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A VERSATILE WORKFLOW FOR 3D RECONSTRUCTIONS AND MODELLING OF CULTURAL HERITAGE SITES BASED ON OPEN SOURCE SOFTWARE

A. Koutsoudis*, F. Arnaoutoglou, G. Pavlidis, D. Tsiafakis, C. Chamzas

Cultural and Educational Technology Institute, Research Centre 'Athena', 67100 Xanthi, Greece - (akoutsou, fotarny, gpavlid, tsiafakis, chamzas)@ceti.gr

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ABSTRACT:

Nowadays commercial 3D range scanning systems have been used for the accurate digitisation of cultural heritage sites by following either terrestrial or aerial scanning approaches. Both approaches require high cost special equipment and software to cope with the vast amount of raw data. These raw data can be characterised as superfluous in cases where the main scope of the reconstruction is a web-based virtual walkthrough for tourism promotion. The low budget of a digitisation project dictates its breadth and scopes. In some cases, even leasing the equipment is prohibitive. Producing affordable 3D reconstructions for real time virtual walkthroughs is still a challenging task. The transformation of raw 3D range scanning data to an optimised textured triangulated mesh is still a non-automated process. On the basis of this description, a set of open source software applications were identified and combined on a practical workflow to be used for such 3D reconstruction projects when funding and infrastructure is at its minimum. We have attempted to evaluate the proposed process by producing a 3D approximation of a small part of the old town in the city of Kavala located in North-Eastern Greece.

1. INTRODUCTION

Numerous cultural 3D reconstruction projects have been crowned with success. Some of them have produced impressive results by introducing the fusion of different digitization methodologies (Alshawabkeh, 2005; Beraldin, 2005; El-hakim, 2002; Forte, 2005; Kersten, 2004; Koutsoudis, 2007; Lerma, 2005; Müller, 2004; Sabry, 2004; Sgrenzaroli, 2005; Sormann, 2004; Sundstedt, 2003; Suveg, 2000; Takase, 2003; Tsioukas, 2005; Tsirliganis, 2001; Valzano, 2005; Van Gool, 2002). The main purpose behind such a combination is no other than acquiring the best of the different approaches. In other cases this fusion aims at the improvement of the '*automation level*' of the whole digitisation process. Nonetheless, it is still a highly active research area as there is still no panacea methodology to comply with the multiformity of the cultural thesaurus. Fully automated methods for transforming the raw data of a 3D range scanner to an optimised triangulated mesh for virtual walkthroughs are still under research. Modern techniques required at least some minimum user input during the initial reconstruction phase and more interactive work for further conversion of the large datasets into web-optimised mesh structures (Žára, 2004).

A key factor that determines the most applicable digitization method for a project is the substantial scope of the final 3D digital model. It is very common to be affected by the importance of the theoretical and scientific aspects of a project, but no one should disregard the primary role of funding. Projects that involve 3D reconstructions of a cultural heritage site are not an exception to this rule. For example, consider a low budget project aiming at the dissemination of a monument over the web. A low polygonal mesh with high resolution texture maps would be efficient for such an application as in fact it doesn't aim at digital archiving, at architectural or any other type of study but only at the cultural heritage dissemination or tourism promotion. Modern range scanners provide accurate and dense measurements. Those can be described as '*superfluous*' in cases where low geometric complexity building facades are to be captured. At the same time, the project's budget might not be able to cover the expenses of even leasing the digitisation equipment. On the other hand, there is an additional cost of the commercial software that is required to filter and align the raw data.

This work emphasizes on a low budget approach to the dissemination of cultural heritage through an influential medium such as the web, by following well established image based reconstruction methodologies based on OSS (Open Source Software), low cost off-the-self components, like consumer digital cameras, on-site empirical measurements and available topographical studies of the area.

2. OPEN SOURCE SOFTWARE (OSS) IN CULTURAL HERITAGE 3D RECONSTRUCTION PROJECTS

In this paragraph we discuss the role of OSS in software development, the selection criteria of an OSS application and our proposed OSS 3D Reconstruction Workflow (3D-OSSRW).

2.1 Selecting Open Source Software (OSS)

Several working groups such as software engineers, computer scientists as well as economists and management scientists are attracted by the production of OSS. It is interesting for someone to understand this apparently unique mode of source code production (Gläser, 2003). More than ten years have passed since the OSS movement came out. Nowadays, numerous OSS applications present tremendous gains in quality, efficiency and cost saving. Functionality, reliability as well as performance can be considered as principal criteria when selecting such software. *Open Source Maturity Model* (OSMM), *Business Readiness Rating* (BRR) and *Method for Qualification and Selection of Open Source Software* (QSOS) are evaluation frameworks that have been arisen in order to compare and assess OSS.

In our case though, the software selection was biased by the limited number of OSS that are capable to perform the specialised functions required in a 3D reconstruction project. Nevertheless, the identified applications have good reputation for performance and they provide some functionality that can also be found in commercial software. Thus, they form a stable while versatile software arsenal which is applicable in low budget 3D reconstruction projects. The following software components compile the proposed toolset:

a) *Panorama Tools* is a collection of software programs used for creating panoramas from multiple images. The core software was originally written by Prof. Helmut Dersch of the Fachhochschule Furtwangen. The software includes *ptpicker* and *ptstereo* software components to create sparse 3D meshes based on the shape from stereo technique from pairs or many images (Dersch, 2003).
b) *Hugin* is a cross-platform open source panorama photo stitching program developed by Pablo d'Angelo. It is a frontend GUI for the Panorama Tools.
c) The *GNU Image Manipulation Program* (The Gimp) is a raster graphics editor for creating and processing bitmap graphics. It also provides partial support for vector graphics. The project was initiated in 1995 by Spencer Kimball and Peter Mattis and is now maintained by a group of volunteers; it is licensed under the GNU General Public License.
d) *Blender* is the open source software for 3D modelling, animation, rendering, post-production, interactive creation and playback. Available for all major operating systems under the GNU general public license.
e) *Voodoo Camera Tracker* is a camera tracking tool for the integration of virtual and real scenes. It can provide a coarse 3D point cloud based on feature points that are automatically detected and extracted from a video sequence. This non-commercial software tool is developed for research purpose at the Laboratorium fuer Informationstechnologie, University of Hannover.
f) *VeCAD-Photogrammetry* is a simple tool for architectural photogrammetry that performs basic processes such as photogrammetric image rectification using vanishing points and photogrammetric rectification based on measured control points (Tsioukas, 2007).
g) *Meshlab* is an open source, portable, and extensible system for the processing and editing of unstructured 3D triangular meshes and point clouds (Cignoni, 2008). It provides a set of tools for editing, cleaning, healing, inspecting, rendering and data format converting.
h) *VCG ShadeVis* computes a simple, static per-vertex ambient term. This effect, commonly known as ambient occlusion, is aimed at providing more faithful shading for realtime rendering (Cignoni, 2008b).

VeCAD-Photogrammetry, *Hugin* and *Panorama Tools* compose the *Image Rectification Toolkit* (IRT) while *Blender*, *Meshlab, VCG ShadeVis* and *Voodoo Camera Tracker* compose the *Geometry Modelling Toolkit* (GMT).

2.2 The Open Source Software 3D Reconstruction Workflow (3D-OSSRW)

The 3D reconstructions that are produced by 3D-OSSRW are mainly considered for promotional purposes and not for digital archiving or scientific study. They are applicable for realistic real time walkthroughs over the web. Figure 1 depicts the two main phases of the proposed workflow. These are:

- The *Data Acquisition Phase* (DAP) that denotes the actual fieldwork.
- The *Reconstruction Phase* (REP) which is performed with the use of the proposed OSS arsenal (IRT and GMT).

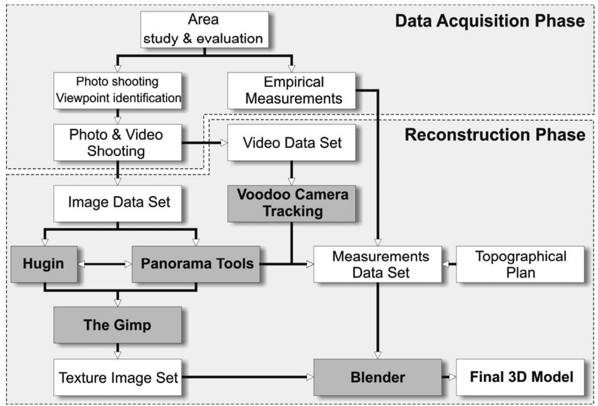

Figure 1: The two phases of the proposed 3D-OSSRW

2.2.1 The Data Acquisition Phase (DAP)

DAP comprises of empirical procedures that do not require the use of any of the proposed software applications. More specifically, during this phase a thorough study of the target site is performed in order to decide on which of the geometric features of the buildings and surroundings are going to be modelled. It is a significant phase as the empiric method that is going to be followed for measurements and photo shooting will be driven by the decisions made at this point. This decision phase could be described as a '*mental polygonal modelling of the site'* performed by the development team. Experience on 3D computer graphics modelling is considered as a subjective criterion on wisely identifying those parts of the real world that are going to be modelled. Thus, DAP is partially dependent on the developer's experience.

It is a fact that our brain has two major paths for processing visual information, the '*where path'* that determines object locations and the '*what path'* for identifying objects (Cho, 2003). The previous statement is highly correlated to real time virtual reality applications such as 3D walkthroughs. The evaluation of the area by identifying characteristic features of the objects is an important factor that affects realism (the '*what path'*) of the final 3D model. It is important for a development team to have in mind that the introduction of real time 3D graphics techniques derived from the multimillion computer game industry is always an advantage in the visualisation of 3D reconstructions. Fundamental techniques such as billboards, tiled textured maps, vertex paint shadowing, ambient occlusion and ray trace *shadow baking* techniques in combination with double texture maps can be applied using the proposed OSS for a realistic result.

Once the decision phase is completed, photoshooting is then performed. But before that a set of viewpoints also need to be identified. The selection of appropriate viewpoints aims at the minimisation of the geometric declinations for images that are going to be used for texture mapping. For example better results are derived for capturing building façades when the camera optical axis is positioned as much perpendicular as possible to the façades. On the other hand, the image sets that are going to be used with the *ptpicker* software for 3D reconstruction during the REP phase should be taken bearing in mind the limitations of the *triangulation principle* as the accuracy depends on the distance of the feature which is relative to the stereo base. In general, distances much larger than the stereo base (eg > 20 times) or features much smaller than the stereo base are not resolved correctly. A topographical design of the area might give an advantage on identifying those viewpoints and it can also provide a well structured document that can be used during the *on site* presence for keeping notes related to viewpoints. The photographic dataset should cover the maximum possible information that is visible to the visitor of the real site. Furthermore, a set of video sequences might be proved also helpful, as it could be used during REP for the production of sparse 3D point clouds with the use of a camera tracking software (e.g. Voodoo Camera Tracker).

The final task of DAP is to manually measure distances between characteristic points of objects within the scene, which is usually referenced as an empiric method. The definition of the coordinates is being done on an arbitrary coordinate system on planar surfaces of the scene. The method is simple and productive, portable and of low cost. On the other hand it is of low accuracy and demanding in terms of time of physical presence on-site. Nevertheless, it can be successfully applied when buildings have simple shapes, or there is a need for recording a sectional plan or sections of interiors (Fritsch, 1999). A good practice might be that the initial recording of the measurements could be done on topographical designs or rough drawings or even on printouts of photographs that were previously acquired. Despite the low density of the measurements and the simplistic scientific aspect, the low cost of the equipment required in combination with the readily available measurements prove to be adequate in situations where high accuracy and dense data are not required.

2.2.2 The Reconstruction Phase (REP)

After the completion of the DAP phase, the REP phase is initiated and it involves the processing of the collected data by using the proposed software collection.

Panaroma Tools can provide a low density triangulated mesh based on the *shape from stereo* technique by using the *ptpicker* and *ptstereo* software components. The output mesh doesn't reflect real dimensions but only proportional distances. This is where the empiric method measurements become practical to transform those proportional distances to real-world dimensions. Alternatively, *Voodoo Camera Tracker* can provide another approximation of parts of the scene in the form of a point cloud. Both data sets can be imported into *Meshlab* for alignment and further processing. Then with the use of *Blender* an optimised polygonal wireframe can be built manually by combining also the empiric measurements and the topographical plans. A very useful approach towards more efficient 3D modelling is to use the topographical plans as backgrounds within the modelling application. This operation can be achieved in *Blender* as it allows the developer to lock the background in respect with the 3D mesh position so that during modelling, camera zooming functions are applied to both background image and 3D geometry.

The modelling phase is, in general, a time consuming process and unavoidable even in situations where different measuring approaches are followed (e.g. 3D range scanners). Assuming that the budget was not an issue and a range scanner was available for the project, the development team would still need to:

- Perform manual polygonal mesh processing in order to generate a web efficient low polygon mesh from the initial dense point cloud.
- Follow mesh simplification and hole filling procedures on the dense polygonal mesh that was automatically derived from the range scanner's data processing software.

According to Žára (Žára, 2004), due to the lack of directly applicable reconstruction techniques, manual 3D modelling from scratch always plays an important role. Additionally, another challenging part during the DAP phase is the modelling of free-form objects usually found in nature. Foliage in general cannot be captured even with high accuracy range scanners due to occlusions and 3D modelling is necessary when realism is required. In general, different approaches can be followed during the modelling phase, i.e. tree representations using billboards, empiric 3D modelling or even freeware 3D models.

The texture mapping of the polygonal triangulated mesh is also proposed to be performed manually within *Blender*. In comparison with the proposed approach, using colour information from 3D scanner range data (e.g. colour 3D point cloud) would allow a faster generation of orthographic photos from the buildings façades. Nevertheless, the texture maps are created based on the image dataset. The IRT is used for image rectifications and stitching. These software tools provide the developer with image processing procedures for warping a digital image on the basis of geometric principles so that perspective is controlled and an orthogonal image is produced (Debevec, 1996; Farinella, 2006; Lingua, 2003; Pollefeys, 2001; Rushmeier, 2000). On the other hand, *The Gimp* can be used as a typical image processing tool, to combine multiple texture maps, to enhance images, to correct colours, brightness and contrast or to create tile maps. The texture mapping of the mesh is performed using the rectified image dataset. *Hugin* and *Panorama Tools* can also generate image panoramas that can be mapped on planar surfaces or hemispheres that could be used as backgrounds in areas where modelling is not applicable.

3. APPLYING THE 3D-OSSRW

In this chapter, we discuss a case study where we have applied the 3D-OSSRW. We discuss an initial project planning and the issues arised during the DAP and REP phases.

3.1 The old city of Kavala

We have selected an area with cultural heritage significance that is located in the city of Kavala (North-Eastern Greece). It is a picturesque area with cobbled roads that lead to an appealing example of Turkish house architecture of the 18th century (where Mehmet Ali Paşa, founder of the last Egyptian royal line, was born) and a Christian Orthodox church dedicated to Virgin Mary. Both are located within the remnants of a Byzantine castle. The house was built in 1720 and it is preserved today in a very good condition. The residence occupies a prime position so that the owners could experience a panoramic view from all sides. The main entrance faces the harbour of Kavala while the other side has a view to a beautiful bay. The house that was renovated before the Second World War was used as a museum until recently and it was one of the biggest (330 m^2) mansions in the city.

3.2 Planning the reconstruction project

With an initial project planning we allocated a total time of 500 person-hours over a two month period for the whole reconstruction project. This initial estimation turned out to be accurate enough as the completion of the project was achieved within these deadlines by only two individuals. It should be noted though that the project duration is related to the complexity of the reconstructed area. Based on the experience gained through this project, and the time needed for each task we came up with the time allocation chart shown in Figure 3. In future works, we will try to improve this type of chart by introducing data from similar projects in order to provide a truthful rough guideline for other projects. Furthermore, the total duration of each task appears in table I. Most of the development time was allocated to mesh modelling and texture mapping. Automation of these processes, in cases where there is a need for optimised geometry, is still challenging and hard to be achieved. Although the workflow provides a simple, yet low cost approach to 3D reconstruction is governed by low mesh complexity, high demands in terms of time of physical presence on-site and basic 3D modelling experience.

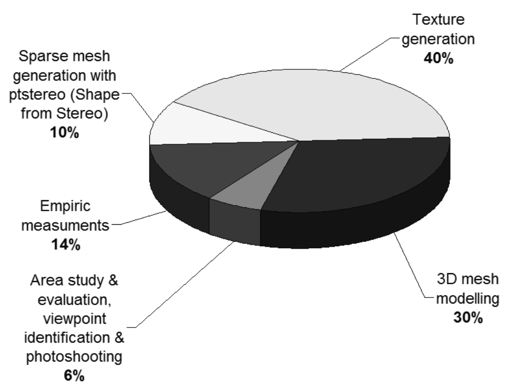

Figure 2: Percentages of total time (500 person-hours) allocated per task for this project

Task	Person hours
Area study & evaluation, viewpoint identification & photoshooting	30
Empiric measurements	70
Sparse mesh generation with *ptstereo*	50
Texture generation	200
3D Mesh Modelling	150

Table 1. Total person hours per task as allocated for this project

For decades now texture maps provide the illusion of details in computer graphics (Rushmeier, 2000). Experiments have shown that pictorial realism plays an important role in an immersive VR system. Such an experiment involved the expression of texture map data as a relative weight contributing to the overall realism metric of a VR system. This weight was usually much higher than the weight of geometric data (Cho, 2003). This is another testimony of the importance of texture mapping when accessing VR systems over the Internet, where the volume of transferred data is still a crucial issue.

3.3 Generating the 3D model

During photoshooting, one can almost instantly understand the difficulties that arise (viewpoint selection limitations and occlusions) as the low budget approach does not allow the use of any special lenses (e.g. wide angle, fisheye lenses) or temporary scaffolding. A total of 900 photos were taken using an 8 Mpixels *prosumer* digital camera along with a total of 250 measurements based on empiric methods. The characteristics of the camera can be found in Table 2.

Sensor Size	2/3" – (8.80 x 6.60 mm)
Sensor Type	CCD
Focal length	6.1 mm
Horizontal field of view	72°

Table 2. Digital camera characteristics

An average of 30 pictures per building were used for both geometry and texture maps creation. Moreover, obstacles appearing on images were manually removed or hidden through image registration or, in worst cases, through manually performed '*image inpainting'*. Before removing the obstacles, the images were processed with the IRT to perform radiometric and perspective corrections of the façades. The final texture maps were produced in most cases by stitching multiple images.

The topology of the area played a key role on identifying appropriate viewpoints. Monitoring weather conditions during photoshooting is crucial in order to avoid heavy shadow casting and severe contrasts. As mentioned before, texture information is the basis of realism in such 3D reconstructions. Thus, it was essential to collect the image data sets under similar lighting conditions (e.g. overcast weather). That way it was possible to provide realistic lighting by using only texture maps. In some cases, though, natural hard shadows were impossible not to be captured. Nonetheless, one could argue that natural shadows appearing on texture maps could significantly improve realism as they capture real world actual appearance. Furthermore, visual quality could be improved by using artificial shadowing techniques such as ray trace and ambient occlusion baked on texture maps or by following the common but less visually effective vertex painting approach.

The user interface of *Blender* proved to be exceedingly efficient for such applications by providing the *One Hand On Mouse, One Hand On Keyboard* (OHOM-OHOK) approach. Figure 3 shows the sparse wireframe (red coloured) that has been imported from *ptstereo* into *Blender* and visualised on the top of a topographical map. The additional geometry that is presented in the same figure has been produced by using the empiric measurements. Trees and bushes were depicted either using billboards or cross planes and in some cases empiric 3D modelling. In order to estimate their height an attempt was made to measure a single point on the top of each tree using *ptstereo*. Once the model's geometry was completed, the use of *shadevis* allowed the per-vertex shadowing of the mesh using the ambient occlusion technique. Then the texture mapping procedure was completed using the rectified textured maps. The final 3D reconstruction covers only those parts of the area that are visible to the real visitor and thus it is not a complete reconstruction.

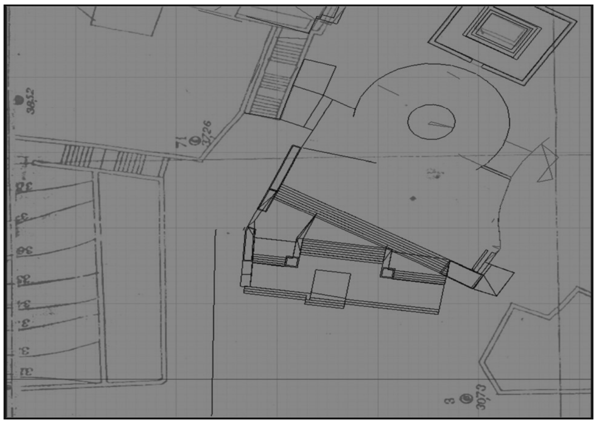

Figure 3: The 3D modelling is performed within Blender based on topographical maps, empiric measurements and sparse triangulated mesh derived from *ptstereo*

3.4 Publishing the 3D reconstruction on the Web

The final model of the reconstructed area (Figure 4) was exported to the ageing VRML, which is now being slowly replaced by X3D. The final model is composed by a total of 11,673 vertices that define a set of 17,832 facets. Such geometric complexity can easily be handled even by low-end graphics cards. The data transfer bottleneck actually resides on the memory size of the graphics card, as the texture data are memory demanding.

Figure 4: Screenshots during a virtual tour inside the reconstructed area

Multiple versions based on different texture qualities can easily serve different bandwidth connections (Table 5). Texture information comprises almost the 90% of the total amount of data. A solution to the texture data transfer problem was given by resizing the texture maps (*JPG and PNG images*) resulting in reduced visual quality whereas maintaining acceptable download times in order to satisfy a larger target group of Internet users. Multiple quality levels of 3D models and geometry compression are active research areas. Unfortunately, the VRML source code is interpreted only after the completion of its transfer to the client. Thus, there is no form of true progressive transfer of the 3D model apart from the ability to manually split the geometry into multiple files. This '*Level of Detail*' approach which is supported by the VRML standard it is not applicable in this case due to the low polygonal mesh data that would be increased if split into multiple files due the textual syntax overhead that would be introduced. Additionally, in most cases the source code is transferred by using the lossless compressed data format GNU zip which reduces drastically the downloading times.

In order to provide some objective metrics to the different versions of the reconstruction, we measured the PSNR on three images (one from each of three quality version we produced) covering the same viewpoint of the reconstruction. Considering the *high quality* version as reference image, a PSNR value of 38.9 dB was derived when comparing with the *medium quality* and a value of 31.4 dB when comparing with the *low quality*.

Transfer Speed	Mesh Data	Texture Data Quality		
		Low	Medium	High
9.6 Kbps	03:10	1:00:10	1:48:20	8:33:29
14.4 Kbps	02:07	40:06	1:12:13	5:42:19
28.8 Kbps	01:03	20:03	36:07	2:51:10
33.6 Kbps	00:54	17:11	30:57	2:26:43
56 Kbps	00:32	10:19	18:34	1:28:02
64 Kbps	00:28	09:02	16:15	1:17:01
128 Kbps	00:14	04:31	08:07	38:30
256 Kbps	00:07	02:15	04:03	19:15
512 Kbps	00:03	01:08	02:02	09:38
1 Mbps	00:01	00:34	01:01	04:49

Table 5: Download times (hh:mm:ss) for the three different texture quality versions of the same 3D scene over networks with different bandwidths. In grey shaded cells appear the acceptable downloading times

Regarding the quality of the resulted 3D model itself, geometry accuracy errors are not constant throughout the 3D model due to the empiric method used. Thus, it is not possible to estimate a uniformly distributed accuracy error factor. This would be possible only in cases where a 3D range scanner would have been used and under certain constraints such as the distance of the scanner from an object. Nevertheless, this variable accuracy error has seamless visual impact when considering the initial purpose of the low-polygon reconstruction which is the promotion of heritage through web by using virtual walkthroughs. Furthermore, many features such as windows or doors are visually depicted through texture maps and are not 3D modelled. It should also be noted that, all empiric measurements are accurately reflected in the final 3D reconstruction when measuring distances between vertices.

In general, the versatility of the 3D-OSSRW allows higher levels of geometry detail to be achieved. However, when considering the additional modelling time as well as the additional extra time required for measurements, then the cost efficiency of the workflow becomes remarkably low and reaches levels that its applicability is questionable. Nonetheless, it has already been proven that there is a limit on creating compelling VR content by only working on improving geometric details (Cho, 2003).

4. CONCLUSIONS

Cultural heritage is primarily promoted over the Internet by digital photographs and textual information, but now it is slowly complemented by virtual walkthroughs based on 3D reconstructions. A 3D model can be virtually explored, providing better perception than a typical photograph. The use of colour point clouds derived from range scanners as the visualisation approach is highly applicable when streaming data over the web but the visual result is adequate only for visualisation of artefacts or monuments from a distant point of view and not for virtual walkthroughs. The use of textured map triangulated meshes has been proven by the game industry, through first person 3D computer games, as more applicable. Furthermore, today's hardware limitations (e.g. graphics cards, processing power, network bandwidth, etc) render the visual realism of an *over-the-net* 3D reconstruction inferior to a photograph in terms of visual details.

In this work, we proposed 3D-OSSRW, an OSS based workflow for the 3D reconstruction of cultural heritage sites. The 3D-OSSRW does not require any programming skills as a prerequisite. Therefore, even a computer graphics enthusiast experienced with 3D graphics can follow the proposed workflow to produce realistic 3D representations of existing urban areas or sites without the presence of any expensive software or hardware. The fidelity of the final 3D model is by far inferior to any other 3D model that could have been created by geodetic measuring equipment such as terrestrial 3D laser range scanners or theodolites. Better results have already proven to be obtainable by combining different techniques only when the cost of leasing or buying the required equipment is within the budget (Beraldin, 2005; El-Hakim, 2002; Sgrenzaroli, 2005; Takase, 2003; Valzano, 2005).

Recent developments of prototype/beta X3D clients could improve the efficiency of the source code that describes the 3D model of the reconstruction as will allow real-time streaming of 3D virtual worlds. VRML lacks many features and requires a lot from the hardware and network connection, a more efficient X3D version could be exported from Blender in order to support new features. In the case of texture information, the ratio between quality and compression can be improved by applying the newly developed JPEG2000 compression scheme that is supported by some X3D clients and results better visual quality, usage of regions of interest and more. Novel VRML/X3D viewers such as the *BS Contact VRML/X3D* provide extensions beyond the VRML standard that allow modern real-time graphics technologies to be used such as double texturing for baked ray trace shadows as well as real-time stencil shadows.

Additional, topographical and historical information could also be collected and attached with the architectural elements of the area. This information is available to the virtual tour visitor by means of tags that VRML/X3D browsers allow to appear when the mouse cursor passes over the buildings. Concluding, the 3D model could be accompanied by an informative website composing a complete on-line tourist brochure.

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