Teaching 3D acquisition for Cultural Heritage: a theory and practice approach

Matteo Dellepiane[1] and Roberto Scopigno[1]

[1]Visual Computing Lab, ISTI-CNR, Pisa

Abstract

The paper presents the experience of a course (3D Graphics for Cultural Heritage) in the context of Humanistic Informatics degree. The goal of the course was to present an overview of the techniques for the acquisition of 3D models of real objects. The focus was put on freeware/open source solutions that could give the students the possibility to experiment directly on the data, and possibly apply them in their future activities.
The acquisition techniques were divided in three groups: 3D scanning, Dense Stereo Reconstruction and Re-Lightable Images. Moreover, general concepts about 3D Graphics, remote visualization, and planning of projects were part of the subjects.
The final project for each student consisted in a practical acquisition of a real objects, using one of the proposed techniques. The results of the projects showed that high quality 3D acquisition is now possible even with low-cost devices and freeware tools, and that it can be a strongpoint for the career of future young CH professionals.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—I.3.6 [Computer Graphics]: Methodology and Techniques —

1. Introduction

In the last few years, 3D acquisition has become a routine action in several activities: Cultural Heritage support is among the most important fields of application. While 3D scanning costs have severely lowered, due to the decrease of hardware cost and post-processing time, low cost alternatives have been proposed by the research and industrial community.

Hence, if the 3D model of a real object has to be acquired, several possibilities are available, based on budget, accuracy and time constraints. In addition, open-source or freeware solutions enhance everybody to freely experiment and learn.

Based on these observations, a "3D graphics for Cultural Heritage" course was started in the context of a Humanistic Informatics degree of the University of Pisa. The students of this particular degree have an hybrid formation, with the main aim to be able to handle new technologies and apply them in the Humanities field.

For this reason, the goal of the course was to give an overview of the state-of-the-art 3D acquisition techniques, focusing mainly on low-cost or free solutions, in order to give the students the possibility to practice on the data.

3D acquisition technique were divided in three groups: 3D scanning, Dense Stereo Reconstruction and Re-lightable images. Moreover, several ongoing projects and success stories were presented to show the increasing importance of 3D in Cultural Heritage.

As a final project for the course, the students were asked to apply one of the technologies to a real object, creating a simple web-site describing their experience, and possibly defining the utility of a 3D acquisition for that particular case.

We will present some comments about this experience, together with some examples of the final projects, which show that 3D technologies are finally mature enough to become an added value for the young professionals in Cultural Heritage.

The paper is organized as follows: Section 2 proposes an overview of the technologies presented in the course, focusing on the low-cost or free solutions. Section 3 describes the structure of the course, and the possibilities given to the students for practical activity. Section 4 presents a selection of the works by the student, and some comments on the gen-

eral quality and the received feedback. Finally, Section 5 draws the conclusions and outlines the possible future improvements.

2. Overview of technology

A detailed overview of all the techniques for 3D acquisition goes well beyond the scope of the paper. Hence, this section will focus mainly on the latest solutions which have been made available to the public.

2.1. 3D Scanning

3D scanning is nowadays considered a "mature" technology. Since the seminal projects [LPC*00] there has been an impressive improvement both in hardware and software solutions. This led to a significant decrease in costs, and the sustainability of even more complex scanning campaigns of huge and very complex objects [IHN*04], even involving the integration of different hardware solutions [CCD*11a].

3D scanned models are currently a typical part of the documentation and dissemination of Cultural Heritage artifacts, and their integration with other data types, like text and high-resolution images, is making them a traditional data format [CDD*10].

However, one of the main issues related to 3D scanning is still the cost of hardware. The purchase of a 3D scanner is still a big economic effort, although low-cost [Nex03] and DIY [DAV03] solutions proved to be valuable especially in the case of small objects.

Another issue is related to the software tools. Although the scanning pipeline for data processing has been extensively studied, and robust solutions have been proposed to the community, most of the software able to cover all the steps of the pipeline is still commercial and expensive. Recently, open source solutions like MeshLab [CCC*08] presented a complete set of tools for the processing and presentation of scanned data. The first examples of the use of this software have been already published [CCD*11b].

2.2. Dense Stereo Reconstruction

The idea of dense stereo reconstruction tools is to obtain three-dimensional data starting from a series of unordered images. The main advantage of having un-calibrated cameras or devices is the possibility to use large datasets like the ones that can be retrieved from the Web.

The process of 3D reconstruction is usually composed by different steps: image matching, camera parameters estimation, dense matching.

Computation effort of large scale structure from motion is dominated by image matching, which is often obtained (except for some real-time applications) by performing exhaustive pairwise image matching. Several approaches have been

proposed [BL05, MP07, VVG06, GSC*07], and most of the current research is focused on how to index and organize the images in order to reduce the image matching operations and possibly clustering similar images [HTP10, FFG09].

The results of this computation may be similar to a series of range map (similar to the one produced by range scanners), associated to each input image. These range maps are then merged together to generate a single triangulated surface. Some other tools may produce as results a single point-cloud or even a triangulated surface.

In general, the amount of time needed for the processing of image sets is in the order of hours. The few methods which have been made available to the public are based on web-services like ARC3D [VVG06], where the user uploads the data to a server connected to a cluster of computers, which process the data and send the results back. Recently, Bundler [SSS06] was released as an open-source software for structure-from-motion reconstruction of 3D scenes from unordered photographic datasets. One notable implementation of the bundler tool is inside the PhotoSynth [Pho03] application, which works quite similarly to Arc3D, since it is implemented as a web service. Bundler, coupled with a dense matching tool (PMVS2 [FP07]) is able to generate a single pointcloud from all the matched points in the input image dataset.

Cultural Heritage may appear one of the most interesting fields of application for this kind of acquisition, being a non-contact, low cost alternative to 3D Scanning. Some experimentation in this direction has started [REMA09], but the main problem in its use for 3D acquisition is the lack of scale information. Previous and current reconstruction processes [GRZ03, REHB*08] still rely on the integration with 3D Scanning or photogrammetry. Hence, although some claim that dense stereo matching is a mature alternative to 3D Scanning, no convincing comparison has been presented until now.

Recently, some starting effort has been made in this direction [HPA*10] has been made, but methodology definition and accurate data assessment are still missing.

2.3. Re-Lightable Images

Extensive literature exists regarding the definition of Reflection Transformation Imaging (RTI) techniques and the adoption of these applications by a wide range of fields. Reflectance transformation has been shown to be useful for relighting human faces, especially for digitally cloned actors used by the movie industry for special effects [DHT*00, WGT*05]. They have also been used for acquiring the lighting behavior and details of a variety of surfaces [MGW01, HBMG02, MC01].

Other authors have extended this approach by defining the framework of the Bidirectional Texture Function (BTF) [MMS*05], an image-based representation that allows variation of both the lighting setup and the viewing position.

Especially in the case of Cultural Heritage objects, visual inspection of RTI images can be even more valuable than 3D scanning or physical inspection. For this reason, some efforts have been made to enhance the readability of data, like the *specular enhancement* and *diffuse gain* techniques described in the original PTM paper [MGW01], the curvature method described by [WV*05], and the surface enhancement presented in [MWGA06]. More recently, additional methods were recently proposed by Palma et al [PCC*10], who also released a freeware tool for PTM inspection.

3. The course

The core of the course was devoted to the three acquisition techniques. However, more general issues, involving all the techniques, were treated separately during short modules. All the material of the course is available on the web (link): it includes the slides of the lessons, some datasets for data processing, a list of useful web links.

In the following, the main modules of the course are presented, together with the choices in terms of practical experience and tools.

3.1. Introduction to 3D graphics

The introductory lessons were devoted to a high-level presentation of the main concepts in the context of 3D graphics. This included: the difference between acquisition and modeling, the definition and representation of a 3D surface, the openGL Rendering Pipeline, the use of shaders, the global illumination paradigms.

These introductory lessons were useful to introduce a key concept: in order to use 3D technologies, it's necessary to know what it possible and not possible to obtain, and what is the price (not only in terms of money, but also in terms of needed hardware and processing time) to obtain it.

3.2. 3D Scanning

This section was divided in two parts: a theoretical and a practical one. The first lessons covered an overview of the Scanning technologies, particularly focusing on some key terms (accuracy, resolution, speed, working distance) and on the advantages and limitations of the approach. Then, the scanning pipeline was analyzed step by step, covering all the data processing steps (editing, registration, merging, cleaning) and presenting all the possible algorithmic and practical approaches.

These sessions were followed by practical activity: for the acquisition part, it was decided to show two kinds of hardware. The first one was NextEngine scanner [Nex03], which is a very interesting example of a low-cost but effective device. The scanner was made available for the students in the case they wanted to use 3D scanning for their final project. This limited the size of the acquirable objects, but the devices for the acquisition of bigger surfaces are unfortunately still expensive and not easy to use.

The second 3D scanning system was David 3D Scanner [DAV03], which is an interesting project aiming at having a low-cost solution which can be built using off-the-shelf components. While not as accurate as commercial products, this represented an appealing alternative for students. Using these two solutions, a practical scanning acquisition of a sample object was shown to the students.

For what concerns the data processing, the reference tool for the course was MeshLab [Mes03]. The main advantages of this software are: the open source philosophy, the multi-platform approach and the coverage of all the scanning pipeline step, with several different possibilities. Hence, the students were given some datasets of simple objects, in order to give the students the possibility to work on data and experiment the most important issues in 3D scanning data processing, like the control of alignment error, the editing and cleaning, the data complexity.

3.3. User-assisted modeling from images and Dense Stereo reconstruction

This part was devoted to show all the approaches which give the possibility to extract three-dimensional information from a set of un-calibrated images.This was particularly interesting for the students, since 3D data can be obtained with almost no cost, since even off-the-shelf cameras can be used with success.

The first lessons presented the semi automatic approaches to obtain a 3D model from single or multiple images. Unfortunately, one of the main drawbacks of this part was that, even though Sketchup [Goo06] proved to be a valuable tool for the single-image modeling, no convincing freeware solution was found for the modeling from multiple images.

The second part of the module was focused on Dense Stereo Reconstruction techniques. After a description of the algorithmic structure of the reconstruction, the analogies and differences among the various software solutions (webservice, local processing, hybrid) were shown.

For what concerns the practical solutions for the students, two systems were chosen:

- **Arc3D webservice**: this webservice [VVG06] asks the user to simply upload the images, and remotely performs the processing on a powerful cluster of PCs. Then the results is sent back to the user by email. The main advantages of this approach are: the fact that the data are processed remotely, the interface with MeshLab (Arc3D output can be directly opened in MeshLab), and the intrinsic multi-platform nature of webservices.
- **Photosynth toolkit**: this toolkit [PT03] was developed as an hybrid solution, where the image matching and cam-

Figure 1: *An example of a website presented as the final project for the course*

era parameters estimation are performed using a webservice [Pho03], and the dense reconstruction is obtained locally [FP07]. The advantages of this method are a higher robustness in reconstruction and the possibility to have a better control on it. While the toolkit was developed for Windows users, it was possible to use virtual machine software to run it also on Mac machines.

Also in this case, some datasets were made available for experimentation. Moreover, since in some cases the results of the reconstruction was a pointcloud, the process to transform it in a triangulated surface was performed using MeshLab.

An extremely important point that was stressed during the course was that Dense Reconstruction methods are not measurement methods, while the goal of the acquisition was to obtain something that could have been measured. Hence, the issue of scaling the obtained models to real size and putting together different acquisitions was accurately treated.

3.4. Re-Lightable images and PTMs

While Re-Lightable images are only an implicit description of the geometry of an object, they present several advantages. First of all, their use permits to acquire and visualize very fine details and complex materials, which usually can't be acquired by other 3D acquisition techniques. Moreover, the acquisition and processing doesn't need expensive hardware or software, ant it can performed very easily.

For this reasons, techniques like PTM have already found a broad application [MMSL, DCCS] in the context of Cultural Heritage. For this reasons, it was decided to present them as a valuable alternative to 3D scanning.

Hence, and overview of Re-Lightable images approaches was given. Then, Polynomial Texture Maps were presented in detail. A practical example of acquisition was shown during a lesson, and all the software components for processing and visualization were made available.

3.5. Visualization and presentation

Especially in the context of Humanistic Informatics, the way a 3D model is presented has the same value as its acquisition. For this reason, a part of the course was devoted to learn to handle illumination and shaders to present content and valorize results. This was obtained mainly using the features of MeshLab, which provide several means to navigate and visualize 3D models.

Moreover, the web navigation was treated as a key issue. Hence, the birth and evolution of the WebGL paradigm was described in detail, and the students were encouraged to use it to present the results of their work directly on the web-page.

Finally, other "hot topics", like success stories, the 3D imagery systems, the multi-resolution techniques, were presented in order to give the students a broad overview of the present and the future of 3D graphics.

4. Results and discussion

In the final project of the course, the students were asked to acquire a real object using one of the techniques presented in the course. While a list of possible candidates for acquisition (essentially buildings and monuments in the center of the city) was proposed, the students were encouraged to propose possibly peculiar and less-known objects, providing also a reason for the necessity to have a 3D model. The results should have been presented in a simple website (see Figure 1), describing not only the technical details, but also the practical experience, the trial-and-error procedure which brought to the final result.

The outcome of the projects was surprisingly high-quality: we will present four representative cases.

4.1. Acquisition of large objects

A first example was Porta S. Marco (Figure 2), one of the historic entrances of the city of Livorno (see also the related website). The acquisition was performed using the Photosynth Toolkit approach. Due to the size of the complex, several independent photo sets were acquired, and the reconstructed portions were subsequently merged using MeshLab. A challenging issue was the fact that some portions of the monument have small geometric details, while others don't. This brought to different approaches in photo shooting and data processing. In particular, the resolution of the proposed model had to be adapted to the geometric detail, in order to
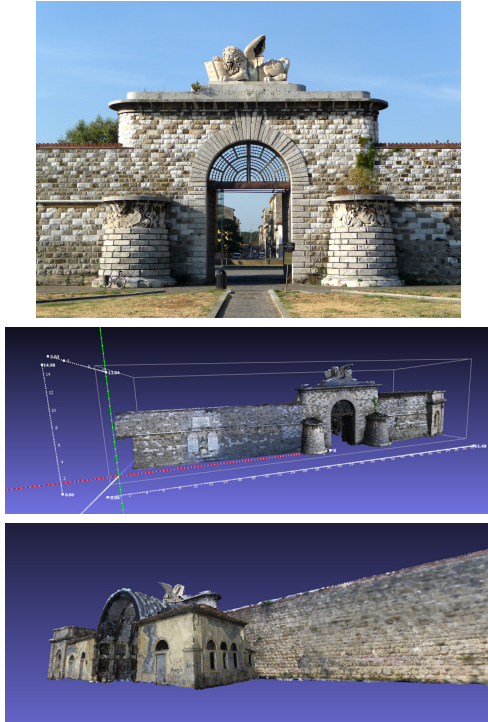
Figure 2: *Top: a particular of Porta S. Marco. Middle and Bottom: two renderings of the obtained model.*

find the best trade-off between accuracy and complexity. The final model was the result of 250 total images, which gave a almost complete coverage of the monument.

4.2. Acquisition of small objects

A second project focused on the acquisition of smaller objects (the masks from 9 to 18 cm in size), again using the reconstruction from images (see also the related website). In this case, the Arc3D approach was chosen. The main issue for these objects was the lack of geometric detail and the reflective materials. For this reason, the student had to work in a "controlled" environment (Figure 3(top)) to provide a diffuse illumination and limit the strong lighting artifacts. Also in this case, the final models (see Figure 3) were obtained by integrating different acquisitions, with a total number of images per object which was between 30 and 60.

4.3. PTMs of very small objects

The third example was about the acquisition of PTM images of two very small bronze statues (four and six cm of height, see also the related website). The acquisition was

Figure 3: *Top: an image of the acquisition setup created by the student. Middle and Bottom: two of the acquired mask, showing an image of the object and a rendering of the 3D model.*

performed with a very simple setup, using a toy (2 cm diameter) black billiard ball to retrieve light direction, and a low-cost light. With a very short post processing time, very detailed re-lightable images were created.

Figure 4 shows some snapshots of the acquired object: the fine geometric details. In addition to the PTM acquisition, the objects were also 3D scanned using the NextEngine device. The comparison between PTMs and 3D models showed that 3D scanning was not able to acquire the details which were clearly visible on the re-lightable images.

4.4. Pitty, a portable PTM acquisition device

The last project was proposed by a student, who designed and created a portable system for the acquisition of PTMs of coins (related website). The entire system was created using low cost material (Arduino for the light control, LED lights and simple aluminium pieces for the structure), and it was designed in order to be easily portable and fully

Figure 4: *Top: two snapshot of the PTM of the same object, showing different illumination. Bottom: a particular of a bronze horse, shown with a real illumination and with specular enhancement, where very fine geometric details are much more visible.*

Figure 5: *Top: a scheme of the acquisition system when it has to be transported. Bottom: an image of the real device.*

controllable.

Using this low cost device (see Figure 5), a PTM of a coin (or of any object of similar size) can be completed in a couple of minutes. This project showed how the gap between students and advanced technology has been reduced, due to research improvements, but also to cultural aspects.

4.5. Discussion and comments

The above presented results certified the success of the course, showing that 3D acquisition is now something that anybody can experiment and use to enhance the experience in presenting and using 3D models in the context of Cultural Heritage.

The proposed tools were used in different ways by the students, and this shows that the new technology should not be accepted "as they are", but they are already easy-to-use and customizable enough to allow for different applications and innovative ideas. This space for innovation is not something

for experts anymore, but it is available for new users and experts of other fields.

Moreover, the practical experience of students was useful to list the current weakpoints that should be fixed in the future. Among them:

- **Lack of documentation**: a common issue for freeware tools is the lack of adequate documentation. This can be extremely frustrating in the first period of usage. A valuable solution to this was the creation of a series of Video tutorials, which proved to be extremely useful.
- **Hardware resource limits**: most of the proposed technologies can require high-performance hardware to process the data. This represented a limit for the work of the students, who were forced to find the best tradeoff be-

tween the quality of the model and the amount of data which had to be processed.

- **Multi-platform solutions**: unfortunately some of the proposed tools were not released for all the platforms. This limited the possibility of the students (especially Mac and Linux users) to use all the techniques.
- **Complexity of data processing**: some of the data processing solutions rely on a set of "tweakable" parameters. This adds possibilities to control the final results, but currently prevents the use of the tools to the wide public (especially when documentation is poor).

5. Conclusions and future improvements

This paper presented the results of a "3D graphics for Cultural Heritage" course which was part of the Humanistic Informatics degree. The goal was not only to give a high-level overview of the state-of-the-art methods for 3D acquisition, but also to teach the use of the freeware and open-source solutions to create 3D models of real objects.

The experience proved to be very valuable, and showed that 3D acquisition techniques are probably ready for a wide range application, and that a short training is enough to start experimenting and having satisfying results. 3D technologies are getting nearer to the public every day, and a future where 3D and images will be treated as a similar and interchangeable kind of data is may be not far.

Anyway, in order to improve the future experiences, some aspects have to be taken into account:

- **The role of color**: the whole course was essentially devoted to the acquisition of geometry. But everyone knows that surface appearance has a key role in 3D graphics. Unfortunately, no freeware (and even commercial) tool is currently giving a solution to acquire and visualize color information of real objects. The announced new release of MeshLab should contain a set of tools to align images on 3D models and transfer the color from 2D to 3D.
- **Documentation and community**: the possibility to have a freeware solution which is widely usable is very much related to the presence of accurate documentation or of a lively community of users (the case of Blender is a positive example). Hence, actions are needed to involve the community in sharing experience, in order to improve the tools and help newcomers.
- **Software maintenance**: one of the main drawbacks of freeware tools is that the cannot always be maintained in the long run. Hence, a software can become obsolete in a short time, leading to the need of finding a substitute.

In conclusion, it was decided to repeat the experience for year 2012, with the aim of improving the quality of lectures and involve the students in a wider range of possible activities.

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