THE USE OF TERRESTRIAL LASER SCANNING IN THE DEVELOPMENT OF MODELS FOR A HERITAGE BUILDING INFORMATION SYSTEM

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Abstract: *The relevance of Building Information Modelling (BIM) as a shared knowledge resource for information to proper management of the built environment is well established. The heart of the BIM is to generate a building model from observed data. The overall objective of this work is to illustrate the capability to rapidly generate 3D models of cultural heritage buildings within the framework of a BIM using terrestrial laser scanning and high accuracy surveying techniques. Two case studies are presented to illustrate the varying digital outputs produced by the accurate 3D models of complex heritage buildings and which can be used as part of an as-built BIM process.*

1. Introduction

The 3D digital reconstruction and documentation of cultural heritage buildings is an active research area which is supported by the World Heritage Centre (WHC) of the United Nations Educational, Scientific and Cultural Organisation (UNESCO). It is a complex process that typically involves the processing and visualization of heterogeneous datasets such as survey data, computer aided design (CAD) drawings, photographs, and 3D non-contact imaging data (terrestrial laser scanning, photogrammetry) (El-Hakim et al. 2005; Remondino et al 2009). In the past decade, a great number of research projects have provided a wide range of workflows, from the digital acquisition of extant buildings to the display of high-accuracy 3D models and animations, with an emphasis on high visual and metric accuracy. One reason for this is the more widespread use of terrestrial laser scanning (TLS) and photogrammetry for recording cultural heritage sites. These technologies have made it possible to efficiently and accurately record complex structures remotely that would have been very difficult with previous survey methods. In recent years, however, heritage documentation has moved toward intelligent data for the analysis and maintenance of cultural buildings (Pauwels et al 2008). To this end, the use of Building Information Modelling (BIM) technology is considered to offer new perspectives in the field of heritage documentation.

Conceptually, BIM is an integrative tool for the design, representation, production, and long-term management of the built environment. BIM software combines multi-dimensional visualization with comprehensive, parametric databases to facilitate collaborative design and facility management among project partners (Russell & Elger, 2008). The use of BIM is a recent advancement for the design and lifecycle management of buildings implementing CAD systems. Their difference from traditional CAD systems is that they use information enhanced parametric building elements, which are combined to create whole buildings within a virtual environment in a 3D presentation. In addition, a BIM offers digital documentation of the building, such as, orthographic projections, cut sections, details and design schedules for economic, structural, environmental and energy functions. Within a BIM structural analysis of a deformed building can also be performed. The essential characteristics of a BIM are that it uses 3D constructive solid geometry (CSG), is parametric representing both geometric behaviour and design intent, and carries semantically meaningful information about its objects (Eastman et al. 2011).

Whilst the adoption of BIM for the design and lifecycle management of new buildings is widespread, there is little research undertaken to explore the value of BIM in the management of heritage buildings and cultural landscapes. This can be attributed to the fact that in real situations, it is extremely difficult to obtain full documentation and documentation of a heritage building of an acceptable quality, since the material, constructive pathologies and systems are often insufficient or deficient (e.g. isolated photographs, 2D designs that simply reflects levels etc). Sometimes the information may exist, but it is not easily accessible, leading to the unnecessary duplication of efforts and resources. The benefits of implementing BIM in heritage building management include remote reviewing of the building interior and exterior, allowing study of the building at different periods of time, evaluation of adaptations and renovations prior to committing to a strategy and full construction documents.

BIM can be used to store the information of a building through the entire building life cycle, including the processes of construction and facility operation. In heritage buildings though, this information is limited to the operation stage. Therefore, the heart of the BIM is to generate a building model from observed data. Recently, high-definition surveying for various types of building and architectural surveys is seen in terms of terrestrial laser scanning. Building and architectural projects are generally considered a natural fit for laser scanning. Many building features are vertical or directly overhead, which provides good line-of-sight and a good angle of incidence for a scanner's beam. Scanners can capture surfaces and points that are otherwise hard to reach or that may not be safe to walk on. Furthermore, many heritage and building projects feature complex geometry that is well-suited to high-definition surveys. Some noteworthy efforts of adopting BIM for heritage buildings include Arayici (2008) who has tried to incorporate multifunctional, intelligent and multi-representational data through the use of BIM for existing buildings. His research focused on adapting automated data processing and pattern recognition that leverages 3D point cloud data towards the generation of a simple building envelope. Penttila et al. (2007) provide a case study that evaluates the possibility of BIM for the retrofit of buildings of significant historical and cultural value. Attar et al. (2010) present the strengths and weaknesses of BIM while dealing with insufficient as-built drawings and the lack of a proper building survey, challenges often encountered with heritage buildings. Fai et al. (2011) present a project in relation to modelling historic buildings and also generating BIM models from laser scanner survey data. Their work concentrated on the problems associated with combining laser scanning and BIM and plotting generic library objects onto the scan in a BIM environment. Also, Brilakis et al. (2010) present their efforts in compiling BIM models from scanning data and other data. In terms of as-built data collection on construction sites, data acquisition via terrestrial laser scanning has matured sufficiently to improve project quality control processes and modelling. Bosche and Haas (2008) proposed a new approach for robust automated retrieval of 3D CAD model objects in construction from range images. Tang et al. (2010) discuss computer science techniques that can be utilized to automate the process of creating as-built BIMs by dividing the overall process into three core operations- geometric modelling, object recognition, and object relationship modelling.

In light of the above, it is clear that the heart of a BIM is the data which needs to be collected in a dense and accurate manner. The overall objective of this work is to illustrate the capability to rapidly generate the 3D model for use in a BIM of the exterior and whenever feasible, the interior envelope of a heritage structure in order to perform any analysis such as for possible deformation. For this purpose, the most promising technology is TLS. Unlike conventional mapping techniques e.g., land surveying and photogrammetry, laser scanners provide rapid and direct description of 3D geometry independent of lighting conditions, and without the need for direct contact with the affected site or for manual data collection. The point-cloud provided by high-resolution scanners is both dense and accurate, providing a detailed description of objects irrespective of their shape complexity. However, the cloud of points provides a geometric description of the scanned scene but carries no semantic information regarding the objects within. Consequently, data interpretation is needed. On the other hand, a building information model (BIM) describes a building with respect to its geometric and its semantic properties. Therefore, it is required to bridge this gap and provide a mapping schema from the point cloud to the structural elements in the BIM. To do this, it is essential to give information not only about the geometry but also on shape diversity, cracking of structural elements, and the varying level of detail in which objects are represented in the different time frames by the data collection. This paper employs the concept of an “inventory model” as an essential base for a BIM for heritage buildings and presents two different case studies whereby the captured data show the existing building condition.

2. Case Studies

As explained in section1, the core of a BIM is the data that needs to be collected in a dense and accurate manner. In this section two case studies are presented to illustrate this point, i.e. the generation of 3D cultural heritage models as an input to a BIM for structural health monitoring purposes.

1) Historic Data

The historic data of a building is an essential part of BIM and includes all the relevant information from historic maps, architectural elements, developmental stages of the building from construction to current usage, etc.

Case study 1, refers to the building of Villa Rossa located in the island of Corfu, Greece, has historical significance and special importance for the island (Fig.1). It comprises basement, ground floor, first and second floors with an area of approximately 270 m^2 in ground floor level. However, the construction (which has many additions, built in different historic phases has not been maintained for several years resulting to a substantial amount of damage internally and externally. Specifically, cracks are deep and serious throughout the building and there are many areas on the ceilings and the walls where the plaster and other materials have worn or broken away. Also, areas of plaster of the ceiling have fallen away and have exposed the rusted steel beams (Tournas et al., 2010).

Figure 1: Photograph of the building of Villa Rossa in Corfu

Case study 2 refers to a stone masonry warehouse, at the outskirts of Thiva. It was built in two phases around 1930 as an auxiliary building for the construction of a part of Athens-Thessaloniki railroad, which was in progress at that time. In 1949 the warehouse was sold to an individual and thus no documentation of any kind was found in the archives of the Hellenic Railways. In 2010 the building was acquired by its present owners, who decided to restore it and assign to it a new use. The more than 80 years old building bares several obvious damages, starting from the heavily damaged roof, which was decided to be replaced by a new one, to a large number of cracks on the stone masonry, damages of the wooden ties etc. Furthermore, for the design of the restoration, any possible non-obvious damages should be detected and investigated, the primary one being the loss in verticality of the walls, as suggested by the cracks' pattern.

Figure 2: Photograph of the industrial building in Thiva area

2) Survey Data

The second stage in a BIM is the collection of survey data for a building with respect to its geometric and semantic properties. An information model of the original state of a building as well as at different time periods is important in order to assess its structural health.

In case study 1, only one set of surveying measurements were acquired which were obtained by high precision topographic techniques, TLS and photogrammetric image data. Specifically, a control traverse network was established around the building which extended inside it at each floor and the basement. In addition, a total of 120 control points which were necessary for the registration of all data into a common coordinate system were also measured with an accuracy of about 0.8cm. The scanning of the building included internal and external acquisitions in order to create facades and ground plans and sections. A total number of 54 scans were acquired, 22 of which were from outdoors and 32 were internal. The scans were performed using the scanner Riegl Z420. The scanning resolution was set up to 1cm. Finally, image data were acquired by an external CCD camera Nikon D100 which was mounted on the TLS. The images were taken according to the basic principles of photogrammetry. For every laser scan one to eight images were acquired depending on the extent of the scan. The analysis of each image was 2000x 3008 pixels.

In case study 2, in the context of geodetic surveying, a horizontal and vertical network of nine control points in a local coordinate system was established. For the collection of the data the terrestrial 3D laser scanner Leica ScanStation 2 was used (Fig. 3). The final 3D model derived from the registration of eleven (11) individual scans, nine of which were from outdoors and two were internal. More than 110,000,000 points were scanned with scanning resolution of 8mm. All distances, scanner – object, did not exceed 40m, that are within the limits where the laser beam of the scanner has the minimum diameter to achieve the best possible accuracy. The registration of individual scans performed with direct georeferencing using special spherical targets (Cyrax sphere target).

Figure 3: Leica ScanStation2 TLS during scanning process

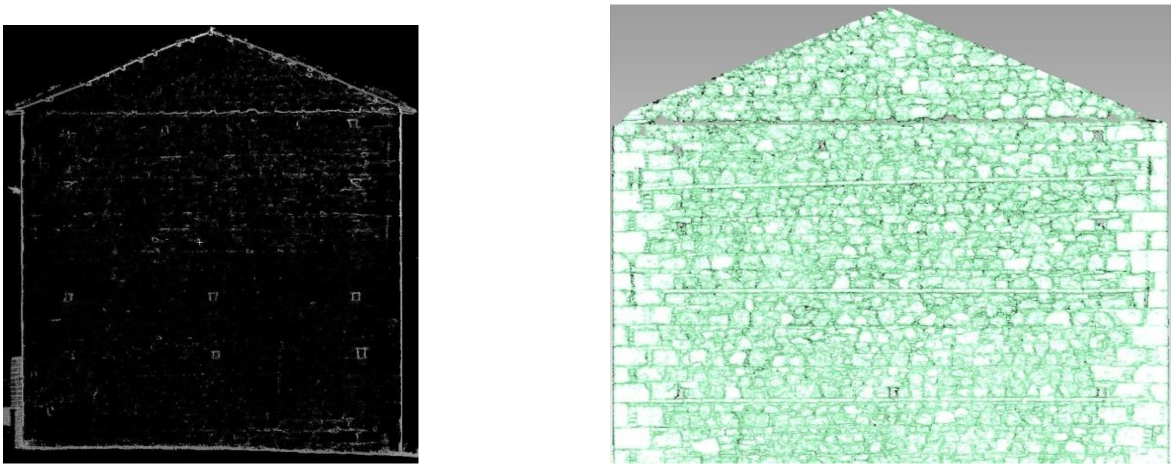
3) Data Processing

The processing of the various types of data requires the use of a common reference coordinate system. Thus, the most critical step preceding the data fusion is the geometric alignment or georeferencing of the separate datasets into the coordinate system.

In case study 1, the reference system was defined by the total station measurements. The georeferencing of the laser scanner data was achieved at an accuracy of 0.01m. With

TLS data, registration and georeferencing are usually carried out in a combined procedure. The next step was to align the individual digital images that were recorded contextually with the scan in the field. For this reason it was essential to ensure that the model's surface points are identified and made the correspondence with the same ones on the images. In this way a point cloud is created, where every pixel of the image is associated with a numeric value and colour. But due to the high number of scans and the resulting large amount of image data it was decided to perform the processing in part.

In case study 2, registration and georeferencing of the individual scans were at an accuracy of 0.8cm. The processing of the 3D model included the semiautomatic procedure for removing noise (redundant information and erroneous points), creation of surfaces (tin mesh) and the final 3D model. The following illustrations (Fig. 4) show a typical example of georeferenced point cloud and corresponding modelled surface.



(a) (b)

Figure 4: (a) Point cloud of the west wall tin (b) mesh for the same wall

4) Visualised products

This stage includes the development of a full surface description of a building in 3D and 2D. Also, other by-products such as sections can be easily extracted in any direction.

In case study 1, apart from the 3D surface model of the building, the orthoimagery of each surface (externally and internally) was created thus forming the photomosaic of the structure. The photomosaic for one part of the building is shown in Figure 5. Digital images contain more texture information about objects and vector drawings make users easier to comprehend the object's geometry. The advantage of the photomosaic is that contains both the above merits. Thus, the produced photomosaic was used in a CAD environment to create scaled vector drawings for plans and sections of the building.

Figure 5: Photomosaic from part of the building

3. Building Information

The usual approach in a heritage BIM, after the collection of 3D point clouds, is mapping vectors onto a scan by automatically placing primitive 2D or 3D shapes onto the point cloud in order to locating/defining shapes on the point cloud. For example a primitive shape of a cylinder can be mapped onto the point cloud to represent a column, which is then textured from the associated image data. An improvement in mapping can be achieved by recognising that buildings are a set of elements, organized by spatial relationships determined by an architectural style. The architectural elements can be represented in libraries as parametric objects and mapped onto point cloud or image-based surveys (Dekeyser et al. 2003).

In the approach used in this work, instead of using primitives which is a good approach only for strictly geometric shapes, modelling is performed either using the creation of orthoimages (case study 1) or direct point cloud information (case study 2). The models that are generated this way can be useful for documentation purposes, for periodic checks on structures preservation and for studies about technological building systems over architecture history.

Figure 6 shows an example from a produced vector drawing, obtained from Fig. 5, which clearly depicts the damages and cracks on the surface of the building wall.

Other information such as cross-sections, varying views of the structure etc can be performed either on a 2D or 3D surface model depending on the requirements of the project. In addition, a variety of combinations such as individual section export, group of section export or all sections export can be executed at a time. For example, in case study 2, apart from the 3D surface model of the building, top and front views, sections in three main directions were extracted (Fig.7). Finally, 3D deviations of the building were calculated and visualized in several maps. Figure 8 shows a detail of the deviations, as derived from the tin mesh surface, from the vertical plane of the north wall of the building. The scale of the deviations refers to meters.

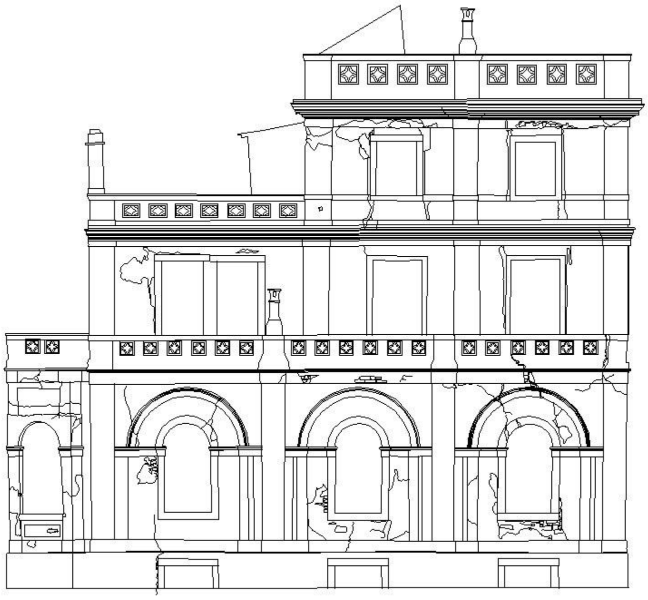
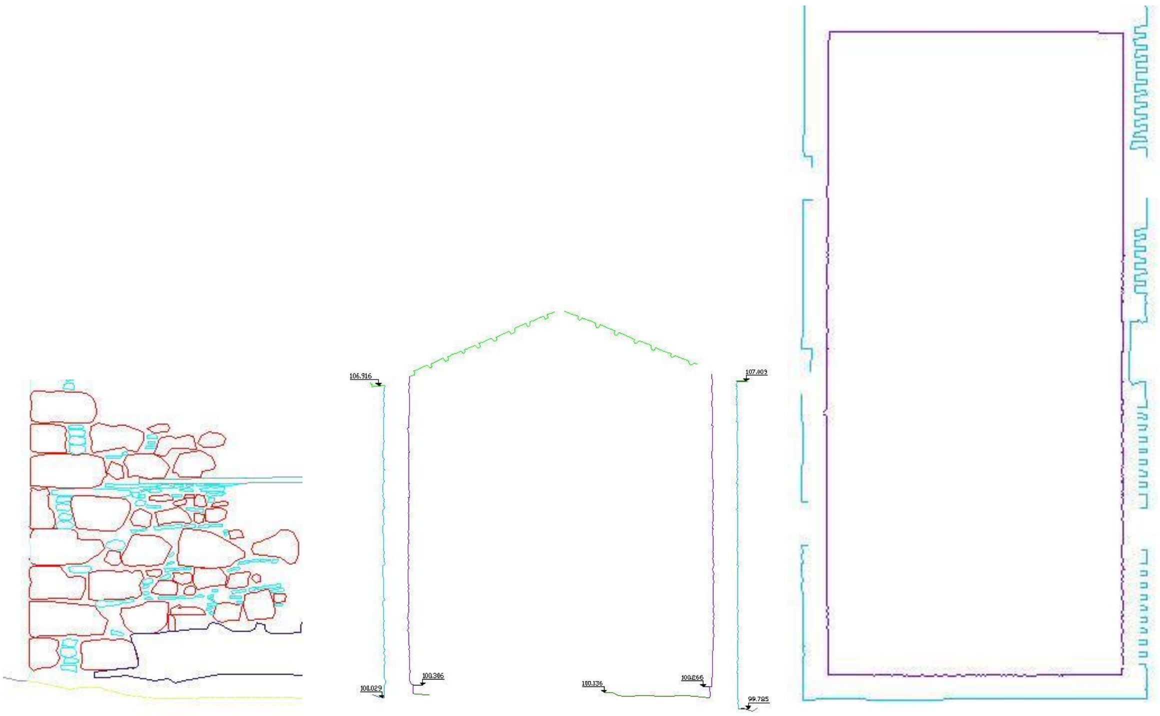


Figure 6: Vector drawing produced from photomosaic showing damages



(a) (b) (c)

Figure 7: (a) detail of front view (b) section of the building (c) top view

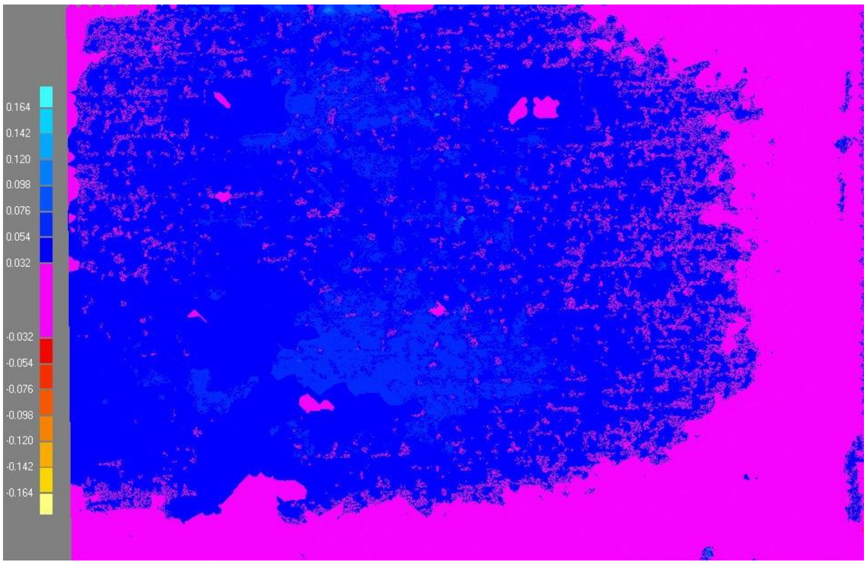


Figure 8: Deviations from the vertical plane of the north wall

All the above accurate drawings compile an information model of a damaged structure in order to prepare the design of the structural restoration. Usually, for restoration purposes the drawings should include the architectural components i.e. doors, windows, lintel beams, decorative elements etc. as follows:

a. Plan of the only storey of the building, plus three horizontal sections at various levels e.g. every two meters in height.
b. Elevations of the four sides.
c. Two longitudinal and four transverse sections.

Prior to the restoration design, the assessment of the building from the structural engineering point of view should be performed and the interpretation of the damages should take place (pathology). To achieve this objective, the general drawings should be enhanced with further information regarding structural details such as:

d. The wooden tie-beams at various levels.
e. The steel ties at various levels.
f. The loss of verticality (out of plumb displacements) of the walls, due to possible external actions such as earthquakes, thrust of the damaged roof, settlement of the foundation etc.
g. A complete survey of the cracks on the walls, plotted on the elevations and sections.
h. A detailed survey of the stones and joints construction pattern, on a typical rectangular area of a wall, of an approximate area of $5m^2$, in order to estimate the percentage of the mortar in the stone wall volume.

All the above mentioned information would be proved very difficult and extremely laborious to be acquired by traditional methods, i.e. by in situ measurements by hand. Traditional methods also would have an inherent limited accuracy, they would be time consuming and, at the end, expensive, due to labour and the need of scaffolds.

4. Concluding remarks

The use of TLS can lead to survey documentation in a very time efficient and accurate way. Prerequisite for this is that TLS is used by engineers because they have a good knowledge of historical buildings or a very close collaboration with the architects in charge. The main benefit over other survey techniques is that it provides a full surface description, instead of measuring only specific points as with total station survey. Once a full surface description is available, sections can be easily extracted in any direction, with the collaboration of architects, who enrich drawings with construction data and details hidden between the external and internal skins of the monument.

In this paper a methodology to produce accurate 3D and 2D models within the context of developing a heritage BIM is presented for historic structures. This process involves the following stages: collection and processing of laser/image survey data, creation of meshed 3D models and finally orthoimages. Having this intelligent data, the HBIM automatically produces full engineering drawings for the conservation of historic structure including 3D documentation, orthographic projections, sections, details other information such as cost decay etc. In this way, dedicated information for complex historic architectures can therefore be generated in order to make it available for researchers, professionals or generic actors involved in cultural heritage preservation.

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