” → P90F.has_value → E60.Number “500K”

→ P91F.has_unit → E58.Measurement_Unit “vertex”

film_path */PATH/TO/OBJECT*

D13.Digital_Information_Carrier “3D of Cylinder Seal” → P48F.has_preferred_identifier →

E42.Identifier “/PATH/TO/OBJECT.dae” → P2F.has_type → E55.Type “path”

As is, this mapping describes the final result of our acquisition process but does not take into account any information concerning the creation of the digital surrogate itself. This means that the experiment is not repeatable and we do not know how we obtained the final model. Following the model suggested in [Theodoridou et al., 2010] we can extend our metadata framework to cover other information on the digitisation event itself including the provenance information (Figure 5.9).

Even with this small subset of data it is easy to demonstrate that CIDOC-CRM, with the extension CRM_{dig}, provides a powerful and flexible infrastructure to document information about data provenance in a very precise way, especially with the complexity of a 3D acquisition where the process acquisition requires many different steps.

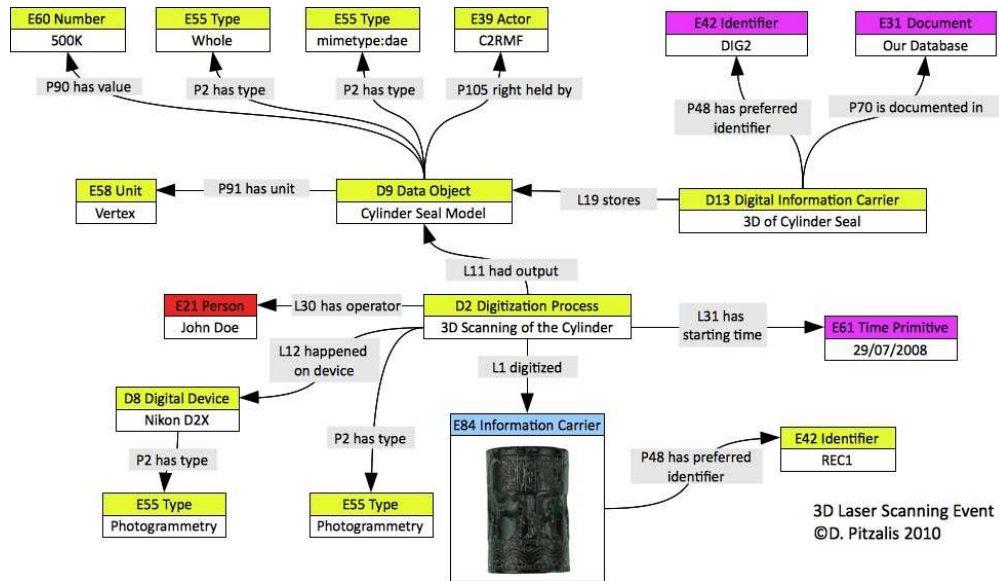


Figure 5.9: CRM_{dig} representation of a photogrammetry acquisition

5.3.2.3 Data Mapping to LIDO

Before to map LIDO to CRM_{dig} to demonstrate that the first can support the metadata Data Provenance principle, I briefly present how we describe an object using LIDO.

LIDO elements are depicted with the familiar scheme path \rightarrow label-content. To map such an approach on CIDOC-CRM and CRM_{dig} , an equivalent triple must be identified. Based on the mapping proposed by [Kutraki and Doerr, 2010] I developed a new mapping between LIDO v1.0 and CIDOC-CRM v5.0.2 using as an example the record of the “Cylinder Seal Ibni-Sharrum” described in the previous section. Here is an extract to demonstrate the mechanism via relevant examples.

As mentioned before both structures, CIDOC-CRM and LIDO, are **data transfer mechanisms** and **metadata formats**, both event centric. As a data transfer mechanism, LIDO is not aimed at covering all collection management needs, but rather at delivering metadata to online services. It is important to understand the difference between the two definitions above: a data transfer mechanism offers a mediation between alternative representations; a metadata format offers a set of rules and recommendations about how to describe the content for a kind of object [NISO, 2004].

Basic information about the object is in the **Object Identification Wrapper**. The title, or the name of the object, is a mandatory field that corresponds to *oeuvre_title*

in our example.

```
LIDO [Obj Id]> titleWrap> titleSet> appellationValue:preferred "Cylinder Seal of Ibni-Sharrum"
CIDOC-CRM E84.Information_Carrier "Cylinder Seal" → P102F.has_title → E35.Title
"Cylinder Seal of Ibni-Sharrum".
```

If there is more than one title in LIDO v1.0 we can repeat the Title Set element as many times as we need and “preferred” or “alternate” can be specified in the pref attribute of the **appellationValue** element. We can use the **sourceAppellation** element to identify the alternative title’s source. Information about the record itself are stored into the **Record Wrapper**.

```
oeuvre_recordId "RECI"
LIDO >RecordID "RECI"
CIDOC E84.Information_Carrier "Cylinder Seal" → P48F.has_preferred_identifier →
E42.Identifier "RECI"
oeuvre_dataEntry "01/01/2010"
LIDO >RecordInfoSet>recordMetadataDate "01/01/2010"
CIDOC E42.Identifier "RECI" → ... → P82F.at_some_time_within → E61.Time_Primitive
"01/01/2010"
```

5.3.2.4 Mapping Lido 1.0 Resource to CRM_{dig}

As we know that CRM_{dig} support Data Provenance, the best way to prove that LIDO support this feature too is to map LIDO against CRM_{dig}. The mapping of the LIDO resource wrapper is similar to the above example. As in the previous case I present just part of the complete mapping.

```
LIDO>ResourceWrap>linkResource
CIDOC D1.Digital_Object → P48.has_preferred_identifier → E42.Identifier → P2.has_type →
E55.Type "Web resource"
LIDO>ResourceWrap>resourceID
CIDOC D1.Digital_Object → P48.has_preferred_identifier → E42.Identifier
LIDO>ResourceWrap>resourceRelType
CIDOC D1.Digital_Object → P2.has_type → E55.Type → P2.has_type → E55.Type "Resource
Relationship"
LIDO>ResourceWrap>resourceType
CIDOC D1.Digital_Object → P2.has_type → E55.Type → P2.has_type → E55.Type "Resource"
LIDO>ResourceWrap>rightsResource
```

CIDOC D1.Digital_Object → P104.is_subject_to → E30.Right → P75B.is_posessed_by → E39.Actor
LIDO>ResourceWrap>resourceViewDescription
CIDOC D1.Digital_Object → P3.has_note → E62.String
LIDO>ResourceWrap>resourceViewType
CIDOC D1.Digital_Object → P3.has_note → E62.String
LIDO>ResourceWrap>resourceViewSubjectTerm
CIDOC D1.Digital_Object → P2.has_type → E55.Type → P2.has_type → E55.Type
LIDO>ResourceWrap>resourceViewDate
CIDOC D1.Digital_Object → L11B.was_output_of → D7.Digital_Machine_Event → L31F.has_starting_date-time → E61 Time Primitive
LIDO>ResourceWrap>resourceViewDate
CIDOC D1.Digital_Object → L11B.was_output_of → D7.Digital_Machine_Event → L32.has_ending_date-time
LIDO>ResourceWrap>resourceSource
CIDOC D1.Digital_Object → P70B.is_documented_in → E31.Document → P67.refers_to → E39.Actor

5.3.2.5 Discussion

In this case study we investigated the problematic of how to record metadata of 3D models and their Data Provenance. We demonstrated that LIDO can manage provenance information in a way that complies with CRM_{dig}. Such possibility, on top of being an event centric metadata format, is a substantial step forward in the direction of guaranteeing the reliability of digital surrogates and the repeatability of model acquisition and processing.

From this case study it is evident how it is possible to use metadata to record data provenance. Although this information is not useful in the context of data exchange within digital collections, it is clear that they represent the evidence of the credibility of an experiment. Such approach is more and more endorsed not only in the academy but also by “memory institutions”.

5.4 Conclusion

In this chapter, I tried to explain the possible benefits of the use of Semantic Web techniques in the cultural heritage field.

Digital Library initiatives such as Europeana, repository systems such as EPrints and DSpace, and the exhaustive choice of standards and interoperability guidelines

make the use of semantic technologies in the field of cultural heritage achievable with little effort. There are huge benefits in having all the Knowledge Resources exposed in a linked system, i.e. an integrated search engine where once can find and identify stolen object.

However, there are still some difficulties to massively introduce these techniques because there are several standards and their implementation is usually very time consuming. It is common, for example, that in cultural heritage institutions, usually for lack of resources and funds, they still store and manage their digital data in forms that are barely suitable to the quality of the data themselves but that match needs for private use. Once the digital repository is installed, one must also consider the highly expensive task of mapping all of the existing material to the chosen semantic representation.

This is the reason why many cultural institutions are tied in to their commercial content management systems, if they use one. Finally, although some of the technical issues, such as triple store scalability, are being overcome, many still have doubts about the applicability of semantic web technologies in practice and their advantage.

With the two case studies I wanted to present how the problematic of digital data provenance can be tackled and how difficult is to define a correct mapping between legacy relationally structured data and modern RDF triples.

During 3D-COFORM we tried also to demonstrate, at the implementation level, the feasibility of Semantic Web techniques for cultural heritage focusing on a different approach for the standard library search: instead of developing new specific 3D shape - based algorithms, the project worked on integrating the text-based and the shape-based search modalities. This is an aspect that does not get too much attention but that it is, in my opinion, part of the contextualization process and thus extremely important in applications such as cultural heritage and should be taken into account for the next implementation of Semantic Web technologies.

The “web of data” is certainly happening. More and more institutions embrace semantic technologies and adhere to standards and good practices to share their data over the web. Initiatives like Linked Data, Open Access, Open Data, Open Graph are now part of our daily life, in more or less transparent ways.

Today users explore the data organized by ontologies and then use REST services to retrieve the corresponding instances in a completely transparent way. This is how Semantic Web techniques should be used to describe the complex multidimensional space of cultural heritage information, a very simple web interface, while a complete framework based on XML and Web Service standards provides a seamless search and retrieval service to access this information.

Chapter 6

Conclusions and Future Work

6.1 Contributions

The goal of this thesis was to investigate the implementation of a protocol for the acquisition, processing and analysis of three-dimensional models of cultural heritage objects.

In Chapter 2 we contextualise the scope of this research and we discuss the problematics we can encounter during the planning phase. Among them, the most important are the identification of the right group of final users we want to address, spacing from the wide public for an online communication, to the experts in painters strokes; the scope of the final model, like for scientific measurement or for reconstruction simulation; and the methodology and the technology to be used during the scan.

In Chapter 3 other variables are introduced. Once the scope of the campaign has been defined then the right technology to be used needs to be decided. I have presented the most used devices and techniques for 3D acquisition and post processing, presenting pros and cons of each one and trying to indicate in which situations they perform best. Certainly, the multi-source work-flow is an interesting approach, but it requires time, material, and competencies that are not always available in a cultural heritage institution. Once the acquisition done all the decisions about the post processing should be carefully taken because the long term preservation (digital preservation) and the trustability of the sources depends on the standards used in this part of the work-flow.

In Chapter 4 I presented a few case studies from my previous professional experiences, demonstrating how different technologies can be used to obtain three-

dimensional models of cultural heritage artworks and landscape. Especially I wanted to demonstrate how important is the use of multiple data source for the acquisition of the most complex scenario.

In Chapter 5 an overview on semantic techniques for cultural heritage are presented, trying to describe their added value in real case application. The two case studies are meant to demonstrate how to implement and what are the benefits of such technologies. Using a proprietary format to store our information is not only useless, but also dangerous (what would happen if we are no longer able to read binary format?) but also counterproductive, in a world moving towards a completely linked critical mass of data. With the case study on the EROS database we also investigated the difficulties associated with the use of “pure academic” frameworks that at the end are not scalable enough to be used in real world scenarios.

One of the main objectives of this thesis was to define not only a functional set of guidelines, but demonstrate how methodologies work in real projects. This has been done through case studies. In my experience all 3D digitisation campaigns or Semantic mapping and data organization is unique in its requirements due to the nature of the data to be acquired, the final scope of the project, and the natural constraints.

Thus it is simply not possible and unrealistic to propose a single, fit-for-all solution. Rather, as demonstrated with the case studies, I showed different solutions, where each one fits a specific set of needs that can be used as an example to solve similar problems. In conclusion, one must consider the benefits to cultural heritage institutions in using three dimensional technologies to document their objects and using semantic technologies to expose their data on the net.

The success of 3D-COFORM can give an idea of the importance cultural heritage institutions are giving to new ICT technologies to optimize their resources and improve the quality of their day to day work. Researched technologies issue of this project have demonstrated to be mature enough to enter in the day by day activity. Indeed the most promising is photogrammetry as a webservice. The advantage of this system is that the final user does not need a specialized equipment, he just need to take images wherever he is; and then you just upload it to the webserver. The rest of the work is done then in a seamlessly and transparent way by a series of computer that recreate a 3D model.

3D digitalisation is a great step forward in the field of cultural preservation, for all the memory institutes, for the traditional museums, that will always keep their place, as for the virtual ones.

6.2 Future Work

Constant increasing of computational power, improvement to devices, and optimization of algorithms is indeed of benefit to both 3D and semantic technologies. However, it is impossible to reap the benefits if we do not focus on facing the major challenges that 3D faces including integration of multiple sources for acquisition, real time rendering for exploitation, and for semantics data provenance and openness for use and reuse.

Integration of Multiple Sources We have shown how it is possible to integrate 3D scans coming from different devices and technologies into a complete three-dimensional model. This possibility is extremely important because most methods complement each other, especially when scanning objects with heterogeneous surface properties. As an example on how this can be done we demonstrated the model of the *Cylinder Seal of Ibni-Sharrum*, a result of 4 different 3D technologies and hours of post processing.

The challenge in this area is in the integration of the technologies themselves. At the actual state too much post processing is required and the result is not always what we would like to see. Defining a common standard for registering the device configurations, the position over the space and so on into a single format would be already of great help for interchange and model fusion.

Real Time Rendering Another barrier is the visualisation of complex 3D models. While on screen visualisation in almost real time can still be achieved, with the hardware limitation of the host machine, one must use some tricks like reducing the number of faces displayed depending on the camera, or switching from mesh to point cloud.

3D models over the web are still in early development. Apart from the physical limitation imposed by bandwidth, all clients for the visualisation use a different version of the standards, even for Collada and X3D. This results in frustration and a certain reluctance in using 3D models freely for website production or collection explorations. For example, with Coronelli's globe, I tried to solve the problem of the texture (more than 1Gb) by sending the single images to the client via an optimized IPIImage server.

Data Provenance Data provenance and long term digital preservation are not problems *di per se*. Working groups work hard to refine standard and policies to make

this happen. The issue lays in the semantic infrastructure. There is not yet a mature solution that permits the management of the huge amount of data required by those standards in a non-invasive way.

The 3D-COFORM repository was a first attempt in the field but demonstrated to be not scalable enough to support enough models. More research in the implementation and the optimization of the metadata repositories have to be planned for the future.

Openness for Use and Reuse Open data does not present any physical or computational obstacle because, in its essence, Open data is more concerned about the openness and the discoverability of the information than the implementation or fruition. From an implementation point of view the only downside is that the data producer must be able to generate its data in machine readable (RDF) format to serve its information to the www. To bypass this issue we should concentrate more on the power of annotation (in 3D known as model annotation). Annotating an existing document is half way between a “web of documents” and the “web of data”, creating a set of documents with annotated data.

Bibliography

3D-COFORM. 3D-COFORM website. <http://www.3d-coform.eu>, May 2009. (Cited on page 4.)

ACOHIR. ACOHIR Website. <http://users.ecs.soton.ac.uk/km/projs/acohir/>, 2000. (Cited on pages 4 and 24.)

Matthew Addis, Mike Boniface, Simon Goodall, Paul Grimwood, Sanghee Kim, Paul Lewis, Kirk Martinez, and Alison Stevenson. SCULPTEUR: towards a new paradigm for multimedia museum information handling. In Dieter Fensel, Katia Sycara, and John Mylopoulos, editors, *The Semantic Web - ISWC 2003*, volume 2870 of *Lecture Notes in Computer Science*, pages 582–596. Springer Berlin Heidelberg, 2003. ISBN 978-3-540-20362-9. (Cited on page 86.)

Ben Adida, Mark Birbeck, Shane McCarron, and Steven Pemberton. RDFa in XHTML: syntax and processing. <http://www.w3.org/TR/2008/REC-rdfa-syntax-20081014/>, 2008. (Cited on page 81.)

Sameer Agarwal, Noah Snavely, Ian Simon, Steven M Seitz, and Richard Szeliski. Building rome in a day. In *Computer Vision, 2009 IEEE 12th International Conference on*, pages 72–79. IEEE, 2009. (Cited on page 73.)

Yahaya Ahmad. The scope and definitions of heritage: From tangible to intangible. *International Journal of Heritage Studies*, 12(3):292–300, 2006. doi: 10.1080/13527250600604639. URL <http://www.tandfonline.com/doi/abs/10.1080/13527250600604639>. (Cited on page 9.)

Pierre Amiet. *L'art d'Agadé au Musée du Louvre*. Editions des Musées Nationaux, 1976. (Cited on page 58.)

Arius3D. Arius3D. <http://www.arius3d.com/a3dscanner.html>, 2013. (Cited on page 31.)

D. B. Arnold and G. Geser. *Research agenda for the applications of ICT to cultural heritage*. EPOCH, February 2007. URL <http://eprints.brighton.ac.uk/3311/>. The report is available online in late draft form as a project deliverable D2.11 at the given URL. (Cited on page 3.)

- ATHENA. ATHENA website. <http://www.athenaeurope.org/>, 2008. (Cited on page 4.)
- Murtha Baca. *Categories for the description of works of art*. Gordon & Breach, New York, NY [u.a.], 1996. ISBN 2884492372 9782884492379. (Cited on page 92.)
- Alban Bajard, Olivier Aubreton, Gonen Eren, Pierre Sallamand, and Frédéric Truchetet. 3D digitization of metallic specular surfaces using scanning from heating approach. In *Proc. SPIE7864, Three-Dimensional Imaging, Interaction, and Measurement*, January 2011. doi: 10.1117/12.872467. URL <http://dx.doi.org/10.1117/12.872467>. (Cited on page 28.)
- L. Barazzetti, F. Remondino, M. Scaioni, M. Lo Brutto, A. Rizzi, and R. Brumana. Geometric and radiometric analysis of paintings. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38(Part 5), 2010. (Cited on page 16.)
- Dave Beckett. RDF/XML syntax specification (revised). <http://www.w3.org/TR/rdf-syntax-grammar/>, 2004. (Cited on page 81.)
- Dave Beckett and Tim Berners-Lee. Turtle - terse RDF triple language. <http://www.w3.org/TeamSubmission/turtle/>, 2011. (Cited on page 81.)
- Colette Bemont, Michel Jeanlin, and Christian Lahanier. Les figurines en terre cuite gallo-romaines. *Revue archéologique de l'ouest*, 10(1):208–209, 1993. ISSN 0767-709X. URL http://www.persee.fr/web/revues/home/prescript/article/rao_0767-709x_1993_num_10_1_1009_t1_0208_0000_2. (Cited on pages 19 and 135.)
- J. Benois-Pineau, F. Precioso, and M. Cord. *Visual Indexing and Retrieval*. SpringerBriefs in computer science. Springer New York, 2012. ISBN 9781461435884. (Cited on pages 54 and 147.)
- Fausto Bernardini and Holly Rushmeier. The 3D model acquisition pipeline. *Computer Graphics Forum*, 21(2):149–172, 2002. ISSN 1467-8659. doi: 10.1111/1467-8659.00574. URL <http://onlinelibrary.wiley.com/doi/10.1111/1467-8659.00574/abstract>. (Cited on page 25.)
- Tim Berners-Lee. Information management: A proposal. Technical report, CERN, March 1989. (Cited on page 79.)
- Tim Berners-Lee. Semantic web roadmap. Technical report, CERN, September 1998. (Cited on page 79.)
- Tim Berners-Lee. Notation 3 logic. <http://www.w3.org/DesignIssues/Notation3>, 2005. (Cited on page 81.)

- Roy S. Berns. The science of digitizing paintings for color-accurate image archives: A review. *Journal of Imaging Science and Technology*, 45(4):305–325, 2001. URL <http://www.ingentaconnect.com/content/ist/jist/2001/00000045/00000004/art00002>. (Cited on page 130.)
- D. Bertani, M. Cetica, P. Poggi, G. Puccioni, E. Buzzegoli, D. Kunzelman, and S. Cecchi. A scanning device for infrared reflectography. *Studies in conservation*, 35(3):113–116, 1990. (Cited on page 126.)
- Francois Blais. Review of 20 years of range sensor development. *Journal of Electronic Imaging*, 13(1):231–243, January 2004. ISSN 1017-9909. doi: 10.1117/1.1631921. URL <http://dx.doi.org/10.1117/1.1631921>. (Cited on page 16.)
- Fred L Bookstein. *Morphometric tools for landmark data: geometry and biology*. Cambridge University Press, Cambridge [England]; New York, 1997. ISBN 0521585988 9780521585989. (Cited on page 139.)
- L. Borgeat, G. Godin, P. Massicotte, G. Poirier, Francois Blais, and Jean Angelo Beraldin. Visualizing and analyzing the mona lisa. *Computer Graphics and Applications, IEEE*, 27(6):60–68, December 2007. ISSN 0272-1716. doi: 10.1109/MCG.2007.162. (Cited on page 43.)
- Alexandre Bourdeu and Denis Pitzalis. Geometric morphometrics for provenance determination of gallo-roman white clay figurines. In *Proceedings of the 11th International conference on Virtual Reality, Archaeology and Cultural Heritage*, VAST'10, page 25–31, Aire-la-Ville, Switzerland, Switzerland, 2010. Eurographics Association. ISBN 978-3-905674-29-3. doi: 10.2312/VAST/VAST10/025-031. URL <http://dx.doi.org/10.2312/VAST/VAST10/025-031>. (Cited on page 21.)
- C2RMF. C2rmf | l'imagerie 3d. <http://www.technologies.c2rmf.fr/3D/coronelli>, 2013. (Cited on page 72.)
- M. Callieri, P. Cignoni, M. Corsini, and R. Scopigno. Masked photo blending: mapping dense photographic dataset on high-resolution sampled 3D models. *Computers and Graphics*, 32(4), 2008. (Cited on page 65.)
- M. Callieri, P. Cignoni, M. Dellepiane, and R. Scopigno. Pushing time-of-flight scanners to the limit. In *Proceedings of the 10th International conference on Virtual Reality, Archaeology and Cultural Heritage*, VAST'09, page 85–92, Aire-la-Ville, Switzerland, Switzerland, 2009. Eurographics Association. ISBN 978-3-905674-18-7. doi: 10.2312/VAST/VAST09/085-092. URL <http://dx.doi.org/10.2312/VAST/VAST09/085-092>. (Cited on page 28.)
- Marco Callieri. *Beyond high-resolution geometry in 3D Cultural Heritage: enhancing visualization realism in interactive contexts*. PhD thesis, Centro Nazionale di Ricerca, ISTI, November 2006. URL <http://>

- [//etd.adm.unipi.it/theses/available/etd-11292006-132636/unrestricted/callieri_thesis.pdf](http://etd.adm.unipi.it/theses/available/etd-11292006-132636/unrestricted/callieri_thesis.pdf). (Cited on page 29.)
- Francesca Casadio and Lucia Toniolo. The analysis of polychrome works of art: 40 years of infrared spectroscopic investigations. *Journal of Cultural Heritage*, 2(1):71 – 78, 2001. ISSN 1296-2074. doi: 10.1016/S1296-2074(01)01107-4. URL <http://www.sciencedirect.com/science/article/pii/S1296207401011074>. (Cited on page 128.)
- CASPAR. CASPAR digital preservation user community. <http://www.casparpreserves.eu/>, May 2009. (Cited on page 93.)
- Jim X. Chen. 3D file formats. In *Guide to Graphics Software Tools*, pages 1–4. Springer London, London, 2009. ISBN 978-1-84800-900-4, 978-1-84800-901-1. URL http://www.springerlink.com/index/10.1007/978-1-84800-901-1_18. (Cited on page 52.)
- P. Cignoni, E. Gobbetti, R. Pintus, and R. Scopigno. Color enhancement for rapid prototyping. In *Proceedings of the 9th International conference on Virtual Reality, Archaeology and Cultural Heritage, VAST'08*, page 9–16, Aire-la-Ville, Switzerland, Switzerland, 2008a. Eurographics Association. ISBN 978-3-905674-14-9. doi: 10.2312/VAST/VAST08/009-016. URL <http://dx.doi.org/10.2312/VAST/VAST08/009-016>. (Cited on pages vii and 68.)
- Paolo Cignoni, Massimiliano Corsini, and Guido Ranzuglia. MeshLab: an open-source 3D mesh processing system. *ERCIM News*, page 45–46, 2008b. (Cited on page 48.)
- Philippe Colantoni, Ruven Pillay, Christian Lahanier, and Denis Pitzalis. Analysis of multispectral images of paintings. *Proc. EUSIPCO, Florence, Italy*, 2006. (Cited on page 132.)
- Nick Crofts, Martin Doerr, Tony Gill, Stephen Stead, and Matthew Stiff. Definition of the CIDOC conceptual reference model. Technical report, ICS-FORTH, March 2009. (Cited on page 83.)
- Brian Curless. Overview of active vision techniques. *SIGGRAPH 99 Course on 3D Photography*, 1999. (Cited on pages v and 27.)
- d2r. The D2RQ platform – accessing relational databases as virtual RDF graphs. <http://d2rq.org/>, 2012. (Cited on page 88.)
- DCMI. DCMI home: Dublin core® metadata initiative (DCMI). <http://dublincore.org/>, 2006. (Cited on page 83.)
- Martin Doerr. Mapping of the dublin core metadata element set to the CIDOC CRM. Technical Report 274, ICS-FORTH, July 2000. (Cited on page 92.)

- Martin Doerr, Stefan Gradmann, Steffen Hennicke, Antoine Isaac, Carlo Meghini, and Herbert van de Sompel. The europeana data model (edm). In *World Library and Information Congress: 76th IFLA general conference and assembly*, page 10–15, 2010. (Cited on page 92.)
- S.F. El-Hakim, J.-A. Beraldin, M. Picard, and G. Godin. Detailed 3D reconstruction of large-scale heritage sites with integrated techniques. *Computer Graphics and Applications, IEEE*, 24(3):21–29, 2004. ISSN 0272-1716. doi: 10.1109/MCG.2004.1318815. (Cited on page 42.)
- EPOCH. EPOCH noe website. <http://cordis.europa.eu/ist/digicult/epoch.htm>, March 2004. (Cited on page 4.)
- EROS3D. Multi-modal framework for data integration and retrieval of 3D objects in artwork databases. <http://eros3d.ensea.fr/>, 2008. (Cited on page 20.)
- Europeana. Europeana website. www.europeana.eu, 2009. (Cited on pages 3 and 4.)
- EVAN Society. EVAN toolbox. <http://www.evan-society.org/node/42>, 2011. (Cited on page 141.)
- Jean-Jacques Ezrati. Two non-invasive techniques for the study of the surface of cultural heritage objects: Optical measurement of micro-roughness and backscattering spectro-colorimetry. In *9th Int. Conference on NDT of Art 2008*, Jerusalem, Israel, May 2008. (Cited on page 60.)
- Jean-Jacques Ezrati, Anne Bouquillon, M. Bormand, Daniel Vigears, and M.-E. Meyohas. La microtopographie pour une meilleure connaissance des oeuvres ; l'étude du poli chez desiderio da settignano, artiste du XV siècle. *Contrôles, essays \$ > \$ mesures*, pages 32–33, 2007. (Cited on page 42.)
- F. Fabbri, P. Mazzinghi, and A. Aldrovandi. Tecnica di identificazione di materiali pittorici attraverso l'acquisizione di immagini digitali multispettrali in fluorescenza UV. *Quaderni di Ottica e Fotonica*, 6:94–104, 2000. (Cited on page 126.)
- Alessandro E. Foni, George Papagiannakis, and Nadia Magnenat-Thalmann. A taxonomy of visualization strategies for cultural heritage applications. *J. Comput. Cult. Herit.*, 3(1):1:1–1:21, July 2010. ISSN 1556-4673. doi: 10.1145/1805961.1805962. URL <http://doi.acm.org/10.1145/1805961.1805962>. (Cited on page 54.)
- R. Fontana, MC Gambino, E. Pampaloni, L. Pezzati, and C. Seccaroni. Panel painting surface investigation by conoscopic holography. In *8th International Conference on "Non Destructive Investigations and Microanalysis for the Diagnostics and the Conservation of the Cultural and Environmental Heritage"*, Lecce, page 15–19, 2005. (Cited on page 16.)

- Raffaella Fontana, Maria Chiara Gambino, Marinella Greco, Luciano Marras, Marzia Materazzi, Enrico Pampaloni, Luca Pezzati, and Pasquale Poggi. New high-resolution IR-color reflectography scanner for painting diagnosis. In *SPIE5146*, volume 5146 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, pages 108–115, Munich, Germany, October 2003. SPIE. doi: 10.1117/12.501235. URL <http://dx.doi.org/10.1117/12.501235>. (Cited on page 126.)
- T. Franken, M. Dellepiane, F. Ganovelli, P. Cignoni, C. Montani, and R. Scopigno. Minimizing user intervention in registering 2D images to 3D models. *The Visual Computer*, 21(8):619–628, 2005. (Cited on pages 51 and 64.)
- Roberto Gabrielli, Nicola Amico, Andrea Angelini, Andrea D’Andrea, and Giancarlo Iannone. Integrating 3D data acquisition techniques for comprehensive study for the ancient hellenistic-roman theatre of paphos, cyprus. In *CAA*, pages 461–464, Granada, 2010. [S.I.]. ISBN 9788469307724 846930772X. (Cited on page 145.)
- A. Gianoncelli, J. Castaing, A. Bouquillon, A. Polvorinos, and P. Walter. Quantitative elemental analysis of della robbia glazes with a portable XRF spectrometer and its comparison to PIXE methods. *X-Ray Spectrometry*, 35(6):365–369, 2006. ISSN 1097-4539. doi: 10.1002/xrs.920. URL <http://onlinelibrary.wiley.com/doi/10.1002/xrs.920/abstract>. (Cited on page 132.)
- Colin Goodall. Procrustes methods in the statistical analysis of shape. *Journal of the Royal Statistical Society. Series B (Methodological)*, 53(2):pp. 285–339, 1991. ISSN 00359246. URL <http://www.jstor.org/stable/2345744>. (Cited on page 139.)
- Simon Goodall, Paul Lewis, and Kirk Martinez. 3-d shape descriptors and distance metrics for content-based artefact retrieval. In Rainer W. Lienhart, Norboru Babaguchi, and Edward Y. Chang, editors, *Storage and Retrieval Methods and Applications for Multimedia*, volume 5682, pages 87–97. SPIE-IS&T, 2005. ISBN 0-8194-5655-1. URL <http://eprints.soton.ac.uk/260365/>. (Cited on page 147.)
- D. Gorisse, Matthieu Cord, M. Jordan, Sylvie Philipp-Foliguet, and Frederic Precioso. 3D content-based retrieval in artwork databases. In *Proceedings of the IEEE 3DTV-Conference*, Kos Island, Greece, May 2007. URL <http://publi-etis.ensea.fr/2007/GCJPP07>. (Cited on page 20.)
- J.C. Gower. Generalized procrustes analysis. *Psychometrika*, 40(1):33–51, 1975. ISSN 0033-3123. doi: 10.1007/BF02291478. URL <http://dx.doi.org/10.1007/BF02291478>. (Cited on page 139.)
- Gabriele Guidi, Fabio Remondino, Giorgia Morlando, Andrea Del Mastio, Francesca Ucheddu, and Anna Pelagotti. Performances evaluation of a low

- cost active sensor for cultural heritage documentation. In *Proceeding of VIII Conference on Optical 3D Measurement Techniques*, 2007. (Cited on page 45.)
- Carlos Hernández Esteban. *Stereo and Silhouette Fusion for 3D Object Modeling from Uncalibrated Images Under Circular Motion*. PhD thesis, Ecole Nationale Supérieure des Télécommunications, May 2004. URL <http://pastel.archives-ouvertes.fr/pastel-00000862>. (Cited on page 27.)
- Carlos Hernández Esteban and Francis Schmitt. Silhouette and stereo fusion for 3D object modeling. *Computer Vision and Image Understanding*, 96(3):367–392, December 2004. ISSN 10773142. doi: 10.1016/j.cviu.2004.03.016. URL <http://linkinghub.elsevier.com/retrieve/pii/S1077314204000542>. (Cited on page 36.)
- Carlos Hernández Esteban and Francis Schmitt. Silhouette and stereo fusion for 3D object modeling. In *3-D Digital Imaging and Modeling*, pages 46–53. IEEE, 2003. ISBN 0-7695-1991-1. doi: 10.1109/IM.2003.1240231. URL <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1240231>. (Cited on page 61.)
- B. K P Horn. Hill shading and the reflectance map. *Proceedings of the IEEE*, 69(1):14–47, January 1981. ISSN 0018-9219. doi: 10.1109/PROC.1981.11918. (Cited on page 126.)
- ICOM. Lightweight information describing objects. <http://network.icom.museum/cidoc/working-groups/data-harvesting-and-interchange/what-is-lido/>, 2010. (Cited on pages 83 and 92.)
- Natraj Iyer, Subramaniam Jayanti, Kuiyang Lou, Yagnanarayanan Kalyanaraman, and Karthik Ramani. Three-dimensional shape searching: State-of-the-art review and future trends. *Computer-Aided Design*, page 509–530, 2005. (Cited on pages 54 and 147.)
- Michael Kazhdan, Matthew Bolitho, and Hugues Hoppe. Poisson surface reconstruction. In *Proceedings of the fourth Eurographics symposium on Geometry processing*, pages 61–70, Cagliari, Sardinia, Italy, 2006. Eurographics Association. ISBN 3-905673-36-3. (Cited on page 64.)
- Konika Minolta. Konica minolta 3D scanners or konica minolta scanners. <http://sensing.konicaminolta.us/applications/3d-scanners/>, 2013. (Cited on page 31.)
- Mary Kutraki and Martin Doerr. Mapping LIDO v0.7 to CIDOC-CRM v5.0.1. Technical report, ICS-FORTH, March 2010. URL http://cidoc.ics.forth.gr/crm_mappings.html#lido. (Cited on page 96.)
- D. La Rie and E. René. Fluorescence of paint and varnish layers (part i). *Studies in Conservation*, 27(1):1–7, 1982. (Cited on page 129.)

- Christian Lahanier. *La Joconde: essai scientifique*. Codex images international, Paris, 2007. ISBN 9782916407081. (Cited on page 31.)
- Christian Lahanier, Geneviève Aitken, Jiro Shindo, Ruven Pillay, Kirk Martinez, and Paul Lewis. EROS: an internal open multilingual platform for image content retrieval dedicated to conservation-restoration exchange between cultural institutions. In *Proc. International Council of Museums Conference*. ICOM, 2002. (Cited on page 87.)
- Christian Lahanier, Denis Pitzalis, Oliver Feihl, Michel Jeanlin, and Francis Schmitt. Three-dimensional modelling of archaeological objects for conservation, visualization, colour and shape characterization: comparison of details. *International Council of Museums. Committee for Conservation. Triennial Meeting (14 : Haag) 2005 14th Triennial Meeting, The Hague, 12-16 September 2005 : Vol. 1 /preprints.*, s. 43-52, 2005. (Cited on page 138.)
- Frédéric Larue, Marco Di Benedetto, Matteo Dellepiane, and Roberto Scopigno. From the digitization of cultural artifacts to the web publishing of digital 3D collections: an automatic pipeline for knowledge sharing. *Journal of Multimedia*, 7(2), April 2012. ISSN 1796-2048. doi: 10.4304/jmm.7.2.132-144. URL <http://ojs.academypublisher.com/index.php/jmm/article/view/7120>. (Cited on page 25.)
- Patrick Le Boeuf, Patrick Sinclair, Kirk Martinez, Paul Lewis, Geneviève Aitken, and Christian Lahanier. Using an ontology for interoperability and browsing of museum, library and archive information. In *International Council of Museums 14th Triennial Meeting*. ICOM Committee for Conservation, 2005. URL <http://eprints.ecs.soton.ac.uk/14790/>. (Cited on page 92.)
- M. Levoy, K. Pulli, B. Curless, S. Rusinkiewicz, D. Koller, L. Pereira, M. Ginzton, S. Anderson, J. Davis, J. Ginsberg, et al. The digital michelangelo project: 3D scanning of large statues. In *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, page 131–144, 2000. (Cited on page 16.)
- David G. Lowe. Distinctive image features from scale-invariant keypoints. *Int. J. Comput. Vision*, 60(2):91–110, November 2004. ISSN 0920-5691. doi: 10.1023/B:VISI.0000029664.99615.94. URL <http://dx.doi.org/10.1023/B:VISI.0000029664.99615.94>. (Cited on page 70.)
- K. V. Mardia and I. L. Dryden. The statistical analysis of shape data. *Biometrika*, 76(2):271–281, June 1989. ISSN 0006-3444, 1464-3510. doi: 10.1093/biomet/76.2.271. URL <http://biomet.oxfordjournals.org/content/76/2/271>. (Cited on page 139.)
- Kirk Martinez, John Cupitt, David Saunders, and Ruven Pillay. Ten years of art imaging research. *Proceedings of the IEEE*, 90(1):28–41, January 2002. ISSN 0018-9219. doi: 10.1109/5.982403. (Cited on page 125.)

- m.c. schraefel, Maria Karam, and Shengdong Zhao. mspace: interaction design for user-determined, adaptable domain exploration in hypermedia. In Paul De Bra, editor, *AH 2003: Workshop on Adaptive Hypermedia and Adaptive Web Based Systems*, pages 217–235, 2003. URL <http://eprints.soton.ac.uk/258803/>. Event Dates: August 26. (Cited on page 89.)
- Meshlab. 3D scanning and unrolling an ancient seal. <http://meshlabstuff.blogspot.org/2009/11/3d-scanning-and-unrolling-ancient-seal.html>, 2009a. (Cited on page 66.)
- Meshlab. Meshing point clouds. <http://meshlabstuff.blogspot.fr/2009/09/meshing-point-clouds.html>, 2009b. (Cited on page 145.)
- Michael Culture. Michael culture website. <http://www.michael-culture.eu/>, 2007. (Cited on page 4.)
- Minerva. MINERVA EC website. <http://www.minervaeurope.org/>, 2006. (Cited on page 4.)
- Jean-Pierre Mohen, Michel Menu, and Bruno Mottin, editors. *Mona Lisa: inside the painting*. Abrams, New York, 2006. ISBN 9780810943155. (Cited on page 31.)
- T. Moon, M.R. Schilling, and S. Thirkettle. A note on the use of false-color infrared photography in conservation. *Studies in conservation*, page 42–52, 1992. (Cited on page 126.)
- Maria Pia Morigi, Franco Casali, Andrea Berdondini, Matteo Bettuzzi, Davide Bianconi, Rosa Brancaccio, Alice Castellani, Vincenzo D’Errico, Alessandro Pasini, Alberto Rossi, C. Labanti, and Nicolangelo Scianna. X-ray 3D computed tomography of large objects: investigation of an ancient globe created by vincenzo coronelli. *SPIE6618 O3A: Optics for Arts, Architecture, and Archaeology*, pages 66180A–66180A, July 2007. doi: 10.1117/12.725986. URL <http://dx.doi.org/10.1117/12.725986>. (Cited on page 41.)
- M.P. Morigi, F. Casali, M. Bettuzzi, R. Brancaccio, and V. D’Errico. Application of x-ray computed tomography to cultural heritage diagnostics. *Applied Physics A*, 100(3):653–661, September 2010. ISSN 0947-8396. doi: 10.1007/s00339-010-5648-6. URL <http://dx.doi.org/10.1007/s00339-010-5648-6>. (Cited on page 16.)
- Gero Müller, Gerhard H. Bendels, and Reinhard Klein. Rapid synchronous acquisition of geometry and BTF for cultural heritage artefacts. In *Proceedings of the 6th International Symposium on Virtual Reality, Archaeology and Cultural Heritage (VAST)*, pages 13–20, November 2005. URL <http://cg.cs.uni-bonn.de/aigaion2root/attachments/mueller-2005-rapid.pdf>. (Cited on page 29.)

- Museumdat. Harvesting format for providing core data from museum holdings. <http://www.museumdat.org/>, May 2009. (Cited on page 92.)
- NextEngine. NextEngine 3D laser scanner. <http://www.nextengine.com/products/scanner/specs>, 2013. (Cited on page 31.)
- NISO. *Understanding metadata*. NISO Press, Bethesda, MD, 2004. ISBN 9781880124628 1880124629. (Cited on page 96.)
- Robert Osada, Thomas Funkhouser, Bernard Chazelle, and David Dobkin. Matching 3D models with shape distributions. In *Proceedings of the International Conference on Shape Modeling & Applications*, SMI '01, page 154–, Washington, DC, USA, 2001. IEEE Computer Society. ISBN 0-7695-0853-7. URL <http://dl.acm.org/citation.cfm?id=882486.884103>. (Cited on page 148.)
- N. Paparoditis, P. Julien, L. Polidori, G. Maillet, A. Dupérêt, O. Jamet, and O. Disard. *Photogrammétrie numérique*, chapter 3. ENSG - IGN. Hermes Science, 2001. (Cited on page 36.)
- Eric Paquet and Marc Rioux. Nefertiti: a query by content software for three-dimensional models databases management. In *3-D Digital Imaging and Modeling*, pages 345–352. IEEE Comput. Soc. Press, 1997. ISBN 0-8186-7943-3. doi: 10.1109/IM.1997.603886. URL <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=603886>. (Cited on page 148.)
- Eric Paquet, Christian Lahanier, Denis Pitzalis, S. Peters, Geneviève Aitken, and H.L. Viktor. Content-based indexing, retrieval and storage of cultural heritage data: an integrated and long-term approach to documentation with application to the EROS database. In Marinos Ioannides, David B. Arnold, Franco Niccolucci, and K Mania, editors, *Proceedings of the Joint VAST/CIPA/EGWS G&CH/EuroMed Conference*, volume Project Papers, Limassol, 2006. Archaeolingua. ISBN 9638046759. URL <http://diglib.eg.org/EG/DL/PE/EuroMed/CIPA-VAST06/CIPA-VAST06P/>. (Cited on pages ix, 148 and 149.)
- George Pavlidis, Anestis Koutsoudis, Fotis Arnaoutoglou, Vassilios Tsioukas, and Christodoulos Chamzas. Methods for 3D digitization of cultural heritage. *Journal of Cultural Heritage*, 8(1):93–98, January 2007. ISSN 1296-2074. doi: 10.1016/j.culher.2006.10.007. URL <http://www.sciencedirect.com/science/article/pii/S129620740600121X>. (Cited on pages 27 and 44.)
- Michel Paysant. OnLab. <http://www.michelpaysant.fr/onlab/>, 2010. (Cited on page 58.)
- Anna Pelagotti, Luca Pezzati, Alessandro Piva, and Andrea Del Mastio. Multispectral UV fluorescence analysis of painted surfaces. In *14th European Signal Processing Conference*, Florence, Italy, September 2006. EURASIP. URL <http://www.urasip.org/Proceedings/Eusipco/Eusipco2006/papers/1568987270.pdf>. (Cited on page 128.)

- Ruven Pillay, Geneviève Aitken, Denis Pitzalis, and Christian Lahanier. Archive visualization and exploitation at the C2RMF. In *ICHIM 2007*, Toronto, Ontario, Canada, October 2007. (Cited on page 127.)
- Denis Pitzalis, Christian Lahanier, Ruven Pillay, Geneviève Aitken, A. Russell, D. A. Smith, Patrick Sinclair, Matthew Addis, Richard Lowe, Shahbaz Hafeez, Paul Lewis, Kirk Martinez, and m c schraefel. Semantically exposing existing knowledge repositories: a case study in cultural heritage. In *The first international conference on Semantics And digital Media Technology (SAMT 2006)*, 2006. URL <http://eprints.ecs.soton.ac.uk/14270/>. (Cited on pages 6, 90 and 92.)
- Denis Pitzalis, Christian Lahanier, Geneviève Aitken, Ruven Pillay, Karina Rodriguez-Echavarria, and David B. Arnold. 3D techniques to create interactive virtual museums: The state of the art in the epoch noe. In *GRAPP (AS/IE)*, pages 197–203. SciTePress - Science and and Technology Publications, 2007. ISBN 978-972-8865-71-9, 978-972-8865-72-6. (Cited on page 5.)
- Denis Pitzalis, Ilenia Cassan, Laurette Thomas, and Alessandra Gianoncelli. Non-destructive analyses for modern paintings: The russian avant-garde case. In *9th International Conference on NDT of Art*, 2008a. (Cited on pages 5 and 14.)
- Denis Pitzalis, Paolo Cignoni, Michel Menu, and Geneviève Aitken. 3D enhanced model from multiple data sources for the analysis of the cylinder seal of ibni-sharrum. In *VAST 2008: The 9th International Symposium on Virtual Reality, Archaeology, and Cultural Heritage*, pages 79–84, Braga, Portugal, December 2008b. Eurographics Association. doi: 10.2312/VAST/VAST08/079-084. URL <http://diglib.eg.org/EG/DL/WS/VAST/VAST08/079-084.pdf>. (Cited on page 5.)
- Denis Pitzalis, Franco Niccolucci, Maria Theodoridou, and Martin Doerr. LIDO and CRMdig from a 3D cultural heritage documentation perspective. In *Proceedings of the 11th International conference on Virtual Reality, Archaeology and Cultural Heritage*, VAST10, page 87–95, Aire-la-Ville, Switzerland, Switzerland, 2010. Eurographics Association. ISBN 978-3-905674-29-3. (Cited on pages 90 and 92.)
- Denis Pitzalis, Jaime Kaminski, and Franco Niccolucci. 3D-COFORM: making 3D documentation an everyday choice for the cultural heritage sector. *Virtual Archaeology Review*, 2(4):145–146, 2011a. ISSN 1989-9947. URL <http://varjournal.es>. (Cited on page 5.)
- Denis Pitzalis, Franco Niccolucci, and Matthieu Cord. Using LIDO to handle 3D cultural heritage documentation data provenance. In *Content-Based Multimedia Indexing (CBMI), 2011 9th International Workshop on*, pages 37–42, Madrid, June 2011b. IEEE. ISBN 978-1-61284-432-9. doi: 10.1109/CBMI.2011.5972517. (Cited on page 6.)

- Denis Pitzalis, Elina Christophorou, Niki Kyriakou, Aristoula Georgiadou, and Franco Niccolucci. Building scholar e-communities using a semantically aware framework: Archaia kypriaki grammateia digital corpus. In *VAST 2012: the 13th EUROGRAPHICS Workshop on Graphics and Cultural Heritage*, pages 89–95, Brighton, UK, 2012. Eurographics Association. ISBN 978-3-905674-39-2. doi: 10.2312/VAST/VAST12/089-095. URL <http://diglib.eg.org/EG/DL/WS/VAST/VAST12/089-095.pdf>. (Cited on page 6.)
- Presious. PREdictive digitization, reStoration and degradatIOon assessment of cultUral heritage objectS. http://cordis.europa.eu/projects/rcn/106904_en.html, 2013. (Cited on page 43.)
- G. Revel and Christian Lahanier. Gallo-roman white clay figurine analysis for provenance characterization. *Fresenius' journal of analytical chemistry*, 341(10):615–618, 1991. (Cited on pages 19 and 135.)
- Alejandro Ribes, Ruven Pillay, Francis Schmitt, and Christian Lahanier. Studying that smile. *IEEE SIGNAL PROCESSING MAGAZINE*, 25(4):14–26, July 2008. ISSN 1053-5888. doi: 10.1109/MSP.2008.923091. (Cited on page 132.)
- Alejandro Ribés, Francis Schmitt, Ruven Pillay, and Christian Lahanier. Calibration and spectral reconstruction for CRISATEL: an art painting multispectral acquisition system. *Journal of Imaging Science and Technology*, 49(6):563–573, 2005. (Cited on pages 128 and 131.)
- Greg Richards, editor. *Cultural tourism in Europe*. CAB International, Wallingford, UK, 1996. ISBN 0851991041. (Cited on page 9.)
- J.T. Richtsmeier, J.M. Cheverud, and S. Lele. Advances in anthropological morphometrics. *Annual Review of Anthropology*, 21:283–305, 1992. (Cited on page 139.)
- Marc Rioux. Digital 3D imaging: theory and applications. In *Proc. SPIE2350*, volume 2, pages 2–15, Boston, USA, October 1994. doi: 10.1117/12.189122. URL <http://dx.doi.org/10.1117/12.189122>. (Cited on page 31.)
- S. Rusinkiewicz and M. Levoy. Efficient variants of the ICP algorithm. In *Third International Conference on 3-D Digital Imaging and Modeling, 2001. Proceedings*, pages 145–152, 2001. doi: 10.1109/IM.2001.924423. (Cited on page 49.)
- Phillipe Salembier and Thomas Sikora. *Introduction to MPEG-7: Multimedia Content Description Interface*. John Wiley & Sons, Inc., New York, NY, USA, 2002. ISBN 0471486787. (Cited on page 85.)
- J. I. San José Alonso, J. Martínez Rubio, J. J. Fernández Martín, and J. García Fernández. Comparing time-of-flight and phase-shift. the survey of the royal pantheon in the basilica of san isidoro (león). In *ISPRS - International Archives of the Photogrammetry, Remote Sensing and*

- Spatial Information Sciences*, volume XXXVIII-5/W16, page 377–385, 2011. doi: 10.5194/isprsarchives-XXXVIII-5-W16-377-2011. URL <http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XXXVIII-5-W16/377/2011/>. (Cited on page 40.)
- Giovanna Sansoni, Marco Trebeschi, and Franco Docchio. State-of-the-art and applications of 3D imaging sensors in industry, cultural heritage, medicine, and criminal investigation. *Sensors*, 9(1):568–601, 2009. ISSN 1424-8220. doi: 10.3390/s90100568. URL <http://www.mdpi.com/1424-8220/9/1/568>. (Cited on page 27.)
- David Saunders, Rachel Billinge, John Cupitt, Nick Atkinson, and Haida Liang. A new camera for high-resolution infrared imaging of works of art. *Studies in Conservation*, 51(4):277–290, January 2006. (Cited on page 128.)
- Martin Schröttner, Sven Havemann, Maria Theodoridou, Martin Doerr, and Dieter W. Fellner. A generic approach for generating cultural heritage metadata. In *Progress in Cultural Heritage Preservation*, volume 7616 of *Lecture Notes in Computer Science*, pages 231–240. Springer Berlin Heidelberg, January 2012. ISBN 978-3-642-34233-2. (Cited on page 78.)
- SCULPTEUR. Sculpteur website. <http://www.sculpteur.ecs.soton.ac.uk/>, April 2002. (Cited on pages 4 and 24.)
- N. Shadbolt, Tim Berners-Lee, and W. Hall. The semantic web revisited. *IEEE Intelligent Systems*, 21(3):96–101, May 2006. ISSN 1541-1672. doi: 10.1109/MIS.2006.62. URL <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1637364>. (Cited on page 78.)
- Yogesh L. Simmhan, Beth Plale, and Dennis Gannon. A survey of data provenance in e-science. *SIGMOD Rec.*, 34(3):31–36, September 2005. ISSN 0163-5808. doi: 10.1145/1084805.1084812. (Cited on page 90.)
- Dennis E. Slice. *Modern morphometrics in physical anthropology*. Developments in primatology. Kluwer Academic/Plenum Publishers, New York, 2005. ISBN 0306486970. (Cited on page 139.)
- Noah Snavely, Steven M. Seitz, and Richard Szeliski. Photo tourism: exploring photo collections in 3D. *ACM Trans. Graph.*, 25(3):835–846, July 2006. ISSN 0730-0301. doi: 10.1145/1141911.1141964. URL <http://doi.acm.org/10.1145/1141911.1141964>. (Cited on page 70.)
- Sarah Staniforth. Retouching and colour matching: The restorer and metamerism. *Maney Publishing on behalf of the International Institute for Conservation of Historic and Artistic Works*, 30(3):101–111, August 1985. ISSN 00393630. doi: 10.2307/1505925. URL <http://www.jstor.org/stable/1505925>. Article-Type: research-article / Full publication date: Aug., 1985 / Copyright © 1985

- International Institute for Conservation of Historic and Artistic Works. (Cited on page 128.)
- Johan W. Tangelder and Remco C. Velkamp. A survey of content based 3D shape retrieval methods. *Multimedia Tools Appl.*, 39(3):441–471, September 2008. ISSN 1380-7501. doi: 10.1007/s11042-007-0181-0. URL <http://dx.doi.org/10.1007/s11042-007-0181-0>. (Cited on pages 54 and 147.)
- P. Targowski, B. Rouba, M. Wojtkowski, and A. Kowalczyk. The application of optical coherence tomography to non-destructive examination of museum objects. *Studies in conservation*, page 107–114, 2004. (Cited on page 16.)
- Maria Theodoridou, Yannis Tzitzikas, Martin Doerr, Yannis Marketakis, and Valantis Melessanakis. Modeling and querying provenance by extending CIDOC CRM. *Distributed and Parallel Databases*, 2010. (Cited on pages 94 and 95.)
- David Tingdahl and Luc Gool. A public system for image based 3D model generation. In André Gagalowicz and Wilfried Philips, editors, *Computer Vision/Computer Graphics Collaboration Techniques*, volume 6930, pages 262–273. Springer Berlin Heidelberg, Berlin, Heidelberg, 2011. ISBN 978-3-642-24135-2, 978-3-642-24136-9. URL http://www.springerlink.com/index/10.1007/978-3-642-24136-9_23. (Cited on page 38.)
- Tony Tung and Francis Schmitt. Augmented reeb graphs for content-based retrieval of 3D mesh models. *International Conference on Shape Modeling and Applications*, pages 157–166, 2004. doi: <http://doi.ieeecomputersociety.org/10.1109/SMI.2004.1314503>. (Cited on page 148.)
- UNESCO. Cultural heritage and tourism development: a report on the international conference on cultural tourism. In *International Conference on Cultural Tourism : and World Tourism Organization*. World Tourism Organization, 2001. ISBN 9789284404841. (Cited on page 9.)
- UNESCO. Convention for the safeguarding of intangible cultural heritage, 2003. URL <http://www.unesco.org/culture/ich/index.php?lg=en&pg=00006>. (Cited on page 10.)
- UNESCO. Convention on the protection and the promotion of the diversity of cultural expressions, 2005. URL <http://www.unesco.org/culture/ich/index.php?lg=en&pg=00006>. (Cited on page 10.)
- Visual Resource Association. Vra core website. <http://www.vraweb.org/projects/vracore4/>, 2011. (Cited on page 85.)
- Michael Weinmann, Christopher Schwartz, Roland Ruiters, and Reinhard Klein. A multi-camera, multi-projector super-resolution framework for structured light.

- In *3D Imaging, Modeling, Processing, Visualization and Transmission (3DIMPVT)*, 2011 International Conference on, page 397–404. IEEE Computer Society's Conference Publishing Services, May 2011. ISBN 978-1-61284-429-9. doi: 10.1109/3DIMPVT.2011.57. URL <http://ieeexplore.ieee.org/search/srchabstract.jsp?tp=&arnumber=5955387>. (Cited on page 55.)
- Wikipedia. Photogrammetry. <http://en.wikipedia.org/wiki/photogrammetry>, May 2013a. Page Version ID: 554872808. (Cited on page 38.)
- Wikipedia. Semantic web. http://en.wikipedia.org/wiki/Semantic_Web, June 2013b. Page Version ID: 561039754. (Cited on page 78.)
- Wikipedia. Semantic web stack. http://en.wikipedia.org/wiki/Semantic_Web_Stack, May 2013c. Page Version ID: 555346242. (Cited on pages vii, 80 and 81.)
- Raymond Williams. *Culture and society, 1780-1950*. Columbia University Press, New York, 1958. (Cited on page 9.)
- Raymond Williams. *Keywords: A Vocabulary of Culture and Society*. Fontana communications series. Fontana/Croom Helm, 1976. ISBN 9780856642890. URL <http://books.google.co.in/books?id=UqkOAAAAQAAJ>. (Cited on page 9.)

Appendix A

Publications

A.1 Papers

- Pitzalis, D., Christophorou, E., Kyriakou, N., Georgiadou, A., Niccolucci, F. (2012). Building scholar e-communities using a semantically aware framework: Archaia Kypriaki Grammateia Digital Corpus. In VAST: International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage (pp. 89-95). The Eurographics Association.
- Niccolucci, F., Spearman, M., Pitzalis, D. (2012). Documenting Abu Simbel: The 3D-COFORM Approach". In Electronic Imaging and the Visual Arts: EVA 2012 Florence (pp. 46–50). Firenze University Press.
- Pitzalis, D., Niccolucci, F., Cord, M. (2011). Using LIDO to handle 3D cultural heritage documentation data provenance. In Content-Based Multimedia Indexing (CBMI), 2011 9th International Workshop on (pp. 37-42). IEEE.
- Pitzalis, D., Kaminski, J., Niccolucci, F. (2011). 3D-COFORM: Making 3D documentation an everyday choice for the cultural heritage sector. *Virtual Archaeology Review*, 2(4), 145-146.
- Bourdeu, A., Pitzalis, D. (2010). Geometric morphometrics for provenance determination of Gallo-Roman white clay figurines. In Proceedings of the 11th International conference on Virtual Reality, Archaeology and Cultural Heritage (pp. 25-31). Eurographics Association.
- Pitzalis, D., Niccolucci, F., Theodorou, M., Doerr, M. (2010, September). LIDO and CRM dig from a 3D cultural heritage documentation perspective. In Proceedings of the 11th International conference on Virtual Reality, Archaeology and Cultural Heritage (pp. 87-95). Eurographics Association.

- Pitzalis, D., Colantoni, P., Pillay, R., Aitken, G. (2008). GPU Spectral Viewer - A Tool for an Enhanced Colorimetric Perspective of Cultural Heritage. In GRAPP 2008, Proceedings of the Third International Conference on Computer Graphics Theory and Applications (pp. 492-496). INSTICC.
- Pitzalis, D., Cassan, I., Thomas, L., Gianoncelli, A. (2008). Non-Destructive Analysis for Modern Paintings: The Russian Avant-Garde Case. In Proceedings 9th International Conference on NDT of Art (pp.). NDT.
- Pitzalis, D., Aitken, G., Autrusseau, F., Babel, M., Cayre, F., Puech, W. (2008). Tsar: Secure transfer of high resolution art images. Electronic Imaging and the Visual Arts: EVA 2008 Florence. Firenze University Press.
- Pitzalis, D., Cignoni, P., Menu, M., Aitken, G. (2008). 3D Enhanced Model from Multiple Data Sources for the Analysis of the Cylinder Seal of Ibni-Sharrum. In VAST: International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage (pp. 79-84). The Eurographics Association.

A.2 Books

- “Heritage in the digital era”, Multi-Science Publishing, Ioannides, M., Pitzalis, D., Addison, A., Georgopoulos, A., Kalisperis, L., Brown, A. (Eds.), 2010.
- “VAST10: The 11th International Symposium on Virtual Reality, Archaeology and Cultural Heritage”, International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage, A. Artusi, M. Joly, G. Lucet, A. Ribes and D. Pitzalis Eds., Paris, France, Eurographics Association, 2010.
- “VAST09: The 10th International Symposium on Virtual Reality, Archaeology and Cultural Heritage”, International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage, K. Debattista, C. Perlingieri, D. Pitzalis, and S. Spina Eds., St. Julians, Malta, Eurographics Association, 2009.

A.3 Previous Papers

- Colantoni, P., Pitzalis, D., Pillay, R., Aitken, G. (2007). GPU Spectral Viewer: analysing paintings from a colorimetric perspective. In Proceedings of the 8th International conference on Virtual Reality, Archaeology and Intelligent Cultural Heritage (pp. 125-132). Eurographics Association.

- Pitzalis, D., Lahanier, C., Pillay, R., Rodriguez-Echavarría, K., Arnold, D. B. (2007). 3D techniques to create interactive virtual museums: The state of the art in the epoch noe. In GRAPP 2007, Proceedings of the Third International Conference on Computer Graphics Theory and Applications (pp. 197-203). INSTICC.
- Aitken, G., Lahanier, C., Pillay, R., Pitzalis, D. (2007). Archive Visualization and Exploitation at the C2RMF. In Proceedings of the International Cultural Heritage Informatics Meeting - ICHIM07.
- Aitken, G., Lahanier, C., Pillay, R., Pitzalis, D. (2006). Database Management and Innovative Applications for Imaging within Museum Laboratories. In Proceedings of the 7th European Conference “SAUVEUR”-Safeguarded Cultural Heritage-Understanding & Viability for the Enlarged Europe, Prague. ITAM (pp. 41-50).
- Colantoni, P., Pillay, R., Lahanier, C., Pitzalis, D. (2006). Analysis of multi-spectral images of paintings. In 14th European Signal Processing Conference (EUSIPCO 2006), Florence, Italy.
- Pitzalis, D., Pillay, R., Lahanier, C. (2006). A New Concept in High Resolution Internet Image Browsing. In ELPUB (pp. 291-298).

A.4 European Project Deliverables

- Pitzalis, D. (2012). Quality Assurance Components. SCAPE.
- Spearman, M., Inglis, E., Niccolucci, F., Pitzalis, D. (2011). Third Year Report WP10-13 – Business Strand Activities. 3D-COFORM.
- Pitzalis, D. (2011). Revised version of “User Requirement analysis and Functional Specifications”. 3D-COFORM.
- Pitzalis, D. (2010). Second Year Report WP10-13 – Business Strand Activities. 3D-COFORM.
- Pitzalis, D. (2009). First Year Report WP10-13 – Business Strand Activities. 3D-COFORM.
- Pitzalis, D. (2009). Initial version of “User Requirement analysis and Functional Specifications”. 3D-COFORM.

Appendix B

The Scientific Documentation Workflow

B.1 Scientific Imaging Techniques

When documenting an artwork the first important analysis is the naked eye observation. An experienced curator or art historian can attribute an artwork to an author by simply inspecting it and carefully look at the details. To validate these hypothesis, we will proceed with the Scientific Imaging techniques. In the field of Cultural Heritage, optical imaging techniques are appreciated and preferred to others for the safety and the effectiveness that characterize these diagnostic methodologies.

Using a painting as example, the first step is to take digital photos in natural light in order to better identify nuances, contrast and the color palette of the artwork. The power of the light source must be chosen carefully in order not to heat the artwork and not to produce any flashing on the surface. Images must be taken at the higher resolution possible, better if with a professional camera. As already demonstrated in [Martinez et al., 2002] and , camera resolution and lenses calibration are important parameters to obtain an image detailed enough to enable the experts to study the network of cracks, the adherence between the canvas and the paint film and of course, the details of the painting itself. Additional information about the artwork history (signature, museums stamp, wood or canvas provenance, etc.) can also appear on the back of the painting.

Scientific imaging or optical techniques is the term used to indicate all the methodologies based on the analysis of the response of an object subjected to electromagnetic stimulus in a spectral region included between the ultra-violet (UV) 400nm and the near infra-red 1100nm bands. If the measured information can be sampled

and represented in a bi-dimensional grid, a simple picture, then the related methodology is called ‘imaging’ technique. Among the imaging techniques we found IR reflectography [Bertani et al., 1990; Fontana et al., 2003], false colour [Moon et al., 1992], and UV fluorescence [Fabbri et al., 2000], all extensively used in artworks diagnostics, especially for paintings.

Here we describe the most common imaging techniques used for artworks study and documentation.

Raking Light Photography Raking light photography is very important in painting examination and is obtained by illuminating the painting’s surface from one side, with the light source placed almost parallel to the picture plane. This technique of illumination is used in the topographical study of a painting. We can highlight features such as undulations, brushwork, and other surface qualities that otherwise remain invisible. These features can easily be seen when photographed or recorded digitally. Conservators use raking light to judge aspects of the condition of a painting. While raking light is still a technique *di per se*, the use of a three dimensional surrogate make the raking light analysis available to more people, using digital visualization methods based on the web, without having to analyse the artwork physically or rely on 2D photos.

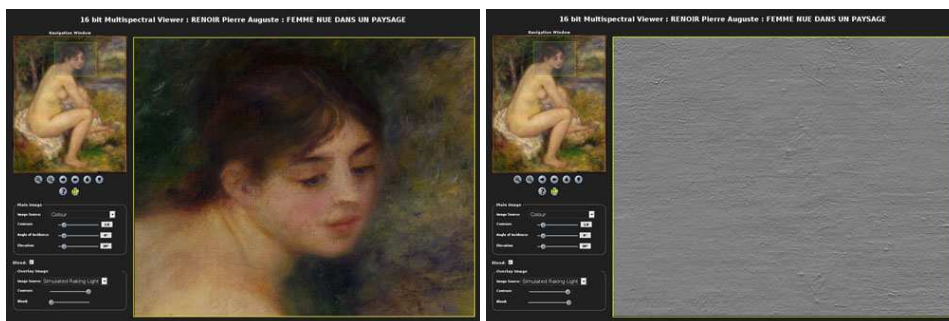


Figure B.1: “Femme Nue dans Un Paysage”, Pierre Auguste Renoir, 650 x 540 mm, oil on canvas, Musée de l’Orangerie, viewed using IIPImage: left) Colour rendering right) Dynamic simulated raking light. Courtesy of C2RMF

This is possible because 3D models of paintings give us height, vector normal and, in some cases, colour data. Drawing inspiration from cartography, we decided to perform dynamic topological shading rendering on top of IIPImage and allow the user to pan and zoom around the relief map. This was achieved by implementing a basic rendering technique of hill-shading [Horn, 1981] where a virtual directional illumination is used to create shading on virtual "hills" and adapting the normal map on a 2D tiff file format.

The big improvement compared to the typical technique is that the light source direction can be dynamically altered to simulate raking light photography from any angle. In [Pillay et al., 2007] we demonstrate how these renderings can be superimposed or blended with a colour image to more clearly visualize the surface topography as shown in Figure B.1.

Macro Photography Indeed one of the oldest and best techniques to observe artworks in detail is macro photography. The technique is not new and is a very simple concept compared to other analysis methods. Nevertheless, the hardware improvement acquisition devices have faced lately give the possibility to obtain great results from this technique. When a curator finds an area that looks interesting due to possible details he must be able to investigate more deeply. To do this, the technician commonly uses a small macro digital camera that, using as a light source a LED matrix, allows the technician to “walk on” the Region Of Interest (ROI) magnifying the surface using optical zoom and, if the acquired image is in good spatial quality, he can then apply a digital zoom as in Figure B.2. To achieve bigger levels of magnification, we must use other techniques like the binocular microscope, an invasive technique.



Figure B.2: “Gontcharova”, Private collection, details (left), digital zoom (right) macro photography (24X)

Infrared Reflectography (IR) Infra-red reflectography is a widely used non-destructive investigation technique mainly applied in the study of ancient paintings. Its simplicity of execution and the quantity of information an expert eye can retrieve from an Infra-red Reflectography image make this tool one of the most used tools in painting investigation. The peculiarity of infra-red reflectography is that it appears to be the best technique allowing under drawing detection, useful to document deeper paint layers and canvas status (this technique is also widely used in forensics).

Under drawing designates the compositional sketches done by the painter usually during the initial phase of the composition. These elements are of great importance to experts and professionals as they can provide crucial information about authorship as “pentimenti” (i.e. Figure B.3), changes in the painter’s original intentions, and previous interventions on the painting layer [Casadio and Toniolo, 2001]. This technique is the natural evolution of the infra-red photography which is limited to the real Near Infra-Red (NIR) 1050nm wavelength.

Modern customized digital “NIR” cameras can obtain images with a wavelength in the near infra-red (800nm – 2000nm wavelength) with a reasonable resolution [Saunders et al., 2006; Ribés et al., 2005]. Often it happens that with infra-red we identify not only under drawing or “pentimenti”, but also signatures, dates, and inscriptions or monograms that help in the characterization of the artwork. The difference in absorption between pigments and drawing creates a high contrast in the IR image and this is even more evident if the preparation layer is made with clear colours.

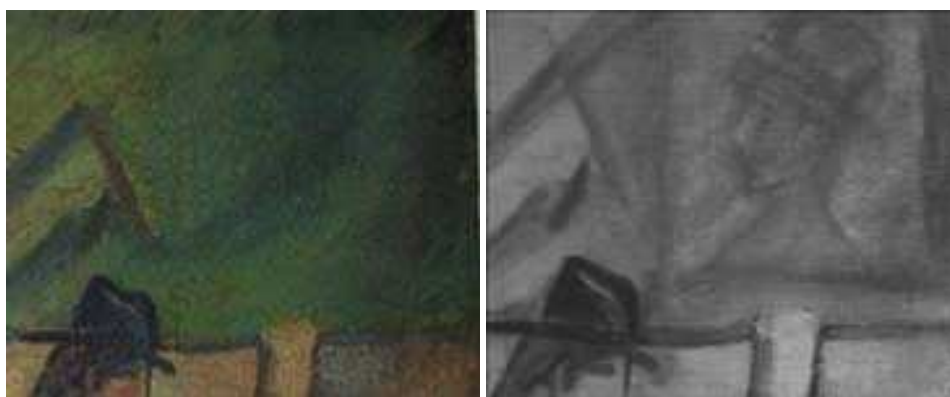


Figure B.3: “Promenade en Province”, M. Larionov, 1909 ca., Private collection, details: a) RGB color image. b) infra-red image, we can clearly see the under drawing otherwise invisible to the naked eye.

Moreover, if we compare the calibrated colour image with the different spectral images, we can assess the order in which the different painting layers have been applied.

False Colors False colour infra-red photography is often used in paintings to differentiate pigments with the same colour under a certain light, but corresponding to different chemical compositions and reflectance spectra. This effect is known as “metamerism” [Pelagotti et al., 2006; Staniforth, 1985] and it is due to the limited capacity of spectral light absorption of human eyes. The false colour effect is achieved by exploiting differences in the pigment reflectance characteristics in the

NIR band of the spectrum.

To perform the false colour, we use the output of the multi spectral digital acquisition (multiple images at different spectral wavelengths: red, green, blue and infra-red narrow bands are used) that we “combine” with a visible colour image. In the resulting colour image, or better, a “pseudo” colour image, we can see the contribution of the infra-red information making visible the differentiation of the material because of the existing differences in the reflectance spectrum.

Ultraviolet Photography (UV) Opposite to infra-red, in terms of human eye perception and spectral signal, there is the ultraviolet light. In the case of cultural heritage artefacts, only near ultraviolet is used (between 320 and 400 *nm* wavelength). Technically speaking, it is an electromagnetic radiation with a wavelength shorter than 400 *nm* but longer than soft X-Rays (1-200 *nm*). Ultraviolet reflectography or photography is based on the measurement of the ultraviolet radiation reflected by the artwork. Typically the sample is illuminated directly with special ultraviolet light and the visible light is filtered using a blocking filter on the camera lens. These filters allow only the ultraviolet light to pass and impress the CCD (charge-coupled device) by stopping the visible and infra-red reflected light.

An improved version of ultraviolet photography is the ultraviolet fluorescence photography. This technique is slightly different than the previous one. The same ultraviolet light sources are used, but instead of filtering the reflected light, we filter directly the light source. In this way we stop the visible light and only the ultraviolet light excites the painting surface. This last method, in artwork studies, allows us to identify different varnishes and over-paintings additions [La Rie and René, 1982].

Indeed, photons in the UV region of the spectrum are absorbed by the painting varnish and this effect allows us to characterize the materials used, to evaluate the artwork’s state of conservation and to localize retouches and previous restorations [Berns, 2001]. Information about the age of the artwork can be retrieved by the interpretation of these images. In an aged painting the original varnish has different fluorescence properties than new layers. On the other hand, in the case of modern pigments we can notice a different fluorescent emission than from traditional pigments, even if they look alike under visible light. That means that the fluorescence of oil paintings under ultraviolet light shows if any restoration or retouch has been done. UV fluorescence can also be applied to other objects like porcelain, ceramics, books and paper.

Radiography (X-Ray) Radiography analysis is one of the oldest scientific image techniques used in the investigation of artworks. The first radiography on a painting was done in Germany in 1896 in the wave of interest arising from the discovery of X-Rays. Different to IR and UV wavelength the X rays cross the media depending on the nature of the chemical elements composing the analysed object and its thickness. Different media have different X-Ray photon absorption.

The radiography technique is well known and extensively applied in medicine. The image we get is a photograph of the artwork obtained by using X-Rays as a light source, and it can provide information about its structure, its assemblage, the state of the canvas, possible restorations, etc. Parameters such as energy, intensity of radiation, and the time of exposition are chosen according to the object characteristics. In cases where radiography cannot be used directly, for example if the painting has a preparation done using “Lead white” or if the support is on metal or if the thickness of the artwork is preventing X-Ray transmission, it is possible to use X-ray emissiography. While X-Ray radiography is measuring the intensity transmitted by the artwork, X-Ray emissiography is based on the measurements of the secondary electrons emitted by the sample, therefore giving only information on the surface of the object.

Multispectral Imaging In Figure B.6 is the representation of the spectra reflectance of the indicated point in the “Mona Lisa” painting by Leonardo da Vinci. The series of images are the result of a multi-spectral acquisition of the painting using a special camera developed during the “CRISATEL” European project [Ribés et al., 2005] in which I have participated.

The CRISATEL camera produces 13 channel images which correspond to the following frequencies: 400, 440, 480, 520, 560, 600, 640, 680, 720, 760, 800, 900 and 1000nm. Only the first 10 planes interact with the visible part of the spectrum (they are visible to the human eye). Considering this, the XYZ() tri-stimulus mathematical representation of the colour for each point is:

$$\begin{cases} X = \sum_{\lambda=400}^{\lambda=760} x(\lambda).R(\lambda).V(\lambda).L(\lambda) \\ Y = \sum_{\lambda=400}^{\lambda=760} x(\lambda).R(\lambda).V(\lambda).L(\lambda) \\ Z = \sum_{\lambda=400}^{\lambda=760} x(\lambda).R(\lambda).V(\lambda).L(\lambda) \end{cases} \quad (\text{B.1})$$

where $R(\lambda)$ is the reflectance spectrum, $V(\lambda)$ is the varnish transmittance (used in simulations) and $L(\lambda)$ is the light spectrum (used as illuminant). Using this formulae we can compute the resulting XYZ values for each pixel of the source image. Of course, the obtained values are only an approximation of the values that would be measured in front of the original painting using a spectrophotometer, but they are close enough. The results of this acquisition have been presented in [Colantoni et al., 2006] and [Ribes et al., 2008].

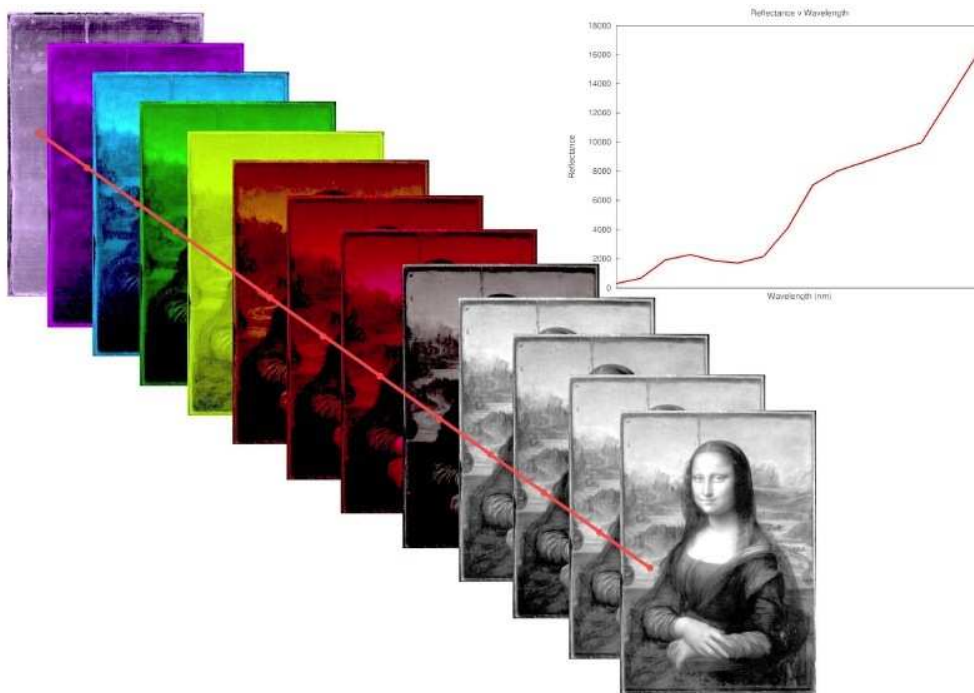


Figure B.4: Multi-spectral acquisition of the Mona Lisa painting from Leonardo da Vinci. Louvre Museum.

B.2 Physical and Chemical Analysis

Once the problematic of the artwork is well contextualized with the imaging techniques, physical/chemical analyses may be needed to confirm what has been discovered about the nature of the materials. X-Ray fluorescence and raman are not invasive (we do not need to sample our object), while SEM-EDS microscopy need a sample of the pictorial layer.

Fluorescence X-Ray X-Ray Fluorescence (XRF) is one of the most utilized elemental analysis techniques in the cultural heritage field, since it's a non-destructive and non-invasive method able to identify the chemical elements present in the sample. When an X-Ray beam is directed on a sample, the radiation can be either absorbed or scattered. During the absorption processes an electron from an inner shell could be ejected creating a vacancy, and therefore an unstable condition. When the atom returns to its stable condition, an X-Ray photon is emitted. Each element has a unique set of energy levels, therefore the produced X-Ray photons can only be characterized by a unique set of energy values, that is a "fingerprint" for each chemical element. XRF can then identify and quantify the different elements

present in the object. Qualitative analyses allow the identification of the chemical element, and quantitative analyses allow us to determine the object's chemical composition [Gianoncelli et al., 2006].

The XRF technique fluorescence X-Ray allows us to identify anachronistic pigments or recognize restorations. XRF analyses on metallic sculpture can also reveal possible later additions. The limitations of X-Ray fluorescence examination is its inability to recognize organic elements (the fluorescence of light elements is easily absorbed by air) and traces of elements. Portable X-Ray spectrometers, as the one I have been using, allow for the analysis of artworks *in situ*, without removing and touching the paintings, reassuring curators that their pieces can be examined safely.

Raman Raman spectroscopy relies on the measurement of the wavelength and intensity of inelastically scattered light from molecules. Typically the sample is illuminated with a laser beam in the visible, near infra-red, or near ultraviolet range. Most of the light is elastically scattered by the sample, while a minimal part (normally less than a difference of one frequency from the incident photons), modifies its wavelength because of the inelastic interaction with the atoms that constitute the material.

A plot of intensity of the scattered light versus the energy difference is a Raman spectrum. The material can be identified by the measurement of the wavelength shift: Raman spectroscopy provides in fact a fingerprint by which the molecules can be identified. Raman spectrometers can be combined with a microscope or camera in order to image the sample and simultaneously the Raman spectrum. Portable Raman instruments are also available and quite commonly used allowing analyses directly *in situ*. Raman analyses are non-destructive and non-invasive therefore this technique became one of the most used for pigment identification in paintings, colored sculptures, manuscripts or ceramics.

A limitation occurring when analyzing artwork pigments with Raman spectroscopy is that the presence of varnish and binders usually distort the asset.

Scanning Electron Microscope SEM analysis is an invasive technique of investigation. It requires sampling the artwork. This sample is normally very small, less than a milligram in weight and it is taken from well-chosen region of interest. Metal specimens require no special preparation, while nonconductive solid specimens should be coated with a layer of conductive material (graphite, gold...).

A high energy electron beam is directed on the sample and from the interaction electrons-sample different signals are generated. Secondary electrons produce a

3D image with the morphological structure; the back scattering electrons give the distribution of elements with different atomic numbers; the X rays emitted by the sample allow qualitative and quantitative identification of chemical elements offering the possibility of acquiring elemental mapping distribution.

This technique is widely used since it makes it possible to observe morphological characteristics of the sample and elemental information, when combined with Energy Dispersive Spectroscopy (EDS), providing high spatial resolution (nm) and high magnification (some SEM models can reach 100000 x enlargements). The main limitations of this technique are the sample preparation, the sample environment (in vacuum), and low detection limits for organic elements.

Appendix C

Other Case Studies

C.1 The Gallo-Roman White Clay Figurines

C.1.1 Methodology

Archaeological studies [Bemont et al., 1993] reveal that these figurines were produced in definite workshops by a reduced number of artists. Although the location of discovery of the statuettes is usually a good indicator of the workshop of origin, evidences such as chemical composition [Revel and Lahanier, 1991] or signatures of known artists found on the figurines reveal that some of the statuettes have been found far from their place of production because of the cultural and economic exchanges between Gallo-Roman settlements C.1.



Figure C.1: Main sites of origin of Gallo-Roman white clay figurines

Dating from the beginning of the Christian era, terracotta statuettes appear in the archaeological remains of the Gallo-Roman settlements of the Allier and Loire

valleys in France. These figurines were made of white clay and had a decorative as well as a religious role. They represent various gods and animals, but the main subjects used in our research are two types of goddesses - “Venus” and “Mother Goddesses”, visible in Figure C.2.



Figure C.2: Virtual models of two Mother Goddesses and a Venus. The second and the third are moulds.

The EROS database of the Centre de Recherche et de Restauration des Musées de France contains hundreds of three-dimensional models of Gallo-Roman statuettes. As all figurines differ by stylistic changes in the representation of their faces, clothes and hairstyles we had to choose carefully the acquisition technology to use to reflect these small variations. We considered photogrammetry, laser scanning and structured light (better explained in the next chapter) to carry out the task taking in account that: we had to scan some hundred of figurines, we had limited budget, white clay figurine have no texture. In this case then photogrammetry, while cheap and well mastered at C2RMF, has been set aside because too time consuming and the result would have high definition texture, not necessary in this case. Structured light would request few scan per statue resulting in a timely expensive operation compared to laser acquisition.

At the end the statues have been digitized using a laser scanner Minolta® VIVID 900 with a resolution of about $150 \times 150 \times 10 \mu m$ which allows the possibility to discern precise measurements and further geometric analyses.

In the past, the production of these figurines starts by the modelling of a *genotype* called, in literature, *archetype*, made by the *coroplaste* who was the artist entitled to work clay. The number of moulds used for each figurine depends on the complexity of the shape the *coroplaste* wants to represent: from 3 moulds, for a *Venus* comprising the two pieces for the front and the back and the base to the 13 pieces for a *Spinario*. Each mould extracted from a *genotype* is generally signed on the outer part to identify the name of the artist.

For our studies it is interesting to note that in the process of creation of the figurine during the drying and the baking process the object reduces in size. When the *genotype* and the moulds are worn, new castings are made using the existing figurines. This process produces generations of artefacts which are progressively smaller (approximately 10% reduction each time).

For the purpose of our research we used three-dimensional scans of Mother Goddesses and Venus to perform the morpho-metric analysis of the statuettes, in order to determinate a correlation between the variability of the shape of figurines and the origin of the figurines. This choice has been done because of the availability of many models coming from the same “ateliers”.

In the next section, we describe the choice for the placement of homologous points on the faces of the statuettes to account for the shape of the objects. Sets of points are used to perform a generalized Procrustes analysis, whose outputs serve for a principal component analysis. The visualization of principal components of the figurines outlines the relationship between the shape of the figurines and their locations of origin.

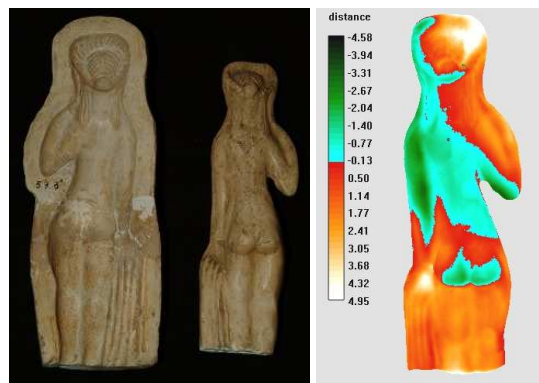


Figure C.3: (left) View of the figurines and the mould (right) minimal distances between the back side of the Venus and the corresponding mould

Choice of Dataset

The used set of figurines consists in 29 3D objects from the large collections of French Museums and conserved into the EROS database:

- 124 figurines conserved at the Bourbon-Lancy museum,
- 200 figurines at the Anne de Beaujeu museum in Moulins.

All chosen models are “Mother Goddesses” or “Venus” coming from 4 different workshop: Alise Sainte Reine (3 figurines), Laignes (1 figurine), Saint Pourçain sur Besbre (2 figurines) and Toulon sur Allier (19 figurine), as shown in Figure C.1. Some of the used models were moulds, which were used in the antiquity to copy figurines or to assort different front and back parts of two models. As we only take into account the “head” parts of the statuettes, this latter technique has no influence on our study. The use of moulds also explains why some statuettes are identical. For a better understanding of our results, we decided to cluster the locations of origins of the statuettes in 3 large groups of close locations:

- Alise Sainte Reine and Laignes;
- Saint Pourçain sur Besbre and Toulon sur Allier ;
- Vichy.

Data acquisition

The three-dimensional models were acquired using a Minolta®Vivid 900 laser scanner, which captures data from several points of view, and a Nikon®D2 to acquire the texture to register into the 3D model. The partial models went through an alignment, manually done, and were then refined by Interactive Closest Point, and a final post-processing step to provide a single virtual model of the figurine with an accuracy of tenths of microns. The laser scanner fits particularly the needs of archaeological and museological data digitization, as it works without contact. We used a laser scanner to get our three-dimensional virtual data, but any other 3D surface scanner technique can be used, including structured light scanning or photogrammetry.

In the specific case of white clay statuettes, laser scanners and structured light scanners are the most adapted because of the relative high resolution of the results which is needed in order to place the landmarks accurately.

Moreover, the white clay of the statuettes limits the possible problems linked to scanning optical devices as it shows limited reflectivity which is one of the conditions for laser acquisition. The acquisition process has been published in [Lahanier et al., 2005].

Computational Methods

In order to identify the landmarks to be used in our computational analysis, we applied a classical morphometric protocol for the analysis of shapes used in modern anthropology as described in [Richtsmeier et al., 1992; Slice, 2005]. The method suggested in consists in placing homologous points on the virtual objects, then applying a generalized Procrustes analysis on the sets of landmarks and finally projecting the aligned coordinates on principal axes. To quantify the variability of shapes, we need to define homologous points on each statuette. These landmarks are chosen to provide reproducible reference points corresponding to one of the three types of landmarks defined by [Bookstein, 1997]:

- Type I: discrete juxtaposition of tissues
- Type II: maxima of curvature or other local morphogenetic processes
- Type III: external points

After conducting a few tests we discovered that, in the case of moulds, mirroring the landmarks was sufficient to compensate the negative geometry of the objects, i.e. landmark # 1 in Figure C.4 becomes landmark # 4 in the mould.

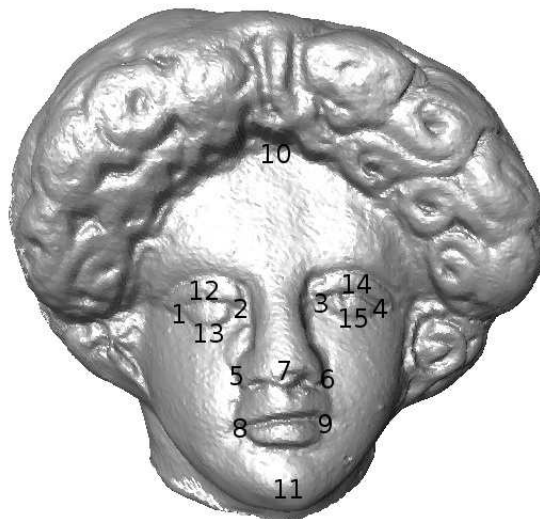


Figure C.4: Position of landmarks on a Venus head

Generalized Procrustes Analysis described in [Goodall, 1991], [Gower, 1975] and [Mardia and Dryden, 1989], is a method for the comparison of sets of landmark configurations. Coordinates of landmarks set to characterize the shape of statuettes

#	Landmark	Type
1	External corner of right eye	I
2	Internal corner of right eye	I
3	Internal corner of left eye	I
4	External corner of left eye	I
5	Right corner of the nose	III
6	Left corner of the nose	I
7	Most advanced point on the nose	III
8	Right corner of the mouth	I
9	Left corner of the mouth	I
10	Middle of hairline	I
11	Most advanced point of the chin	III
12	Upper point on the right eye line	III
13	Lower point on the right eye line	III
14	Upper point on the left eye line	III
15	Lower point on the left eye line	III

Table C.1: List of landmarks used to describe the shape of figurine faces

vary according to location and orientation of each object in the coordinates system of the digitizing device space. Generalized Procrustes analysis (GPA) solves this issue in scaling, rotating, and translating each object to minimize the sum of squared distances between homologous landmarks on each configuration and a mean configuration, which is iteratively computed. As already said, we know that each time a mould was put in an oven, it used to lose 8% to 10% of its volume because of water evaporation. Apart from the changes in size due to the artistic choices, this phenomenon is the reason why we have been forced to use a scale-invariant method, now described, for the analysis of the statuettes.

We consider n configurations matrices X_1, \dots, X_n , i.e. matrices of $k = 15$ landmarks in $m = 3$ dimensions.

1. *Translation.* Each configuration is centred to remove location, by calculating the centroid of each shape and translating it to the origin.

$$X_i^t = X_i - \frac{1}{k} \sum_{j=1}^k X_j \quad (\text{C.1})$$

2. *Scaling.* The configuration X_i^t is scaled to the Centroid Size, which is the square root of the sum of squared distances of a set of landmarks from their centroid.

$$CS = \sqrt{\sum_{j=1}^k \left(\left\| X_{i(j)} - \frac{1}{k} \sum_{j=1}^k X_{i(j)} \right\|^2 \right)} \quad (\text{C.2})$$

where $X_{i(k)} = (X_{i(k1)}, X_{i(k2)}, X_{i(k3)})^T$ is the coordinate vector for the k^{th} landmark.

$$X_i^s = \frac{X_i^t}{CS} \quad (C.3)$$

3. *Rotation.* For each configuration i , minimize the difference between the mean matrix and the configuration matrix. The mean matrix \bar{X} is the mean of all configuration matrices.

$$X_i^r = \min(\|X_i^s - \bar{X}\|) \quad (C.4)$$

After these 3 steps, a new mean configuration is calculated and the process is iterated until the mean configuration is stable. This process brings all landmark configurations to the same coordinate system in which the variations of coordinates of the landmarks expresses the variability of shapes.

High dimensionality (45 dimensions) of the shape vectors resulting from the GPA makes the interpretation of shape variability complicated without any further treatment. To address this issue, the morpho-metrical work-flow usually has recourse to Principal Component Analysis (PCA) to reduce the set of values accounting for the shape variability. PCA allows the provision of a basis for the visualization of the covariation among the shape variables and is the last step before the interpretation of data.

All morpho-metric and statistical analysis has been conducted using the EVAN tool kit [EVAN Society, 2011], an open-source framework specific to anthropology, already used and known by my colleague. The EVAN Toolbox is a software package developed by the European Virtual Anthropology Network and the EVAN-Society to facilitate form and shape analysis of objects featuring a complex geometry in three dimensions. It uses Geometric Morphometrics (GM) which includes methods such as General Procrustes Analysis, Principal Component Analysis, Thin-Plate Spline Warping or Partial Least Squares Analysis. The software also supports data acquisition, i.e. to locate landmarks and semi landmarks on surfaces.

C.1.2 Results

The superimposition of the 15 landmarks configuration (see Figure C.5) reveals that the shape of the faces of some groups of statuettes seems especially homogeneous. In particular, the statuettes coming from Vichy form a separate group which seems to have its own morpho-metric specificities. For the other groups of statuettes, a first analysis is more difficult, but the PCA allows the extraction of more information from the sets of landmarks.

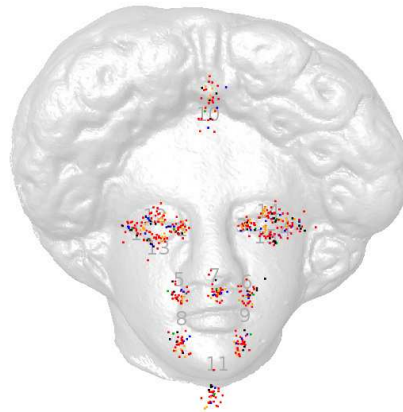


Figure C.5: Superimposition of the 29 landmark configurations after the GPA. Red: Toulon-sur-Allier, black: Alise-Sainte-Reine, blue: Saint-Pourçain-sur-Besbre, orange: Vichy, green: Laignes.

PCA reveals that the first and second principal components account for 99.3 % of the total variance. The repartition of the specimens along these two principal axes (see figure C.6) shows that the statuettes coming from Vichy are characterized by a negative score on PC1, while the ones coming from Alise-Sainte-Reine or Laignes are characterized by a positive score along PC2.

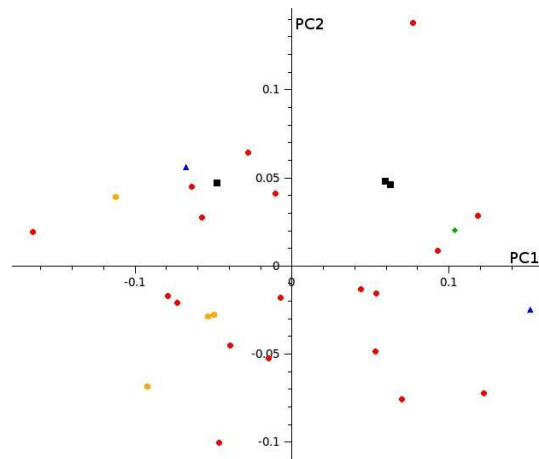


Figure C.6: First and second PC scores for the set of statuettes. Red: Toulon-sur-Allier, black: Alise-Sainte-Reine, blue: Saint-Pourçain-sur-Besbre, orange: Vichy, green: Laignes.

Shape variability The GPA and PCA process allows the visualization of the main axes of shape variation. A positive variation of landmark configuration along PC1 corresponds particularly to distant and large eyes, a large nose and a high mouth, while a positive variation along PC2 is connected to a high nose, a low chin and horizontal eyes. Warpings of landmark configurations along PC1 and PC2 are shown

on figures C.7 and C.8.

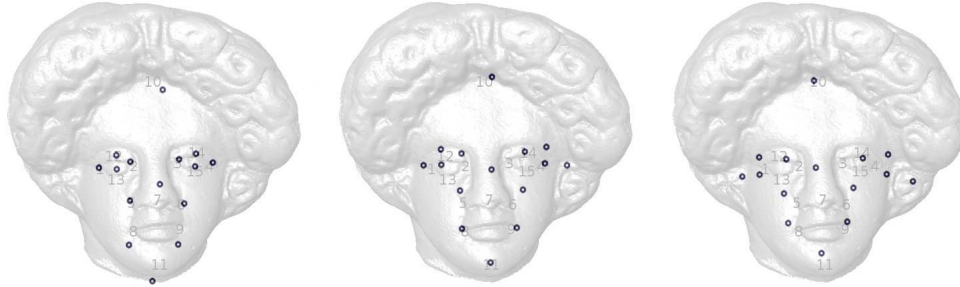


Figure C.7: Variation of configuration along PC1. Up: $PC1 = -0.2$, center: mean configuration, down: $PC1 = 0.2$

More in detail, PCA allows to reduce the dimensionality of the problem and to decompose variability into orthogonal components. Each successive principal component explains the remaining highest variability in the data. In the case of independent and isotropic points (i.e. random shapes) the eigenvalues are approximately equal. On the contrary, in the case of a strong dependency between landmarks, the largest amount of the variability would be carried by the first principal components.

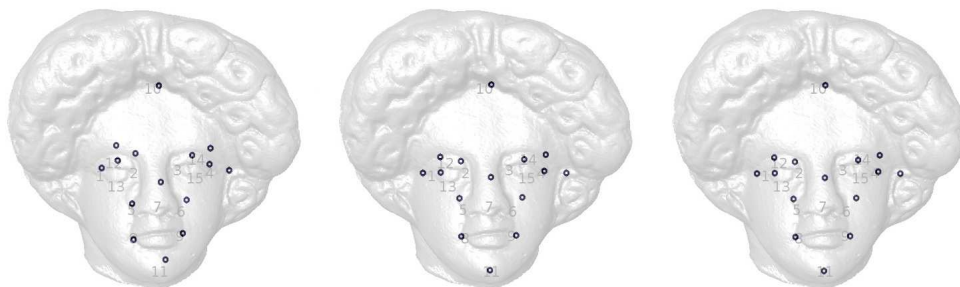


Figure C.8: Variation of configuration along PC2. Up: $PC2 = -0.2$, center: mean configuration, down: $PC2 = 0.2$

Localization determination based on shape classification Figure C.9 presents the typical shapes for some origins of statuettes. It is noticeable that Vichy statuettes are characterized by a narrow face and a low mouth, corresponding to a negative displacement along PC1, while the figurines coming from Alise-Sainte-Reine are recognizable by their large nose and low chin, typical of a positive displacement along PC2. The unique figurine from Laignes has also a shape close from the ones of Alise-Sainte-Reine.

Nevertheless, the set of figurines from Toulon sur Allier is scattered in the shape space and shows the limitations of interpretation of the shape analysis based only on the faces of the statuettes.

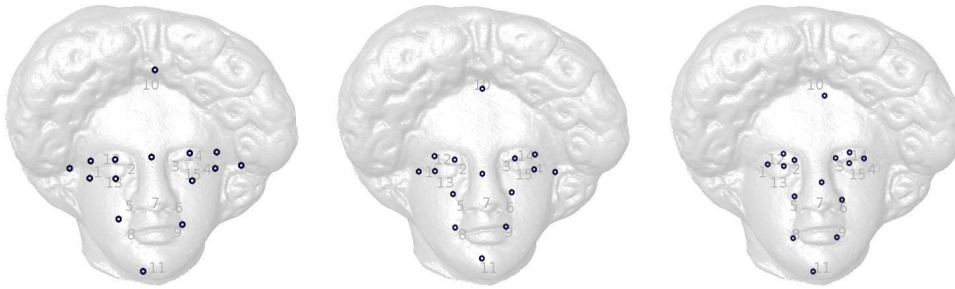


Figure C.9: Mean configuration for several origins of statuettes. The deformation is exaggerated 5 times to help visualize the shape differences. Up: Alise-Sainte-Reine, center: Toulon-sur-Allier, down: Vichy

C.1.3 Conclusion

Geometric morpho-metrics provide tools that have the potential to help to characterize the location of production of Gallo-Roman white clay figurines if applied to a bigger dataset. Generalized Procrustes Analysis (GPA) allows for the identification of separate groups of figurines according to their spatial provenance and shows that shape analysis based on three-dimensional surface digitized models are an alternative or complementary method to confirm chemical analyses for the geographic identification of archaeological objects. Unfortunately, however, the interpretation of the results of this experiment has been limited by the size of our dataset, but the results are encouraging, especially in comparison with the chemical analysis, and would have been even more precise if we had been able to access a larger pool of three-dimensional virtual models.

C.2 The Paphos Theatre

The ancient theatre of Nea Paphos, located near the town of Kato Paphos in Cyprus is a very well conserved example of ancient Roman theatre. It has been built using the southern slope of a hill, and measures about $90m \times 195m$ from side to side permitting to fit over 8000 spectators, according to archaeologist calculations. The angle of rise of the seating is 26.5 degrees. The theatre has been built around 300 BC. It is possible to identify a few phases of remodelling during its period of activity following the changing nature of performance during Greek and Roman representations. It was most likely abandoned after the big earthquake of 365 AD and much of the stonework has been reused for other constructions.

For the digital acquisition of the theatre, the digitization group used two technolo-

gies: aerial photogrammetry with an aerial balloon, to acquire the whole surface of the theatre with texture, and phase shift scanning for more precise measurements from the ground [Gabielli et al., 2010]. The first was measured to have an error of 2cm, while the latter is claimed to have a precision of 1mm.

Both methods produced coloured point clouds. The aerial photogrammetry produced a more complete overview of the site, while the phase shift produced a more precise dataset. The interest of this experiment is the method used to transfer the colour from vertex to mesh, once the two datasets have been fused.

The point cloud resulting from photogrammetry has colour and geometry information but not normals, while the one from phase shift has normals too. The resulting point cloud does not have normals (cannot be shaded), is not uniform (more dense in the phase shift area, sparse in the photogrammetry area), and has some biased error (alignment, data integration). The full model is about 9 million points.

Again, all the operations on the dataset have been done using Meshlab [Meshlab, 2009b] and the reconstruction pipeline, after the fuse of the two datasets, consisted in subsampling and regularizing the point cloud (Figure C.10). Subsampling is a necessary task because it not only reduces the number of points of the model, but also put them “in order” removing redundant points and “spikes”. In this way we obtain a more manageable dataset and we slightly improve the computational time.

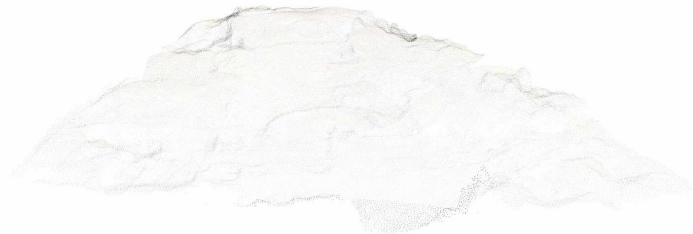


Figure C.10: The theatre dataset after applying the subsampling algorithm. The model is now only about 60K points.

I then computed the normals on the subsampled model, to speed up the computation and started the surface reconstruction. Many different algorithms are available for surface reconstruction, and Meshlab offers the Poisson Surface Reconstruction (Figure C.11).

In this example I decided to go for a “per-vertex” colour solution. With this config-

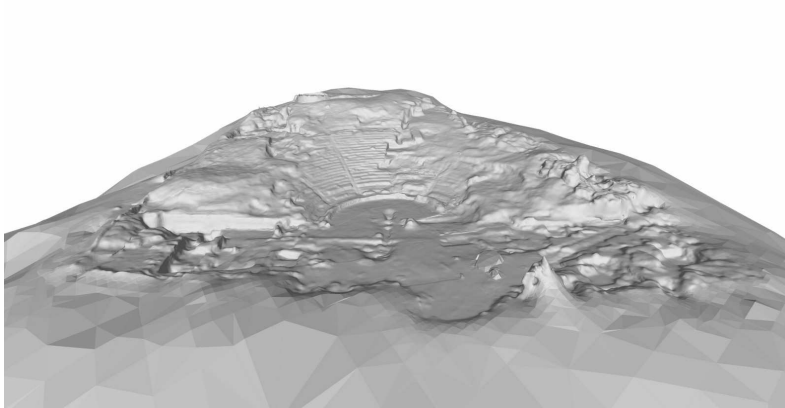


Figure C.11: The theatre model after applying Poisson Surface Reconstruction.

uration it was the best solution and the mesh and the texture were detailed enough to be transformed into a 3D animation. Here again Meshlab offers a plugin for the transfer of colour attribute from a source point to the corresponding reconstructed surface. To obtain the best result, the mesh must be as dense as the starting point cloud.



Figure C.12: The theatre model with the Phase-shift “inclusion” in evidence, bright.

In conclusion the final model was so satisfying (Figure C.12) to the archaeologists that they used it as a documentation and assessment of the site. The two systems used proved to complement each other in terms of costs, time of acquisition, data registration and post processing.

C.3 Indexing and Retrieval of Three-dimensional Objects

As the user has been used to searching in large databases with keywords first, and similar images after, it is the next logical step that we apply the same search paradigm to three-dimensional models.

However, even if the logic behind is the same, indexing three-dimensional models differs a lot from the process of indexing images [Tangelder and Veltkamp, 2008], [Benois-Pineau et al., 2012] and [Iyer et al., 2005]. 3D geometry represents an unambiguous description of the physical geometry of the artefacts we are searching for. It is easy to imagine how shape constitutes a semantic in its own right. This is particularly evident in fields like art and architecture where the descriptive language is “standardized”.

This is why the “query by example” approach is a powerful tool for the retrieval of similar three-dimensional models, as well as it is for two-dimensional images, with just more ways to search: for 2D we search per colour, shape of the figures, etc, whereas in 3D we search for texture colour, for shape of the model, shape of the figures in the textures, etc. Concerning the structural shape, the three-dimensional artefacts retrieval system does not differ too much from its two-dimensional counterpart; the collection of 3D models is indexed offline and a database of feature vectors, or signatures, is created.

Once the database is in place, a query can be initiated by uploading or choosing an existing prototype. From the latter an index is calculated on the fly, stored into the database and thus compared to the rest of the database with the help of a metric to the feature vectors of the collection in order to retrieve the most similar models in terms of three-dimensional shape.

It is logical to think that the main difference between the three-dimensional and the two-dimensional search systems lays on the generation of the indexes. Defining a feature vector for a three-dimensional model is not easy and must be based on some assumption like the fact that we are analysing a mesh or a point-cloud, because the two representations lead to different approaches. In the case of a mesh, we must specify which kind of mesh we are using, triangular or not. Furthermore, as well as for two-dimensional signatures, the indexing algorithm must be invariant to translation, scale and rotation because a three-dimensional model can be represented in any arbitrary location and pose in a 3D space.

Many different two-dimensional and three-dimensional indexing algorithms have been developed using the EROS database as dataset. Among them libFVS is still in use [Goodall et al., 2005]. LibFVS was developed during the SCULPTEUR project by the joint effort of the Southampton University and the École de Télécommunica-

tions and to which I contributed to the port of the EROS framework, and with a module that improved the 3D thumbnail generator. This tool projects a 3D model into one of several primitive 3D shapes, a sphere, a cone, or a cylinder, before unwrapping it into a 2D plane using the appropriate projection.

LibFVS is a collection of several 3D matching algorithms put together to provide a 3D content-based retrieval framework and, as is, works only on triangular meshes. Apart from the previous one, the library include:

- The D2 Shape Distribution descriptors from the Princeton Shape Retrieval and Analysis Group [Osada et al., 2001];
- The histogram descriptors from [Paquet and Rioux, 1997] developed for the Nefertiti system;
- An area to volume ration descriptor [Tung and Schmitt, 2004], which can be used to reduce the search space, being a single valued statistic giving the ratio of the surface area of the model to its enclosed volume.

The Shape Distributions are a collection of descriptors that capture distributions of various features of the shape of an object. The D2 variants, the one used in the libFVS library, measure the distribution of the distance between random pairs of points on the shape surface. This approach is invariant to rotation and translation, but it is sensitive to scale. A strong point is its robustness to mesh changes in resolution.

The Histogram Descriptors can be described as follows [Paquet et al., 2006]. The centre of mass of the artefact is calculated and the coordinates of its vertexes are normalized relatively to the position of its centre of mass. Then the tensor of inertia of the artefact is calculated. In order to take into account the tessellation in the computation of these quantities, the algorithm uses the centres of mass of the corresponding triangles, the so-called tri-centres. In all subsequent calculations, the coordinates of each tri-centre are weighted with the area of their corresponding triangle (Figures C.13 and C.14). The histograms so calculated are rotation and translation invariant too, but they are sensible to scale operations.

To have a real impact in cultural heritage professional daily work, searching instruments should be able to offer an integrated interface to both search specification and visual presentation of results.

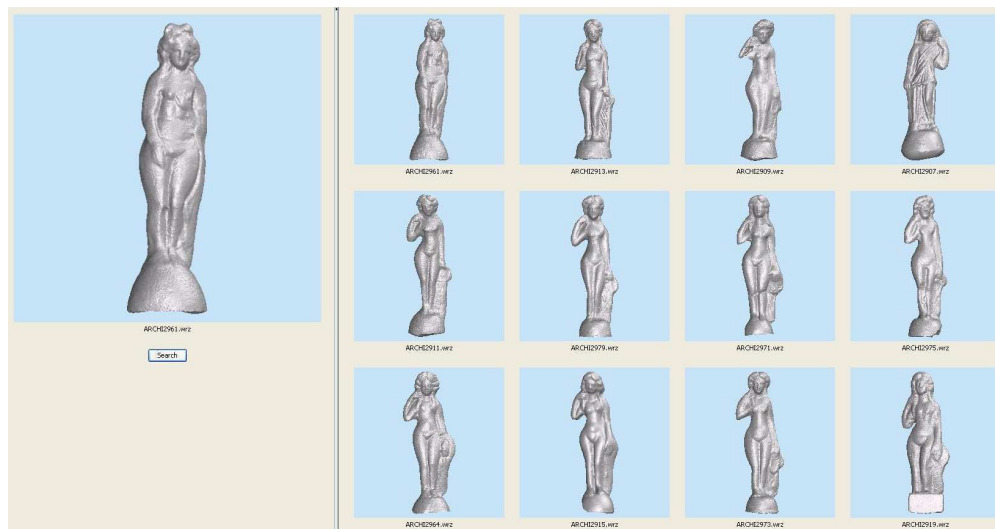


Figure C.13: “Pudic venus” - France, Moulins, Anne de Beaujeu Museum, inv. 5.7.6. Results obtained searching for similarity starting from the top left image, using the histogram descriptors algorithm presented in [Paquet et al., 2006].

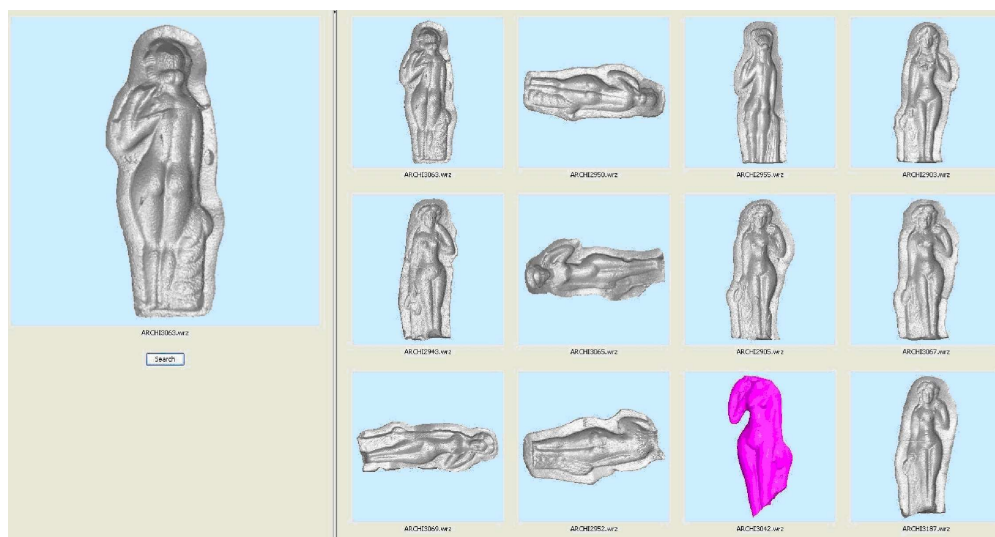


Figure C.14: “Anadyomene Venus” - France, Moulins, Anne de Beaujeu museum, inv. 5.3.33. Results obtained searching for similarity starting from the top left image, using the histogram descriptors algorithm presented in [Paquet et al., 2006]. In pink a wrong result.

Appendix D

Examples of RDF notation

In Figure D.1 is the graph representing the concept “Leonardo da Vinci is the author of Mona Lisa”, used as example for the different RDF notations.

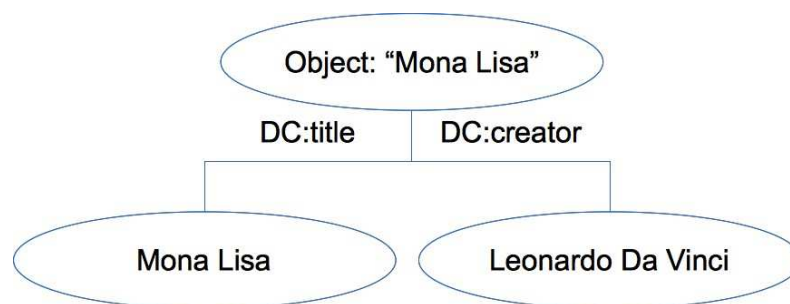


Figure D.1: RDF representation of the “Mona Lisa” painting using Dublin Core metadata format.

N-triple N-Triples is the most basic format. It provides a simple line-based, plain text way for serializing RDF graphs. Each line represents an RDF triple defined as its subject, predicate, and object, separated by white space.

```
<http://www.example.org/item/monalisa/>  
<http://purl.org/dc/elements/1.1/creator>  
'Leonardo da Vinci'@en .
```

```
<http://www.example.org/item/monalisa/>  
<http://purl.org/dc/elements/1.1/title>  
'Mona Lisa'@en .
```

N3 Is a superset of the turtle representation. It is supposed to be more readable (and writable by hand) from the human perspective.

```
@prefix dc: <http://purl.org/dc/terms/> .
<http://www.example.org/item/monalisa/>
dc:creator <http://www.example.org/person/leonardodavinci>;
dc:title 'Mona Lisa';
rdfs:label "Mona Lisa"^^xsd:string .
<http://www.example.org/person/leonardodavinci>
dc:title 'Leonardo da Vinci';
rdfs:label 'Leonardo da Vinci'^^xsd:string .
```

RDF/XML Another technique to serialize an RDF graph is as an XML document. This improves significantly the readability of the structure, but loses the perception of the RDF graph. RDF/XML is the more easy to read RDF format for humans.

```
<rdf:RDF
xmlns:rdf='http://www.w3.org/1999/02/22-rdf-syntax-ns#'
xmlns:dc='http://purl.org/dc/elements/1.1/'>
<rdf:Description rdf:about='http://www.example.org/item/monalisa/'>
<dc:title>Mona Lisa</dc:title>
<dc:creator>Leonardo da Vinci</dc:creator>
</rdf:Description>
</rdf:RDF>
```

Turtle Turtle provides a convenient syntax for RDF graphs, allowing syntax contraction when compared with N-Triples or N3, such as the support for namespaces. Turtle provides a good trade-off between ease of writing, ease of parsing and readability.

```
@prefix dc: <http://purl.org/dc/elements/1.1/> .
@prefix : <http://www.example.org/#> .

<http://www.example.org/item/monalisa>
dc:title 'Mona Lisa' ;
dc:creator 'Leonardo da Vinci' .
```

RDFa In contrast with the other formats, RDFa is a set of specifications that adds attribute extensions to HTML (and more in general to XML based) documents for

embedding inline rich metadata. A very minimalistic example for the “Mona Lisa” could be:

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE html PUBLIC "-//W3C//DTD XHTML+RDFa 1.0//EN"
  "http://www.w3.org/Markup/DTD/xhtml-rdfa-1.dtd">
<html xmlns="http://www.w3.org/1999/xhtml"
  xmlns:dc="http://purl.org/dc/elements/1.1/"
  version="XHTML+RDFa 1.0" xml:lang="en">
  <head>
    <title>The Mona Lisa painting</title>
    <base href="http://www.example.org/monalisa/" />
    <meta property="dc:creator" content="Denis Pitzalis" />
  </head>
  <body about="http://www.example.org/monalisa/">
    <h1>The Mona Lisa painting</h1>
    <p>The <span property="dc:title" xml:lang="en">Mona Lisa</span>
      painting was created by
      <span property="dc:creator">Leonardo da Vinci</span></p>
  </body>
</html>
```

