Application of 3D Laser Scanning to Computer Model of Historic Buildings

J. Szolomicki

***Abstract*— The paper contains an analysis of the application of 3D scanning in the process of creating a very precise numerical model of historical buildings. 3D scanning is used in inventory documentation with the visualization of a building and the creation of 3D models in most cases. As a result of 3D scanning a point cloud consisting of million points creating the spatial image of the scanned building is received. It is possible to convert this point cloud to the form of the geometrical mesh of triangles or the set of parametric surfaces using the appropriate software. Next, by using CAD programs can get the appropriate numerical model for FEA and static-strength analysis. The measurement technology based on 3D scanning is slowly replacing traditional measurement inventory methods meeting the needs of the monitoring and protection of historical buildings. The evolution of the 3D laser scanner is developed in order to increase the speed and accuracy of measurements and extend the research area from one measuring position.**

***Index Terms*— 3D laser scanning, FEM analysis, historic building**

I. INTRODUCTION

One of the many possible applications of reverse engineering, dealing with the process of transferring real structures to the virtual world, is scanning real objects to obtain geometric data to create their graphical computer models. Possession of such information for historical buildings, which often have a complex structure, is extremely important in the context of the implementation of numerical static-strength analysis and the design of any reinforcements.

The name reverse engineering is related to the methodology which creates the engineering design. In this methodology a real object is first is examined and then a virtual computer model is obtained by using 3D laser scanners. So it is a reverse process compared with the traditional design. Reverse engineering which uses laser scanning technology is an important element in the structure of computer-aided design (CAD). 3D laser scanning is used in the digitization of historical buildings with an aim to receive detailed geometric data [1]. The resulting point cloud consisting of millions of points can then be used to create a three-dimensional image of the scanned structure. The point cloud can be converted into a geometric grid of triangles or a set of parametric surfaces by using appropriate software [2]. Then with the use of CAD programs, the correct numerical model for the Finite Element Method (FEM) is obtained [3, 4]. The article aims to investigate the process of analysis of historical buildings with the use of 3D laser scanning and also the processing of the obtained virtual image in the FEM numerical model.

II. APPLICATION OF 3D LASER SCANNERS TO DETERMINE THE GEOMETRY OF HISTORICAL BUILDINGS

The principle of laser scanner operation is based on illumination of the investigated object with a laser beam, which when encountering this object is reflected and recorded by the device. An effect of line distortion in the form of a light beam illuminating the surface of the object, the so-called Moire pattern [5], is utilized. The measured object is illuminated by a raster with known parameters (set of lines with known density). Control software allows the distance of the point from the scanner on the basis of the phase shift between the input and output light beam to be determined. This distance and information on the current position of the mirror and the angle of rotation of the scanner allow the coordinates x, y, z for each point of the object to be calculated. In order to produce colour scans the execution of a series of digital images are also required. Then, using the software, the resulting images are automatically superimposed on the resulting scanning point cloud in such a way that every point is assigned to an appropriate colour. It is necessary to carry out several measurements in order to fully scan objects that are only partially located in the field of view of the scanner. For the purpose of scanning, measuring control points are assumed around the object by using the technique of global navigation satellite systems GNSS. Measuring control points are used for geo-referencing and connection of the particular scans. Ground-based laser scanning is performed with positions oriented on measuring fields set on measuring control points. The scan of the object is made up of dozens of stations, with an average resolution of approximately
1 cm. The combination and transformation of scans can be performed in a variety of programs (e.g. Cyclone) [6], with a view to reaching the exact fit for the horizontal and height components. The type of scan described above belongs to terrestrial scanning. Terrestrial scan data are usually insufficient to model roofs. Such information can be obtained from aerial scan data, but this technique is not suitable for the complete modeling of a building façade. Therefore, complete data needed for geometrical modeling

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of analyzed structures can be obtained by combining the sets of data from aerial and terrestrial laser scanning. However, in this case problems can arise at the stage of combining data sets, resulting from different accuracy of both techniques. In the case of needing to improve the match between aerial and terrestrial sets of data, appropriate transformation algorithms can be used. These algorithms may match homologous surfaces by using a model of the method of least squares [7].

The elements constituting the process of creating the historical buildings model are the following:

a) Approximation of scan data by using planes (all elements of the building and architectural details are approximated by planes).

b) Modeling of the building edge as a result of the intersection of the various planes.

c) Checking and possible adjustment of topology which occur during the modeling of roofs.

d) The creation of a 3D vector model for construction.

III. 3D Modeling in Analysis of Historical Buildings

Modern technology related to 3D scanning significantly influences the process of research and documentation of historical buildings [8, 9]. The first step in this process is to acquire digital data which defines the geometry of the structure. The measured values are shown in formatted files (ASCII, PTS, LAS, E57, etc.), presenting the position, intensity and colour of each point in the resulting point cloud (Fig. 1). Appropriate processing of digital data makes it possible to apply collected information in the next step. The data received are converted to the following file formats: DXF, DWG and edited in appropriate programs CAD, FEA and BIM (Building Information Modeling). The process of modeling and numerical static-strength analysis of historical buildings is implemented by means of these programs. Generally, BIM programs are used to easily define a space with a small number of polygons. In contrast, 3D graphics programs and then FEM programs are used for the parametric design and analysis of complex geometric shapes created with polygons and splines. An important advantage of 3D programs is the generation of form by means of a polygon mesh, which affects its very precise definition (Fig. 2). It is very important for the analysis of historical buildings because of the possibility of drawing up detailed documentation, accurate representation of geometry and making a calculation in 3D space by using FEM. Objects are created with a small and large number of polygons due to the assumed degree of accuracy level and priority in the model. Many graphical 3D programs allow the execution of Boolean operations by using the CSG technique (Constructive Solid Geometry) [6]. These operations include defining objects by a particular action executed on solids, i.e. union, subtraction and intersection. The presented technique is particularly useful in generating a model which allows for gap filling or the restoration of missing elements within a building. When carrying out analysis of historical buildings, it is very important to examine the precise geometry of the structure. The basic objective is to understand the actual condition of the structure concerning the damage and destruction of material and to perform numerical statical-strength analysis. It is necessary to precisely identify the geometry of the structure and its individual components (e.g. for historical churches: pillars, walls, buttresses, and many different types of vaults) before adopting the appropriate mathematical model based on FEM. The geometry of these structures is often very complicated and preparation of a complete geometric model is only possible by using the technology of 3D scanning [10,11,12]. Despite this support, this task is very difficult and time-consuming. However, the biggest advantage of this approach is the ability to carry out a comprehensive analysis of the structure. This analysis illustrates the behavior of the structure in 3D.

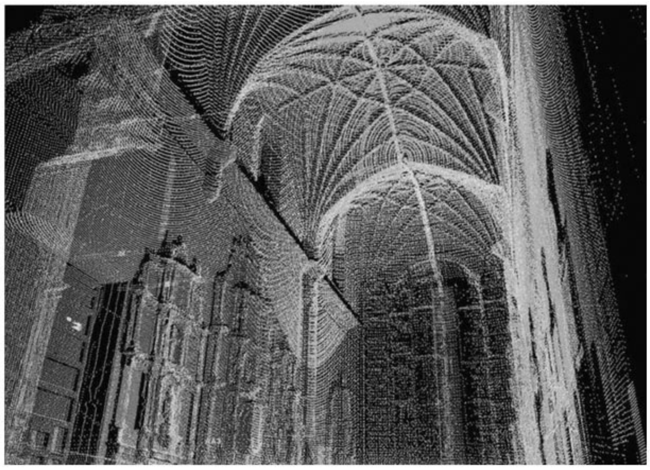

Fig. 1. Digital image of the interior of a historical building with the imposed point cloud characterized by colour intensity.

However, there are many relevant parameters for the examination of these structures. These parameters include: dimensions of elements, shape of masonry blocks, bonding patterns, type of mortar and general homogeneity of the material. All historical buildings must be analyzed individually due to the wide variety of historical buildings in terms of geometry and static scheme [10].

Fig. 2. A digital image of the Franciscan church in Gniezno (3D Scanning,www.scanning3d.pl).

IV. The Procedures Needed to Obtain a Digital Model of the Analysed Structure

The numerical model of the building can be represented

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in many different ways after obtaining the point cloud with the use of 3D scanning. However, the most important in engineering practice are the following models [7], in the form of a regular square grid (GRID), which may be completed by characteristic points and digital lines (hybrid method), in the form of an irregular triangle mesh (TIN). Selection of mesh type is very important for the presentation of surface shape. The most commonly used mesh is TIN triangle and GRID regular square. The irregular triangle mesh is spread between the points designated in the measurements. An interpolation algorithm which enables the calculation of the height of the mesh node is used for the construction of the GRID mesh.In the method of creating a digital model of buildings by using 3D scanning we can distinguish the following stages [6]:

1. 3D scanning of a building

In the first stage the execution of 3D scanning of a building which gives the disordered point cloud is carried out. The resulting point cloud is then recorded by using a mesh of control points (i.e. markers). It is impossible to capture the entire building using a single scan, so a scan with different positions is required. Therefore, the automatic correlation of images plays a very important role in the process of model generation. It is based on the automatic search and measurement of homologous points in two or more scans. For this purpose, numerous correlation methods (e.g. Area-Based Matching, Based Feature Matching, Relational Matching) have been developed [7].

Regardless of the method, the correlation process consists of the following activities:

- selection of elements which will be matched,
- finding their counterparts in subsequent images,
- calculation of the spatial coordinates of the matched elements,
- calculation of fitting accuracy.

The main correlation algorithm used in the process of creating a digital model of the 3D scan is an algorithm from the FBM group (Feature Based Matching). It is based on comparison of objects on the image. During the visualization process, local objects (points, edge elements, sections, small regions) as well as global objects (polygon, complex structure) are compared. Each of these elements has its own attributes, such as: coordinates in the imaging system, average optical density, orientation, gradient, length and curvature of the line. For each image a list of objects is compiled, which are then subjected to a process of matching. The method of least squares (minimum sum of the squares of deviations between attributes) is used to determine the similarity measure.

2. Filtering and cleaning up the point cloud

This stage involves improving the quality of the point cloud in order to make the best representation of the analyzed object. For this purpose an appropriate filtering tool is used (e.g. software CATIA), which allows unnecessary points to be removed (called noise) as well as those that are repetitive. This tool can work in the unification and adaptive mode of the mesh. This stage is very important, because by removing unnecessary and incorrect points, the amount of data used by the system in subsequent steps is substantially reduced.

3. Generation of the polygonal surface

In this step, the point cloud is combined into an adjacent triangle mesh. Delaunay triangulation is mostly used for creating the triangle mesh [7, 13]. The elements of Delaunay triangulation should be based on the circle criterion. It is satisfied if the circle which is circumscribed on the triangle does not contain points other than the vertices of the triangle.

Moreover, interior angles should be fulfilled, which is related to the condition of maximizing the minimum angles. After the division of the triangle containing the data point on three smaller triangles (if the point does not lie on the edges), it is checked whether the operation satisfies the criterion of angles. This criterion determines the relationship that for any two adjacent triangles the sum of the interior angles adjacent to the common side is greater than the sum of the other two angles.

Optimal triangulation is defined by measuring angles, edge length, height or surface elements, whereas finite element approximation error in the FEM is usually associated with a minimum angle of elements. In order to eliminate gaps in the polygonal model new vertices can be added and the coordinates of existing vertices can be adjusted. Additionally, imperfections of the triangle mesh can be removed using a smoothing function. However, despite the filling of gaps in the mesh and smoothing of the surface, the model may be characterized by insufficient accuracy in certain zones. This model cannot be qualified as incorrect. This is due to the specific nature of 3D scanning. Intersection curves are smoothed in the next stage and occurring inaccuracies practically do not affect the final model of the analyzed structure.

4. Creating the wireframe model

At this stage, there is a digital model, which is burdened with some errors. Because it is not parameterized, it cannot be modified. The purpose of further analysis is to obtain a parametric surface model. A key element of activity is the use of family intersection curves which are parallel with the others and located at equal intervals both horizontally and vertically. Their orientation may coincide with the main coordinate system, or be correlated with other systems and geometries. When selecting the position of the planes, attention should be given to characteristic places, i.e. areas where the shape of the surface is changed accordingly. This is particularly important in view of the representation of the final surface of the analyzed building model. In this way a mesh of profiles is obtained which are required to define the surface elements.

5. Creating the base area and surface model

The next step is to generate surface elements based on the mesh that was previously created. Adjustment of the formed surface to an existing wireframe is possible after generating the control points. When modeling all surface elements, they should be cut and consolidated. It is important to check the correct direction of material orientation, as well as the proper sequence of combining planes (Fig. 3).

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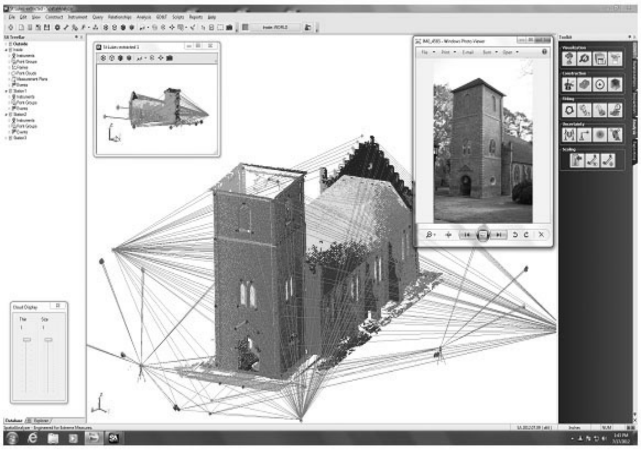

Fig. 3. Creating a surface model for St. Luke's Church in Smithfield, USA (made by New River Kinematics)

Fig. 4. Digital model of the façade of the historical church (performed by True Point LLC, http://truepointscanning.com)

Creating a digital model of the structure obtained from 3D scanning can be performed using a variety of software packages (Fig. 4), such as: AutoCAD, Revit, Microstation, Geomagic, PolyWorks, Rapidform, Maya, Blender, Skyline, ArcGis, ArcInfo, Erdas, etc. The most popular programming languages used for the visualization of 3D models are VRML (VRML1, VRML2) and X3D. Very useful tools in this process are the library OPEN GL and DirectX / Direct 3D. They enable the creation of computer graphics in 2D and 3D, and draw complex three-dimensional structures from simple primitives.

V. FEM ANALYSIS OF HISTORICAL BUILDINGS

The last step in the process of creating a digital model of historical buildings is to use the final form of the model for Finite Element Analysis. The obtained point cloud from 3D scanning can be converted to DWG or DXF files. Next, after importing the point model of the structure into FEM programs, each point is assigned a number and position in the coordinate system. These points are treated as nodes. In the next step, after performing a series of geometrical transformations, it is possible to generate a finite element mesh. For Finite Element Analysis of historical buildings various types of elements are used. Solid elements are used for modeling walls, pillars and buttresses, while for vaults shell elements are applied. The main problem of this analysis is the adoption of an appropriate model for a masonry structure, after obtaining the exact geometry of the scanned building. Basically, the calculation should take into account the two-component characteristic of masonry. Currently, the most accurate type of analysis is micro-modeling which assumes the separate properties of bricks, mortar and contact surface between brick and mortar. This type of analysis is suitable for structures with particularly strong heterogeneous areas of stress and deformation. When using micro-modeling all possible failure mechanisms can be identified and this enables mechanical phenomena at the level of the microstructure to be examined. However, this type of analysis has large limitations for applications in engineering practice. In this analysis, finite element discretization of masonry must be at least equivalent to the real brick bonding with mortar. Additional density of finite element mesh is often necessary. Application of this method is related to a considerable amount of computing time at relatively high hardware requirements. Also needed are a very large number of material parameters of masonry components supported by experimental studies.

In such a situation, implementation of homogenous material with equivalent uniform mechanical properties seems to be the ideal solution. This approach is referred to as homogenization. The mechanical parameter values of the homogenized masonry model, including Young's modules, Kirchhoff's modulus and Poisson's ratio is determined from the model of the representative masonry cell [14].

The historical masonry church (Fig. 5) with cross-ribbed vaults was analyzed with the use of FEM. To span over rectangular bays, cross-ribbed vaults were applied. A cross vault is obtained by the intersection of two or more cylindrical vaults forming diagonal arches over the space to be covered. The arch action of each barrel vault brings all the loads as compressive forces down to the springing with an outward thrust at the supports. Buttressing forces are required to stabilize these diagonal ribs.

Computer calculations were performed using the LUSAS system ver. 14.7 (Fig. 6, 7).

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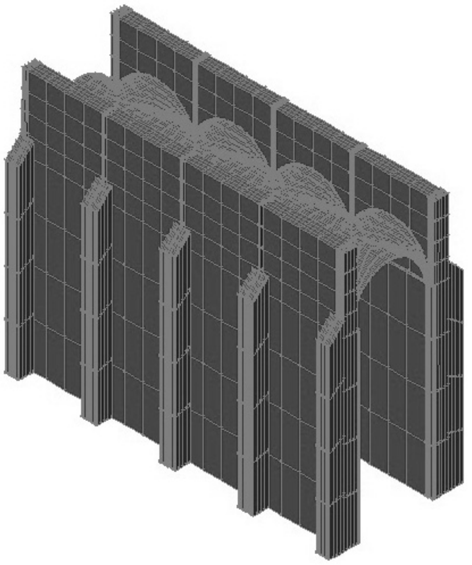

Fig. 5. Numerical model of a fragment of the historical masonry church

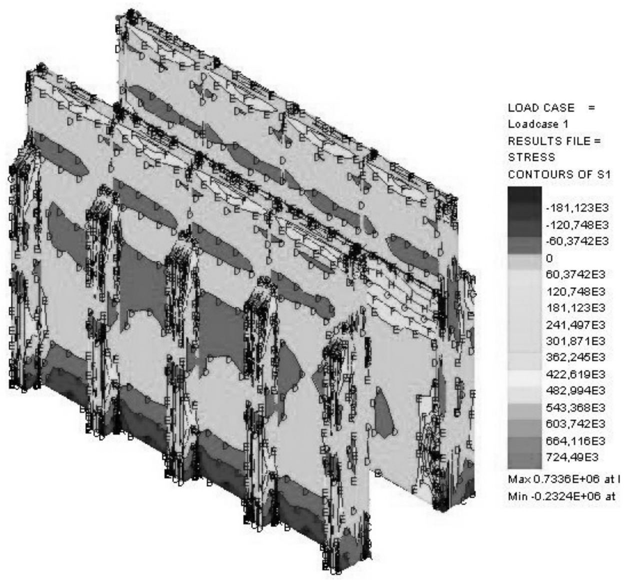

Fig. 6. Distribution of stresses S1 (kPa) in part of the historical masonry church

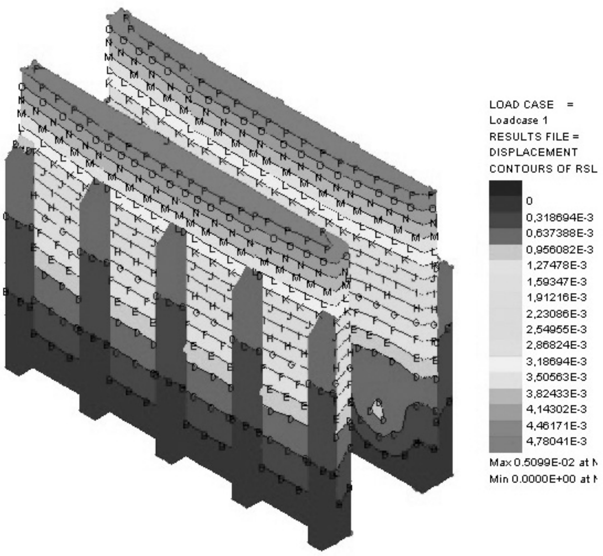

Fig. 7. Distribution of displacements RSL (m) in part of the historical masonry church

VI. CONCLUSIONS

The article contains an analysis of the application of 3D scanning in the process of creating a very precise numerical model of historical buildings. The obtained digital model allows for FEM analysis to be performed. 3D scanning is used in inventory documentation with the visualization of a building and the creation of 3D models in most cases. Despite the fact that laser scanning is now a leading and constantly developing measurement technique, processing and conversion of data in the form of a point cloud is still complicated and time-consuming. In the case of using a digital model of historical buildings, complexity of this model is twofold. Firstly, it is complexity of the architectural elements. Apart from walls and roof structures, there are balconies, cornices, pediments, columns, vaults, domes, carved decorative elements etc. These elements may come from different periods of the history of architecture and constitute themselves as complex structures. The second type of complexity of this subject is based on the number of architectural elements required to create the analyzed structures. Such an understanding of the building structure (with plans, images and a point cloud obtained from laser scanning) is important to correctly fit all parts of a structure in relation to adjacent elements. However, only simple geometric shapes are automatically adjusted to the points in the cloud, so they do not include such architectural elements as column grooves, volutes and vaults. Furthermore, only visible parts of the structure are visualized. There are always parts of the components that cannot be captured by the camera or laser scanner. However, for architectural elements their location is predictable. For example, the hidden or damaged part of the capital of Corinthian columns can be determined by knowledge of its construction. Finally, all used measurement techniques require knowledge of architecture and geometric design to restore constructional elements of an analyzed structure according to structural rules.

The overall conclusion is that measurement technology based on 3D scanning is slowly replacing traditional measurement inventory methods meeting the needs of the monitoring and protection of historical buildings. This technology not only allows a reduction in working time, by improving the efficiency, but also enables the creation of a 3D model, making precise drawings in CAD software and performing accurate statical-strength FEM analysis. The evolution of the 3D laser scanner is developed in order to increase the speed and accuracy of measurements and extend the research area from one measuring position. It provides the necessary impetus for further development of the use of laser scanning to protect historical buildings on a larger scale.

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