3D Reconstruction and Visualization of Alternatives for Restoration of Historic Buildings

A New Approach

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Abstract: This paper puts forward a 3D reconstruction methodology applied to the restoration of historic buildings taking advantage of the combined speed, range and accuracy of a total geodetic station. The measurements of geo-referenced points produced a fully interactive and photorealistic geometric mesh of an historic monument named ‘Neoria’. ‘Neoria’ is a Venetian building located by the old harbour at Chania, Crete, Greece. The integration of tacheometry acquisition and computer graphics puts forward a novel integrated software framework for the accurate 3D reconstruction of a historical building. The main technical challenge of this work was the production of an accurate 3D mesh based on a sufficient number of tacheometry measurements acquired fast and at low-cost. Interpolation methods ensured that a detailed geometric mesh was constructed based on a few points. Advanced interactive functionalities are offered to the user in relation to identifying restoration areas and visualizing the outcome of such works in a fully interactive application based on game engine technologies. Moreover, the user could photorealistically visualize the actual or restored monument and calculate distances between points.

1 INTRODUCTION

During the last decade, the heritage community has witnessed an increase in three-dimensional (3D) photorealistic reconstructions of archaeological structures which focused more on pleasing visuals often overriding the question of scientific accuracy. Assisted by advances in technology and cheaper technical costs, museums, archival institutions and heritage attractions have been frequently developing digital content. However, archaeologists and computer scientists have urged caution in the abundant use of inaccurate and rushed 3D reconstructions because of the possibility of misleading the public. 3D reconstruction methods should promote and ensure that scientific and historical accuracy is driving such developments. The ability to reconstruct a historical building’s current or past structure is an invaluable tool which could drive its potential restoration.

Restoration of historic buildings is conducted by a team of historians, archaeologists and engineers working together to provide restoration solutions after the diagnosis and evaluation of each restoration issue. 3D digitization of current historical structures and 3D reconstruction of restoration areas should be based on accurate on-site measurements (Sifniotis et al., 2010). Tacheometry acquisition methods (Boochs et al., 2006) use modern total stations that result in high accuracy point measurements as well as quick and efficient spatial data acquisition in order to create a geometric mesh of existing geometry structures. The aim of realistic image synthesis and computer graphics techniques is the creation of accurate, high quality imagery that faithfully represent the geometric structure and light propagation in a physical environment, the ultimate goal being to create a 3D visualization which is perceptually indistinguishable from an actual scene. Reliable geometric measurements are necessary to create a canvas of geo-referenced co-ordinates which could be manipulated by expert users. In this paper, the integration of tacheometry acquisition and computer graphics puts forward a novel integrated software framework for the scientifically accurate 3D reconstruction of an historical building in Crete, Greece. Initially, a detailed 3D geometric model of

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the monument is created based on acquired terrestrial points on-site. Novel interpolation methods ensure that a detailed geometric mesh is constructed fast based on far fewer points available compared to laser scanning. The geometric mesh is lit utilizing modern global illumination algorithms. Advanced interactive functionalities are offered to the user based on game engine technologies. The user can interactively manipulate as well as navigate the geometric model. Based on adequate point acquisition, the user can determine the position and extent of erosions in the material surfaces, whether the surface is smooth or includes bumps, whether there are cleaved and damaged pieces or cracks and the size of determined areas that subsequently require full restoration. It can also be investigated whether the edges of the walls and roof are vertically aligned or whether there are related discrepancies. The goal is to offer to the expert user an interactive scientific tool which determines whether the building needs maintenance and what interventions need to be pursued.

1.1 Motivation

The building named ‘Neoria’ (Figure 1) is a beautiful historic building located at the old harbor of the old city of Chania, Greece. It was completed in 1599 by the Venetians, consisting of seven continuous domes and used for ship repair during the winter time.

Figure 1: Neoria Historical Building, Chania, Crete.

The current state of this monument is compromised as it stands a few meters from the water facing, at times, adverse climate conditions. As shown in Figure 2, parts of the monument’s stone walls have fallen, entire sections of walls are loose and certain edges of the building are partially or entirely destroyed. Significant structural elements are impaired and, as a result, Neoria is slowly losing its original beauty. Cracks are now appearing and restoration efforts had been limited or wrongly conducted. For instance, in order to repair cracks, craftsmen had often applied unsuitable modern materials such as cement. The outcome of such badly managed restorations was that at times, repairs had destroyed neighboring elements to the restoration areas rather than preserving them.

Figure 2: Damaged areas of Neoria in need of restoration.

The scope of this work is to provide archaeologists with a technological and relatively low-cost solution which will enable them to reconstruct the monument at its current state fast. Tacheometry measurements on-site are part of a detailed dataset of the monuments facades and interior. Such measurements could provide a geometric mesh which enables expert users to further inspect the digitally reconstructed monument in detail and at every angle when planning its restoration. Unlike time-consuming and lengthy laser scanning processes, the methodology proposed is fast, low-cost and of high scientific accuracy. In this paper, we present the integrated software framework based on game engine technologies for the scientific 3D reconstruction and visualization of Neoria in Chania, Crete employing a modern total station and advanced computer graphic techniques.

1.2 Previous Work

Two 3D data acquisition methods have been widely documented in research literature as part of the 3D reconstruction process of archeological monuments: photogrammetry and laser scanning. Photogrammetry is a widely-adopted image-based process requiring specialized hardware and software such as a non-standard digital camera for photogrammetry and a digital station (Gruen, 1998); (Mayer et al., 2004); (Kersten, 2006); (El Hakim et al., 2007); (Schaich, 2004). It is widely used for the 3D digitization of historical monuments (Lingua et al., 2003). Although photogrammetry’s end result is a high-resolution 3D model including geometric data for restoration, it is a complex procedure that requires specialized equipment and software. Dark shadows and low luminance areas of structures prevent efficient data acquisition resulting in uncompleted geometry. On the other hand, laser scanning technology extracts high resolution point clouds and it is widely used for the scientific documentation of historical monuments (Boehler et al., 2004). 3D laser scanning allows the reconstruction of individual parts of historical monuments producing a fine geometry mesh (Allen et al., 2003). Laser scanning supports the maintenance, preservation and restoration of monuments based on a highly detailed spatial data set (Balzani et al., 2004); (Julia et al., 2010). Both photogrammetry and laser scanning create an accurate geometric mesh and provide rich detail. However, in the process, both produce a large amount of data and the post processing is quite complicated (Grussenmeyer et al., 2008). In our approach we use as an alternative geodetic total stations which are portable, inexpensive, widely available, requiring less training and having a wide range of other applications. The goal of this approach is to deploy a relatively low-cost total station in order to acquire the co-ordinates of specific surface points of Neoria in Chania's harbour area. The advantage of using a total station to acquire measurements on-site is that it performs fast digital data collection of spatial co-ordinates of archaeological monuments. It is an optical instrument used to measure horizontal and vertical angles in order to determine relative position. The main technical challenge was to produce an accurate 3D geometric mesh based on an efficient amount of spatial co-ordinates that the total station captured in the field. The end-goal was to implement an interactive visualization framework based on game engine technologies enabling experts to identify areas for restoration.

1.3 Methodology

In this paper, we propose an optimized tacheometry surveying technique employing a total station for the monument surveying. The measurement technique put forward is quick, flexible and accurate, requiring a small number of points acquired in interest areas which at the final stage of processing are connected to form a geometric mesh (Andrews et al., 2009). If needed, additional points can be easily acquired in places and used in conjunction with previously acquired datasets.

The 3D model is constructed by connecting the acquired 3D points in order to reconstruct a geometric mesh of a surface. Surface reconstruction algorithms take as input a set of sample points that describe the shape or topology of an object in three dimensions and convert these points into a 3D model. There is a vast variety of algorithms which reconstruct the topology surface from sample points in three dimensional space. The input of such algorithms is a set of 3D coordinates utilized to construct a polygonal mesh. A mesh consists of vertices, edges and polygons. The 3D points are considered vertices forming edges and polygons.

Reconstruction algorithms which compute geometries either create the mesh using the existing points as vertices or employ implicit functions to approximate the surface. Algorithms utilizing implicit surfaces documented in research literature are the Poisson surface reconstruction (Kazhdan et al., 2006) and Hoppe's algorithm (Hoppe et al., 1992). Popular algorithms which compute geometries are the powercrust algorithm (Amenta et al., 2001) and the ball pivoting algorithm (Bernardini et al., 1999). After the surface is reconstructed, subdivision is often needed. Subdivision surfaces are polygon mesh surfaces generated from a starting mesh through an iterative process that levels the mesh while increasing its density. Complex smooth surfaces can be derived in a reasonably predictable way from relatively simple meshes. There are two kinds of subdivision schemes; approximating subdivision surfaces and interpolating subdivision surfaces. Approximating means that the result surfaces approximate the initial meshes and that after subdivision, the newly generated points are not included in the initial surfaces. Examples of such subdivision algorithms are Catmull–Clark (Catmull and Clark, 1978), and Doo-Sabin subdivision surface (Doo and Sabin, 1978). Interpolating subdivision means that after the subdivision, the control points of the original mesh are interpolated to form the resulting surface. A popular method of interpolating subdivision is the butterfly subdivision (Zorin et al., 1996). Although widely used when dealing with laser scanning point clouds, these algorithms require dense point clouds to produce an accurate model. The workflow of 3D reconstruction based on a rather small amount of acquired measurements utilizing a total station is detailed in the following sections.

2 RECONSTRUCTION IN 3D

2.1 Data Acquisition

The outlines of the seven buildings of the Neoria complex were initially measured, along with the edges of the doors and the windows. Due to the extent of the erosion, the framework proposed provides measurements of the angles and distance to surveyed points recorded digitally. Subsequently, the *x*, *y* and *z* coordinates of each point were calculated and connected, offering a 3D model of the monument. A distance accuracy of ±2mm to ±5mm was inherent to each point. In order to survey the whole monument, the total station acquired measurements based on selected positions called ‘stations’. The number of spatial points that were measured was about 780.

2.2 Data Processing

The raw data were acquired in the form of the Greek geodetic system coordinates. Civil3d by Autodesk, processes geodetic data in the form of coordinates as input and converts them to 3D points. The raw data were imported as Greek Geodetic Reference System GGRS 87 coordinates. A survey database was created and the points were treated as point groups, processed concurrently or in parts as needed. The coordinates acquired are now treated as 3D points in space, forming a sparse 3D point cloud. The main technical challenge of this phase was to produce an accurate 3D mesh based on a low resolution 3D point cloud. The spatial data acquisition method adopted, although quick and efficient, it doesn’t provide a large volume of information in the form of a high resolution point cloud that other methods such as laser scanning achieve. We will explain, in the following sections, how an accurate geometric mesh was produced based on a sufficient number of geodetic measurements rather than on a dense, often complex, point cloud.

2.3 Surface Reconstruction

Surface reconstruction algorithms vary depending on how they handle available spatial data (Tang et al., 2013). In order to reconstruct a 3D surface based on total station measurements, approximating algorithms were quickly dismissed. These algorithms require dense point clouds to produce an accurate model. In this case here, the exact geodetic measurements acquired in the field were to be interpolated in order to produce a finer geometric mesh. An appropriate interpolation algorithm would take as input a sufficient amount of points recorded via the geodetic total station and identify spatial areas where interpolation is needed in order to fill in gaps appearing in-between measurements. An example of the implementation of the ball pivoting algorithm as applied to a small subset of the total station measurements is shown in Figure 3. There are holes and geometry discontinuities due to lack of surface information and varying density of the data. The best approach would be to use Delaunay triangulation to form a Triangular Irregular Network (TIN surface) (Lee and Arthrur, 1986); (Edelsbrunner, 2000).

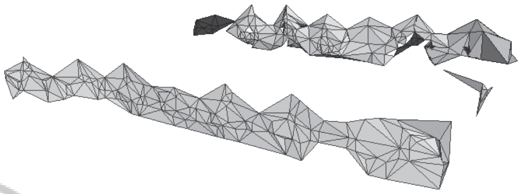

Figure 3: Implementation of the ball-pivoting algorithm. Holes and discontinuities are visible.

2.4 Delaunay Triangulation

Given a set of data points, Delaunay triangulation produces a set of lines connecting each point to its natural neighbors. The Triangular Irregular Networks are used to represent surfaces in Geographic Information Systems (GIS - earth surfaces). In order to produce surfaces consisting of the four walls of the building, the axis of data was rotated 90 degrees facing upwards. The points belonging to each wall were processed separately. The x, y, z dimensions of each wall were designated appropriately to achieve the desired rotation. After implementing the necessary changes, four separate groups of data were derived subsequently processed as TIN surfaces. The points were connected to form triangles according to the Delaunay methodology. These networks were used as base surfaces (Figure 4), however, further processing was necessary in order to add further surface detail so that the real-world surface is approximated.

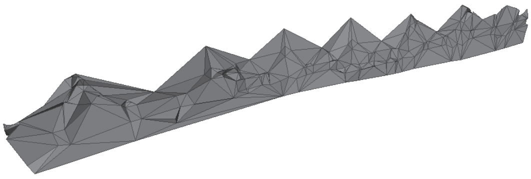

Figure 4: Delaunay Triangulation of the survey points.

2.5 Surface Processing

Initially, each wall was rotated so that they were correctly aligned attached to each other, forming the complete mesh of the monument. Depth information was integrated around the monument’s windows and doors and the mesh was ‘tweaked’ wherever needed in order to correct limited mesh discontinuities. Each side of the building was processed and then subsequently aligned to form the complete building (Figure 5, 6).

At this point, a basic shape of the outline of the monument including details of its structure was completed. In order to integrate further detail, the surface was further subdivided. It was significant to maintain the original position of the vertices so that an interpolating subdivision could be deployed to fill in the gaps.

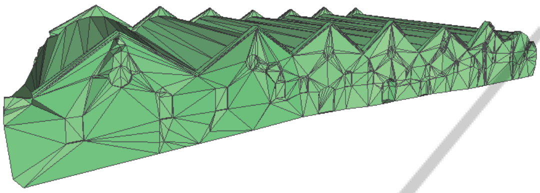

Figure 5: The base surface after corrections (South side). The depth of the doors and windows is visible.

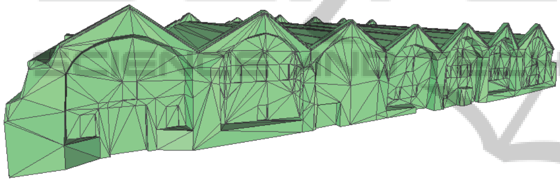

Figure 6: The North side of Neoria after geometry processing.

The next step was to take into consideration the shape and quality of the surface. Large segments of the monument included insufficient spatial information because of the small amount of points recorded. For example, there were sparse blank spaces between windows. Additional spatial information around these areas was paramount in an effort to maintain the monument's initial shape. It was evident that interpolating subdivision methods deform such areas. By not succeeding to find surface information, they randomly add points in blank spaces, deforming the surface and negatively affecting the geometric fidelity of the model. A simple midpoint subdivision was applied to the spatial dataset (Chen and Prautzsch 2012). The subdivision scheme was applied at the point where every edge was split on its midpoint. A finer mesh with no distortion was acquired at the end of this process (Figure 7, 8).

To further approximate the real-world surface, the subdivided mesh was refined. A finer and smoother surface enables the application of detailed texturing on the surface making it more realistic. The problematic areas such as the circular windows and doors were initially brought into focus. To accomplice a realistic circular window, the edges of the windows were further subdivided by applying a Meshsmooth modifier in a standard modeling software, which subdivides the geometry while interpolating the angles of new faces at corners and edges. This process resulted in the desired geometric shape around the problematic areas (Figure 8).

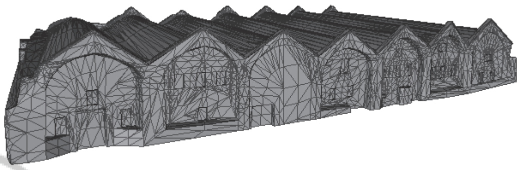

Figure 7: The 3D model after implementing midpoint subdivision.

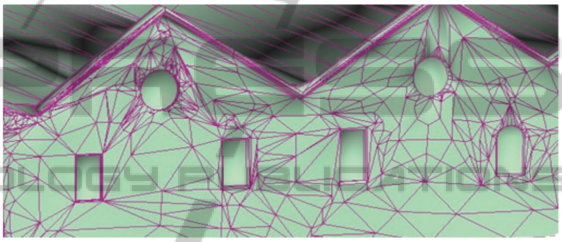

Figure 8: Window details after further refinement.

2.6 Texturing

The 3D surface was textured applying images acquired on-site. In order to begin the process of texturing, the current, largely un-restored condition of the monument was taken into account. There are cracks, damages and alterations on the walls. Parts of the brick walls are missing and there are add-ons of modern materials applied to certain parts. The challenge was to apply such complex effects on the available plane polygonal faces. For this purpose, multi-texturing was employed. The primary set of textures included mostly images taken on the field. Normal mapping was applied which simulated the bumps and abnormalities of the surface by detecting the edges of the surface's constructed elements such as bricks, break lines, etc. offering the illusion of an uneven surface.

UV mapping is the process of forming a 2D image representation out of a 3D model, in order to correctly project a texture map on the model. During this process, the model's derived 3D mesh was unwra90pped to a flat 2D image. This process involved splitting the geometric mesh into clusters by selecting similarly-looking parts and faces. In each cluster, the appropriate texture was applied as a diffuse map. The diffuse map is a texture used to define the surface's main colour. It sets the tint and intensity of diffuse light reflection on the surface. A simple diffuse map, however, does not communicate photorealism. The perception of realism as well as 3D depth is attained by normal mapping. Normal mapping simulates small displacements of the surface while the surface geometry is not modified. Instead, only the surface normal is modified as if the surface had been displaced. This is achieved by perturbing the surface normal of each object and using the perturbed normal during lighting calculations.

Normal maps consist of red, green, and blue. These RGB values translate to x, y, and z coordinates, allowing a 2D image to represent depth. The 2D image is applied to the surface. This way, a 3D surface simulates the lighting and ultimately the color associated with 3D coordinates. In the normal map, each pixel's color value represents the angle of the surface normal.

After texturing, the model was imported in the Unity3D game engine. Game engines have become a tremendous asset in archaeological and architectural visualization. Unity3D is a powerful cross-platform game engine developed by Unity Technologies. It is used not only to develop video games, but also for any kind of sophisticated 3D visualization which can be ported to the web or on any mobile platform.

2.7 Lighting

Photorealism relies heavily on lighting. After texturing, it is essential to apply a global illumination algorithm so that the lighting of the scene simulates real-world lighting conditions. Unity3D uses the Beast lighting algorithm. Unity Pro extends this functionality by *Global Illumination*, allowing for the so-called ‘baking’ of realistic and beautiful lighting, that would otherwise be impossible in real-time.

Global illumination represents a group of algorithms used in 3D computer graphics offering physics-based rendering by emulating inter-reflections in a scene. Such algorithms take into account not only the light which comes directly from a light source (*direct illumination, local illumination*), but also perceives all surfaces in the scene as lights sources which, in turn, affect the lighting of other surfaces, whether reflective or not (*indirect illumination*). In fact, this is a recursive process which should be terminated when the global illumination algorithms are utilized. It is user-defined when the algorithm will terminate; in most cases this occurs when subsequent iterations do not produce perceivable additional lighting effects and shadowing compared to the previous ones. Diffuse inter-reflection is a global illumination effect applied to architectural visualization and to the interior or exterior of buildings producing beautiful subtle shadowing and color-bleeding effects, integrated in the radiosity global illumination algorithm. The Beast lighting algorithm is a radiosity-like renderer that enhances the photorealism of the geometric mesh and offers a realistic as well as scientifically accurate simulation of the Neoria monument (Figures 9, 10).

Figure 9: The North side of the Neoria monument photorealistically rendered.

Figure 10: The South side of the Neoria monument photorealistically rendered.

3 DIGITAL RESTORATION

The goal of this work was to develop an interactive visualization tool which offers expert users the capability of interacting with a scientific 3D reconstruction of an existing monument acquiring information concerning its future restoration. The visual impact of such restoration is rendered after user interaction and presented to the user. Unity3D offers sophisticated tools for the development of 3D interactive applications and a programming interface utilized for the development of complex geometry behaviors, user interaction, etc. The final application’s functionalities were programmed in Javascript.

3.1 3D Interactive Visualization

Interactive functionalities are provided to the user who dynamically manipulates as well as navigates the geometric model (Figure 11). The expert user can zoom on parts of the geometry for closer inspection and identify interest areas relevant to monument maintenance, erosion, wall alignment, cracks, measurements, etc.

Figure 11: Interactive walkthrough of the monument and sea.

Figure 12: Currently, there is a missing part on top of the building.

Advanced functionalities allow the user to alter the geometry provided. This operation is implemented in damaged areas which are in need of restoration represented as geometric mesh (Figure 12, 13). For instance, added cement can be removed and replaced visualized by acquiring textures derived from non-damaged areas. Hotspots of interest and restoration areas can be activated through the on-screen menu. By interacting with the menu, the user can toggle between surfaces; for example, the user can visualize the monument surface as it exists today and the restored surface rendered in red color (Figures 13, 14). In order to render the restored surface, the appearance of the non-damaged parts was taken into consideration, as well as the measurements of structural elements of neighbouring areas of interest. This process recreated missing surfaces while there was lack of architectural information.

Figure 13: Digital restoration of the missing part; the red part does not exist at present.

Figure 14: Currently, the door opening is blocked.

Figure 15: Door opening restored as appearing in the past.

Scientific information is offered to the expert user in relation not only to potentially restored areas but also to measurements between areas, existing and restored. The user could select specific points on the surface and the system calculates the distance between them. Moreover, the user could actually visualize the co-ordinates of the original tachometry measurements and identify areas where the points are dense or scarce (Figure 16). The user could also visualize the current condition of the monument lit under different lighting conditions. In order to aid further the specialists in restoration to extract architectural information, a functionality which can display information was implemented. This operation can be chosen from the screen menu, prompting the user to pick two points anywhere on the model and information regarding the position and relation of the chosen points is displayed. Their distance in 3d space is calculated, as long as their depth difference on the vertical surface (Figure 17).

Figure 16: Display of original tacheometry measurements (green points) and their coordinates.

Distance 1.006775m
Depth 0.05299759m

Figure 17: Distance calculated between points. The upper corners of a window were chosen for measurement.

The units are in meters. In that way each user can measure the dimensions of a particular feature or can gain information on the size and exact place of a restored part.

4 CONCLUSIONS

In this paper, the integration of tacheometry acquisition and computer graphics puts forward a novel integrated software framework for the scientifically accurate 3D reconstruction of a historical building in Crete, Greece. The interactive framework presented was based on game engine technologies which provide powerful tools for photorealistic visualization. The main technical challenge of this work was the production of a scientifically accurate 3D mesh based on a rather small number of tacheometry measurements acquired fast and at low-cost. Novel interpolation methods ensured that a detailed geometric mesh was constructed fast based on far fewer points available compared to laser scanning. Advanced interactive functionalities are offered to the user in relation to identifying restoration areas and visualizing the outcome of such works. Moreover, the user could visualize the co-ordinates of the points measured, calculate distances at will and navigate the complete 3D mesh of the monument. Future work will produce an advanced visualization system operated on a mobile platform, investigating the effectiveness of complex visualization techniques linked to diverse restoration strategies by local authorities, visualizing the visual impact of such restorations.

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