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APPLICATION OF LASER SCANNING TECHNOLOGY IN ENERGY ANALYSIS AND STRUCTURAL HEALTH MONITORING OF HERITAGE BUILDINGS

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Abstract: Integrating Building Information Modeling (BIM) with 3D laser scanning (LIDAR) technologies enhances the process of documenting heritage buildings. Many efforts were directed toward utilizing these technologies in the documentation and restoration of heritage buildings, adopting Heritage Building Information Modelling (HBIM). This paper presents a framework for HBIM application in Egyptian Heritage. The proposed framework is capable to utilize the processed point clouds to create different purpose BIM models at the different levels of development to suit the different applications in heritage buildings. It is capable to analyze the different parameters that affect the thermal behavior of the heritage buildings to identify the most suitable energy optimized strategies and techniques. Further, it simulates the structural performances under different types of actions. The proposed framework provides a guideline for heritage buildings conservation. The guideline can be integrated through a holistic approach that would encounter both safety and comfort without the compromise of the loss of heritage identity. A case study of Omar Tosson palace is presented to illustrate the practical aspects of the proposed framework.

1 INTRODUCTION

The 3D laser scanning advances have been presented in the field of surveying and can obtain 3D data about physical objects of different shapes and sizes in a cost and time effective way. Laser scanners enable a large number of points to be recorded in a few minutes. Because of their common sense and flexibility, these sorts of instruments can possibly be broadly utilized as a part of the field of architectural, archeological and environmental surveying (Valanis and Tsakiri 2004). Nex and Rinaudo (2010) worked on an algorithm that automatically combines information gathered from digital imaging and LiDAR to automatically segment and detect heritage building features, such as building break lines. The result of their automation algorithm has the potential to save time and human intervention in the process of documenting heritage buildings using high-density point clouds. Hesse (2010) developed a data processing method for the extraction of Local Relief Models from airborne LiDAR high-density point clouds, which results in color-coded maps of local Relief Models. The proposed method was applied to LiDAR data (acquired by airborne 3D laser scanners) of Baden-Württemberg, and proved valuable and accurate in mapping large archeological sites scanned with airborne 3D laser scanners. Haala et al. (2008) utilized a kinematic terrestrial laser scanning approach to capture the dense point cloud of a historical town. The approach "Street Mapper" depends on four vehicle-mounted 2D laser scanners and a high performance GNXX/inertial navigation system which accurately provides the required dereferenced information which enables the automatic combination of the four 2D dense point clouds. The proposed approach achieved a 30 mm level of accuracy when good GPS conditions were available, thus providing a more feasible 3D laser scanning approach for large heritage sites with an accepted level of accuracy for many urban mapping applications of historical towns. Coren et al. (2005) integrated LiDAR data with hyper-spectral data to evaluate irregular behavior of major ground indices which in turn improve the discovery of new archeological sites. LiDAR provided the accurate surface geometrical data while the hyper-spectral survey provided the specific humidity, vegetation, and thermal conditions of the target area. The integration of both technologies generated an accurate Digital Terrain Model (DTM). Sánchez-Aparicio et al. (2018) diagnosed the historical structures through multilayered point cloud analysis using the technology of laser scanning to observe the built pathologies. In which, radiometric and geometric data provide a 3D methodology to extract and quantify the different deformations and biological conquest on the masonry. The Fortress of Almeida, in Portugal was examined for restoration activity, where the complex diagnostic results of the radiometer were validated and compared with realistic photographs. Salts and moisture were concluded from the deformation layers within the analysis results that revealed the direct relation between the visual diagnosis and that of the point cloud. Głowienka and Michałowska (2017) worked on a project named cultural Heritage through time as a basis for web-based published material to provide 4D data that include time interventions of architectural and structural alterations. The UNISCO listed historical site of Krakow was examined to forecast and analyze the facility modifications over time. Using LIDAR, UAE, TLS and archived data, accurate 3D models are obtained that enhanced restoration even of the underground unseen parts of the facility. The accurate date is provided for the excavation work that includes deepness, slope, and thickness of buried masonry.

2 DIGITAL DOCUMENTATION OF HERITAGE USING LIDAR

Several research efforts have been directed towards the process of generating 3D parametric HBIM models from point clouds, generated using terrestrial 3D laser scanners, along with some efforts in documentation, analysis, and dissemination of several historical sites using HBIM models generated from high density point clouds. Barazzetti et al. (2015) described the procedures of developing the HBIM model starting from point cloud data. The developed models were then reformatted to be displayed in mobile apps using augmented and virtual reality visualization technologies. Their purpose was to deliver HBIM models through widely available platforms for both expert and non-expert operators, which is very valuable in the tourism and heritage dissemination sectors. Dore et al. (2015) deployed the Dublin historical BIM framework to perform structural and conservation analysis for the Four Dublin courts. The analysis was intended to assess the damage subjected to the structure during the war. They developed a model using historical data, and another model using 3D laser scanning. The two models were subjected to simulations to both assess the structural damage that still affects the structure till now, and to serve conservation and documentation purposes. Aside from buildings and terrestrial sites, some naval artifacts are considered of great heritage value, and it is of great difficulty to display and effectively disseminate a multitude of naval vehicles out of their context (water masses) in museums. Cooper et al. (2018) utilized LiDAR 3D laser scan and digitally model 14 watercraft from the Qatar Museums collection. The research assessed the pros and cons of 3D laser scanning as a survey technology for nautical scholars in terms of the time, cost, and skillset, as well as logistical considerations. Oreni et al. (2014) created an HBIM model using terrestrial 3D laser scans and 3D images of the Basilica di Collemaggio in L'Aqualia as part of the restoration process of the site after the earthquake of 2009. The resulted model was used for structural analysis purposes to assess the feasibility of restoration methods. Brumana et al. (2013) carried out a 3d laser scanning and a photogrammetric survey for the Church of S. Maria di Scaria (Vall' Intelvi). They processed the raw data from the survey and generated an HBIM model for the church which captures the construction methods and the various rehabilitations and expansions from the Romanic to the Baroque eras. Also, the developed an object library that can be used for modelling such buildings across Europe. The resulting model was easy to interpret and was used for dissemination purposes in the multimedia section of a local museum. Amans et al. (2013) proposed a framework for documenting heritage sites in West Africa. The framework pivots on the generation of 3D HBIM model from LiDAR high-density point clouds. Their approach overcomes the limitations of the traditional methods, in terms of accuracy and time consumed. The resulting digital documentation provides a guide to the preservation of the heritage sites along with 2D, 3D and virtual visualization and dissemination of heritage sites. Also, they implemented their approach in several heritage sites in Nigeria.

Dore and Murphy (2012) outlined the use of the Dublin institute of technology Historic BIM (HBIM) in modelling historic structures. This approach depends on acquiring special data using 3d laser scanning and photogrammetry to develop an HBIM model using modelling objects from libraries of historical buildings elements. Moreover, the developed model is integrated with GIS data through the CityGML framework, thus creating in accurate 3D GIS models. Such approach bridges the gap between 3D GIS, and HBIM in documenting heritage sites. Murphy et al. (2009) outlined in details the procedures of historical BIM (HBIM) system which starts with point cloud and digital imagery and results in a textured 3D parametric model. They extended the ability of the geometric descriptive language (GDL) to generate 3D parametric objects, which they used to develop a library for historical 3D parametric objects of historical buildings' elements. Further research efforts utilized 3D laser scanning (LiDAR) to document heritage sites. Cheng et al. (2016) developed a method to automatically detect ancient walls features and extract its geometry from LiDAR point clouds. They applied their method to Nanjing city wall, along with the eight city walls of Min and Qing dynasties in China. Their work was used in understanding the current state of the historical walls, and added to their digital document, which represents the means of their construction rehabilitation, and exhibition and promotion. The integration of LiDAR and UAV (unmanned airborne vehicles) proved very efficient in mapping large heritage sites in China. However, due to the vibrations the collected data suffers from some distortions. Li et al. (2015) designed, developed and tested two platforms which are most suitable for mounting liDAR to collect high-density point clouds for heritage mapping projects in terms of stability, capacity, reliability, and vibrations.

Rubinowicz and Czynska (2015) examined the possibilities of applying LiDAR data coupled with digital 3D-city models for evaluating city landscape parameters for heritage rich contemporary urban areas. Such parameters will enable the evaluation of strategic city views, mapping landscape absorption limits, and delineation of heritage-rich zones that needs protection from modern urbanization. Their efforts were crowned by developing the Visual Protection Surface (VPS) method of computational analysis which enables the automatic collection and evaluation of city landscape parameters, and was successfully implemented in the city of Dresden. Fernández-Lozano et al. (2015) used 3D laser scanning to in archeological works for discovering humane-made structures and building ruins. They developed a detailed map of Roman ancient mining works in the areas of Las Medulas and Omanas, along with Duerna and Eria river valleys. Their work provided insights into the Romans' exploitation hydraulic engineering techniques and geometry; which in turn highlighted the scope and impact of the Roman mining works which turned out to be more important than previously estimated.

3 Building Thermal and Daylight Analysis

Building Thermal and Daylight are considered the main influential factors in assessing the whole building performance levels. Usually, it is difficult to analyze one of them solely without the other for their counter effect in performance. I.e., daylight adequacy participates in increasing the solar gain levels that participate in high energy demands. Thus, high performance levels would always require a balance between the thermal and visual comfort. Daylighting simulation tools make it possible to evaluate the quantity and distribution of daylight in a room, while taking into account key influential parameters such as window placement, building geometry, external obstruction, interior divisions and material properties. Nebia and Aoul (2017) studied thermal gain and daylight in residential units and proved their strong connection with the window glazing, apartment unit orientation, and floor level position. "Integrated Environmental Solutions Virtual Environment (IES VE)" software was used to perform a design optimization was performed in order to avoid the clear conflict between heat gain and daylight enhancement. The effect degree of the design factors is compared and the most effective ones are used in the analysis. They provided a suitable tool for evaluation and comparison between different combinations of design variables to which high performance combination achieve both solar radiation satisfactions for low internal heat gain and daylight factor suitability for high daylight performance. Al Qadi et al. (2017) developed an approach to create a successful building performance assessment method and investigated the different factors that affect the building energy performance. They utilized a method that aims to reduce the gap between the actual building measurements and the simulated ones. They stated that not all energy simulation tools have the same accuracy, on top that hourly simulations are more accurate than yearly and monthly ones. they provided additional information. That should be considered in measuring the building performance that is socio-oriented, in a way to involve the users' actual behavior in a space. While identifying the main factors that participate in the performance gap related to design, construction, and operational phases. They emphasized the argument to consider climate uncertainties and future climate changes in building performance assessment.

Existing buildings should *retrofit* and conserved to become a value added not to be neglected and found in a deteriorated state as our current case. *Several research efforts were* conducted to upgrade existing structures utilizing simulation tools for performance assessment. Ahmad et al. (2017) studied the setting of a sensitive historic museum retrofit, attention to preserve artifacts and provide visual comfort at recommended illuminance levels for artifacts. They compared the daylight performance of a flat ceiling and a pitched roof ceiling model of a historical museum. In a side lit configuration, they assumed workplan measurement at 1m which is suitable for exhibition in a museum, simulated in critical daylight provision, i.e., maximum and min. values in specific days and hours of the year. The results revealed the better illuminance distribution of the pitched roof than the flat ceiling. However, values were above the preservation limits and they recommended the usage of flat roof over the pitched one to minimize the illumination to be less than 50 Lux for highly sensitive artifacts in most display areas. Onuwe et al (2015) reviewed different museum designs to discuss the significance of daylight in providing most desirable and comfortable light for users and tackled the fact that most museum designers rely on artificial light to avoid the negative effect of glare and high daylight levels on artifact preservation. they recommended avoiding turning old buildings into museums and avoiding direct sunlight exposure. Proposed that museums should be originally designed in a manner that introduces daylight while preserving low light levels such as clearstory windows and light shelves that provide indirect illumination in spaces.

4 CASE STUDY

Tosson Palace is considered as a case study which is located in Shubra (Road El-Farag). Tosson Palace in Road ElFarag – Cairo, Egypt. It is advocated to be documented in a BIM format as applied by most recent heritage conservation entities. LiDAR data and HBIM are the pivots of the proposed framework in order to overcome the weaknesses of the traditional methods. It is composed of three tiers (see Figure 1): 1) Aquire Raw LiDAR data; 2) Process point cloud; and 3) Build HBIM model. The output and benefits of every tier is inherited to the following because every tier is dependent on the product of the previous tier. The project team performed the required scans for Tosson Palace as shown in Figure 2.

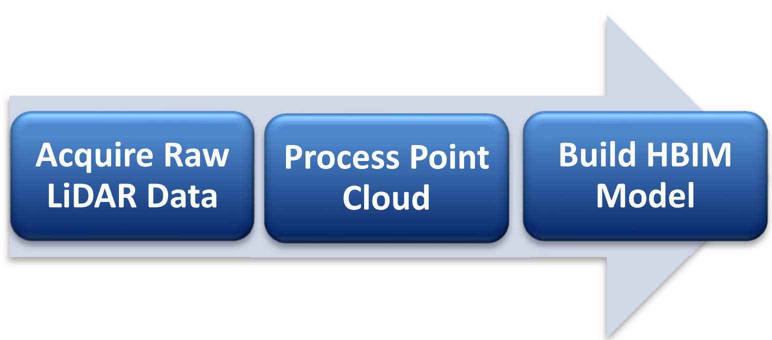

Figure 1: Proposed digital documentation framework

Figure 2: Scanning Tosson Palace

The process of applying the proposed framework is divided into three phases; Phase 1: planning; Phase 2: 3D laser scanning of the site; Phase 3: processing of the High-Density Point Cloud (HDPC). Phase1 is initiated by acquiring the layout of the site with all information collected via a total station survey and manual distance measurements. The team utilized a Z+F 3D laser scanner to acquire the HDPC. The planning depends on the number of scans required to capture the features of the palace from all directions, while maintaining an adequate level of accuracy (HDPC density). Phase 3 was performed utilizing a Dell OptiPlex 7020 Dell Alienware Area 51 workstation for the processing purposes. Phase 3 started with the registration of the individual HDPC generated from multiple scans. Z+F software is used to register the scans. The registration process is achieved through identifying the same targets in different scans. The registered raw HDPC was produced as shown in Figure 3. The purpose of employing HBIM for Tosson Palace was to perform an accurate structural and energy analysis. Autodesk Revit 2018 was used for modelling as it provides quick modelling and allows changes to the 3-D model, as well as a high standard of structured documents. Point Cloud was used within Revit to Model the structural elements and architectural elements of the palace. Modelling the structural elements was very important to enable the calculation of loads on the walls and the floors for structural analysis. Also, modelling architectural elements (e.g., windows, balconies, stonework and ornaments) is for very important for accurate energy analysis results.

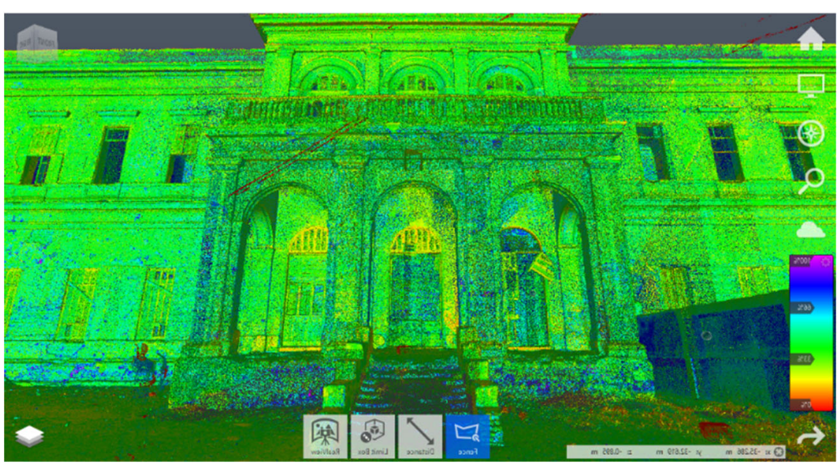

Figure 3: Point Cloud of Tosson Palace

4.1 Palace Energy Simulation and Analysis

It is significant to analyze the palace daylight performance levels to ensure adequate daylighting that also satisfies the visual comfort levels of users. After adding all the related parameters to the palace model in the software, the hole building illuminance analysis is carried out using two metrics, the Daylight Factor (DF) which is the ratio of the light level inside a structure to the light level outside the structure, and the Lux (see Figure 4). The figure shows inadequate Daylight Factor in most inner spaces (highlighted in grey color) that reaches 2.0 in the darkest regions. While very high Daylight factor that reaches 10 beneath the skylight and close to the windows. Also, it is noticed the Lux reading in the red highlighted regions is average 1005 Lux which is an obvious indication of intolerable glare (visual discomfort) as normal Lux levels would not exceed 300 Lux.

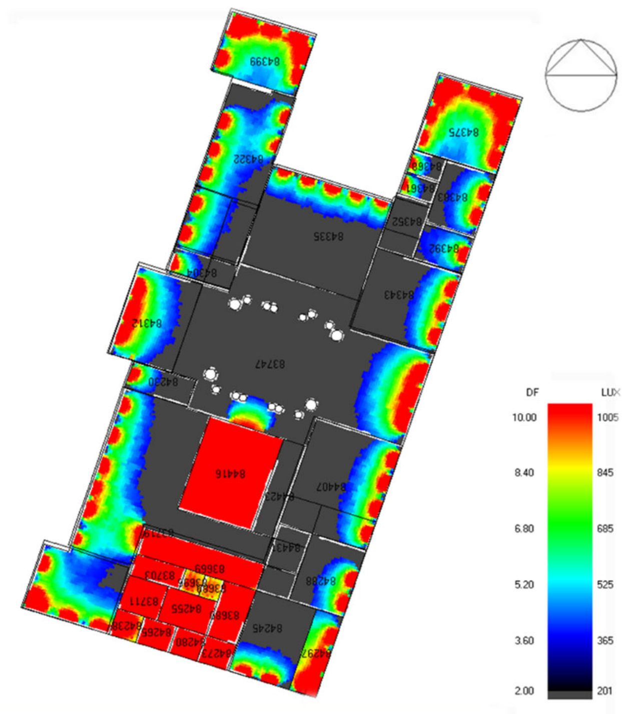

Figure 4: Daylight Analysis for Palace in Lux and Daylight Factor (DF)

4.2 Structural Performance Assessment

In order to establish the numerical model, information gained from the geometrical survey as well as geotechnical and material properties in order to construct a finite element model. The finite element model is used to simulate the behavior of the structure and estimate the stresses in different elements under various loading conditions. The structural model is used to examine various loading scenarios and predict the crack patterns based on estimating the maximum tensile stresses in the structural elements. The model shall also be used to examine the dynamic characteristics of the structure (natural frequencies and corresponding mode shapes). Analysis of the model output (deformations, stresses, etc.) is used to draw conclusions and recommendations to judge the safety of the structure.

A 3D model will be used to analyze Omar Tosson Palace walls under various loads. The 3D model is used to simulate the response of the structural elements under static loads and used for checking settlement and internal stresses in walls. The ready-made software ANSYS is used to conduct the finite element model. Solid elements with variable thickness will be used to represent the walls and floors. Solid elements are removed from opening locations such as doors and windows. Figure 6 illustrates the 3D model finite element model of the Omar Tosson Palace that will be used to perform structural assessment under full dead and live loads from different levels.

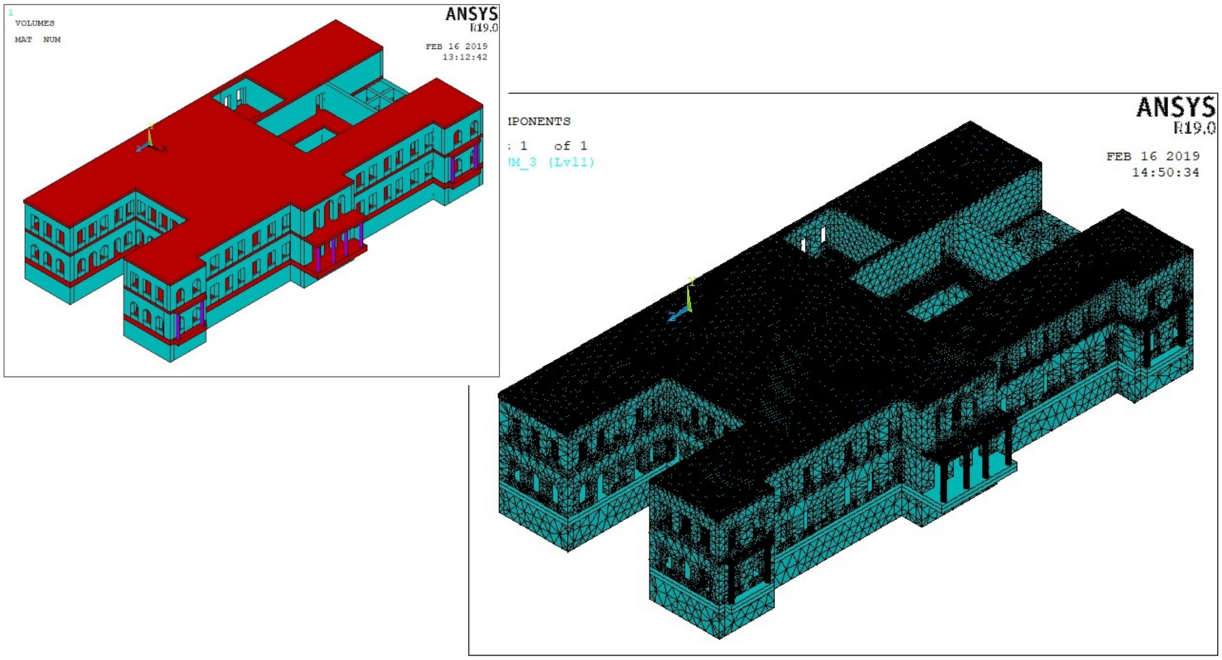

Figure 5: 3D Finite Element Model of the Omar Tosson Palace

5 Conclusion

This research presented a framework for HBIM application in Egyptian Heritage. The proposed framework is capable to utilize processed point clouds to create different purpose BIM models at the different levels of development to suit different heritage documentation needs. The framework is composed of three tiers: 1) Aquire Raw LiDAR data; 2) Process point cloud; and 3) Build HBIM model. A case study was presented to illustrate the 3D laser scanning protocol for Egyptian heritage buildings. The paper presented the analysis that has been performed on Omar Tosson Palace case study on daylight performance levels to ensure adequate daylighting that also satisfies the visual comfort levels of users. Also, the finite element model was developed to simulate the behavior of the structure and estimate the stresses in different elements under various loading conditions.

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