Beyond manual drafting:
a restoration-oriented system

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Abstract

The production of drawings is a basic activity in restoration, archeology and Cultural Heritage (CH) didactics. The manual production of technical drawings is a complex process, both in terms of time and skills required. In this paper we present a computer-aided methodology to produce technical drawings of CH artifacts. A pre-requisite of our methodology is the acquisition of an accurate digital 3D model of the artifact, which is now possible at affordable costs using 3D scanning technology. We discuss the specific needs that a drafting system oriented to the CH domain should satisfy and we present the design, features and performances of a computer-aided drafting system, called *Cavalieri*. *Cavalieri* allows to manage the huge digital models produced with 3D scanning devices and supports easy specification of orthographic drawings and cut-through sections, which are given in output as very high resolution images (with user-selected reproduction scale and printer resolution). We conclude with some results of *Cavalieri*'s assessment in the framework of two restoration projects.

Keywords: Cultural Heritage, restoration, technical drafting, 3D range scanning, 3D mesh visualization, large print formats.

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1 Research Aim

The research aim of this paper is to propose a semi-automatic drafting approach for the production of large formats prints of cultural heritage artifacts. The availability of 3D scanning devices allows to acquire very accurate digital models in sufficiently short times and with an affordable cost. The potential use of those digital models has to go beyond pure visualization. We propose to replace manual drafting (at least partially) with a flexible system which allows to produce large format prints from the available 3D model, making computer-aided drafting a very profitable instrument in the hands of restorers or archaeologists.

2 Introduction

Cultural heritage (CH) artifacts are often the subject of an intensive drafting activity, especially in the framework of archeology or restoration. Technical drawing are produced, often in 1:1 scale, and together with photographs they make up the iconographic documentation of the restoration or archeological activity.

Drawing is still mainly a *manual process* in the CH domain. This can be considered a positive point, because the draftsman can often enrich and extend its product with *interpretations* or *reconstructions* coming from his experience and knowledge of the field. On the other hand, negative points of the manual approach are the *unknown precision*, the *long time* needed to make sufficiently accurate drawings of complex objects, and the *technical/artistic skills* required.

The overall goal of the project presented here is to reduce the gap between the potentialities of digitization technology for 3D objects (usually called 3D scanning [1]), able nowadays to produce highly accurate digital 3D models of CH artifacts, and the diffusion and real use of these models in CH applications. Most of the 3D digital models are used just to produce still images or [interactive] animations for *didactic* applications or *multimedia presentations*: the classical rendering-oriented applications are still predominant. On the other hand, people working in the CH field, initially satisfied by the simple images, are now asking for tools actually useful for their work.

In this project we focus our attention on one of these *day by day* activities - technical drafting - and we propose a new computer-assisted approach. The production of technical drawings is an ideal research focus because, on one side, we have a methodology that is time-expensive and heavily dependent on human contribution/skill while, on the other side, we could make a keen use of all the incredibly rich details and accuracy of the digital models produced with 3D scanning technology. The goal of this project is therefore the design of a semi-automatic drafting system for the reproduction of accurate technical drawings on large scale printing formats.

The paper starts with a brief introduction to technical drawing in CH applications, presenting the specific needs of this field and the pitfalls of the current manual techniques. Then a short overview on 3D scanning is provided to better focus the data acquisition technology us. Next we highlight some important needs and constraints of drafting in the CH domain. Those considerations are

followed by a detailed description of the *Cavalieri* system, including functionalities provided and implementation details. Finally some experimental results of the use of *Cavalieri* system in the Minerva and Michelangelo's David restoration are presented.

3 Manual drafting in restoration

Let us introduce first why technical drawings are used in restoration and archeology. Technical drawings of archeological findings are produced with two main motivations: (a) to have a graphic documentation (more synthetical and rich of meta-information than photographs) of the shape and of the preservation conditions of the artifact, and (b) to be used in restoration to plan, design and document the actions to be done.

If we consider the first motivation, technical drawings are produced to give graphic evidence to the artifact shape, measures, lengths, morphological features, etc. All these information are often synthesized in the drawing and are needed to perform style comparisons, to determine the origin of the finding or to study the antique technologies used to mold/cast/sculpt it.

In the case of a restoration project, drawings are part of the basic documents (such as photographs, X-ray investigation, chemical analysis, etc.): they preserve memory of the condition of the finding before the restoration which might change in a significant manner the appearance of the artifact. Changes can affect the artifact chrominance (removal of patinas), the surface texture (polishing the surface from crusts or deposits), or even its shape (for example a bronze object, deformed by some accidents and brought back to its original shape during restoration).

Moreover, a second important reason for producing high quality technical drawings is to support the restorer with a permanent document on the original morphology of the artifact. Some examples which could clarify this need are as follows. An artifact can be discovered in damaged/incomplete conditions and documentation about the current state is needed. Another example is the case of highly fragmented objects with missing components (e.g. pottery). In this case drawings are produced to represent the available fragments, but also to place all of these fragments in the space according to the original shape, making at the same time some hypothesis on the structure and shape of the missing parts. This is probably the most complex task, where the experience and knowledge of the art historian or the archaeologist plays (and will also play in the future) a fundamental role. From the examples above, it is clear that *drafting* can encompass two very different activities: first, to produce an *accurate graphic representation* of the artifact shape (reproducing at a known scale and accuracy its dimensions, curvature, decorative elements or "stilema", etc.); second, to *draw some hypothesis* on its original shape or overall structure, according to an interpretation which heavily depends on the culture and experience of the human being in charge of the action. These two activities have to be clearly considered as two logically different stages. In the work described here we focused on the first task. While we consider the second stage as an exciting research topic, we do not think that current technology could give "sound solutions" to the latter problem.

Let us briefly introduce which are the requisite to produce useful and correct technical drawings, considering at this point just the requirements of the first task introduced above. Technical drawings used either for documentation purposes or as supporting material in a restoration project are in general done using the *orthographic projection*. This is because this type of projection allows to encode the metric attributes of the artifact in the drawing and to perform comparisons between either different cut-through sections of the same objects or different drawings. Given a three-dimensional cartesian space, the draftsman selects a set of views corresponding to the set of drawings he has to produce. The number of different views depends on the shape complexity of the artifact, its importance and the time and resources available to produce the drawings. In general, at most five or six views are used to build up the graphic representation of the artifact. A common approach is to select views which are aligned to each pair of cartesian axis (front, back, left and right side, top, bottom; see Figure 1). Such a complete set of drawings is produced for valuable artifacts (for example a statue); since manual drawing is a costly task, just one or two drawings are usually made for less valuable findings. Moreover, a second basic manner to represent the shape of an artifact is to produce a set of cut-through sections (often, drafted over-imposed one to the other together with the top or bottom views; see Figure 2). Due to the orthographic projection used, these drawings can be overlaid one on the other (using semi-transparent prints), for example to find the correspondence between features detected on the front and the corresponding areas on the back.

To give an idea of the complexity of the manual drafting phase, let us take as an example the case of the "Livia" statue (Figure 1), that is part of the gilded bronze complex of Cartoceto (first half of 1st cent. B.C. [13]). The restoration and the production of the associated set of drawings was performed at the Centro di Restauro Archeologico[1] (CRA). We choose here the Livia experience as an example because the morphological characteristics of this statue and the manual drafting complexity is extremely similar to the ones of the Minerva of Arezzo, that has been the first experimentation testbed for the assessment of our computer-aided approach (see Section 5).

The Livia statue represents an old woman standing up, and it has been discovered decomposed in a number of fragments. The classical set of 4 views of the statue has been drawn by a professional illustrator (Marida Risaliti) together with some cut-through sections (see Figures 1 and 2). These drawings represent the statue in the re-assembled condition, i.e. at the end of the restoration. The 3D cartesian reference system adopted to produce the drawings is obviously aligned with the vertical axis of the statue and its frontal plane. The instruments used to do these drawings are the classical mechanical tools such as: a *plumb-line*, a *compass* and a *caliper* to measure distances and thicknesses, a *contour gauge* or *molding comb*[2] to reproduce curved profiles. The tools used are therefore not too much different from the ones used in the past. All the measures taken by hand with these instruments have been drawn on paper using a 1:1 scale, to maintain as much as possible the precision of the manual sampling. Among the basic information is the spatial location of a small number of *principal points*, which have been sampled with these instruments and recorded on paper (most of these are marked using labels and small crosses in the

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[1]Archeological Restoration Laboratory.
[2] It is a comb with sliding iron teeth which adjust their position along the object curvature.

drawings, see Figure 2). Then, starting from these points, the draftsman produces the drawing according to the [subjective] inputs of his/her visual inspection and to his/her technical ability. It is therefore very difficult to evaluate the final accuracy of the drawing, because it depends on a large set of variables (shape complexity, wise selection of the principal points, ability and precision of the draftsman, etc.).

The manual drawings produced depict the overall structure of the statue and are in general considered of sufficient quality by the restorers. In some cases, depending on the artistic skills of the drawer, they can be of high "pictorial" quality. On the other hand, this approach becomes clearly not adequate when we need high accuracy in the representation of lengths, shape features, or small scale decorative/functional details. Manual drawings usually show just a few principal feature lines, selected by the drawer according to his/her experience, as it is evident in the nice drawings presented in Figures 1 and 2. Conversely, documenting in an accurate manner the small scale detail is often either impossible or impractical when we adopt a manual drafting approach.

Two other disadvantages of the manual drafting approach are the *time* needed and the *high level of artistic skills* required. The production of drawings such as the ones shown in the figures above requires weeks of work, and this often introduces a large delay in the management of the restoration action. The time required also implies that we have to choose a very small set of views (usually, no more than the five views presented above), and these have to be planned in advance. It is very impractical for a restorer to ask the illustrator for a new drawing, unless he can stop his work awaiting for the drawing. Moreover, the type of professional ability needed is always less and less common, and finding qualified personnel is neither easy nor cheap.

4 An automatic drafting approach

We describe in this section an automatic drafting methodology, which gives to the restorer the capability of producing in real time any drawing he needs to plan or to document the restoration. A pre-requisite of our approach is the construction of an accurate *three-dimensional digital model* of the object of interest. This task can be performed by using 3D range scanning technology and it is described in brief in the following subsection. Given an accurate 3D model, the production of drawings to be used in restoration should satisfy some specific needs and constrains, introduced in Subsection 4.2. Given those specifications, the features and the architecture of our automatic drafting tool are presented in Subsection 4.3.

4.1 Building accurate 3D models

Range scanning technology [1, 5] was initially developed for industrial and movie applications, but the CH domain is becoming an ideal field of application. Pioneering activities were started in US and Canada [21, 18, 10] and many of them focused on Italian artistic masterpieces.

3D scanning is in general performed using active optical technology [5], based either on laser or incoherent structured light. In both cases, most of the instruments available ensure very high

accuracy (in the order of 0.1 mm). Some instruments allow also the acquisition of the color detail. Each shot of a 3D scanner acquires only a partial view of the object surface and returns the sampled geometry data in a raster format (called *range map*).

Once a set of range maps covering all the object surface have been acquired, the post-processing phase starts. The tasks to be accomplished are: mutual alignment of all range maps; merging these range maps in a single triangle mesh; mesh editing and simplification (to reduce the potential excessive complexity). Data post-processing is in general much more time consuming than the actual acquisition of the range maps, and requires special purpose software tools. At the end of the scanning process the result is an accurate digital representation of the geometric shape of the scanned artifact; this digital representation is usually provided as a single very large unstructured triangle mesh. This kind of representation usually is not the most appropriate one for CAD systems designed to work with structured and feature oriented descriptions. The accuracy and speed of the 3D scanners and the efficiency of the software tools improved a lot in the last few years (as an example, since the beginning of the Digital Michelangelo Project [10]). As an example, we report here some figures relative to our Minerva scanning [17, 8, 22]. We performed four independent acquisitions of this statue, to document restorers' work: the first acquisition was done on November 2000 [16] while the fourth one on October 2002 (when approximately 40% of the restoration was done). All scans were done using a similar sampling step (0.5 - 0.3 mm). The number of range maps taken and the post processing times are shown in Table 1. The impressive reduction of the acquisition time is due to the progress of the technology used. The last two acquisitions were performed using a commercial laser scanner (Minolta VIVID 900) and improved releases of the post-processing tools developed by the Visual Computing Laboratory of ISTI-CNR. The Minolta scanner is sufficiently fast to allow us to take a complete sampling of both the shape and color of the statue in just one day of work. Post-processing a large set of range map and reconstructing an accurate digital model is in general an hard job. Thanks to the advanced techniques designed and implemented in our post-processing tools [4], we were able to reconstruct the Minerva model in only four days, that is a very valuable result.

4.2 Producing drawings from digital 3D models: specific needs

Producing drawings for a specific application context often requires to fulfill peculiar needs or constrains. The drawings needed in CH documentation or restoration should satisfy the following technical specifications:

- Drawings are in general requested in orthographic projection to preserve distances and slopes and to perform comparisons and metrical evaluations;
- Reproduction on paper should be provided using: (a) multiple known scales and (b) these should be easily selected by the user, according to the forecasted use of the particular drawing. Moreover, it should be possible to produce output on large paper formats (e.g. A0, A1) maintaining good quality and definition of the prints. Therefore, the resolution of the

images produced should be extremely large (much higher than standard screen resolutions). If we consider the case of a print on the A1 format, current plotters requires at least an image of size 7000*9900 pixels to print it at the standard 300 dpi resolution.

- Since drawings should be ideally at the same accuracy obtained with 3D scanning, the drafting system should be able to manage huge 3D models.

- Since *annotations* have often to be added to the drawings, it should be possible to save the images produced instead of providing just direct printing features; saving on the file system allows then to edit the images with any 2D drafting application.

Considering now the semantic content of the output, what do restorers or art experts want to draw?

- The minimal requisite is the possibility to produce the classical front, side and back views of the artifact; a valuable improvement would be to support the production of any possible view (either with the entire object visible, or just framing a subregion).

- Another basic requisite is the production of standard cut-through sections (sagittal, coronal, transverse) or of sections on any other cut-through plane defined by the user.

The standard restoration or conservation user is in general not an expert in Information Technology (IT) and in 3D graphics. Therefore, the user interface of an automatic drafting system should be as easy and intuitive as possible. The success of an automatic drafting tool depends heavily on its ease of use.

Given the requirements above, a basic question is if current systems (e.g. common CAD tools) are adequate for producing the requested drawings out of a complex and accurate 3D model. In general they are not the best solution because:

- 3D models produced with range scanning systems can be more complex than the usual models managed by a standard 3D modeling system. Managing a mesh composed by many millions faces is hard on standard CAD systems. Simplification techniques can be used to reduce the complexity of the digital model [9, 6], but using a simplified 3D model may reduce considerably accuracy and quality of the final drawing: we often need to reproduce drawing to a 1:1 scale on large prints, and approximation errors which are considered negligible when we render the full model on the screen may become visible inaccuracies when printed at this scale;

- Moreover, the graphical user interface of CAD tools is in general very complicated (because of the large number of features supported by these systems, and also because they are generally oriented to IT experts). These systems are definitely not easy to use for our target users (i.e. the standard restorer or the art historian).

As an example, when we were requested to produce technical drawings from the 3D model of the Minerva our first attempt was to use a state-of-the-art *CAD system*[3] running on the PC platform. The main problem encountered was the size (i.e. number of triangular faces) of the 3D scanned models. Usually, CAD programs impose limitations on the size of the input 3D model, or/and

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[3]We prefer to omit the brand name of this system just to avoid that the evaluation reported could be interpreted as negative advertising.

became unstable when very large models are imported. Similar considerations hold for rendering systems. Standard CAD and rendering systems are tailored to large structured representations built up of many compound primitives and support editing and browsing of these structures. On the other hand the result of 3D scanning is a very large unstructured *triangle soup*. For this reason the internal data structures, used by these programs to represent 3D shapes, impose an overhead that become strictly prohibitive when we have to manage meshes composed by tens of millions of triangles. Moreover, the principal aim of CAD systems is the *construction* of a complex structured 3D model or the *rendering* of photo-realistic images.

4.3 The *CAVALIERI* drafting system

We describe here the design choices, the interface and the functionalities of our system, called *Cavalieri*. *Cavalieri* has been designed to be a highly interactive system, maintaining interactive response even when we manage a very high-resolution 3D model. Therefore, the internal data representation structures and the rendering kernel (described in detail in Subsection 4.3.2) have been designed to guarantee interactivity of the system.

The graphical layout of *Cavalieri* is presented in Figure 3. The main window is divided in two parts: on the left we have an area mainly devoted to the graphics user interface (GUI), while on the right we have the visualization section. Visualization can be operated under the *view selection* mode or the *preview* mode. The *view selection* mode is set to define views and cut-through sections; the goal of this mode is to visualize both the 3D model and the view selection widgets and tools (i.e. to allow the user to select interactively which parts of the model should be included in the image and how). Once the user has selected a given view, he can switch in *preview* mode, which presents a screen-resolution preview of the final result according to the selected view (Figure 3). The preview mode can be used to check the correctness of the selected view and to allow a fine tuning of the parameters (by switching in sequence between *view selection* and *preview* modes).

4.3.1 View and Cut-through Definition

Our goal in the design of the user interface was to simplify as much as possible the user selection of views and cut-through sections. To define a view, we need to specify some variables which are standard in 3D graphics:

- ViewCenter: the 3D coordinates of the center point of the view;
- Roll: the angle of the view with respect to the Y axis;
- Azimuth: angle of view with respect to the X axis
- View size (width and height): extent in both direction of the projection size (in millimeters).

Additionally, it is possible to select different type of projections: the *orthographic* projection is the default and probably the most useful one; the *cavalieri* projection (also known as *military*) and the *isometric* projection are also available. The latter two projections are useful for specific categories of objects: the Cavalieri projection is good to reproduce buildings, while the Isometric one can be used to draft statues.

The definition of a *cut-through* is slightly different. A common approach is to select independently each cut-through plane. Since in general users need to produce multiple cut-through, we preferred to organize the task by selecting first the axis along which the cut-through plane can slide orthogonally (defined by giving two 3D points), and then the offsets which determine the different sections. This allows the user to easily extract sections orthogonal to the given axis and interleaved at a fixed distance (e.g. along the vertical axis at every 10 centimeters). Therefore, to define a cut-through section in principle the variables to be setup are:

- StartPoint, EndPoint: the two 3D points which defines the guideline axis in 3D space;

- Offset: offset position (in millimeters) of the cut-through plane along the guideline axis;

- View size (width and height): extent in both direction of the projection size (in millimeters).

Views and cut-through sections can therefore be set by selecting numeric values for all the variables defined above, but this is not very much user-friendly. To improve usability of the system we have implemented also two alternative approaches:

- **Preset Buttons:** users often require a standard set of views or cut-through sections. To speedup user selection, a set of standard views can be specified simply using the provided buttons (front, back, left, right, top and bottom views framing the entire model; cut-throughs along the X,Y or Z axis). Parameters are automatically adjusted to fit the model.

- **Manipulators:** non standard views or cut-through sections can be selected interactively with the aid of *3D manipulators*[4] ; in this way the user can operate directly on the model space, just dragging the location of the control points (see an example of cut-through selection with the associated manipulator in Figure 4). Interaction is intuitive and the interface provides immediate visual feedback.

The interface contains some more buttons to perform a fine-tuning of the current view or cut-through by slightly moving the view space (panning), modifying the cut-through offset and increasing/decreasing the view size (zooming).

Obviously, defining just a single view or a single cut-through is not very flexible. *Cavalieri* supports the specification of multiple views and sections for each 3D object; the user can switch from one view to another, to check and/or to modify any of them. The sets of views and sections defined by the user can also be saved on file for a future use. In this case we save the parameters of those drawings (just a few byte for each of them, thus allowing very efficient storage), and not the drawing itself. Before discussing the rendering options and how the final drawings are produced, we have to give some info on how our system represents the digital 3D model.

4.3.2 Internal 3D data representation

Cavalieri can operate using two different types of input:

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[4]With the term *manipulator* we mean some 3D widgets which are added dynamically to the 3D model and can be directly manipulated by the user; example of manipulators are: the *trackball* which allows to easily rotate the object; or the one presented in Figure 4 which supports the interactive selection of the section axis.

1. low-to-medium size 3D models (i.e. triangle meshes with size up to a few million triangles) are accessed using the .PLY format[5] . Other common formats, like 3DS, are also supported;

2. very large 3D models are represented using a proprietary format, which supports out-of-core management of the 3D data.

The first class of meshes are those which can be loaded entirely in RAM memory. To give some hints, *Cavalieri* allows to load models up to 10M triangles on a standard PC with 512MB RAM memory. For these models, the plain representation is loaded and stored on core memory. A simple LOD approach is used to improve system efficiency: all the interactive visualization/manipulation tasks are managed by adopting a point-based rendering approach [14, 19], with just a subset of the model vertices is rendered for each frame (see Figure 4). The original high-resolution input data are used only in *preview* mode and when the final drawings have to be produced.

On the other hand, a very large 3D model can exceed the available RAM memory. The second data representation and loading approach has been designed to cope with very large models (for example a slightly simplified Minerva mesh, composed by around 20 million triangles). The 3D mesh is partitioned in separate files, according to a regular 3D space decomposition based on the octree scheme [20]. Different subtrees of the octree are stored in different files, implementing an out-of-core methodology. The partitioned representation of the high resolution mesh is enriched with a simplified version of the object, produced off-line [6] while converting the original very high resolution mesh into the partitioned, out-of-core, render-efficient representation. This simplified representation is loaded in memory and used as a dummy to manage user interaction in all phases of the view set selection; the complete model remains on disk. Only when *Cavalieri* effectively produces a drawing at printing resolution, the set of *visible* mesh portions (i.e. visible octree leafs) is loaded from disk and stored in RAM for just the time needed to produce the drawing. In this way we are able to render models with resolution higher than 50 million faces on a standard PC.

4.3.3 Rendering Options

Obviously, *Cavalieri* allows to control various aspects of the rendering stage: the model can be rendered with *per face* normals (flat shading) or *per vertex* normals (smooth shading); the wireframe structure of the mesh can be shown on the shaded surface; the model material can be changed (color and reflectance); and multiple lights can be disposed to obtain a proper presentation of the shape detail (e.g. to reduce the surface sections which are under shadows or insufficiently lighted). If available with the 3D model, texture maps or per-vertex colors can also be used in rendering.

An important feature is the capability to add extra features in the final drawing, such as: a *metric grid* plotted on the background of the drawing, a *ruler* superimposed to the mesh surface

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[5]The PLY format (see the web at: `http://graphics.stanford.edu/data/3Dscanrep/` and `http://astronomy.swin.edu.au/ pbourke/geomformats/ply/`) has been defined by Stanford University and UNC and widely used in the graphics community, in particular in the case of non-commercial 3D scanning systems. Converters to the .ply format are widely available.

and an iconic representation of the whole model to improve orientation. The *metric grid* is fixed with respect to the absolute coordinate system, to be used for measurement and correlation between different images. User can control the (two level) stepping of the grid (deciding the cell size in metric units), the line color and style (normal or dotted). If the user selects a very detailed zoomed drawing, it may happen that no background is visible, making the grid useless; in such cases it's possible to use a *ruler* (a thin section of the grid super-imposed on the upper-left border) just,like many commercial drafting programs. To improve the drawing readability (i.e. to better localize highly zoomed views), *orientation information* can be included in the drawing by showing a small representation of the model with the extent of the current view highlighted with a different color.

A *quoting subsystem* is currently under development: it will be possible to mark single points, segments and areas on the model by picking or by specifying exact coordinates. Information about quotes (distances, areas and so on) could be printed on a corner of the image.

4.3.4 Production of printable images

During the definition of views and sections, the view width and height are specified in millimeters. Then, to produce the printable image the user selects a *scale* and a *resolution*: the scale is used to specify the physical reproduction size of the image (e.g. 1:1, 1:1/2, 1:1/4, etc.) with respect to the original size; the resolution is the DPI (Dot Per Inch) density of the printing device. Scales and DPI resolution determine the final image size in pixels.

Using OpenGL for rendering 3D models, raster images can be easily obtained by just reading the screen buffer content and saving the rendered pixels as an image. However, the screen resolution is not sufficient to produce high quality prints on modern large formats printers/plotters. A simple solution for the production of very high resolution images is as follows: for each drawing we split the corresponding raster space in chunks compatible with the resolution of the available graphics subsystem; multiple partial renderings are performed (split rendering) and every partial result is read back from the frame buffer and used to compose the single large image. To avoid excessive memory load, the reconstruction phase does not take place in memory but the partial images are directly wrote on the final image file as soon as they are generated. Since a high resolution model loaded into memory can take up hundreds of MB of RAM, allocating a very large image in memory could result in disk swapping and a degradation of performances. Writing directly on disk can avoid this problem without introducing significant overhead. This approach allows *Cavalieri* to produce raster drawings of any size without memory limitation but restricting the saving format to *Tiled Tiff* (a lossless compressed image format [11]) or BMP.

The resulting raster images can then be imported in any image-processing or 2D drawing program, to add any legend or annotation text and to be printed. Therefore, print management is demanded by *Cavalieri* to third party imaging tools.

5 Experimental evaluation

In this section we report the results of the experimental evaluation of the *Cavalieri* system, used in the on-going restorations of the Minerva of Arezzo [17] and of the Michelangelo's David [2, 3].

The Minerva's restoration is a rather complex one, changing in a significant manner the appearance and shape of the statue both at the large and small scale level. We planned to document all those potential changes through multiple complete acquisitions of the statue. Moreover, drawings produced with *Cavalieri* are the main documentation used by the restorers. An image of a plot of the Minerva in 1:1 scale is presented in Figure 5.

In the case of the Michelangelo's David, a 3D model was already available before the beginning of the restoration project (thanks to the results of the Stanford's *Digital Michelangelo Project* [10]). We were asked by the David restoration committee to evaluate on the digital model the position of the barycenter, together with the volume and mass of the statue. Once computed, the barycenter location can be visualized using a standard graphics approach, but the restoration committee asked us also a different presentation: a plot of the statue seen from the top, with indication of the plumb-line projection of the barycenter on the ground, together with a set of sections of the statue legs cut at different heights (ankle, knee, groin). The resulting plot, produced with *Cavalieri*, is in Figure 6. Another set of maps has also be produced with *Cavalieri* to be used as the supporting layers onto which all the results of the different scientific investigations will be mapped (to support cross-correlation of the different analysis and investigations).

We compare here the standard hand-made drafting and the proposed computer-aided drafting approach, considering different aspects:

1. **Time required to perform the drawings.**

   In the case of the manual drafting approach the time required is measurable in terms of weeks or months (see Section 3). The duration depends on the artifact characteristics and on the number of views. The drawers at the CRA estimated that a couple of man-months should have been required to produce the classical 5 views for the Minerva statue.

   On the other hand, the adoption of a computer-based drafting system allows to select a new view in a matter of seconds; the production of the corresponding image is performed also in few seconds, depending on the size of the 3D model and on the resolution chosen. Since we also require a 3D model of the artifact, one could object that the 3D scanning time should be included in the overall time required to produce the drawings. We do not think this is due because, in general, we do not reconstruct a digital model only to produce drawings; therefore, the reconstruction time should be considered an overhead shared by many different applications or uses of the data, and therefore should be considered just in a fraction here. Readers should also note how the time needed to scan a complex artifact steadily decreased in the last few year (data on the Minerva scanning are presented in Subsection 4.1). Moreover, these times becomes much lower when the size of the object is small. For objects of size smaller than 50*100*50 cm. the time needed to scan and post-process a set of 20-50 range maps is in the range 1-4 hours (according to our experience)..

To conclude, our drafting system allows restorers to produce any drawing requested in real time and, even considering the scanning time, we are still very far from the times requested by the manual process.

2. **Cost and skills required.**

An evaluation of the costs depends on the times and labor cost per unit of time, and on the instrumentation cost. Time cost is obviously in favor of the computer-aided approach. An increased IT-awareness of the restoration people can be forecasted for the near future, and it is also very simple to find a collaborator with sufficient skills in IT. On the other hand, it has to be considered that the skills required to produce high quality manual drawings are not so common on the market and are becoming a disappearing profession; this type of professional contribution is very expensive if contracted in out-sourcing.

The instrumentation is very cheap in the case of the manual approach. As far concerns computer-aided drafting, instrumentation is just a low-cost PC. 3D scanning devices are still expensive (approximately 40K Euros) and costs for servicing activity are in the range of 0.5-1.5K Euros per day.

3. **Reproducibility.**

An important advantage of the automatic approach is that we can easily reproduce any previous drawing, or to easily modify any parameter selected to produce it. If during the restoration it appears that a slightly different view direction could give a better representation, this can be done in a few seconds. Moreover, producing drawing under the same view for different digital models which represent the state of the same artifact in different instant of time is also very easy.

4. **Integration with manual drafting.**

The drawings produced with *Cavalieri* can also be used to speedup the production of highly synthetic or artistic manual drawings. The maps produced by *Cavalieri* can be used by a human drafter working on translucent paper as a background layer containing all the spatial information, thus avoiding measurement and improving the spatial accuracy of the drawing.

6 Conclusions

We have presented the design, features and performances of Cavalieri, a computer-aided drafting system designed to fulfill the pressing requests of the restorers for a computer-aided tool for the production of technical drawings from accurate digital 3D models of artifacts. The production of large formats drawings is a basic activity in restoration, archeology and didactics of art. Producing them manually is a complex process, both in terms of time and skills required. Therefore, an alternative approach can be to produce large format drawings from accurate scanned 3D models. The features of our *Cavalieri* system have been presented in detail. We reported also the results of its evaluation in two mainstream restoration projects concerning the Minerva of Arezzo and the Michelangelo's David.

Among the possible extensions to the system, we are planning to work on the inclusion of non-photorealistic rendering techniques [12, 15, 7], to emulate manual drafting techniques, e.g. stippling or hatching. These techniques are capable to convey to the viewer detailed information on surface curvature and shape but, at the same time, produce more schematic drawings where information on shape is encoded using a few vectorial elements (lines, points). This kind of line-art techniques are also more robust to low quality photocopying and printing devices.

Moreover, another interesting extension could be to support the *integration of other information* on the 3D model, and the selective presentation of this info while producing drawings. The forecasted evolution is from a system for the production of paper-based drawings to a more flexible and complex data base or restoration-oriented information system, an extensions of our current system where the digital model does not represent only the shape, but also maps on the geometry all restoration-oriented or historical/artistic data concerning the artifact. The drafting system can therefore evolve to a *restoration information system* that, in analogy to the Geographic Information Systems, will integrate and link those data with the shape of the object, providing tools for the presentation of the information (either on screen or paper).

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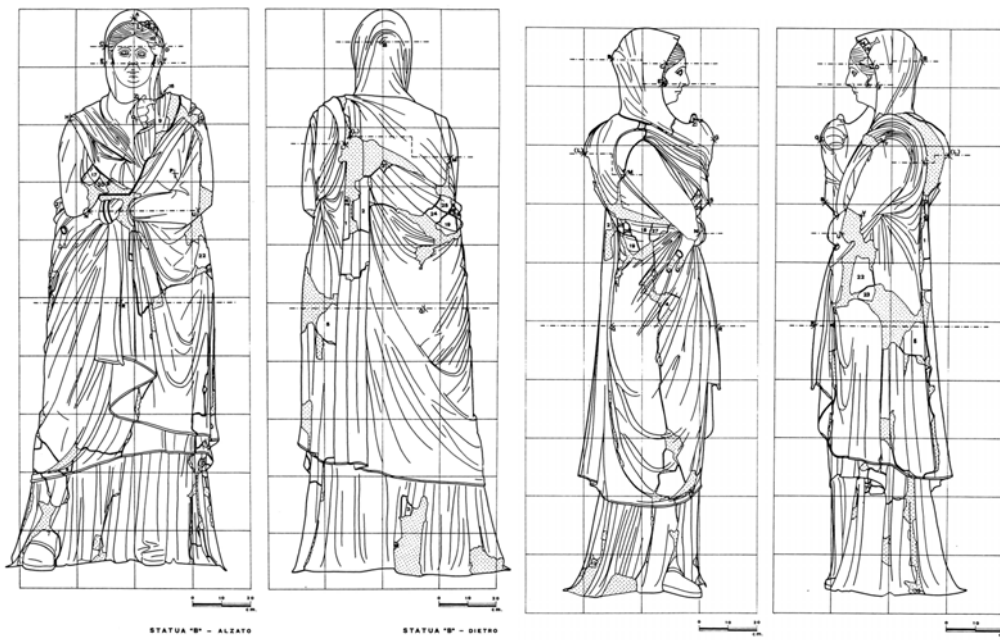
Figure 1: Results of a complex hand-made drafting session (produced for the restoration of the Livia bronze statue by Marida Risaliti).
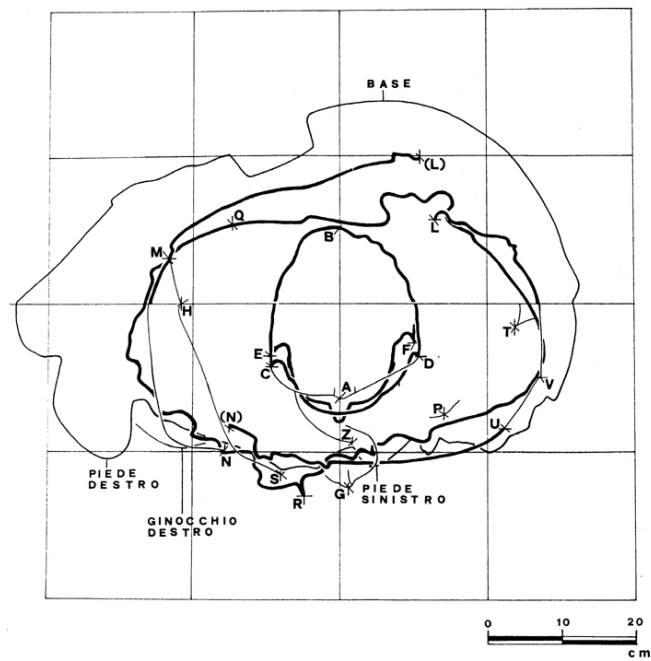

Figure 2: A set of cut-through sections (top view) of the Livia bronze statue.

	Model 1 (Oct.2000)	Model 2 (Apr.2001)	Model 3 (March.2002)	Model 4 (Oct.2002)
Scanner:	structured light scanner [16]	laser scanner[8]	Minolta Vivid900	Minolta Vivid900
Scanning:	146 range maps, 5 days	172 range maps, 4 days	297 range maps, 1 day	306 range maps, 1 day
Post-processing SW:	MeshAlign v.1 MeshMerge v.1 Mesh Simplify v.1 Time: 6 weeks	MeshAlign v.1 MeshMerge v.1 Mesh Simplify v.1 Time: 3 weeks	MeshAlign v.1.5 MeshMerge v.1 Mesh Simplify v.2 Time: 1.5 weeks	MeshAlign v.2 MeshMerge v.2 Mesh Simplify v.2 Time: 4 days
Results - Final Mesh :	30M faces (sampling 0.57mm)	30M faces (0.5mm)	65.6M faces (0.3mm)	68.5M faces (0.3mm)

Table 1: Some figures on the four acquisitions of the Minerva of Arezzo, preformed using theISTI-CNR post-processing tools ..
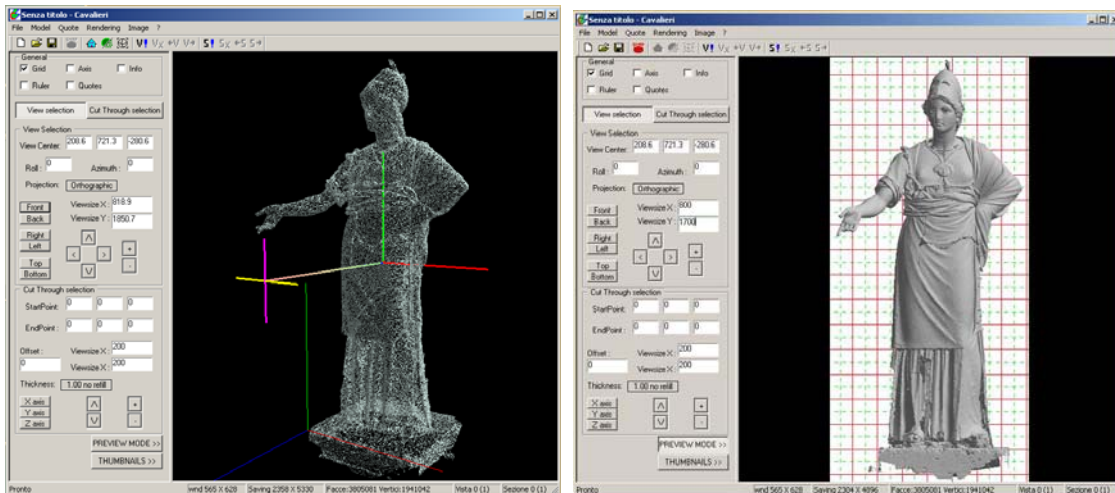

Figure 3: The user interface of *Cavalieri*. Left: the interface is used to specify the desired view Right: in *preview* mode, *Cavalieri* renders a preview of the selected view.
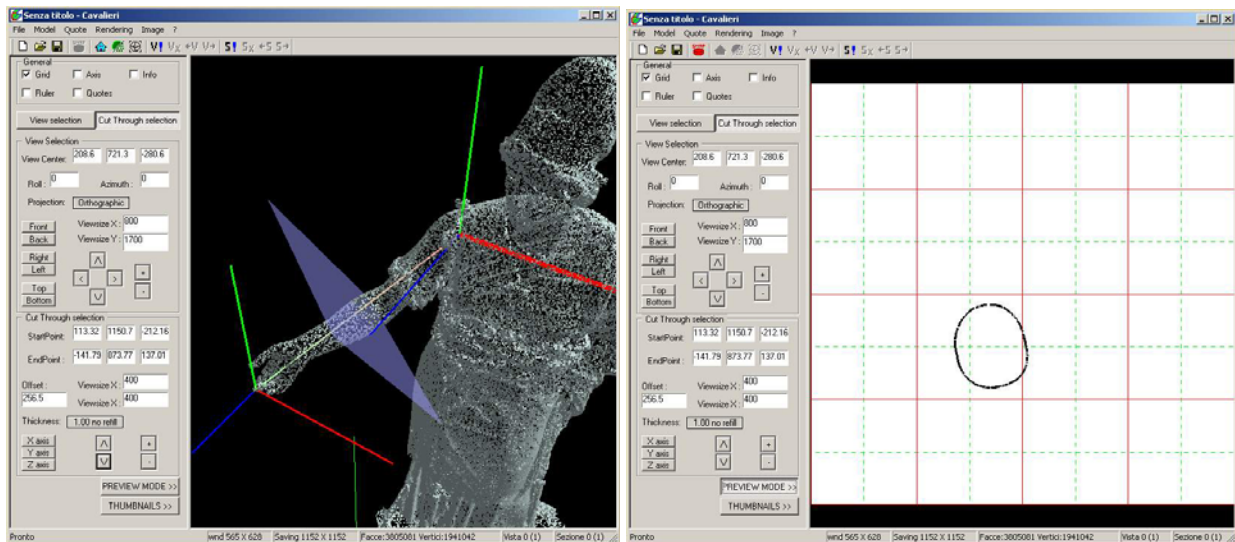
Figure 4: An example of the *manipulator* provided by *Cavalieri* for the selection of sections; the section axis has been approximately aligned with the Minerva right arm (left), and the corresponding section is shown in *preview* mode (right).

Figure 5: An output of *Cavalieri*, representing the Minerva in 1:1 scale.
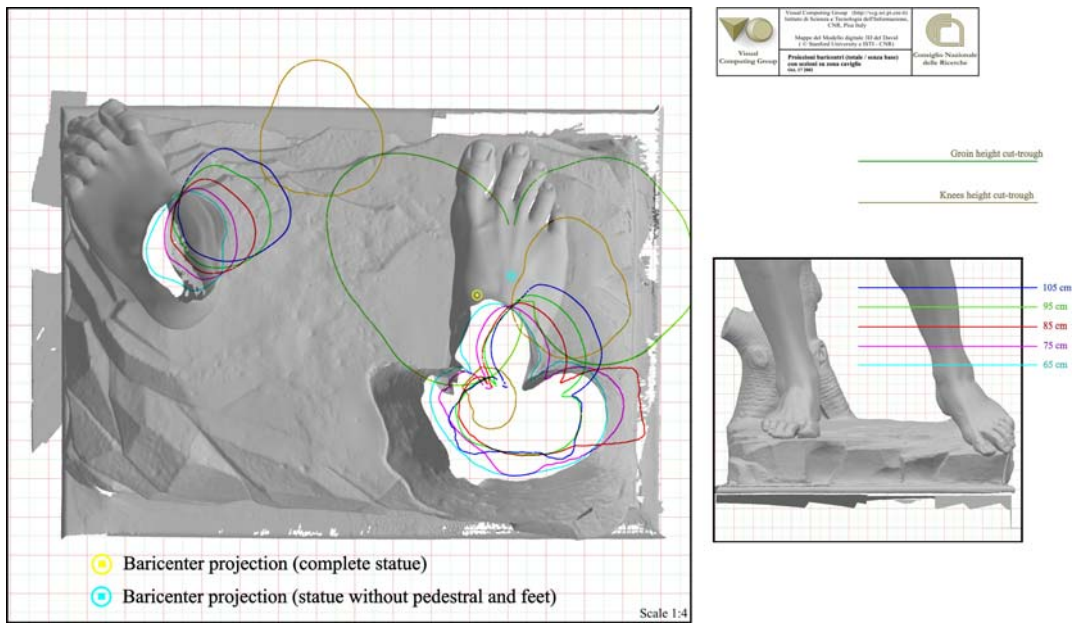
Figure 6: An output produced with *Cavalieri* to document the results of the digital evaluation of the barycenter of the David, with cut-through sections of the legs cut at different height (The 1:4 scale factor depicted in the image is obviously related to the original print).