Chapter 8
Virtual Fort San Domingo in Taiwan: A Study on Accurate and High Level of Detail 3D Modelling

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Introduction

Cultural heritage is evidence of past human activity. Appropriate and correct documentation of cultural heritage is critical for the purposes of conservation, management, appraisal, assessment of the structural condition, archiving, publication and research. As the importance of cultural heritage documentation is well recognized, the necessity to document our heritage has been increasing globally (Patias 2006).

Regarding methods of documentation, monument restoration projects were traditionally performed based on archive literature review and on-site investigations. Together with interpretations of style and materials of construction, the historic buildings and monuments were repaired and preserved. Due to the rapid development of hardware and software for 3D object displaying and manipulation, digital archiving has become a trend nowadays for preserving and demonstrating heritages instead of the traditional method. Hence, this study focuses on the digital preservation of historic buildings and scenes. Digitalization techniques from the fields of geomatics engineering and virtual reality (VR) are introduced in this paper.

Models produced by techniques of geomatics engineering and virtual reality offer various advantages. The geomatics models emphasize geometric accuracy, while the models produced in virtual reality focus on the level of detail (LOD) of the buildings and scenes. To maximize the benefits contributed by the two models, this chapter aims to integrate the two techniques to provide models with both high accuracy and high level of detail.

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Fort San Domingo is one of the oldest buildings designated as a first-grade historical site in Taiwan. Having been affected by the colonial domination of different countries, the outlook and structure of Fort San Domingo was consequently modified. In order to preserve history, document and record the heritage, digital archiving of Fort San Domingo was performed using the proposed integrated 3D modelling techniques. Firstly, geomatics techniques were applied to model the terrain and historical buildings across the site of Fort San Domingo. Then the geomatics models were updated using VR models, thereby providing a virtual scene with high geometric accuracy and high level of details. The 3D models of the two buildings on the test site were constructed based on integrated strategy. The overall workflow, assessment and discussion are described below.

Literature Review Regarding Geomatics Techniques for 3D Modelling

In order to investigate solutions for modelling the Fort San Domingo, geomatics techniques currently used for measurement and modelling were reviewed. The review included terrestrial surveying methods adopting total station instruments and terrestrial laser scanners, and image-based method of photogrammetry. Through the introduction of the techniques and discussion of the related applications, appropriate methods to be applied and noteworthy principles were determined.

Terrestrial Surveying with Total Station Instruments

The essential task of building modelling is to determine the 3D coordinates of feature points on the buildings of interest. This is achieved by the measurement of angles and distances to the specific points (Bannister et al. 1998; Uren and Price 2006). In order to investigate the feasibility of automated measurement of terrestrial surveying, total station instruments are selected for considering the possibility in the modelling task.

The total station first appeared in the late 1980s as a result of the development of electronics and computerisation of surveying instrumentations (Kavanagh and Bird 1992; Sakimura and Maruyama 2007). With the rapid development of electronics and computer technology in the 1990s, the total station underwent a rapid refinement in its functionality, precision and lowering of the cost. Total stations are precision electronic instruments, which incorporate a theodolite with an Electromagnetic Distance Measurement (EDM) unit, an electronic angle measuring component, data storage and a computer or microprocessor (Wolf and Ghilani 2002). With EDM equipment, either phase shift or time pulsed methods are used to measure distance. The phase shift (or phase comparison) method utilises continuous electromagnetic waves. Here the distance is measured as a phase difference with ambiguity resolution. The pulsed method uses the pulses of laser radiation to derive the distance from computing transit times. This technique is also known as the time-of-flight method. It is noticeable that the accuracy obtained with a phase shift method is typically higher than with time pulsed instruments, but the instruments using pulsed laser technology can measure longer distance than the ones using the phase shift method (Uren and Price 2006).

Total station instruments have been broadly applied in various 3D modelling projects. Considering the characteristics of low cost and high effectiveness, Matori and Hidzir (2010) adopted a total station to collect terrain data for producing digital terrain model (DTM). Further applications employed resultant DTM, such as engineering simulations of cut-and-fill volume calculation and hydrology flow direction and flow accumulation, were demonstrated. Based on the same method, Bevan and Conolly (2004) used this instrument to generate a terrain model of Kythera Island in Greece for an archaeological research purpose.

In a structural documentation and analysis project, a modelling system was designed to survey the scissors arches of Wells Cathedral in the U.K. (D'Ayala and Smars 2003). Considering the on-site accessibility problems, non-contact geomatics techniques were favorable in the project. A solution was therefore identified in the form of a hybrid approach, combining elements of terrestrial survey using a total station and digital photogrammetry. The total station was used to measure points on the specific structural components. Similar applications applied total station instruments were found in the modelling of the Oudenoord building at the University of Applied Science of Utrecht in Netherlands (Goedhart and Wolters 2008) and a construction of an augmented reality environment (Newman et al. 2005).

Total stations also introduced in modelling 3D objects of interest. The Maritime Archaeology Programme carried out in University of Southern Denmark aims to protect and record the underwater cultural heritage (Maarleveld 2009). In this programme, Hyttel (2010) applied a total station to model an iron 12 pounder lifted from the wreck of British ship "St. George". Points at important angle and curve which would later be used to create 3D models were observed. As a result the gun was reserved in a 3D format and could be visualized in any digital environments.

Terrestrial Surveying with Terrestrial Laser Scanning

As defined by Boehler and Marbs (2002), terrestrial laser scanning (TLS) is a technique which allows the collection of high-density point clouds distributed over a given region of an object's surface by measuring their three-dimensional coordinates automatically in near real-time. Since the early 1990s, terrestrial laser scanning has been increasingly adopted in the surveying market as an efficient alternative 3D measurement system with respect to photogrammetry or geodetic methods (Guarnieri et al. 2005). Due to the capability of measuring an enormous amount of points at a high rate in near real-time, complete and detailed 3D models of objects can be efficiently and easily created from acquired point clouds. These features have allowed laser scanning technologies to be widely applied in industrial metrology, deformation analysis, civil engineering, city modelling, cultural heritage, topographic surveying, and engineering geodesy (Tucker 2002; Barber 2003; Schulz and Ingensand 2004).

The general laser scanning workflow involves placing the laser scanner at locations about the survey site and measuring to a number of control points (e.g., retro-reflective targets or identifiable features) and the actual object of interest. The scanner is then moved to the second location and at least three common control points from the first scanner location are measured. The common measurements to the control points are then used to relate the scans together by registration (Lemmon and Biddiscombe 2006). At the last stage, the modelling of the whole combined point cloud or specific components is performed depending on the requirements of the application. In addition to the general workflow, specific details noteworthy during the scanning procedure are introduced below.

Prior to the implementation of scanning, laser scanning network design is essential if multiple scans are required. To achieve this, Lahoz et al. (2006) emphasize that the optimal station number is decided by considering the efficiency of the multi-station orientation procedures and the assurance of a global coverage of all desired surfaces. In addition, the positions of the scanner are arranged considering the incidence ray angle at the façade and the maximum scanning distance. Once the network of the scanner has been resolved, the network of the control points is designed and arranged accordingly. At the data acquisition stage, scanning density is one of the parameters required in the laser scanning settings. Hoffman (2005) suggests that an ideal spatial resolution should be equal to half of the measurement accuracy, ensuring the project receives the amount of data required.

There have been many research projects involving the scanning of historical structures for cultural heritage documentations. For example Levoy et al. (2000) used a custom laser triangulation scanner built by Cyberware to scan ten statues by Michelangelo. The images of the statues shot by a still video camera were mapped onto the resultant meshed model, rendering full-resolution and full-colour 3D models of the statues. A project sponsored by English Heritage Archaeology Commissions Team employed various terrestrial laser scanners, including a Leica HDS2500, a Zoller and Froelich Imager 5003 system and a Riegl LMS Z320 system, to measure Tynemouth Priory and Clifford's Tower in the UK (Barber et al. 2003; Bryan et al. 2004), for cultural heritage recording. Bonora et al. (2005) used a Leica HDS2500 scanner to create a 3D scanned model describing the dome intrados of the Colleoni Chapel in Italy. In addition to the 3D scanned models, 2D cross-sections were also extracted for architectural describing and investigating historical buildings in the Meldorf Cathedral in Germany, a measurement was performed with a Zoller and Froelich Imager 5003 system (Sternberg 2006). After long-term observations, deformations were determined by comparing the grid points, linear structures and surfaces acquired at different epochs. Another example for deformation monitoring using TLS technique could be found in Vezočnik et al. (2009).

Terrestrial laser scanning was introduced in geophysical and archaeological survey fieldworks conducted at the site of Tiwanaku in Bolivia, which was recognized as a birthplace for the people of the Andes (Goodmaster and Payne 2007). In this project, two scanning systems were used for long and short range scanning respectively. An Optech ILRIS-3D system was applied to collect 3D point clouds of large area with a resolution of approximately 1–3 cm. While a Konica-Minolta VIVID 9i system was adopted to perform high-resolution scanning (sub-centimeter resolution) on small artifacts, osteological elements, etc. The fusion of the scanned data formed the basis for scientific visualizations and virtual reconstructions of the site. For a detailed scanning purpose, the Maritime Archaeology Programme used FARO Arms along with a 3D laser scanner to create digital renderings of timbers from the early modern "Wittenbergen" wreck that sank in the Elbe (Stanek and Ranchin-Dundas 2010).

Image-Based Measurement Method

Among image-based measurement methods, photogrammetry is the most recognized technique in the field of geomatics. Fryer (2001) defines photogrammetry as "the science and art of determining the size and shape of objects through image analysis". The 3D coordinates of a specific object in space can be computed from the corresponding 2D information extracted from recorded photos through photogrammetric processing. Thompson (1962) further stated that photogrammetric methods of measurement are especially useful in conditions where the object to be measured is inaccessible, or when the object is not rigid and its instantaneous dimensions are required. Due to the features of rapid data acquisition, non-contact measurement, permanent recording, and capabilities of measuring deformation and movement, photogrammetry demonstrates its capacity to be used in many applications involving measurement (Torlegard 1980; Waldhausl 1992). Along with the developments in micro-electronics and semiconductor technology since the 1990s, digital photogrammetry has been driven by the development of new sensors (such as solid state cameras) and more powerful computers. The improving efficiency in image processing and automated measurement has resulted in an increasing number of fully automated systems and diversity of photogrammetric applications (Mills 1996; Wolf and Dewitt 2000; Fryer 2001; Gruen 2001).

Due to the characteristic of non-contact measurement and capability of offering accurate products, the image-based method of photogrammetry has remained a popular technique in 3D modelling for some time. According to the characteristics of the objects to be measured, cameras can be arranged on airborne platforms or on the ground to take images. For example, when performing topographic mapping tasks, a camera is fitted onboard an airborne platform and the so-called aerial photogrammetry is carried out to generate 3D digital terrain model and ortho-rectified images. This method has been well accepted. The applications and related discussions can be found in Baltsavias et al. (1996), Acharya et al. (2000), Sauerbier (2004), Zhang and Gruen (2004), Barnes and Cothren (2007) and Ion et al. (2008).

In addition to aerial photogrammetry, close range photogrammetry has also been introduced to a variety of non-topographic modelling projects. D'Apuzzo and Kochi (2003) developed an imaging system consisting of five IEEE-1394 video cameras to construct 3D human face model. The results were of great potential for automatic person identification from image data. Dunn (2009) adopted consumer-grade digital cameras to produce surface model of mining land. It was suggested that close range photogrammetry was a low cost technique but could yield accurate measurements even under a constrained environment.

In the project conducted by Psaltis and Ioannidis (2006), a concrete beam was monitored. By employing photogrammetry technique, its deformation occurred during a loading experiment was accomplished. Also, the results showed that the standards of an automatic, inexpensive, almost on-line calculation of displacements with accuracy better than 1 mm were fully met. In the research presented by Jauregui et al. (2003), photogrammetry was suggested as an attractive method for the purpose of structural health monitoring. A photogrammetric monitoring system was therefore developed to determine the vertical deflection of a bridge, and the damage occurred was further detected. The applications for modelling and monitoring using photogrammetry technique can be found in the projects conducted by Shortis (1986), Woodhouse et al. (1999), Li and King (2002), Fraser et al. (2003), Heath et al. (2004), McClenathan et al. (2006) and Luhmann et al. (2007). The broad applications are mainly due to the advantages of non-contact measurement, rapid data acquisition and capability to simultaneously sample all of the data points within the field of view of the camera (Blandino et al. 2003; Lin et al. 2008).

Summary

A review of the potential geomatics techniques for 3D modelling has been presented above. In order to produce a 3D model of the Fort San Domingo, the feasibility of terrestrial surveying with total station instruments was inspected firstly. Due to the feature of reflectorless measurement, total stations are employed in many 3D modelling applications. However, the measurement time is long, making it inefficient for the Fort modelling task. Alternatively, terrestrial laser scanning demonstrates the capability of rapid, intensive and non-contact data acquisition, and therefore is considered as a more suitable technique for undertaking the modelling task. Moreover, as the technique of convergent photogrammetry is also of potential for this mission, the feasibility will be explored as well.

To comprehensively simulate and produce the model of Fort San Domingo, the creation of terrain surface over the area is another important task in this modelling scheme. To this end, the stereo aerial imagery is applied and the photogrammetry technique is used again to generate the DTM of the test site. As a result, the constructed building models can be accurately integrated with the terrain model.

Methodology for Geomatics Modelling of Fort San Domingo

Introduction of Fort San Domingo

In order to understand the 380-year-long story, the history of the fort is following described. The early seventeenth century was about the time western empires extended their colonial force to the north of Taiwan. Having conquered Keelung in 1626, the Spaniards entered Tamsui and started the construction of Fort San Domingo in 1628. Fort San Domingo was located on a hilltop by Tamsui Town, previously a small fishing village in northern Taiwan, and at the mouth of the Tamsui River. The unique location made it was easy to defend but hard to besiege. The Spaniards accounted for this advantage and thus built the fort for the sake of governing (Tamsui Historic Sites Institute 2008). In 1642, the Dutch expelled the Spaniards and took over the fort. Later the Dutch rebuilt the main structure of the fort and named it Fort Anthonio. This is the structure embodying the present scale and still standing today. Since the local inhabitants in Tamsui at that time referred the Dutch as red hairs, the fort was nicknamed as the “Hong Mao Chen”, meaning the fortress of red-haired people. The name was inherited to represent the historical site (Danshui Historic Sites 2006).

The Dutch was defeated by General Cheng-Gong Zheng of Chinese Ming Dynasty in 1661 and left Taiwan in 1668. Consequently Fort San Domingo remained deserted until 1683 when Zheng’s army came to Tamsui. From 1683 to 1867, the Qing Dynasty Chinese government controlled the fort and built a stone wall with four gates around the fort during this period.

Following the Opium War in 1868, Tamsui harbor was open for commercial use. Due to its critical location, the British government leased the fort from the Qing government as their consulate. A throughout renovation was made accordingly for the consul business. To accommodate the need of consul and consul’s family, the consul’s residence was added on the east side of the fort in 1891. The consulate was closed during World War II and reopened after the end of the war. The consulate was closed again in 1972 as the British government broke off her diplomatic relations with the Republic of China (ROC) government. In 1980, the fort was formally returned to the ROC government.

As introduced above, it is realized that the site of current Fort San Domingo comprises two main historical buildings, including Fort Antonio (former Fort San Domingo) and former British Consular Residence (Fig. 8.1). The main structure of Fort Antonio is a two story square building. The wall of the building was laid with bricks and then covered with layers of stone outside and therefore provided the fort strong and effective fortification. The former British Consular Residence was

Fig. 8.1 Fort Antonio (*left*) and former British Consular Residence (*right*) located in the site of Fort San Domingo

distinguished by its Victoria style. The characteristics of red-brick structure, verandas, four-sided steep roof, and a high staircase were well reserved (Danshui Historic Sites 2006; Tamsui Historic Sites Institute 2008).

In order to provide an overall accurate scene over the site of Fort San Domingo, the solution of geomatics modelling was to produce the terrain and building models separately, to which the aerial photogrammetry was applied to generate terrain model while close range photogrammetry and terrestrial laser scanning were used to construct building models. The detailed workflows are introduced below.

Digital Terrain Model (DTM)

Digital terrain model of the test area was generated using aerial photogrammetry technique. To achieve this, a stereo pair of aerial images taken by an UltraCamD large format digital aerial camera (Leberl and Gruber 2005) was employed. The images were captured on 27th of April, 2009 from a flying height of 2,200 m with a nominal focal length of 100 mm. The image format was 11,500 pixels by 7,500 pixels and the pixel size is 9 μm × 9 μm. Given the photo scale of approximately 1:22,000, the image spatial resolution was about 20 cm × 20 cm per pixel.

The acquired imagery was input and processed in the SOCET SET workstation. SOCET SET is a digital photogrammetric and mapping software, which allows a full photogrammetric processing flowline to be performed – from import of digital imagery to the creation of DTMs, ortho-rectified images and export of CAD model. Due to the full capability, imagery from the UltraCamD camera was processed in this software throughout the experiment.

Along with the aerial images, the known interior and exterior orientation parameters were input to SOCET SET for producing the digital surface model (DSM). Subsequently the manual terrain editing was carried out to remove trees and buildings existed in the DSM. As a result, the digital terrain model showing the true terrain surface was produced. The 1-m resolution DTM represented by point cloud, triangulated irregular network (TIN) mesh and contour plot are illustrated in Fig. 8.2. Based on the DTM, an ortho-rectified image was generated as well.

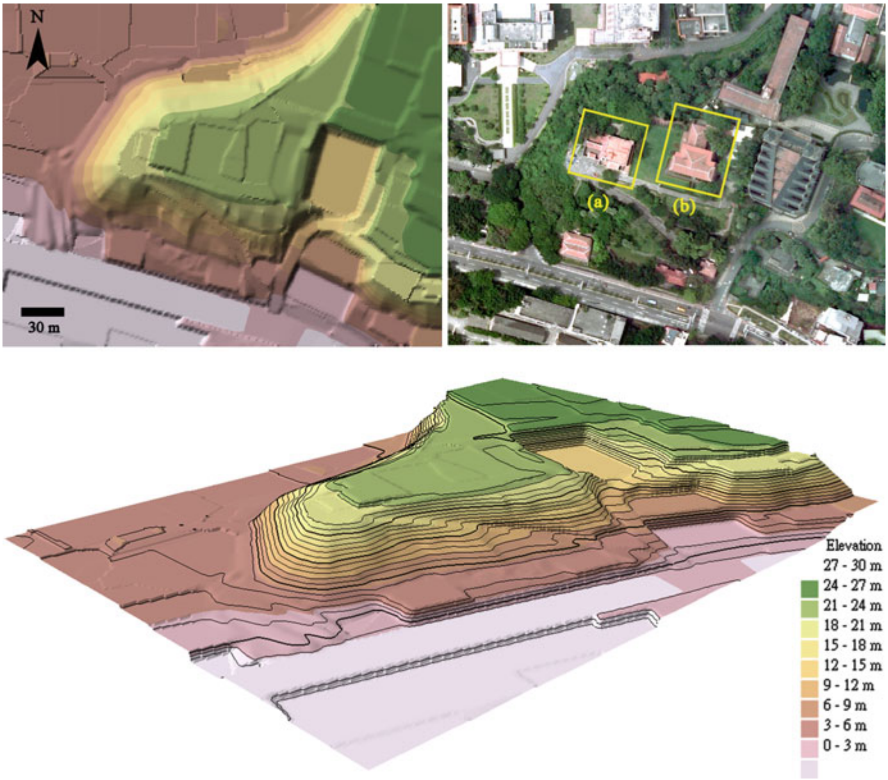

Fig. 8.2 *Top left*: The top view of hill-shaded DTM of the site of Fort San Domingo. The DTM is colorized by elevation. *Top right*: Ortho-image generated based on the DTM, in which Fort Antonio and former British Consular Residence are indicated by (**a**) and (**b**). *Bottom*: the perspective view of 1-m interval contour map superimposed on the TIN mesh DTM

Building Model

Techniques of close range photogrammetry and terrestrial laser scanning were adopted separately to generate building models located in the test site. The methods and results are following described.

Close Range Photogrammetric Building Models

A consumer-grade digital camera, Canon EOS 5D, was employed in the modelling scheme. In order to efficiently distinguish detailed features shown in images, the format of the image acquired was set as 43,68 pixels × 2,912 pixels. Additionally, a 50 mm lenses was fitted to the camera to effectively cover the buildings of interest at the test site. With this setting, the camera was calibrated using the PhotoModeler

Calibration Module before being used for image acquisition (a standard procedure independently verified in Hanke and Ebrahim (1997)). As a result, the geometric accuracy of using the non-metric digital camera could be assured.

A certain number of control points located on or near the objects of interest are required for orientating cameras and also geo-referencing the observed building models in the close range photogrammetric processing. In order to acquire absolute 3D coordinates of the control points, a two-stage method was followed in this modelling task. Firstly, a series of ground control points were selected and their absolute 3D coordinates were stereoscopic measured using the stereo aerial images in the SOCET SET workstation. To verify the accuracy of the positions of the ground control points, the distances between the ground control points were measured using a Leica TCR 803 total station (quoted angular precision of $\pm 3''$ and range precision $\pm$(2 mm + 2 ppm)) on-site. The results were then compared with the distances computed from the stereoscopic measurement. The mean value of the differences was 0.218 m, revealing that the coordinates of ground control points derived from photogrammetric stereoscopic measurement achieved about one-pixel accuracy.

At the second stage, coordinates of control points located on façades of the buildings were obtained. As it was not allowed to attach physical targets on the buildings, some reliable features on the building façades were selected as control points. To derive the absolute coordinates of these points, the Leica TCR 803 total station featuring reflectorless measurement was set up in proper positions and oriented using the ground control points acquired. Subsequently the total station was aimed at the control points on the building façades and the “Free Station” program available in the total station was executed to compute their absolute 3D coordinates. These points were mainly used for geo-referencing the observed building models.

While the control surveying was carried out, a total of 17 images of the two buildings located in the test site was taken by the Canon EOS 5D digital camera. (Refer to Fig. 8.3 for the applied camera network) The images were downloaded

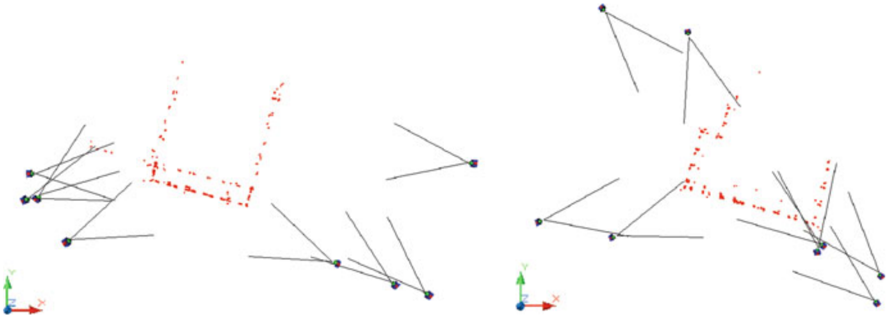

Fig. 8.3 The camera networks comprising eight and nine camera stations in Fort Antonio (*left*) and former British Consular Residence (*right*) respectively. The orientations of each camera are demonstrated. *Red points* indicate the positions of solved building features

into local computer for further processing. In order to produce geo-referenced 3D models of the buildings, 33 control points with known 3D coordinates and important feature points of the buildings with unknown 3D coordinates (e.g., end points of the rooftop, intersection points of walls, etc.) were measured in the images. The derived 2D image coordinates, along with camera's interior orientation parameters and control points' 3D global coordinates were then input into the PhotoModeler software for a bundle adjustment computation. As a result, the 3D coordinates of the feature points of the buildings measured in the images were solved. Subsequently these points were connected for constructing the building models. The resultant building models are demonstrated in Fig. 8.4.

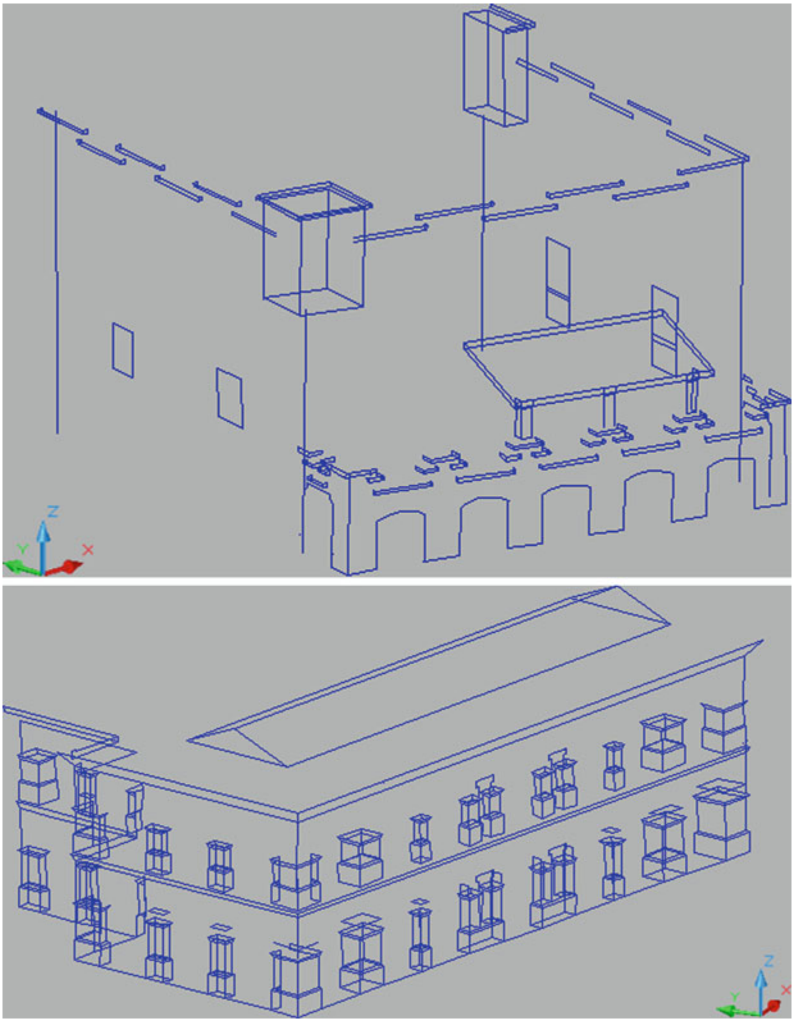

Fig. 8.4 The CAD model of Fort Antonio (*top*) and former British Consular Residence (*bottom*) produced by close range photogrammetric method

Terrestrial Laser Scanned Building Models

To acquire the as-built models on the site of Fort San Domingo, the technique of terrestrial laser scanning was also applied. In this modelling scheme, the Riegl LMS-Z420i laser scanning system was employed to observe the buildings. The scanner, with a quoted single-point position accuracy of ±10 mm, gives a 360° by 80° field of view in the horizontal and vertical directions (Riegl 2010). To completely cover the Fort Antonio and the former British Consular Residence, it was necessary to scan the two buildings from 11 scanner stations on the site. Moreover, following normal terrestrial laser scanning procedures, reflective targets were arranged and also scanned in the field of view to permit the registration of each scanned model. Once the scanning was finished, the registration was performed in RiSCAN PRO software. It was revealed that the amalgamated model has a registration error of 16.1 mm.

While the scanning was carried out on the test site, a calibrated Nikon D200 digital camera mounted on the scanner shot a series of images at each scanner station. These images were also registered with the point cloud at the processing stage in RiSCAN PRO software. As a result, the point clouds could be colorized using the color information provided by the registered images.

In order to geo-reference the amalgamated scanned model to the common global coordinate system, the control points used for producing close range photogrammetric building models (refer to Sect. "Close Range Photogrammetric Building Models") were applied. The control points appeared in the scanned point cloud were selected and the geo-referencing was performed accordingly. The resultant geo-referenced models of the Fort Antonio and the former British Consular Residence are shown in Fig. 8.5.

Geomatics Model of Fort San Domingo

The comprehensive geomatics model of the Fort San Domingo was accomplished by integrating the terrain and building models. As the control points used for the generation of these models were based in an identical spatial reference frame, the terrain and building models could be integrated without any transformation. Figure 8.6 shows the alignment of the CAD photogrammetric building models and the contour DTM. Figure 8.7 illustrates the laser scanned model along with the terrain model, which are both in the point cloud format.

Assessment of Geomatics Model

In order to evaluate the accuracy of the photogrammetric building models, independent observations from a Leica TCR 803 total station were introduced. To

Fig. 8.5 The scanned model of Fort Antonio (*top*) and former British Consular Residence (*bottom*). The models are textured with color extracted from the imagery acquired by the digital camera mounted on the scanner

achieve this, some common identifiable points in both the photogrammetric model and physical structure are selected as check points. Then their coordinates, derived from the photogrammetric model and measured by total station, are compared to determine the accuracy. Therefore, during the control surveying for constructing close range photogrammetric building models (described in Sect. "Close Range Photogrammetric Building Models"), a total of 22 and 13 feature points on the façades of Fort Antonio and former British Consular Residence were measured

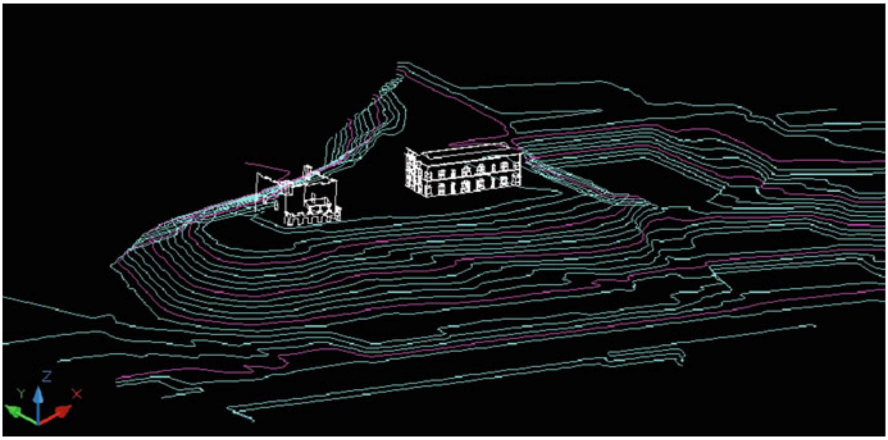

Fig. 8.6 The integration of CAD photogrammetric building models and the contour DTM

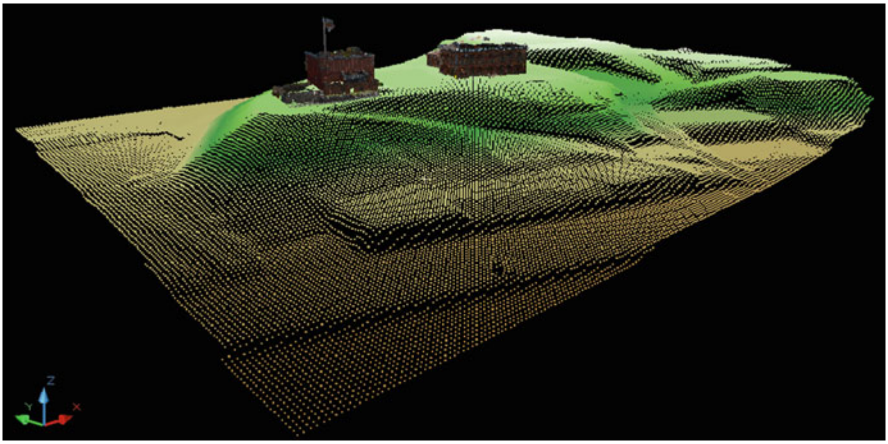

Fig. 8.7 The alignment of the laser scanned model along with the terrain model, which are both in the point cloud format

respectively. Of which 17 and 8 points were introduced correspondingly as control points in the bundle adjustment, while the remaining points were treated as check points for examining the accuracy of the resultant building models. After comparing the coordinates solved from the bundle adjustment with the coordinates measured by the Leica TCR 803 total station, it was found that the root mean square error of the check points reached 11.3 and 28.9 mm respectively.

Independent observations from the total station were also applied to determine the accuracy of the TLS model. However, as the laser scanned model was presented as a discrete point cloud, it was difficult to identify exact common points in the TLS model corresponding to those on the physical structure. To address the issue, the

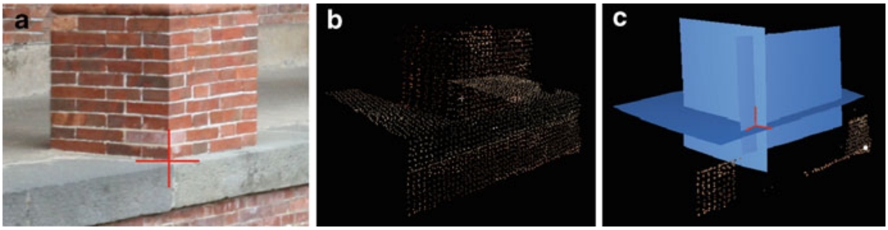

Fig. 8.8 The strategy of extracting check points from a dense point cloud

intersection of three modelled planes was used as check points. Figure 8.8 illustrates the method to locate a check point from point cloud model. Figure 8.8a is the photo showing the position of the selected check point (the red cross). In order to obtain accurate positions of the corner point, the object was scanned with a dense point cloud (Fig. 8.8b). Subsequently the plane primitive was repeated to model three faces of the point cloud (Fig. 8.8c). The corner point could be extracted by selecting the intersection of the three modelled planes and it was taken as the check point for examining the model accuracy. In this evaluation four check points in the two scanned building models were applied. The overall root mean square error of the check points compared with total station measurements was solved as 25.8 mm. From the accuracy assessment, it was realized that the resultant photogrammetric models and the laser scanned models was capable of achieving cm-level accuracy. The comparable accuracy can be observed in Fig. 8.9 by viewing the fitness of the two models.

Integration of Geomatics and VR Models

Virtual Reality Modelling

The applications of architectural design in virtual reality have increased significantly worldwide. For applications in heritage documentation, historical buildings can be preserved and shown via the images derived from the database of archival digital imagery. Furthermore, virtual reality also provides the possibility for modeling the buildings and scenes of interest. By introducing the digital image data, with further processing, 3D structures, buildings and information can be constructed and visualized in a virtual reality environment (Chen 2008). The method has been successfully used in heritage documentations conducted by Obertreiber and Stein (2006), Jabi and Potamianos (2007) and White et al. (2007). The resulting models are of benefit in regard to the high level of detail, making the interactions between browsers and virtual objects highly achievable.

The VR modeling task follows two-stage processing. The first step is the data collection of traditional media. In terms of data collection, the aim is to collect

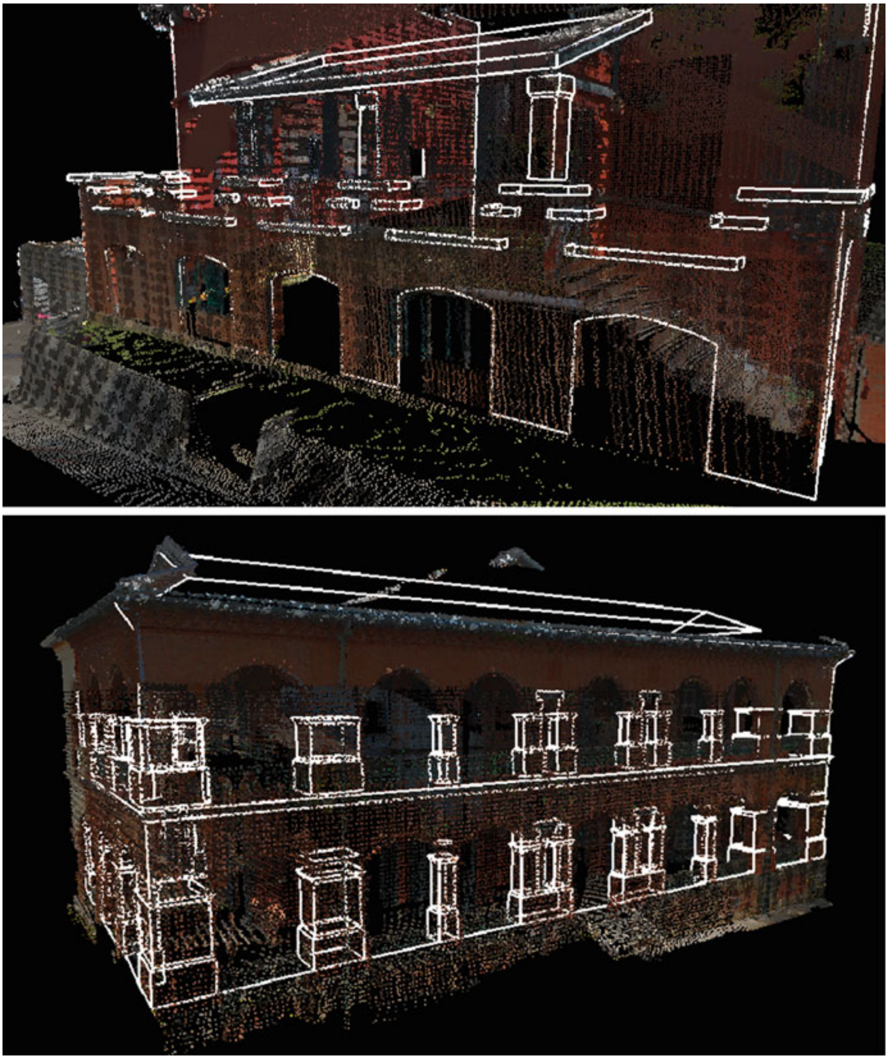

Fig. 8.9 The alignment of the photogrammetric CAD model and laser scanned model

historical descriptions of each building such as text, pictures, photos, plane, façade, architectural section and other useful information that can comprehensively illustrate the building. At the second stage, digital simulation technology is applied to construct the 3D plane, façade and architectural section of the building based on the data acquired. Images acquired on-site are applied subsequently to perform the texture mapping. The resulting models can be demonstrated by any suitable virtual reality software and environment. The workflow of VR modeling is shown in Fig. 8.10a.

After the accurate geomatics models covering Fort San Domingo were produced, high LOD VR models were constructed to simulate the physical buildings. In order to integrate advantages inherited from the two models, an integration of the geomatics and VR models was performed. The integrated strategy was proposed as follows, and the 3D models with characteristics of high geometric accuracy and level of detail were produced in the end.

Integrated Strategy

For the model integration, two phenomena including pre- and post-VR modelling integration, are considered. For the former case, the integration is conducted before VR models are produced. In the original workflow the 3D modelling task is accomplished using digital image data. However, the image data is replaced by the introduction of CAD structures at the modelling stage in this integration operation. It is noted that the acquisition of digital image data is still necessary as they are required for model mapping. The flowchart of this case is illustrated in Fig. 8.10b. The post-VR modelling integration refers to the integration with existing VR models. In this case CAD structures are introduced prior to the mapping stage. The scale and orientation of the VR models are examined and adjusted accordingly if there is any disagreement between the two models. The workflow is shown in Fig. 8.10c.

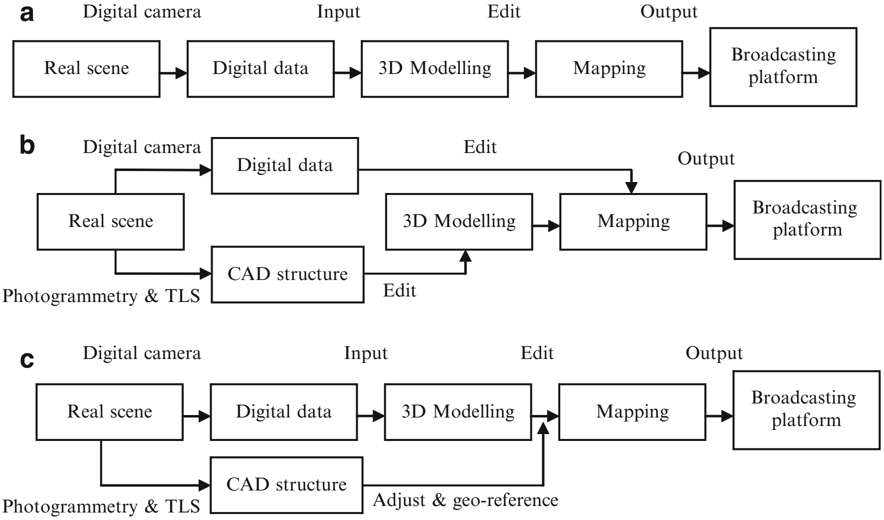

Fig. 8.10 Integrated procedure of the topographic scene making and historical building assembly

Illustration of Integration and Comparison of Geomatics Models and 3D VR Models

Case of Fort San Domingo

As the VR models of Fort San Antonio and the former British Consular Residence were constructed, the post-VR modeling integration was performed in this paper. A reference model was created using the geomatics models mentioned in Sect. "Building Model" (shown in Fig. 8.11, the one in white). The model was then imported and compared to the VR model in 3ds Max software. The misalignment of the two models is observed from various viewing angles in Fig. 8.11. As a deviation in scale of model remained unsolved after the initial adjustment (refer to Fig. 8.12), further improvement was carried out using control points derived from free-form deformation (FFD) modifier, which is similar to building scaffolding in real life. The processing of refinement of the building in the virtual simulation is shown in Fig. 8.13. Once the overall adjustment was finished, the accurate VR model was derived (Fig. 8.14).

Case of the Former British Consulate

The integration of the geomatics model and 3D VR models for the former British Consular Residence was carried out using the same method applied in the adjustment of Fort San Antonio. The model comparison, adjustment and final refinement are illustrated in Figs. 8.15, 8.16 and 8.17.

One of the goals of this study was to achieve a new spatial experience through the integration of image visualization and various 3D digital techniques. From the successful implementation of the model integration, of which the accurate

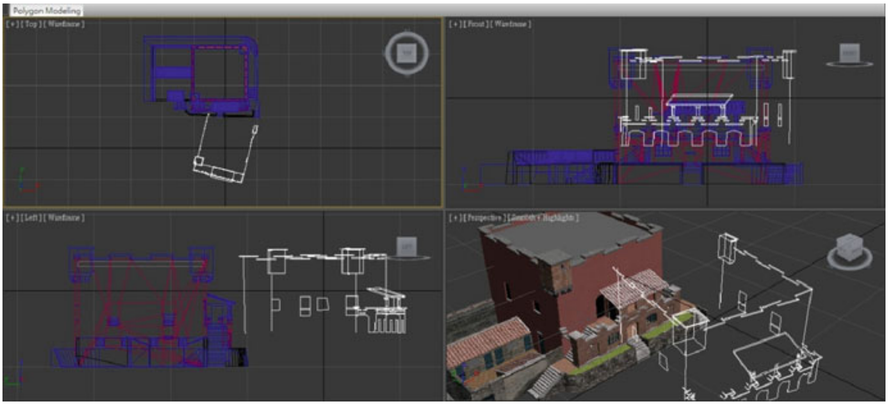

Fig. 8.11 Misalignment of the geomatics model and the original 3D VR model of Fort San Antonio (displayed in 3ds Max software)

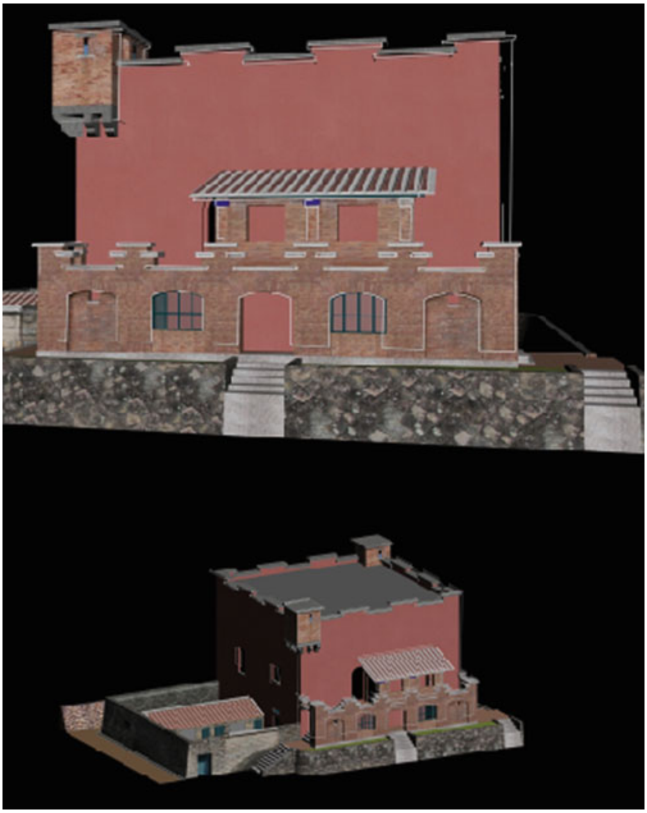

Fig. 8.12 Differences, in particular the model sale, are shown by visualizing the superimposition of the two models

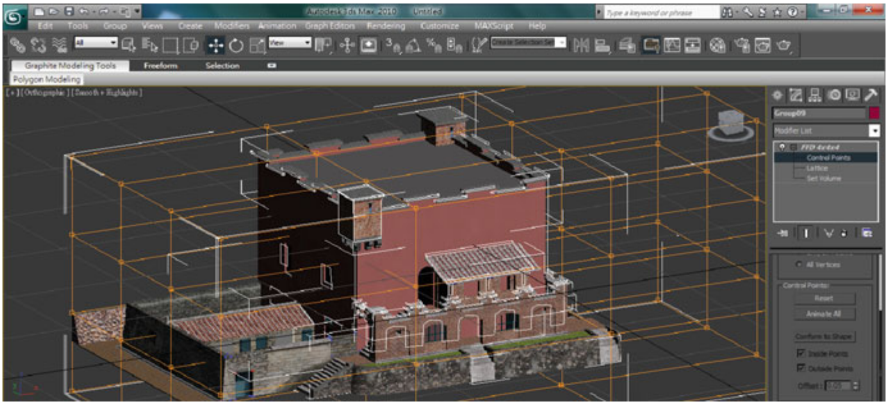

Fig. 8.13 Refinement of the VR building model, in which the free-form deformation is performed in 3ds Max software

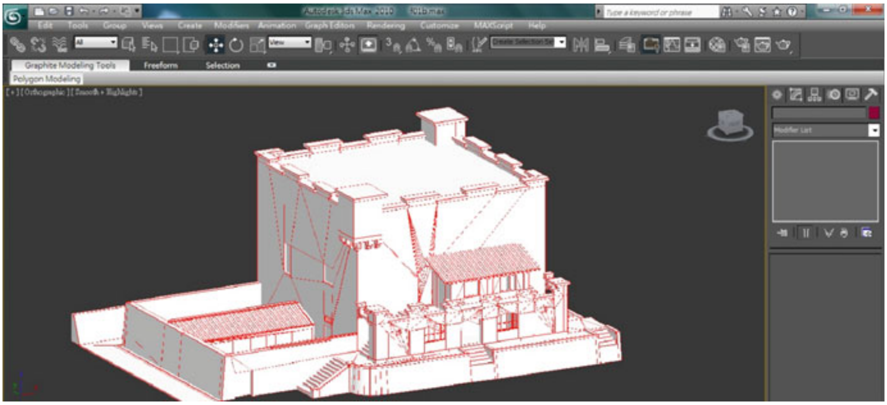

Fig. 8.14 Final 3D uncolored model after the overall adjustment

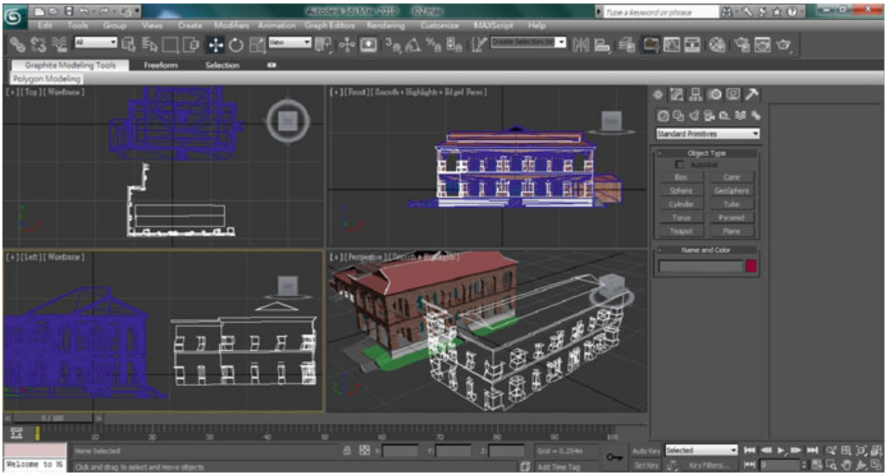

Fig. 8.15 Misalignment of the geomatics model and 3D VR model of the former British Consular Residence displayed from various angles

photogrammetric CAD models were utilized for geo-referencing, adjusting and refining the high LOD VR model, the goal was fulfilled satisfactorily. The final 3D model of Fort San Domingo and its surrounding areas are shown in Fig. 8.18.

Discussion

Non-contact Geomatics Techniques

Due to the limited accessibility to the heritage, non-contact geomatics techniques were proposed to construct 3D models of the Fort Antonio and former British

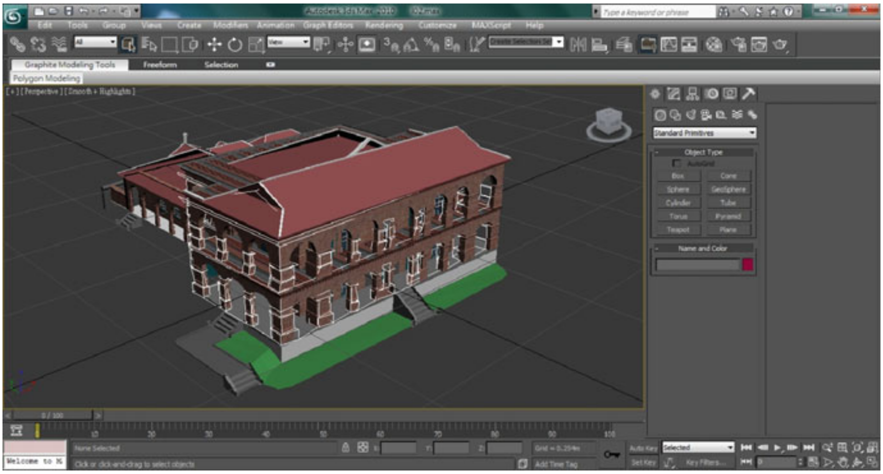

Fig. 8.16 An improved fitting achieved after the initial adjustment

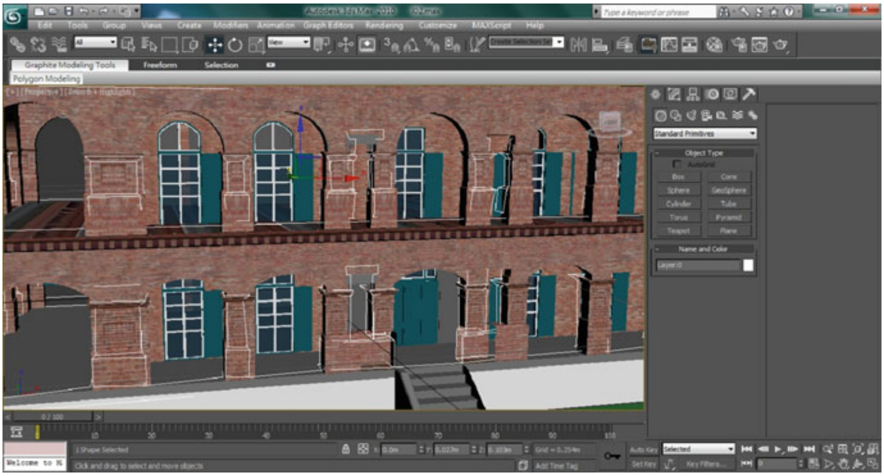

Fig. 8.17 Detailed evaluation and refinement of the VR model are performed using the accurate geomatics model

Consular Residence. Based on the results demonstrated in Sects. "Close Range Photogrammetric Building Models" and "Terrestrial Laser Scanned Building Models", close range photogrammetry and terrestrial laser scanning were proved very capable of producing as-built models. However, there were also some issues during the operations that are now discussed.

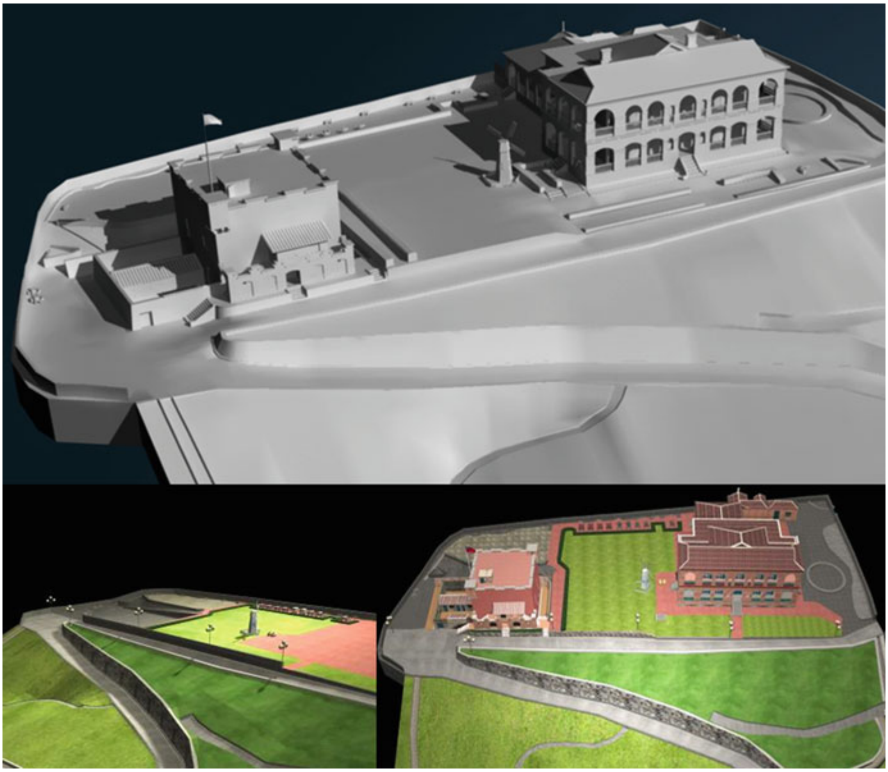

Fig. 8.18 Uncolored (*top*) and texture mapped (*bottom*) VR models of the Danshui historic site

Efficiency of the Techniques

The first issue relates to the efficiency at surveying and processing stages. At surveying stage, close range photogrammetry and terrestrial laser scanning both need observations of control point. For the former technique, consideration of number and position of control points are required as these are critical factors for correctly solving orientation parameters of camera stations. Furthermore, the solved orientation will affect the quality of intersected feature points. For the TLS technique, control points are used for model co-registration. Ideally the control point should be arranged in the overlapping areas between each scan. Some other techniques (e.g., surface matching) are also applicable for co-registration even if no control points are available. Therefore the requirement of control point in TLS operation is not as serious as in close range photogrammetry task. As a result it takes less time to arrange control surveying when performing terrestrial laser scanning. Nevertheless, regarding the time required for data acquisition of the whole buildings, it is found that photogrammetric acquisition is more efficient than TLS technique.

Main task in photogrammetric processing is to select corresponding points, including control points and building features, among multiple images in the software. Once these points are verified and computed, they are connected to derive the CAD model. To achieve this, no special techniques but manpower and cost of time are required. As for processing of laser scanned data, the co-registered point cloud can be accomplished manually or automatically in the specific software. However, it is worthwhile noting that the format of point cloud is not fully accepted yet in the field of 3D modelling. Hence a heavy modelling work is necessary for extracting CAD models from point cloud. In summary, the overall effort to derive a photogrammetric CAD model or TLS point cloud model is comparable. However, considering the required format of 3D building model, the employment of TLS technique takes more time to achieve if a CAD format is the final product required.

Completeness of Geomatics Models

Secondly, the level of completeness of the resultant models is discussed. Due to various characteristics of the models derived, the discussion focuses on completeness of CAD structure of photogrammetric model and surface continuousness of laser scanned model respectively. As shown in Sect. "Close Range Photogrammetric Building Models", the façade of photogrammetric model of Fort Antonio facing north and façades of former British Consular Residence facing north and northeast were not constructed. The failure was caused by obstructions of heavy vegetations in the test site. Due to the constraint, the setup of camera stations and a clear view field of important building features became unachievable. The camera network and the positions of observable building features illustrated in Fig. 8.3 explained the influence of limited exposure stations. Since a comprehensive image acquisition was not available, the level of completeness of constructed photogrammetric model was affected accordingly.

Regarding TLS performance, as dense scanning was carried out to collect point cloud of Fort Antonio and former British Consular Residence, building models with high level of completeness were obtained (Fig. 8.5). However, some areas with broken surface were also observed. This was mainly caused by obstructions occurring between the building and the scanning system. Normally such discontinuities could be re-constructed by repeated scanning from different stations, but as the same constraints met in photogrammetric modelling, some broken surfaces still failed to be covered due to unavoidable vegetation and difficult scanning angles. As such on-site constraints are unavoidable in the applications of the two geomatics techniques, this is treated as natural limitation and should be carefully considered in the fieldwork plan.

Accuracy of Geomatics Models

The final discussion involves measurement accuracy. The accuracy of the two resultant models was examined by independent observations using total station instruments. It was indicated that the models were able to achieve a cm-level accuracy although a specific accuracy was not requested in this case (refer to Sect. "Assessment of Geomatics Model" for details). For the request of advanced accuracy in close range photogrammetric models, increasing the number of exposure stations would be beneficial. However accompanying issues, such as image storage space, processing efficiency and on-site limitations, would also need to be considered. The final solution would be a compromise between required accuracy, processing time and budget limitations.

Level of Visual Application of VR Models

As the purpose of application of VR model is to provide the highest visual quality and most realistic presentation, a sophisticated method and high resolution images are required for modelling and simulation. To achieve this, the level of detail of the models and operation of light in the VR scene are critical factors. For high LOD models, very high resolution images are required for constructing detail components and also simulating the materials of the buildings. When simulating light effects in this paper, it was found that the use of advanced "ray tracing" and "radiosity" techniques provided the best simulation results. However, it was also realized that the application of such data and techniques occupied heavy computer resources and reduced the performance of display of VR models and scenes. In order to improve the displaying efficiency, the techniques of texture mapping, culling, fog effects and polygon reduction were applied to upgrade the instant screen display. The performance of the virtual presentation of the models was improved by sacrificing the visual effect of the resultant simulations in virtual reality.

The human-computer interaction (HCI) also benefitted the modification. In this 3D digital heritage project, one of the objectives was to surpass the traditional presentation of 2D pictures/animation for building structure and offer visitors an interactive experience closest to reality. For instance, when a person is visiting an architectural space in real life, he is free to walk around instead of observing the space passively. The instant 3D virtual reality simulation allows users to participate actively and freely during visits, which is vastly different from the traditional 2D web browsing. As the efficiency of computer computing capacity was improved by applying the proposed method, smooth interactions between visitors and VR heritage models are achievable in the VR environment. In summary, it is realized that the optimum level of visual effect should be determined considering the balance between the necessary LOD and the computer capacity being employed.

Data Interoperability Issues

In this project three types of 3D building models were produced, including VR model, photogrammetric CAD model and laser scanned point cloud. As the

Table 8.1 The techniques, software and compatible data formats involved in this project

Technique	Software	Compatible data format
VR modelling	Autodesk 3ds Max	3D Studio (*.3DS) Autocad DWG (*.DWG) Autocad DXF (*.DXF) Autodesk FBX (*.FBX, *.DAE) IGES (*.IGS) Wavefront (*.OBJ) StereoLitho (*.STL) Shockwave 3D (*.W3D) VRML (*.WRL) VIZ Material XML (*.XML)
Close range photogrammetry	PhotoModeler	ASCII (*.*) Autocad (*.DXF) Wavefront (*.OBJ) VRML (*.WRL) 3D Studio (*.3DS, *.PRJ)
Terrestrial laser scanning	RiSCAN Pro	ASCII (*.*) 3DD with SOP (*.3DD) point cloud (*.3PF) Autocad (*.DXF) Wavefront (*.OBJ) VRML (*.WRL) PLY (*.PLY) LAS (*.LAS) PointCloud for AutoCad (*.PTC) Google Earth (*.KMZ)

principles of modelling techniques are different, specific software are applied to handle building modelling accordingly. Furthermore, according to the integrated strategy proposed in Sect. "Integrated Strategy", the photogrammetric and TLS CAD models are treated as the primitive structure for geo-referencing and adjusting the VR model. However, as reported by Kolbe et al. (2005), 3D building modelling techniques have been continuously developed in various fields. Each of which has established its own standard. Hence the appropriate software for performing the model integration should be considered.

The techniques and software involved in this project, and their compatible data formats are listed in Table 8.1. It is noted that several data formats are exchangeable among the three pieces of software. That is, the three pieces of software are all of potential for performing model integration. However, it was found that some components of the models were missing or misaligned during the processing of data exchange. To address the issue, the three pieces of software were assessed to examine stability of model interoperability and efficiency of model processing. Based on the result of the assessment, Autodesk 3ds Max software was selected as the main working environment for model integration. Also, the Autocad DXF file was used as the common format of building models.

Hence, the photogrammetric and TLS CAD models are saved as drawing exchange format DXF and then imported into 3ds Max directly for model editing and integration. Once the VR model is adjusted, the final product with high accuracy and LOD is constructed.

Conclusions and Suggestions for Future Work

In order to accomplish digital preservation of historic buildings and scenes, digitalization techniques from the fields of geomatics engineering and virtual reality were introduced. The background, overall workflow and assessment of the techniques, as well as the resultant models have been demonstrated in this paper. Moreover, an appropriate procedure capable of integrating the advantages inherited from the geomatics and VR modelling techniques was proposed. The feasibility of the method was proved through the integration and assessment in the 3D modelling scheme carried out in the historical site of Fort San Domingo. The overall techniques and integrated method have great potential to be transferred and applied in various areas.

Although the successful modelling method was demonstrated, a number of limitations occurring during the modelling tasks were raised and discussed. To overcome the limitations and broaden the potential field of applications, two further topics are suggested.

The first work aims to improve the efficiency of TLS modelling applications. As summarized in Sect. “Efficiency of the Techniques”, intense effort was required for extracting CAD models from the laser scanned point cloud and this may reduce involvement of the TLS technique in 3D modelling. To address the issue, the images shot on-site can be of helpful. Once the images and the laser scanned point cloud are orientated in an identical reference system, the orientated images can then be introduced as a visual tool supporting the extraction of CAD models from the point cloud. The rationale has been introduced in commercial software, such as Phidias, Kubit PointCloud and Pointools Edit, and the modelling efficiency can be improved accordingly. Another issue mentioned in Sect. “Completeness of Geomatics Models” was broken scanned surface caused by obstructions occurring between the building and the scanning system. To overcome the limitation, an introduction of a terrestrial laser scanner which is capable of receiving multiple return signals is suggested. As the density of points being reflected from the scanned object is greatly increased, detection of the objects obstructed by vegetation becomes possible. The completeness of the laser scanned surface can be upgraded. Overall, the solutions proposed will be examined for increasing the involvement of TLS in 3D modelling tasks.

As discussed in Sect. “Level of Visual Effect of VR Models”, the optimum level of visual effect was determined by the trade-off between necessary LOD and the computer capacity employed. Hence, innovative approaches capable of increasing efficiency and saving resources should be developed to achieve enhanced visual effect and smoother HCI. To this end, potential research topics include:

1. Innovative visualization of multiple data for understanding and analysis
   In order to broaden the applications of HCI, multiple data, such as archival audio and video files, information of user's behaviors and characteristics, etc., are collected and stored in the data storage system. For turning such large and complex data into visual presentation efficiently, innovative approaches are required. The results are also expected to be helpful for analysis of multi-information analysis.
2. Suitability and practicality of the operation and analysis environment
   As described above, the collection of multiple media data becomes essential in HCI applications. Since each data set has its own specific processing software and required hardware, a combination of various technical requirements is inevitable. Hence, an ideal environment capable of handling data storage, data processing and data conversion will be studied. To perform the innovative visual presentation, this topic should be considered comprehensively.
3. Task-oriented designed and user-friendly graphic user interface
   User interface is a critical element for successful HCI applications. To avoid confusion occurring during operation and functions with low access frequency caused by ambiguous interface design, development of task-oriented design will be introduced in the HCI in the near future. Along with innovative design and upgrading of new hardware devices, the gap between the digital environment and users can be eliminated.

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References

Acharya, B., Fagerman, J. and Wright, C., 2000. Accuracy assessment of DTM data: a cost effective approach for a large scale digital mapping project. International Archives of Photogrammetry and Remote Sensing, 33(B2): 105–111.

Baltsavias, E.P., Li, H., Stefanidis, A., Sinning, M. and Mason, S., 1996. Comparison of two digital photogrammetric systems with emphasis on DTM generation: case study glacier measurement. International Archives of Photogrammetry and Remote Sensing, 31(B4): 104–109.

Bannister, A., Raymond, S. and Baker, R., 1998. Surveying, seventh edition. Addison Wesley Longman Limited, Essex, UK. 502 pages.

Barber, D.M., 2003. Terrestrial Laser Scanning for the Metric Survey of Cultural Heritage Structures. PhD Thesis, University of Newcastle upon Tyne, Newcastle upon Tyne, UK (unpublished): 222 pages.

Barber, D., Mills, J. and Bryan, P., 2003. Towards a standard specification for terrestrial laser scanning of cultural heritage. CIPA International Archives for Documentation of Cultural Heritage, 19: 619–624.

Barnes, A. and Cothren, J., 2007. Mapping Tiwanaku: Using modern photogrammetric methods to analyze an ancient landscape. http://cast.uark.edu/assets/files/PDF/DO_workshop_Barnes&Cothren.pdf [assessed 15th October 2010].

Bevan, A. and Conolly, J., 2004. GIS, archaeological survey and landscape archaeology on the Island of Kythera, Greece. Journal of Field Archaeology, 29: 123–138.

Blandino, J.R., Pappa, R.S. and Black, J.T., 2003. Modal identification of membrane structures with videogrammetry and laser vibrometry. AIAA Paper 2003–1745: 11 pages.

Boehler, W. and Marbs, A., 2002. 3D scanning instruments. Proceedings, International Workshop on Scanning for Cultural Heritage Recording. Corfu, Greece: 9–12.

Bonora, V., Colombo, L. and Marana, B., 2005. Laser technology for cross-section survey in ancient buildings: A study for S. M. Maggiore in Bergamo. Proceedings, CIPA 2005 XX International Symposium. Torino, Italy: 6 pages.Briese, C., 2006. Structure line modelling based on terrestrial laser scanner data. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 36(5): 6 pages.

Bryan, P.G., Barber, D.M and Mills, J.P., 2004. Towards a standard specification for terrestrial laser scanning in cultural heritage – one year on. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 35(B7): 966–971.

Chen, S.-C., 2008. Virtual Fort San Domingo: A Preliminary Process of Digital and Virtual Preservation. Ph.D. Thesis, National Chiao Tung University, Hsin-Chu, Taiwan (unpublished): 144 pages.

Danshui Historic Sites, 2006. Fort San Domingo. http://www.tshs.tpc.gov.tw/fore/en1-1.asp [assessed 19th October 2010].

D'Apuzzo, N. and Kochi, N., 2003. Three-dimensional human face feature extraction from multi images. Proceedings, Optical 3-D Measurement Techniques VI (Eds. A. Gruen and H. Kahmen). Zurich, Switzerland. Volume I: 140–147.

D'Ayala, D. and Smars, P., 2003. Architectural and structural modelling for the conservation of cathedral. Journal of Architectural Conservation, 9(3): 51–72.

Dunn, M.L., 2009. Recent developments in close range photogrammetry for mining and reclamation. http://www.techtransfer.osmre.gov/ARsite/Publications/Dunn_billings_crp1abstract.pdf [assessed 17th October 2010].

Fraser, C., Brizzi, D. and Hira, A., 2003. Vision-based, multi-epoch deformation monitoring of the atrium of Federation Square. Proceedings, the 11th FIG Symposium on Deformation Measurements. Santorini, Greece: 6 pages.

Fryer, J.G., 2001. Introduction. Close Range Photogrammetry and Machine Vision (Ed. K. B. Atkinson). Whittles Publishing, Caithness, UK. 371 pages: 1–7.

Goedhart, W. and Wolters, M., 2008. 3D models, University of Applied Sciences Utrecht, Faculty of Nature and Technology. http://www.michelwolters.nl/huen/huen.html [assessed 17th October 2010].

Goodmaster, C. and Payne, A., 2007. 3D laser scanning at Tiwanaku: Potentials for documentation, visualization, & analysis. http://cast.uark.edu/assets/files/PDF/DO_workshop_Goodmaster&Payne.pdf [assessed 15th October 2010].

Gruen, A., 2001. Development of digital methodology and systems. Close Range Photogrammetry and Machine Vision (Ed. K. B. Atkinson). Whittles Publishing, Caithness, UK. 371 pages: 78–104.

Guarnieri, A., Pirotti, F., Pontin, M. and Vettore, A., 2005. Combined 3D surveying techniques for structural analysis applications. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 36(5/W17): 6 pages

Hanke, K. and Ebrahim, M.A.-B., 1997. A low cost 3D-measurement tool for architectural and archaeological applications. International Archives of Photogrammetry and Remote Sensing, 32(5C1B): 8 pages.

Heath, D.J., Corvetti, J., Gad, E.F. and Wilson, J.L., 2004. Development of a photogrammetry system to monitor building movement. Proceedings, 2004 Annual Technical Conference of the Australian Earthquake Engineering Society (Eds. K. McCue, M.C. Griffith and B. Butler). Mt. Gambier, South Australia: 19 pages.

Hoffman, E., 2005. Specifying laser scanning services. Chemical Engineering Progress Magazine, 101(5): 34–38.

Hyttel, F., 2010. Guns in 3D. http://maritimearchaeologyprogramdenmark.wordpress.com/2010/01/06/guns-in-3d/[assessed 15th October 2010].

Ion, I., Dragos, B. and Margarita, D., 2008. Digital photogrammetric products from aerial images, used for identifying and delimiting flood risk areas. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 37(B7): 361–364.

Jabi, W. and Potamianos, I., 2007. Geometry, Light, and Cosmology in the Church of Hagia Sophia, International Journal of Architectural Computing, 5(2): 303–320.

Jauregui, D., White, K., Woodward, C. and Leitch, K., 2003. Noncontact photogrammetric measurements of vertical bridge deflection. Journal of Bridge Engineering, 8 (4): pp 212–222.

Kavanagh, B.F. and Bird, S.J.G., 1992. Surveying Principles and Applications, third edition. Prentice-Hall, Inc., New Jersey, USA. 667 pages.

Kolbe, T.H., Grger, G. Plumer, L., 2005. CityGML – interoperability access to 3D city models. Proceedings, the 1st International Symposium on Geo-information for Disaster Management (Ed. P. van Oosterom, S. Zlatanova and E. M. Fendel). Delft, Netherlands: 883–899.

Lahoz, J.G., Aguilera, D.G., Finat, J., Martinez, J., Fernandez, J. and San Jose, J., 2006. Terrestrial laser scanning metric control: assessment of metric accuracy for cultural heritage modelling. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 36(A5): 6 pages.

Leberl, F. and Gruber, M., 2005. ULTRACAM-D: Understanding some noteworthy capabilities. Photogrammetric Week 2005 (Ed. D. Fritsch): 57–68.

Lemmon, T. and Biddiscombe, P., 2006. Laser scanners improve survey workflow. Professional Surveyor Magazine, 26(3): 14–18.

Levoy, M., Ginsberg, J., Shade, J., Fulk, D., Pulli, K., Curless, B., Rusinkiewicz, S., Koller, D., Pereira, L., Ginzton, M., Anderson, S. and Davis, J., 2000. The digital Michelangelo project: 3D scanning of large statues. Proceedings, SIGGRAPH 2000. New Orleans, USA: 131–144.

Li, C. and King, B., 2002. Close range photogrammetry for the structural monitoring. Journal of Geospatial Engineering, 4(2): 135–143.

Lin, S.-Y., Mills, J.P. and Gosling, P.D., 2008. Videogrammetric Monitoring of As-built Membrane Roof Structures. Photogrammetric Record, 23(122): 128–147.

Luhmann, T., Robson, S., Kyle, S. and Harley I., 2007. Close Range Photogrammetry: Principles, Techniques and Applications. Whittles Publishing, Caithness, Scotland, UK. 528 pages.

Maarleveld, T., 2009. Boomstamboot Kadoelerveld Opgravingsrapport. University of Southern Denmark, Esbjerg, Denmark. 31 pages.

Matori, A.N. and Hidzir, H., 2010. Low cost DTM for certain engineering purposes. Proceedings, Map Asia 2010 & ISG 2010. Kuala Lumper, Malaysia.

McClenathan, R.V., Nakhla, S.S., McCoy, R.W. and Chou, C.C., 2006. Use of photogrammetry in extracting 3D structural deformation/dummy occupant movement time history during vehicle crashes. SAE 2005 Transactions Journal of Passenger Cars: Mechanical Systems. 3099 pages: 736–742.

Mills, J.P., 1996. The Implementation of a Digital Photogrammetric System and Its Application in Civil Engineering. PhD thesis, University of Newcastle upon Tyne, Newcastle upon Tyne, UK (unpublished): 252 pages.

Newman, J., Fraundorfer, F., Schall, G. and Schmalstieg, D., 2005. Construction and maintenance of augmented reality environments using a mixture of autonomous and manual surveying techniques. Proceedings, Optical 3-D Measurement Techniques. Vienna, Austria.

Obertreiber, N. and Stein, V., 2006. Dokumentation und Visualisierung einer Tempelanlage auf Basis von Laserscanning und Photogrammetrie, in: Luhmann, T. and Mueller, C., eds., Photogrammetrie Laserscanning Optische 3D-Messtechnik - Beitrage der Oldenburger 3D - Tage 2006, Wichmann Verlag, Heidelberg: 317–323.

Patias, P., 2006. Cultural Heritage Documentation. http://www.photogrammetry.ethz.ch/summerschool/pdf/15_2_Patias_CHD.pdf [assessed 16th October 2010].

Psaltis, C. and Ioannidis, C., 2006. An automatic technique for accurate non-contact structural deformation measurements. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 36(5): 242–247.

Riegl, 2010. Terrestrial scanning. http://www.riegl.com/nc/products/terrestrial-scanning/produktdetail/product/scanner/27/[assessed 15th October 2010].

Sauerbier, M., 2004. Accuracy of automated aerotriangulation and DTM generation for low textured imagery. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 35(B2): 521–527.

Sakimura, R. and Maruyama, K., 2007. Development of a new generation imaging total station system. Journal of Surveying. Engineering, 133(1): 14–22.

Schulz, T. and Ingensand, H., 2004. Influencing variables, precision and accuracy of terrestrial laser scanners. Proceedings, INGEO 2004 and FIG Regional Central and Eastern European Conference on Engineering Surveying. Bratislava, Slovakia: 8 pages.

Shortis, M.R., 1986. Close range photogrammetric measurements for structural monitoring, deformation surveys and engineering surveillance. Australian Journal of Geodesy, Photogrammetry and Surveying, 45: 55–64.

Stanek, A. and Ranchin-Dundas, N., 2010. Recording in 3D. http://maritimearchaeologyprogramdenmark.wordpress.com/2010/04/30/recording-in-3d/ [assessed 15th October 2010].

Sternberg, H., 2006. Deformation measurements at historical buildings with terrestrial laser scanners. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 36(5): 6 pages

Tamsui Historic Sites Institute, 2008. Fort San Domingo: General information. Taipei County, Taiwan. 2 pages.

Thompson, E.H., 1962. Photogrammetry. The Royal Engineers Journal, 76(4): 432–444.

Torlegard, A.K.I., 1980. An introduction to close range photogrammetry. Developments in close range photogrammetry, volume I. (Ed. K.B. Atkinson). Elsevier Applied Science, London, UK. 222 pages: 1–14.

Tucker, C., 2002. Testing and verification of the accuracy of 3D laser scanning data. Proceedings, ISPRS Technical Commission IV Symposium 2002. Ottawa, Canada: 6 pages.

Uren, J. and Price, W.F., 2006. Surveying for Engineers, fourth edition. Palgrave Macmillan, Hampshire, UK. 824 pages.

Vezočnik, R., Ambrožič, T., Sterle, O., Bilban, G., Pfeifer N. and Stopar, B., 2009. Use of terrestrial laser scanning technology for long term high precision deformation monitoring. Sensors, 2009(9): 9873–9895.

Waldhausl, P., 1992. Defining the future of architectural photogrammetry. International Archives of Photogrammetry and Remote Sensing, 29(B5): 767–770.

White, M., Petridis, P., Liarokapis, F. and Plecinckx, D., 2007. Multimodal Mixed Reality Interfaces for Visualizing Digital Heritage. International Journal of Architectural Computing, 5(2): 321–338.

Wolf, P.R. and Dewitt, B.A., 2000. Elements of Photogrammetry: with Applications in GIS, third edition. McGraw Hill, New York, USA. 624 pages.

Wolf, P.R. and Ghilani, C.D., 2002. Elementary Surveying: An Introduction to Geomatics, tenth edition. Prentice-Hall, Inc., New Jersey, USA. 900 pages.

Woodhouse, N.G., Robson, S. and Eyre, J.R., 1999. Vision metrology and three dimensional visualization in structural testing and monitoring. The Photogrammetric Record, 16(94): 625–641.

Zhang, L. and Gruen, A., 2004. Automatic DSM generation from linear array imagery data. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 34(B3): 128–133.