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Modern 3D scanning in modelling, documentation and conservation of architectural heritage

Współczesne skanowanie laserowe 3D w modelowaniu, dokumentacji i konserwacji zabytków architektury

Keywords: Analysis, Construction, Architectural heritage, Documentation, TLS

Słowa kluczowe: Konstrukcja, zabytki architektury, konserwacja, dokumentacja, laserowe skanowanie 3D

1. INTRODUCTION

Twenty two years ago, in 1990, Ben Kacyra, Iraqi expatriate and civil engineer, launched in USA the world's first 3D commercial laser scanner. Since that time, the new technology – terrestrial laser scanning (TLS) has been gaining momentum, both advancing technologically and ensuring broader and broader recognition as a reliable measuring instrument in many disciplines. Not surpassingly, it has also found its way into civil and structural engineering, as well as into documentation in the field of conservation of architectural heritage. It is enough to type only *Laser scanner and heritage* phrase into Google Scholar to see more than six thousand papers published on this subject since 1990. Typing *Laser scanner and structural applications* phrase will end with an even higher number – nearly 16 thousand search results for the same period (Fig. 1). It is necessary to note, that due to the simplicity of such query, some of these references might be irrelevant to the main subject. Nevertheless, more than 5 thousand publications on this subject expected in the year 2012 alone clearly show that TLS is already recognised as a well established and trusted technology. What is perhaps equally interesting is the fact that the number of related publications shows yearly exponential growth.

By now most structural engineers and specialists in conservation of architectural heritage are not interested if, but rather what for and how as far as TLS is concerned. Different authors show results of successful TLS application in more and more sophisticated cases [1], some others are working on the theoretical background of TLS usage or its measurements accuracy and repeatability [2], still others concern themselves with attempts to establish a good code of practice and TLS applicability standards in different disciplines [3], some are interested in using TLS for detecting displacement and deformations [4]. Since it is virtually impossible to encompass such a broad scope of interest in a limited frame of this keynote paper, I will concentrate on main differences in standards and good code of practice as required from the point of view of three particular scanning aims – structural analyses, architectural design and visualization – all of them mostly in the context of heritage conservation. As the main discriminant, the accuracy of final deliverables and the loss of original data fidelity in the process of data elaboration will be analyzed. Therefore the main leading idea of this paper can be paraphrased as: *documentation or visualization*.

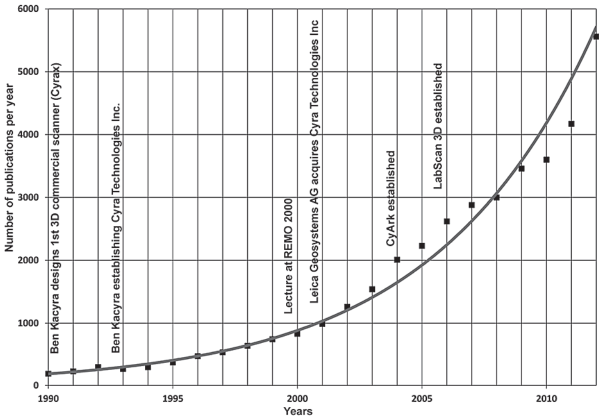

Fig. 1. Results of Google Scholar search on Laser scanner and structural applications phrase (access on 03.05. 2012). Some events in TLS and LabScan3D history are additionally marked

However, from this point of view, one more general question should be answered at the beginning – namely, what is the place of TLS among other modern measuring technologies? Terrestrial laser scanning can be positioned between two other

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surveying technologies: close range digital photogrammetry and kinematic scanning (Fig. 2). All surveying technologies shown in Fig. 2 are characterized by three factors: the size of measured object ranging from a few centimetres to hundreds of kilometres; the density of probing (from friction of a millimetre to several meters); and accuracy (from under a millimetre to several decimetres). Obviously, not all surveying technologies shown in Fig. 2 are in the scope of our interest.

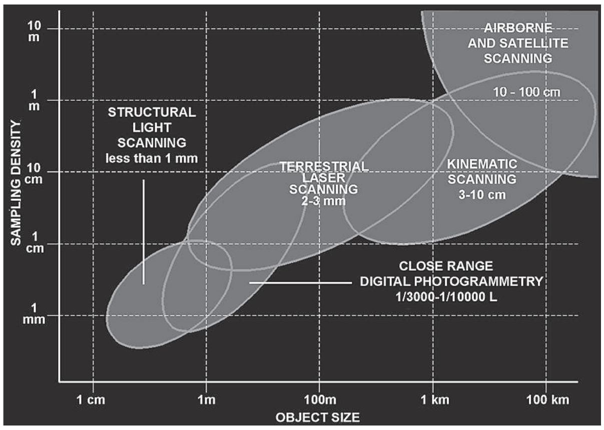

Fig. 2. Modern surveying technologies comparison. Adopted from [3]

Another important factor, which we should take into consideration, particularly from the point of view of the measurement accuracy demanded in most of structural analysis, is the precision of TLS confronted with the desirable precision for this sort of application, as well as with the precision offered by analogous surveying technologies (Fig. 3).

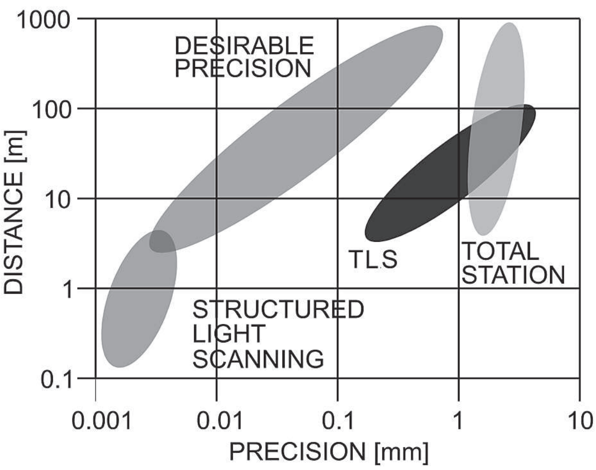

Fig. 3. Precision of some surveying technologies in relation to the measuring distance. Adopted from [5]

Theoretically, the parameter which will satisfy even the most demanding applications can be described as a proportion of the distance from which measurements are recorded to the achieved precision. This desirable proportion falls in a region of 10^{-6} part of the distance and preferably should be constant. However, the existing technologies do not provide us with a single method which will keep such a precision across different scales (Fig. 3). The most advanced methods of structured light scanning can offer even higher precision, but it is practically impossible to maintain this highest parameter above the measuring distance of a few meters. In turn, in case of classical surveying methods utilizing total stations, this proportion will change, ranging from nearly 10^{-3} part for distances around few meters up to ca. 10^{-5} part for distances of several hundred meters. TLS technology shows still different characteristics. The parameter in focus falls in range of 10^{-4} part of the measuring distance and seems to be relatively constant within the range starting from few a meters and ending up at around 100 meters, which is usually the limit for applications of our interest.

2. TLS DELIVERABLES IN RELATION TO THEIR ACCURACY AND LOSS OF ORIGINAL DATA FIDELITY IN THE PROCESS OF DATA ELABORATION

The most important factor from our main point of view, namely the suitability of TLS in documentation and conservation of architectural heritage with special respect to structural analysis, is accuracy and loss of original data fidelity in the process of preparing final deliverables. We can state that accuracy and loss of original data fidelity is the main discriminant which separates *documentation* from *visualization*. Here the last two terms are used to distinguish between deliverables which meet accuracy standards required in certain fields of application from these which are merely providing us with a pictorial illustration of the studied object. For example, *documentation* for museum purposes, for architectural design or structural analyzes, deterioration studies, displacement and deformation monitoring, etc., each will require their own accuracy, precision and data density, as opposed to *visualization* meant only to illustrate or describe the studied object in a broad sense. Unfortunately, these distinctions between credible *documentation* and often very impressive *visualization* is in many cases not fully recognized. This situation calls for establishing certain standards in using TLS as a method for documentation and conservation of architectural heritage or in structural analyses. Despite many attempts of different authors [1], [6], it is difficult or even impossible to come across a comprehensive and fully satisfying approach for such standardization. Neither does this humble lecture aim to solve this issue.

In table 1 represented below, the author tries to classify main types of TLS deliverables in relation to their accuracy and loss of original data fidelity in the process of data elaboration. The lower position in the table, the inferior the accuracy and data fidelity.

As can be seen from the table 1, viewing (visualizing) 3D point cloud (Fig. 4) in its 3D digital environment does not affect original data accuracy and fidelity. Depending on hardware and workflow used, the recorded 3D point cloud can include or not, information about RGB colours for each 3D point. When no RGB values are recorded we are only offered pure geometric information (X, Y, Z coordinates of each 3D point) supplied with the value of reflection intensity. The last can be represented with a colour palette of any choice, including grey scale palette which to some degree resembles black and white photo representation. In turn, RGB values information can be acquired either directly from sensors built into hardware equipment or ported from digital imagery and added in post-processing. However, in both cases we must expect certain degree of inaccuracy. Much smaller in case of colour sensors built directly into hardware equipment and rectified by the manufacturer – in this case the parallax between X, Y, Z geometry and the colour information is usually negligible. However, the quality of colour and its resolution plays also very important role. In the case of colour sensors built directly into hardware equipment, the quality of colour tends to be inferior, while image resolution is usually higher. When adding RGB information in post-processing mode, the risk of discrepancy between X, Y, Z geometry and colour the information is much higher. It depends on several factors – the quality of digital camera used, quality of software used to merge colour information with 3D point data, and obviously skills and experience of the software operator.

Table 1. Main types of TLS deliverables in relation to their accuracy and lose of original data fidelity in process of data elaboration

3D data as recorded by TLS – 3D point cloud	
2D representation	3D representation
black & white (intensity scale) orthophoto delivered directly from 3D point clouds	viewing (visualizing) 3D point cloud in reflection intensity mode
colour (RGB) orthophoto delivered directly from 3D point clouds and colour photomosaics* calibrated with 3D scan data	viewing (visualizing) 3D point cloud in colour (RGB) mode
2D line drawings (plans, views, sections) delivered manually or semiautomatically directly from 3D point clouds	3D line wireframe drawings (plans, views, sections) delivered manually or semiautomatically directly from 3D point clouds
orthophoto delivered from mesh models textured with black & white or colour information	3D mesh models delivered from 3D point clouds
2D line drawings (plans, views, sections) delivered from 3D mesh models	
2D line drawings (plans, views, sections) delivered manually or semiautomatically from 3D surface models	3D surface models delivered manually or semiautomatically directly from 3D point clouds
2D line drawings (plans, views, sections) delivered automatically from 3D solid models	3D solid models delivered manually or semiautomatically directly from 3D point clouds (BIM models)
2D line drawings (plans, views, sections) delivered by manual or semiautomatic on-screen digitizing of orthophotos or photomosaics	–

** in fact, colour photomosaics calibrated with 3D scan data only roughly and in some particular conditions meet orthophoto accuracy. However, they bring much better textural information.*

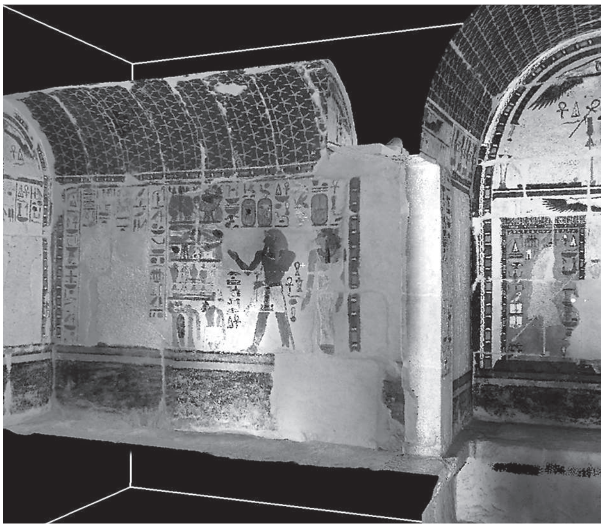

Fig. 4. Example of viewing (visualizing) 3D point cloud in colour (RGB) mode. Upper Anubis Shrine in Hatshepsut Temple in Deir el Bahari (Egypt)

One of the side problems, which should be again mentioned, is lack of standards. There is no worldwide recognized standard for 3D laser scanning for world heritage documentation, or for any other particular fields of 3D laser scanning application including structural analyses. This situation often results in an approach *let scan as dense as possible in given circumstances*, which for many reasons does not always seem to be the best choice, if at all. The situation is made even more complex by lack of common standards of 3D point cloud data formats. Each hardware manufacturer develops their own proprietary format, with capabilities of interoperability which often prove limited. There is currently no general-purpose, open standard for storing point-cloud data, yet there is a critical need in the 3D-imaging industry for open standards that promote data interoperability among hardware and software systems [7]. Among other initiatives, recent activities of SPIE (an international society advancing an interdisciplinary approach to the science and application of light), particularly works on establishing ASTM E57 file format are likely to change this situation [8].

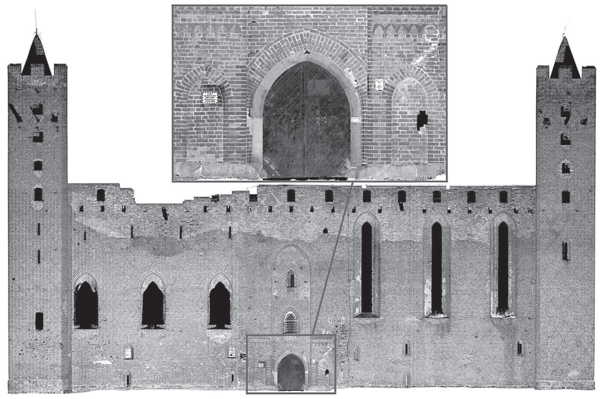

Fig. 5. Example of black & white (intensity scale) orthophoto acquired directly from 3D point cloud. Eastern façade of mediaeval Teutonic Knights castle in Radzyń (Poland)

Nevertheless, storing original 3D cloud point databases may be considered as the best way to document objects for archival purposes. Such the data deposited in safe repositories can be later consulted at any time and in any case. Unfortunately, usefulness of 3D point clouds in its original form as a direct data for design or structural analyses, to mention only these two possible fields of application, is very limited. The most recent attempts to immerse 3D design files directly into 3D point clouds representations might solve this problem in a near future. At least, all leading CAD vendors seem to work hard on this issue.

There is, however, a big discrepancy between current software's abilities to handle 3D point cloud data and the way typical designers and engineers used to work. Still most of us tend to work rather in 2D data format. How can this group enjoy benefits of TLS technology? The only answer is to work with 2D representation of 3D point clouds. Among many types of 2D TLS deliverables, black & white (intensity scale) orthophoto acquired directly from 3D point clouds is the first answer if we still consider data accuracy and loss of original data fidelity in process of data elaboration as an important factor (Fig. 5). High accuracy data with resolution of around 2-3 mm can be directly inserted into any CAD application assuring good representation of documented object.

A still inferior choice are, again from the point of view of data accuracy, colour (RGB) orthophotos delivered directly from 3D point clouds. Depending on the way how the colour information has been ported into 3D point cloud we may expect smaller or bigger accuracy issues. However, additional information obtained from colour representation has high value by itself (Fig. 6). Both kinds of raster orthophoto files can be inserted directly into any CAD application as a background for design or any analyses. It is important to stress that there is no particular necessity to redraw this raster information in vector format. To the contrary, such an action will affect data introducing interpretation and simplification errors.

Fig. 6. Example of colour (RGB) orthophoto acquired directly from 3D point cloud. Southern façade of mediaeval bishop palace in Milicz (Poland)

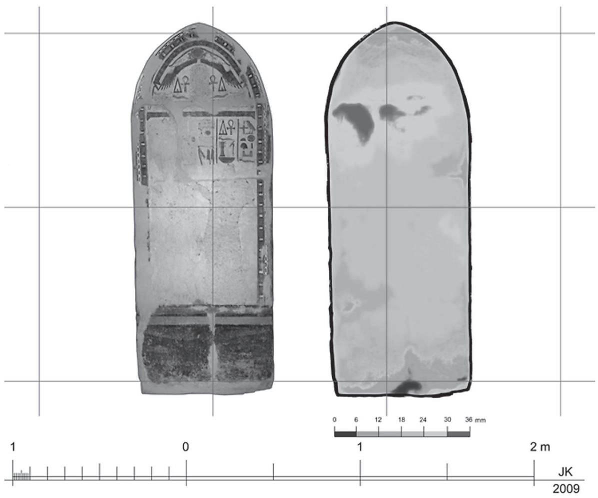

Fig. 7. Example of displacement map delivered directly from 3D point cloud. Southern wall of Upper Anubis Shrine in Hatshepsut Temple in Deir el Bahari (Egypt)

The possibility to represent 3D cloud points in any arbitrarily chosen colours opens another field of application. When turning the coordinates system in such a way that Z axis is perpendicular to the surface of our interest, we can represent all 3D points in different colours according to their Z value (the so called elevation maps). This is perhaps the fastest, the most simple and at the same time still very accurate way to represent defects in any planarity and can be successfully used for example in wall displacement detection (Fig. 7).

There are however situations when 2-3 mm resolution offered by orthophotos acquired directly from 3D point cloud is fairly not satisfactory and much higher data resolution is demanded. A typical example are documentation works on wall paintings or bas-relief. In such a situation, particularly when the depth of the object (a relief for example) is negligible if compared to the distance from which the photography is taken, we can use colour photomosaics calibrated with 3D scan data (Fig. 8). Thus however, we are trading geometrical data accuracy for higher resolution. If we accept the resulting inferior data accuracy, resolutions of 0,3 mm are relatively easy to obtain [9].

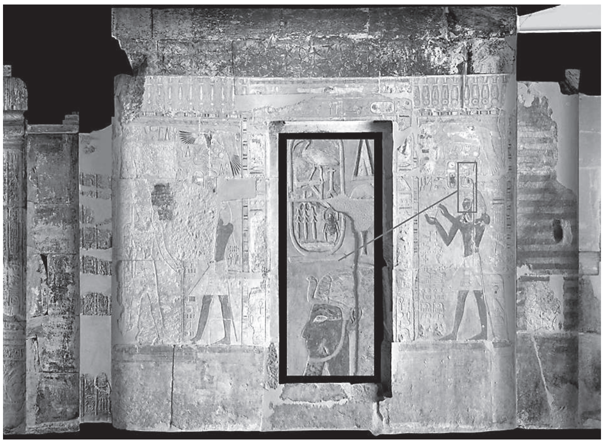

Fig. 8. Example of 0,3 mm resolution photomosaic calibrated with 3D scan data. Northern wall of Statue Room in the Main Sanctuary of Amun in Hatshepsut Temple in Deir el Bahari (Egypt)

Going back to the direct use of 3D data (Table 1) we should mention 3D line wireframe drawings (plans, views, sections) delivered directly from 3D point clouds. Most of software applications meant do deal with 3D point cloud data have built in algorithms to extract such data in manual, semiautomatic or even fully automatic mode. Aside from the data simplification, the resulting wireframe 3D models are of limited use both in documentation and design, as well as in structural analyses. 2D representation of such models, which still inherits all the handicaps of data simplification, can be, according to my experience, used in a bit broader range of applications.

Next in Table 1 comes the 3D mesh models delivered from 3D point clouds. Obviously, implemented meshing algorithms introduce some unavoidable interference into original data. Depending on applied the meshing parameters this could be data density decimation, smoothing, filtering, hole detection and surface reconstruction, etc. Thoughtfully used, all these algorithms are likely to improve obtained results, but the degree of interference into original data should be kept in mind all the time. Generally speaking, 3D mesh models show high potential for representing documented surfaces with good fidelity, but at the cost of large size of data files. The more detailed mesh file, the bigger the file size. Mostly for this reason, the usage of 3D mesh files directly in 3D CAD applications is rather limited. However, mesh files offer a good starting point for many kinds of different deliverables ranging from orthophotos textured with black & white or colour information which can be also produced from mesh models (Fig. 9), up to 2D or 3D line drawings (plans, views, sections) obtainable from mesh models often just by 1 mouse click (Fig. 10). Mesh models also constitute valuable basic data to enter the world of finite element method (FEM) analyzes. Additionally, mesh models can be successfully used in deformation analyzes. Scanning the object of our interest in certain time intervals and then representing its surfaces as mesh models permits detection of any changes caused by many different factors. This method has recently been successfully and broadly used in landslides and constructions monitoring (Fig. 11).

Fig. 9. Example of orthophoto delivered from 3D mesh model with some overlaying 2D vector lines. Mediaeval chapter-house in Wrocław (Poland)

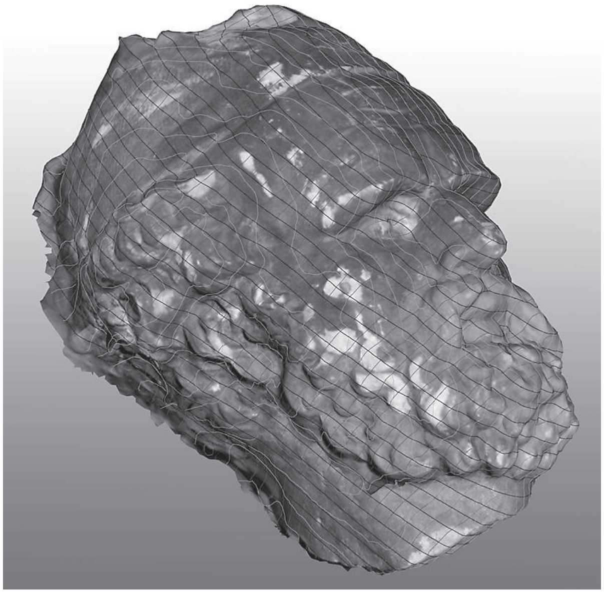

Fig. 10. Example of 3D mesh model with overlaying 3D vector lines. Head of a statue of unknown provenance (deposit of Institute of History of Architecture, Arts and Technology, Faculty of Architecture, Wroclaw University of Technology)

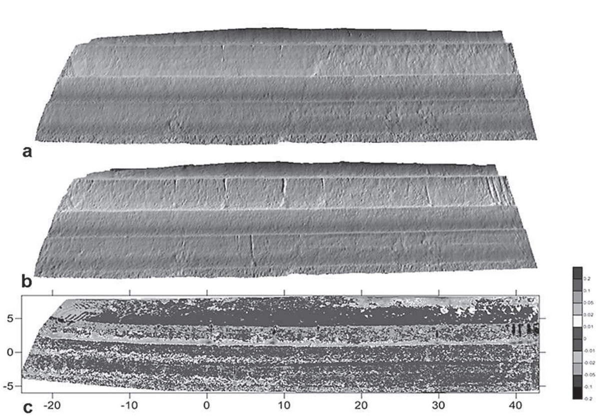

Fig. 11. Example of deformation analyses based on 3D mesh models. a – 3D mesh model of primary stage of ground slope, b – 3D mesh model of the same ground slope after erosion, c – results of 3D mesh models subtracting shows amount of ground slope displacement. Adopted from [10]

The next step of simplification of real 3D world representation are 3D surface models delivered manually or semiautomatically directly from 3D point clouds (Table 1). In this case, the degree of simplification is much higher but the resulting files are at the same time much smaller in size, and therefore easier to handle by CAD applications. As before, a similar kind of 3D and 2D deliverables can be achieved out of such models. Although the usage of 3D surface models in CAD application is much broader, it still does not fully meet possibilities offered by the functionality of contemporary design software. This stage can be fully implemented only with solid modeling which is the entry point for building information modeling software (BIM). There all the objects are represented as much simplified true solids (Fig. 12) which are easy to handle by CAD algorithms. At the same time we lose most of the detailed information about the documented objects. All the walls used to be represented as perfectly planar, while beams, posts etc. loose all the information about their imperfectness (cracks, deflection, twisting, etc.).

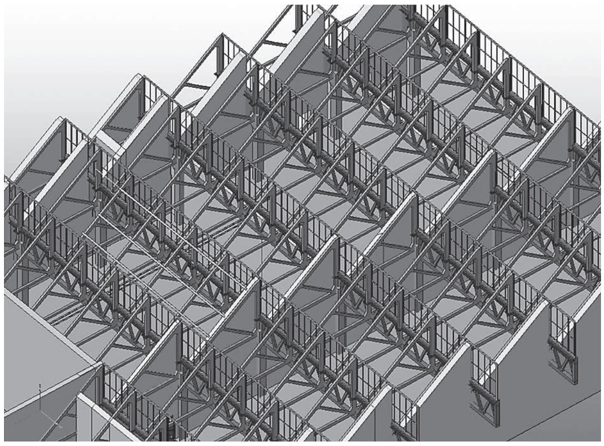

Fig. 12. Example of 3D solid model delivered directly from 3D point cloud (BIM model). Prefab concrete industrial building in Wrocław (Poland)

Despite the loss of so much detailed information about the geometry of the documented object, there is however one big advantage. Solid models can be easily incorporated into the abovementioned BIM software and, when supplied with additional data-based information (material, weight, physical and mechanical properties, etc) constitute a contemporary high-end standard for design as well as analytical and struc-

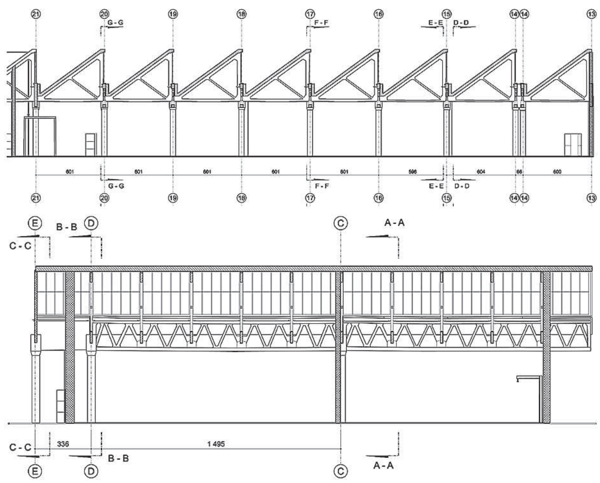

Fig. 13. 2D vector drawings delivered automatically from the BIM model represented on Fig. 12

tural applications. Such models are equipped with a kind of their own intelligence – all elements are not only described in terms of spatial geometry, but they also *know* how to present (visualize) themselves in perspective views, plans and sections, so automatic production of 2D documentation is fully possible (Fig. 13). Solid models are also best suited for structural FEM analyses (Fig. 14).

There is still one category of 2D deliverables which has been omitted from a more detailed discussion – 2D line drawings (Fig. 14.) delivered by manual or semiautomatic on-screen digitizing of orthophotos or photomosaics, which in turn are products of 3D laser scanning. There we must recall all what has been previously said about the production of orthophotos or photomosaics. With some reservations concerning the accuracy of RGB colour mapping, orthophotos produced directly from 3D point cloud can be considered a very accurate 2D representation of 3D world. What happens when such the data undergoes on-screen digitizing?

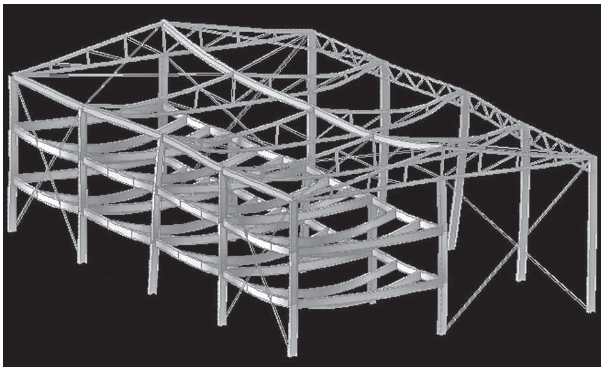

Fig. 14. Example of solid model of steel construction during FEM analyses

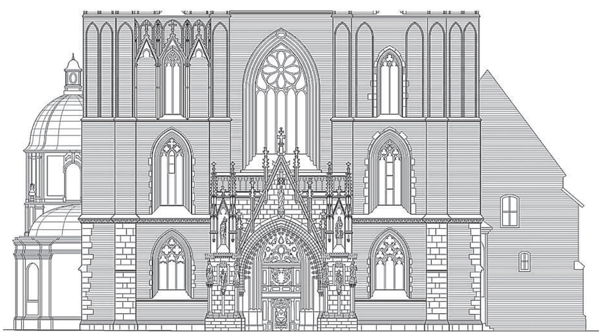

Fig. 15 . Fragment of western façade of Wroclaw Cathedral. 2D line vector drawing delivered from on-screen digitizing. © Archikon s.c.

On-screen digitizing of raster data is commonly used in cartography, where specially tailored software applications are used in order to assure demanded accuracy. However, when using such software for digitizing orthophotos produced directly from 3D point cloud we encounter some problems. In this case, raster data we deal with are of a slightly different character. Neither are they full halftone colour pictures as it is in case of airborne imagery, nor sharp, limited colour palette images as typical cartographic maps. This results in certain difficulties in proper usage of algorithms designed to trace certain colour differences yielding with decreasing accuracy of vectorized data. Situation becomes even worse with digitizing orthophotos delivered from mesh models. As it was previously pointed out, such orthophotos are inheriting all the faults of the meshing process, so the final degree of accuracy constitutes the sum of errors from the two steps: meshing and digitizing. There is of course no problem as long as we are aware of it and as long as final accuracy meets our demands.

However, in daily practice I have observed so often, on-screen digitizing done manually without help of any dedicated software. Can we consider such the data as fully credible 2D documentation – deliverables of high-end TLS technology – or do they rather fall into *visualization* category which only merely illustrates the real world? Fully arbitrarily chosen vectorization criteria, no control upon the resulting accuracy – all this makes me perceive such data fall as belonging rather to the *visualization* category. They might still be useful in some cases, but it is rather hard to consider them true documentation. Their usage in structural analyses is also highly problematic.

3. CONCLUSIONS

When trying to summarize what has been previously said, we may end up with something similar to the Table 2 represented below.

Table 2. Applicability of different TLS deliverables according to their suitability for certain purposes

Field of application / Types of deliverables	archival documentation*	architectural design	structural design	structural analyses	deterioration analyses	deformation and displacement monitoring
black & white (intensity scale) orthophoto delivered directly from 3D point clouds	+/-	+	--	---	+	+
colour (RGB) orthophoto delivered directly from 3D point clouds	++	++	--	---	+	++
colour photomosaics* calibrated with 3D scan data	++	++	---	---	++	---
2D line drawings (plans, views, sections) delivered manually or semiautomatically directly from 3D point clouds	+	+/-**	+**	--	+**	+**
orthophoto delivered from mesh models textured with black & white or colour information	+	+	--	-	+	++
2D line drawings (plans, views, sections) delivered from 3D mesh models	+/-	++	+	++	+	++
2D line drawings (plans, views, sections) delivered manually or semiautomatically from 3D surface models	-	++	++	+	-	+
2D line drawings (plans, views, sections) delivered automatically from 3D solid models	--	+++	++	+	+/-	+/-
2D line drawings (plans, views, sections) delivered by manual or semiautomatic on-screen digitizing of orthophotos	---	+	--	---	--	---
original 3D point cloud	+++	+/-	+/-	+/-	+/-	+
viewing (visualizing) 3D point cloud in reflection intensity mode	---	---	---	---	---	+/-
viewing (visualizing) 3D point cloud in colour (RGB) mode	--	--	---	---	---	+
3D line wireframe drawings (plans, views, sections) delivered manually or semiautomatically directly from 3D point clouds	-	---	--	+	---	+**
3D mesh models delivered from 3D point clouds	+	--- ***	---	++	+++	+++
3D surface models delivered manually or semiautomatically directly from 3D point clouds	--	--***	--	++	--	+
3D solid (BIM) models delivered manually or semiautomatically directly from 3D point clouds (BIM models)	---	+++	+++	+++	---	-

note: number of +/ – signs describe suitability of certain deliverables for different purposes.

* *archival documentation is meant there as a possibly full and exact geometrical and textural representation of a given object.*

** *high accuracy but time-consuming*

*** *too large files and too detailed representation for most of architectural software*

The classification presented above is fairly subjective and results from author's merely twelve years of theoretical and practical experience with TLS technology, rather than from particular scientific research and as such can be questionable. Despite possible criticism and different points of views resulting from different practical experiences or research, I suggest that problems presented in this paper should be always kept in mind, both by those using TLS technology and by the end clients expecting to get credible results, which will meet their requirements concerning accuracy and data fidelity.

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Abstract

The paper deals with broad field of terrestrial 3D laser scanning (TLS) data application in documentation and conservation of architectural heritage. Position of TLS among other surveying technologies is shown in respect for density of information, size of surveyed objects and expected accuracy. Different kinds of 2D and 3D deliverables are characterized with the main focus on their accuracy and loss of original data fidelity in process of data elaboration. Finally, the problem of applicability of different TLS deliverables is discussed.

Streszczenie

Artykuł dotyczy szeroko rozumianych zastosowań naziemnego skanowania laserowego (TLS) w dokumentacji i konserwacji zabytków architektury. Omówiono miejsce technologii TLS wśród innych technik pomiarowych z uwzględnieniem gęstości próbkowania, wielkości mierzonych obiektów i oczekiwanych dokładności. Scharakteryzowano także podstawowe rodzaje opracowań 2D i 3D otrzymywanych w wyniku laserowego skanowania w odniesieniu do uzyskiwanych dokładności i utraty części pierwotnej informacji w procesie opracowania danych. W zakończeniu przedstawiono potencjalny zakres zastosowań dla poszczególnych rodzajów opracowań uzyskiwanych w wyniku naziemnego, laserowego skanowania 3D.