Chapter 18
Integration and Analysis of Sampled Data: Visualization Approaches and Platforms

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Abstract The evolution of digitization technologies (2D and 3D) and the consequent wide availability of digital representations of artworks has ignited a number of works aimed at providing tools and platforms for archival, visual presentation, and integration of all those media. This chapter reviews some available instruments, focusing first on the platforms that could support the CH/DH professional in the single or cross-analysis of multimedia representations. Then, we discuss the available approaches for structuring and integrating the available data, presenting both the GIS-based solutions and the more recent Web-based systems. Some discussion on open issues concludes the contribution.

Keywords 3D models • Cultural Heritage • Visualization • Data archival • Multimedia data • Web-based data visualization

18.1 Introduction

The technological progress of digital sampling instruments (2D and 3D) has been impressive in the last two decades. We have many different technologies for acquiring digital representations of an object of interest, which can produce either 3D data (3D scanning or photogrammetric solutions sample at high-resolution the external surfaces, whereas tomographic systems also produce data on the internal structures) or 2D samplings (high-resolution imaging, HDR, RTI, multispectral images, video, etc.). But acquiring visual representations is not the ultimate goal of scholars or practitioners in digital humanities, or of people working in museums or in conservation. Given the mature status of the acquisition technologies, the emphasis is now moving to the design of instruments able to make proficient use

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of those digital models, supporting inspection, insight, and sharing of knowledge (Scopigno et al. 2011; Pintus et al. 2015). A pioneering experience was done in the framework of the restoration of Michelangelo's David (Callieri et al. 2004), where a number of visualization and data presentation approaches have been experimented with on top of the digital 3D model produced by Stanford's Digital Michelangelo Project.

Visual data are only a subset, even if an important one, of the overall *data* DH professionals use to support or facilitate the analysis and insight processes. Moreover, we also need to consider the issues concerning the creation, archival, and access to *metadata*, that is, the information that describes the available data and enables integration and *discoverability* of CH data.

All those data have to be stored and made accessible to the community. Therefore, a large number of different approaches for 3D/2D data visualization and archival emerged out of the intense research and tool design of the last decade. Moreover, in many cases coping with just a single visual representation is not sufficient: especially in digital humanities applications, an artwork has to be studied by sampling it with multiple technologies, each one producing a single data stream. This originates the need of being able to browse and inspect multiple types of media at the same time, possibly using a common visual analysis tool/platform. Data integration is therefore needed, both to have better input (e.g., to produce a more complete set of visual media describing the conditions of the artwork under study) or a better output (e.g., to document the reasoning process used to produce a given hypothesis). The scope of Sect. 18.2 is to review the approaches proposed thus far for supporting data integration and the visual media inspection and analysis tasks.

But the work does not stop at the visual representation stage and the subsequent data analysis. Together with multiple visual representation modes, we also have a large number of different sources of data that we need to store, interlink, and access. Those types of data depend on the specific application domain; unfortunately, not all subdisciplines of the digital humanities domain have the same requirements in terms of supporting data.

CH restoration is a good example of a DH subdomain showing sophisticated data management needs, in as much as it requires the management of both many different types of visual representation media (standard 2D, multispectral, RTI, 3D, etc.) and a very wide number of different sources of information that contribute to the characterization of the artwork. An information system supporting CH restoration should enable the management of all the data acquired during the preliminary phase of the restoration process (i.e., the data related to the nature of the artwork and its state of conservation) as well as the information produced during the actual restoration work (cleaning tests, restoration materials and methods, final reports, etc.). All those data have to be linked and correlated.

Different approaches have been proposed to enable data linking, either based just on databases where the data are represented and stored, or adding georeferences to each specific data token and adopting data management platforms that allow encoding the geolocalization in an explicit manner (this is the case of the GIS systems, described in Sect. 18.3) or, more recently, using Web approaches and the related HTML5 technologies to support sophisticated data linking and integration (described in Sect. 18.4).

Because the themes and the related technologies touched on in this work are a wide set, we have to be very synthetic in the description. For a more detailed presentation we suggest a number of bibliographic references.

18.2 Platforms to Support Cross-Analysis of Multimedia Assets

Visual representations can be easily acquired and constitute an excellent resource to document the status of an artwork and to support remote and cooperative study and analysis. For each single medium we need technologies granting efficient encoding and visualization and, possibly, the capability to present those data on the Web.

18.2.1 Tools for Single Medium Visualization

Efficient visualization means taking into account a number of technical issues (data simplification, multiresolution encoding, compression, progressive transmission, GPU-enabled rendering). All those themes have been subjects of intense research and nowadays we have an arsenal of efficient technical solutions that can be adopted for the implementation of efficient visualization tools. Therefore, for each single medium we have plenty of solutions supporting efficient visualization.

Most image types are visualized natively by most Web browsers. Specific image types, such as reflection transformation images (RTI) (Malzbender et al. 2001) or high dynamic range (HDR) images (Debevec and Malik 2008) still require specific browsers or tools.

3D models are rendered by many systems, either using an encoding based on triangulated surfaces or adopting a representation and rendering approach based on point clouds. MeshLab is an example of a mesh processing system that is also often used as a visualization platform (Cignoni et al. 2008). Listing or presenting even just a subset of the existing 3D viewers is far beyond the scope of this chapter. We mention a viewer designed for a specific narrow class of artworks (Pal et al. 2013). It is an example of a specialized tool providing enhanced visualization features for degraded *parchment manuscripts*. These manuscripts may present severe distortion of the surface and wrinkles that increase the complexity of reading and deciphering the textual content, both on the original and on digitized replicas of the manuscript. This interactive viewer has been designed to enable on-the-fly counterdeformation on the specific (small) area analyzed by the scholar; it also applies a rotation to the same area to make the line of the writing as horizontal as possible. By means of those real-time local modifications of the geometry, the tool allows enhancing the visual analysis of the digital representation nicely.

Until very recently, 3D browsers were delivered as applications to be installed on our desktops or portable PCs. With the advent of HTML5 and WebGL, more and more media browsers are built as components of standard webpages, thus allowing us to inspect even very complex visual data using only standard Web browsers. An example of a recent work that follows this trend is the Visual Media Server recently implemented in the EC INFRA "ARIADNE" project (Scopigno et al. 2015), where browsers for very high-resolution images, RTI images, and 3D models have been implemented on top of WebGL (Marrin 2011). An added value of the work done in ARIADNE is the automatic service for: (a) converting any visual media files in a Web-compliant, multiresolution format; and (b) supporting automatic publication on the Web. A simple front end allows users (the ARIADNE focus is oriented to the archaeological community) to upload the media file on a Web server; this media file is automatically converted into an efficient Web-compliant format (e.g., in the case of a 3D model, it is converted into a multiresolution model, also incorporating data compression features) and the user receives the URL from where the model is now freely accessible (see Fig. 18.1).

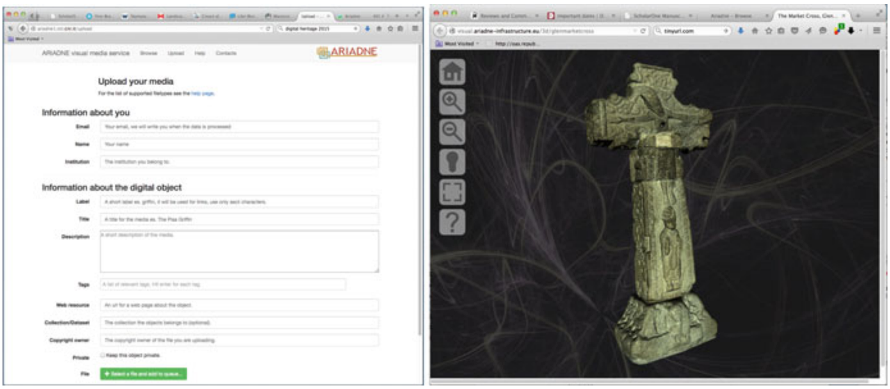

Fig. 18.1 The *ARIADNE* service for easy and automatic publication of visual models on the Web: The snapshot on the *left* presents the Web form for uploading the visual file; on the *right*, a snapshot of one of the 3D models contributed by users (See at: http://visual.ariadne-infrastructure.eu/), rendered inside a standard webpage

18.2.2 Tools for Cross-Media Visualization

An approach where each different medium has its own visualization tool severely impedes the analysis and study of a CH asset, because by definition no medium is better than the others and each one adds knowledge. Therefore, DH applications impel us to design technologies able to support the contemporary analysis of different media.

This requirement was at the basis of the design of the Cenobium system in 2006 (Corsini et al. 2010). This system was designed to support art scholars and students in the study of medieval sculptures (in this specific case, decorated capitals) by means of multiple representation media. From the very beginning, the Cenobium system was designed to provide what we called a *light table*, that is, a facility to support the side-by-side visual analysis of different media. The Cenobium system hosts many high-resolution images and 3D models for each capital; the user can select any image or 3D model (belonging to the same or to different capitals) and can selectively activate his or her visualization in a common interactive space (see Fig. 18.2).

A more comprehensive approach has been endorsed by Yale University while designing the Hyper3D system (Kim et al. 2014). Their starting point was that many different media types and formats are needed in CH and that most of them are

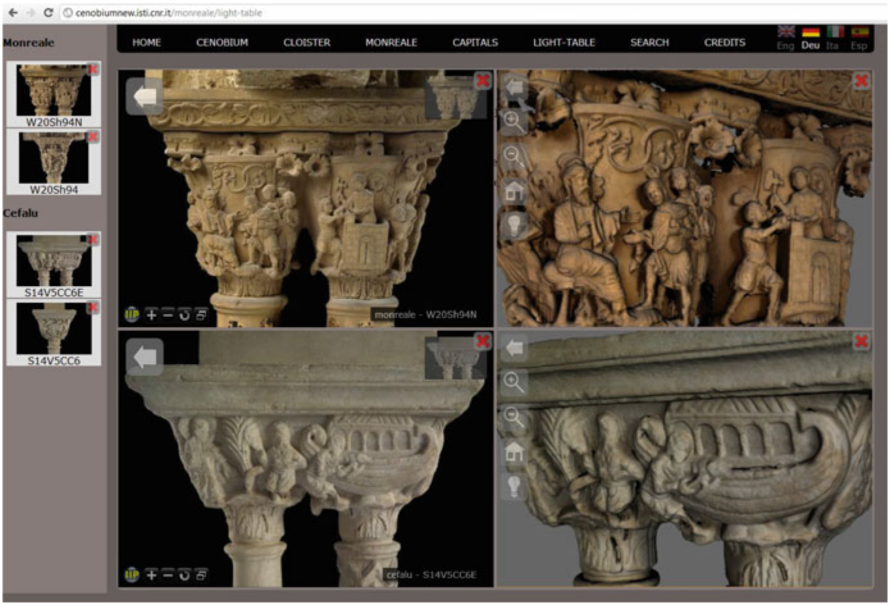

Fig. 18.2 The *light table* component of the Cenobum system, supporting side-by-side analysis of a selected group of 2D/3D representations

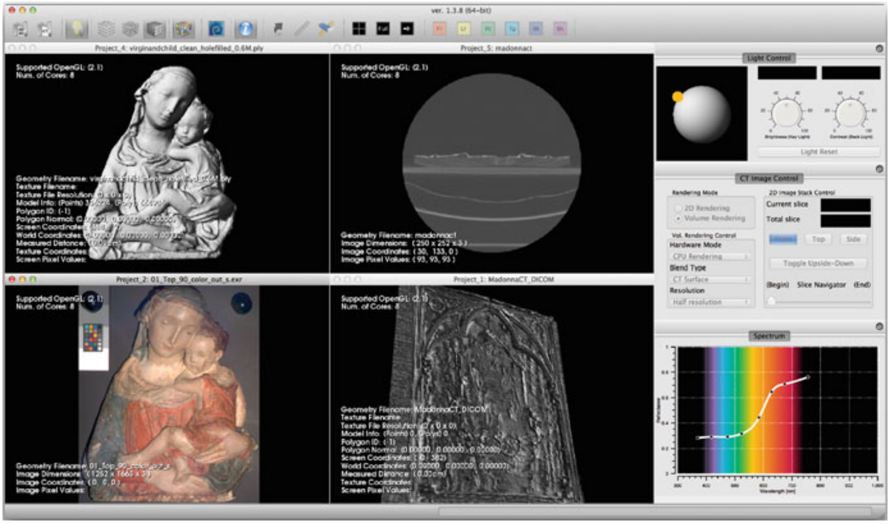

Fig. 18.3 A screenshot from the Hyper3D open source system developed by Yale University

available only inside specific tools, in most cases designed for non-CH communities (some clear examples are the medical or industrial tomographic devices/tools). The cost and complexity of use of many of those solutions originate a sustainability issue and this reduces the impact over the CH domain. Complexity of use also depends on the different terminologies and GUIs supported by the different tools (just a single example is the manipulation modality, implemented frequently in graphics systems with different interpretations of the trackball concept). Therefore, the Yale group has designed the Hyper3D system as an open source software tool, having a single intuitive interface consistent with conservators' needs. The system handles various types of 2D and 3D data and preserves user-generated metadata and annotations (see Fig. 18.3). According to our experience, this is the first complex open source tool focusing on data visualization of CH digital assets, rather than on geometry processing.

It provides tools for the integrated visualization of various types of visual data (2D images, hyperspectral images, volume data encoded using the DICOM standard, and triangulated 3D models, with or without textures). Among the peculiar features implemented are color conversion and visualization techniques to deal with hyperspectral and multispectral images. Visualization features are paired by coherent features for saving and retrieving user-generated metadata, for bookmarking specific visualization setups and procedures, and finally for creating annotations alongside the displayed images (implemented as hotspots laying over the image/3D model, with which text can be associated).

The system has been designed as a publicly accessible open source framework to enable extensive future modification; it is available under the GNU General Public License v3.0 via SourceForge at http://sourceforge.net/projects/hyper3d/. It is based on several other open source libraries: the Visualization Toolkit (VTK)

(Schroeder et al. 2006), the Insight Segmentation and Registration Toolkit (ITK) supporting volume rendering (Taka and Srinivasan 2011), QT for the design of the user interface (Dalheimer 2002), the Armadillo linear algebra API (Sanderson et al. 2010), and the OpenEXR API for HDR images (Digital 2009).

18.3 The GIS Approach to CH Documentation

Geographic information systems (GISs) have often been used to support documentation of CH assets, covering a wide spectrum ranging from the medium scale (a statue) to the large scale (an entire city or an archaeological site). GISs have been a major resource in archaeology for documenting the digging process and the findings (because in that case having a precise geolocation is of paramount importance). Many papers have been proposed in this specific subdomain. In as much as reviewing the use of GIS technology in archaeology is beyond the scope of this chapter, we cite here only a few papers that contain good lists of references (Chapman 2006; De Reu et al. 2013; Dell'Unto et al. 2015).

GIS solutions have also been proposed to encode knowledge and data concerning the state of conservation or to support restoration of artworks. In this case, the GIS approach is used to characterize the surface of the artwork, linking available knowledge (e.g., all the results of scientific investigation analysis) to specific regions defined over the artwork surface. An example of system following this approach is SICAR (Fig. 18.4).

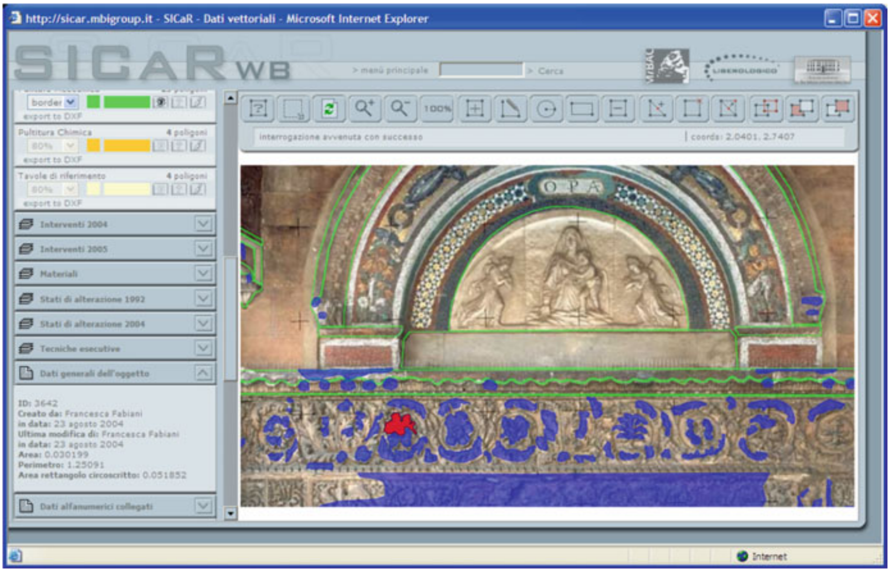

Fig. 18.4 The image presents the GUI of SICAR, showing the results of a surface characterization of the architrave of the S. Ranieri portal (Dome of Pisa, Italy)

18.3.1 SICAR Web: A GIS Approach to Support Documentation of Restoration Data

SICAR Web is a Web-based system for the management of information gathered during restoration analyses and intervention (either alphanumeric or raster data) that is mapped and georeferenced onto a 2D representation of the artwork (Baracchini et al. 2007, 2003; Fabiani et al. 2012; LiberoLogico 2015). It permits linkage to the digital representation of all data gathered during the analysis and intervention phases of the restoration process (e.g., raster images, documents in TXT format, hypertext (HTML), or semi-structured text (XML)). SICAR is based on a (raster) 2D representation of the artwork, on top of which the restorer can build any number of layers, each one containing regions drafted over the 2D raster representation and linked to specific data stored in the database. As with any other GIS platform, SICAR offers features to cross-compare different layers (overlay function) and to support the analysis of the data.

SICAR manages three classes of data, respectively related to: the artwork story (that includes two subcategories: historical documentation and constitutive materials and techniques), the artwork state of conservation (chemical, biological, or physical diagnosis of its decay, the detection of previous restorations, their nature, their location etc.), and, finally, data on the restoration in progress (materials used, techniques, and methods).

SICAR is configurable and accessible via the Web both for consultation and data entry. The application is designed to allow gathering and entering the documentation onsite and provides transversal access to all the data categories managed (geometric information, images, text documents, alphanumeric cards, etc.) ensuring crossed search between them and extreme ease of reference.

SICAR was adopted by the Italian Ministry of Cultural Heritage (MIBACT) in 2012 and is intended to be the infrastructure for encoding data on CH restoration produced by the restoration and conservation institutions belonging to the Italian Ministry of Cultural Heritage.

18.3.2 Pro and Cons of the GIS Approach

GISs have proved to be an extremely valuable resource in many DH applications. The use of this technology for data archival and management is extremely powerful because it allows us to support sophisticated data analysis features (cross-correlation of different types of data and production of new data layers as a computation/intersection of previous ones).

On the other hand, because by definition the GIS approach requires a precise characterization of the surface (i.e., precise definition of each specific parcel of the surface to which we want to assign a specific data value or interpretation), adopting a GIS approach requires the investment of considerable time in data input and some skills or extensive training of the operator.

The supporting space managed by GIS platforms was perceived as a limitation for some CH applications. GIS technology was originally developed to represent 2D 1/2 models (i.e., terrain models); it has been used both to represent 2D domains (e.g., painted surfaces, or facades of buildings projected on a plane, as in the case of the SICAR system) and terrain models. More recently, GIS systems have been extended by also supporting the direct representation of 3D domains (Dell'Unto et al. 2015). Again, this extends the capability of the system and its flexibility of use: we are no longer forced to work on projection planes, but can draw our regions directly over the 3D surface of the artwork. Unfortunately, moving to a full 3D space also requires increased expertise of the operator and a slightly more complex selection process of each single region over the represented 3D surface(s). The complexity of use and the time required to produce the documentation are the most critical limiting factors of the GIS-based approach.

18.4 Web-Based Platforms to Support Data Integration and Easy Accessibility

Several applications do not require the most important characteristic of the GIS approach (the layer concept and the possibility to cross-compare layers, using this feature as an analysis instrument) and thus impose much lighter requirements in the design of a data management approach. In many cases, the main feature required is just the possibility to create links interconnecting different data tokens, even in a georeferenced manner (i.e., linking a data token to a specific location/region of the surface of the artwork). In all those cases, we are not obliged to select a GIS platform, in as much as most of those features can also be implemented in a standard Web context. We can make proficient use of the hyperlink concept to implement systems that fulfill those categories of users.

We have already briefly mentioned in Sect. 18.2 that the progress of the Web platform (HTML5, WebGL) makes it possible to manage any visual medium in an efficient way, making it an integrated component of standard webpages and enabling visualized over standard Web browsers.

We have recently designed and implemented a software framework, called 3DHOP (3D Heritage Online Presenter) (Potenziani et al. 2015). 3DHOP has been designed to simplify the creation of interactive visualization webpages including high-resolution 3D models and other media and offering intuitive user interaction

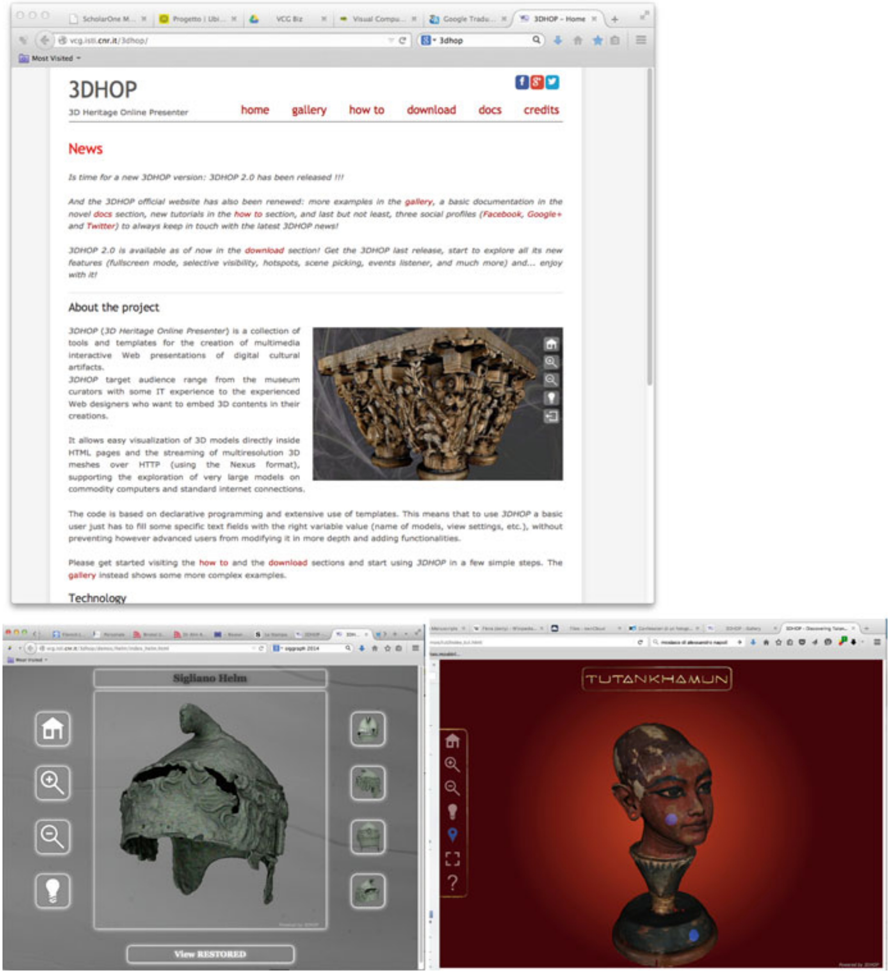

Fig. 18.5 3DHOP: The main webpage and snapshots from two 3DHOP instances

and manipulation features; moreover, these resources can be deeply and easily connected with the rest of the webpage elements (see Fig. 18.5). The most interesting characteristics of the 3DHOP framework are:

- The ability to work with extremely complex 3D meshes or point clouds (tens of millions of triangles/vertices), using a streaming-friendly multiresolution scheme.

- The easiness of use for developers, especially those with a background in Web programming, thanks to the use of declarative-style scene creation and exposed JavaScript functions used to control the interaction.
- The availability of a number of basic building blocks for creating interactive visualizations, each one configurable, but at the same time providing default behaviors and comprehensive documentation.

3DHOP was released as open source (GPL license) in April 2014. The downloadable package is available at the website: http://3dhop.net and it includes documentation, a series of tutorials (how-tos), and a gallery of examples.

3DHOP has been designed with the aim of being easy to use, especially for people having a background in Web development, thus without requiring solid knowledge of CG programming. 3DHOP is not a “silver bullet,” able to support any possible application or visual communication project, but a framework designed to deal with specific needs. It is an ideal tool to visualize high-resolution single objects, especially with dense models coming from 3D scanning or collections composed of a few models. Conversely, 3DHOP is not suited to manage complex scenes made of low-poly objects (this is a common case when working with CAD, or procedural or hand-modeled geometries).

3DHOP makes possible a fast deployment process when dealing with simple interaction mechanisms, making it a good choice for quickly creating interactive visualization for a collection of models. Additionally, 3DHOP integrates extremely well with the rest of the webpage, thanks to its exposed JavaScript functions. The ideal situation is having the logic of the visualization scheme in the page scripts, and using 3DHOP for the 3D visualization. The 3DHOP tool has been designed with different levels of entry, to be as straightforward as possible for the simpler cases but, at the same time, able to provide enough configurable features to support the huge variability of cultural heritage artworks and applications.

The 3DHOP platform has been used recently to design a new instance in the overall 3DHOP family, aimed at presenting a single artwork (in this case, the Roman Annona sarcophagus, from the last third of third century AD, Museo Nazionale Romano and Palazzo Massimo, Rome, Italy) and a corpus of related data (Siotto et al. 2015). This artwork has been studied, subject to several different scientific investigation protocols, analyzed, and finally some hypotheses on its original polychrome decoration have been proposed. All this work and the related data have been stored in this specific 3DHOP installation. Therefore, we provide Web access to the high-res 3D model, with visual indication of the regions where scientific analyses have been done; users can open the related images or textual description of their results. Finally, two alternative preliminary reconstruction hypotheses of the original polychrome decoration have been encoded on the 3D model and are shown in Fig. 18.6.

Fig. 18.6 Three snapshots from a 3DHOP instance designed to store and present all the data gathered in the study of a Roman sarcophagus (including results of scientific investigations)

This is an example of the potential of a Web-based platform to present artworks and the documentation corpus that describes our knowledge of the same asset. 3DHOP is just an example of what can be done with Web-based technology. The work on the Annona sarcophagus has only been started. The documentation material has been mapped over the 3D models and the corresponding 3DHOP instance can be accessed at http://vcg.isti.cnr.it//roman-sarcophagi/annona-sarcophagus/index.html (which also includes a grabbed video: http://vcg.isti.cnr.it//roman-sarcophagi/annona-sarcophagus/img/video-ISTI-CNR.mp4).

The second phase of this work is under construction: creating the 3DHOP documentation to allow other colleagues to understand the structure of the sarcophagus setup and to support them in the design of similar installations on the basis of the provided sarcophagus sample.

Similar systems for 3D visualization and integration of other types of data exist: one of the most interesting examples is represented by the Smithsonian Museum X3D visualizer http://3d.si.edu/, where several examples of acquired and modeled 3D objects can be visualized. X3D enabled the attachment of additional information to the models, to follow a "tour" of the objects by moving among the various hotspots on it, and also to have tours covering several objects that were grouped following a common concept. Additional tools for advanced visualization (e.g., measurement and cross-section) are already available. Although really efficient and visually pleasing, the viewer is currently owned by the museum, so its use cannot be extended to other use cases for now.

Although 3DHOP has been designed by focusing first on how to support the presentation of sophisticated visual media over the Web, another interesting Web platform has been designed following the inverse path, that is, thinking first about how to support structuring and interlinking CH documentation.

Modus Operandi is a documentation system developed by an Italian company, Culturanuova s.r.l., in collaboration with a primary restoration institution (Opificio delle Pietre Dure-OPD, Florence, Italy) (Chimenti 2010; Culturanuova 2015). Data are organized on the basis of standardized procedures and guidelines defined by major restoration and documentation institutions, such as OPD and the Istituto Centrale per il Catalogo e la Documentazione (ICCD), Rome, Italy. The system allows us easily to produce a structured report of all the data gathered in a restoration project; it also supports publishing and consultation of the data on the Web. Some examples of its use are available on the Web at http://www.modusweb.net/ (see also Fig. 18.7).

According to some feedback received from OPD colleagues, the system is easy to use and extremely effective as far as concerns the provided functionalities.

A peculiar characteristic of Modus Operandi is the automatic production of a formatted report (in MS Word format) that is returned to the user after completion of a documentation project and that can be used in all those cases where a formatted and printable document is needed.

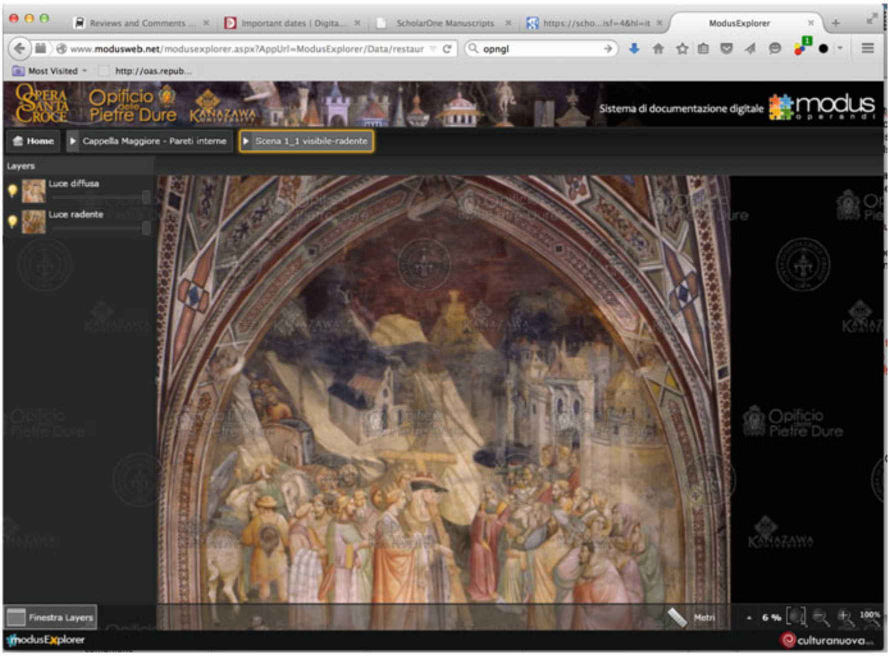

Fig. 18.7 A snapshot of one of the documentation systems implemented with the Modus Operandi platform (http://www.modusweb.net/)

The Scuola Normale Superiore (Pisa, Italy) has also developed an information system oriented to documentation of CH, called SIAS (System to Integrate Art and Science). It has been designed as a collaborative Web 2.0 system, supporting archival and access to the data produced in the study or restoration of an artwork (Barone et al. 2012, 2015).

18.5 Conclusion: Towards an Infrastructure for Multimedia CH Data?

The DH domain is extremely rich and complex, both in terms of types of visual media used in the study/analysis process and in terms of different types of knowledge/data that have to be linked to the virtual clone. The usual paper-based linear approach to present knowledge on a CH artwork shows all its limitations. We need systems able to break the linear approach, supporting sophisticated capabilities for integrating and creating correlations between different media. We have seen that at least two different approaches are possible to try to advance on this path:

1. Systems oriented to the *analysis* and *investigation* phase, that allow us to work with many different media types in a single context and enabling the use of a unified and common interface (e.g., Kim et al. 2014). Those media should support encoding and preservation of the reasoning path (annotation, bookmarks), to support scholars in preserving the *provenance* data that describe the analysis and comprehension process.
2. Systems oriented to *documentation* and *dissemination*, which by definition should work on the Web, to provide easy and ubiquitous access to the data (e.g., Culturanuova 2015). Again, the capability to browse over different media with a common interface has to be provided. But here an important focus is also to provide easy tools to create the links interconnecting the different information tokens with one or multiple digital representations of the artwork.

The Web is nowadays perceived as the main channel of publication and dissemination of knowledge. It could also become the container where programs are running, thus also allowing the design of systems of type 1 defined above as applications directly accessible from a webpage, thus removing the need of installing and updating applications on users' computers.

The Getty Conservation Institute has recently organized an experts' meeting to discuss the themes related to the integration of imaging and analytical technologies for conservation practice (held on September 10–12, 2013). The report produced as a followup of this meeting (Schmidt Patterson and Trentelman 2014) presents a comprehensive list of requirements and suggestions that we briefly enumerate here:

- Development of standards for more successful integration of data coming from different institutions and experiences (this includes work on metadata, ontologies and vocabularies, and policies for data sharing).
- Implementation of pilot studies/projects, which should have a short duration in time and should be instrumental in assessing the available data organization, archival, and presentation policies. Results from these pilots should be fed back to the design and standardization activities. The report suggests a set of criteria for the selection of those pilot projects.
- Consolidate a community of users and developers that is instrumental in gathering a solid view of user requirements and in establishing common and widely accepted good practices. This requirement is definitely concordant with the current policies of the EC, which has issued several calls aimed at consolidating DH communities and providing them with common e-infrastructures.
- Finally, an increased effort of funding agencies to issue calls on those themes, to support interdisciplinary projects aimed at designing and implementing a common infrastructure and tools.

The Getty report concludes by addressing the need for a new paradigm for data collection, archival, access, sharing, analysis, and interpretation; it stresses the need for a more cooperative approach to CH study. Visual media can become the instrument to support cooperation and encoding of partial results; this vision requires the design of a specific platform or infrastructure.

Let us add a last comment concerning sustainability issues. Due to the still-limited economic impact of DH/CH applications, development is still mostly on the shoulders of academic/research partners, with only a few companies struggling with a market characterized by fast technical evolution and limited financial resources. Open source could be an important asset to stimulate development and further exploitation. Public funds invested in infrastructure projects shall also play a highly beneficial role, aiming to join forces between academia and industry.

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