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APPLICATION OF 3D LASER SCANNING IN STATIC ANALYSES OF STRUCTURES
PRIMENA 3D LASERSKOG SKENIRANJA U STATIČKOJ ANALIZI KONSTRUKCIJA

Originalni naučni rad / Original scientific paper
UDK /UDC: 620.179.16:725.4 725.4.025
Rad primljen / Paper received: 20.04.2015

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Keywords
- 3D laser scanning
- 3D scan processing
- industrial heritage
- static analyses

Ključne reči
- lasersko 3D skeniranje
- obrada 3D snimaka
- industrijsko nasleđe
- statička analiza

Abstract

In heritage protection there are always demands for quick and non-invasive techniques of documentation which can provide a wide spectre of information. In practice often used are insufficiently precise techniques that do not give adequate amount of data. In the last decade, digital documentation through use of a 3D laser scanner has become very developed. The aim of the paper is the presentation of the rapid survey of industrial heritage objects at the Old ironworks complex in Smederevo, but also a description of pre-processing and editing of 3D scans as a basis for further static analyses of structural systems. Here described are the basic principles of laser scanner operation as a workflow of performed operations. Special focus is aimed at advantages of this method, but also on its limitations.

Izvod

U zaštiti nasleđa uvek je postojala potreba za brzim i neinvazivnim dokumentacionim tehnikama koje mogu pružiti širi spektar informacija. Trenutna praksa koristi često nedovoljno precizne tehnike koje ne nude dovoljnu količinu podataka. Poslednjih deset godina veoma je razvijeno digitalno dokumentovanje putem laserskog 3D skeniranja. Cilj rada je prikaz brzog premera industrijskih objekata u kompleksu Stare železare u Smederevu, kao i obrada i priprema 3D snimaka za podloge koje bi se koristile u statičkoj analizi zatečenih stanja konstruktivnih sistema. Opisan je opšti princip rada laserskih skenera, kao i radni tok izvršenih operacija. Takođe skrenuta je posebna pažnja na pogodnosti ovog metoda ali i na ograničenja koja postoje.

INTRODUCTION

In the last twenty years, significant progress has been made in the long history of laser measurement developments (the first ruby laser rangefinder was constructed by Mayner, /1/), which have become a technology revolution in many systems, from devices that measure particular distances (laser meter, total station, etc.) to 3D laser scanners that collect spatial information. Today there are a lot of models of commercial laser scanners that are applied in different fields, as the forensic science, mining, oil industry, civil construction and architecture. Heritage protection always has a need for very precise and fast documentation of the condition and look of monuments, so use of the laser scanner is very acceptable and in some cases is necessary (e.g. when there is a very limited time for the survey of an object, /2/, at very high buildings, where the instalment of scaffolds is hardly manageable, /3/, at structures which have a demand for very precise documentation of huge surfaces, /4/). Together with complement 3D documentation techniques, as photogrammetry, scanning with structural light, and georeferencing, a most complete and the truest digital proof of the present shape and positions of unmovable cultural heritage objects can be produced. Now, there are a lot of ongoing projects of digitalisation and scanning of monuments (Heritage3D project /5/, CyArk /6/, Scottish Ten /7/, ViHAP3D /8/).

The Central Institute for Conservation in Belgrade has started in 2012 with the application of this technology in the field of heritage protection in our region, with provisional equipment and professional training (seminars: Architectural Conservation Course and Architectural Survey trough 3D Laser Scanning Course, organised by the High Institute for Conservation and Restoration – ISCR from Rome, and the Central Institute for Conservation in Belgrade, 2012). We are using a Focus3D 120S model, manufactured by FARO Company, for scanning. Computer processing of 3D scans is done by using specialised software JRC Reconstructor 2. Till now, we have scanned several buildings and sites, from different periods – Gate of Charles VII, Kalemegdan (1736); Franciscan monastery in Bač (12th c.); Monastery Bođani (15th c.); Archaeological site Belo brdo, Vinča (6th c. BC); Facades of Dunavska street, Novi Sad; Medieval fortress Mileševac (13th c.), etc.

In this paper, 3D scanning of the Old Ironworks Complex, SARTID in Smederevo, is presented as well as the processing of 3D scans for receiving an information base for further analyses of buildings' conditions, in this case a static stability analyses. The scanning is performed in cooperation with the Regional Institute for Protection of Monuments of Culture in Smederevo, during a workshop 'Industrial Heritage of Serbia', organised by Conservators Society of Serbia, in September 2014, in Smederevo. This industrial complex represents the beginning of the Serbian modern metal processing industry. The idea for building a facility has started with the creation of Serbian Shareholding Mining and Smelting Industrial Society – SARTID in 1903, and selection of Smederevo as a strategic position and the construction of the factory continued in 1921. In the beginning, the factory produced and repaired locomotives and rail wagons, and has manufactured steel structures in the period 1922-1937, and since then are the oldest buildings of the complex – Coal warehouse, Boiler house (1923), Electric power plant (1923), and Smiting workshop (1925). Later, the production programme is expanding, and new buildings emerge - Sheet metal rolling facility (1933), Steelworks with Siemens-Martin open hearth furnace (1937), Rolling Mill (1937), and Gas generator power station (1937). Documentation of these objects are done in combined techniques of classical survey and 3D laser scanning, due to a very limited time and large amount of work, with using laser scanning for creating complex frames with positions of the object which can be surveyed in a classical way, and for the total documentation of high and spatial big industrial halls. The workshop represents the most complex object in a structural manner, so it needed special attention during the scanning process.

WORK PRINCIPLES OF 3D LASER SCANNER

There are different types of 3D scanners whose work is based on different technologies. Here presented is the functionality of terrestrial LiDAR (Light Detection and Ranging) scanners. They use a laser light beam, usually of specific frequency, but also a specific spectrum of frequencies for determining the range of a point from the scanner. There are two methods of range measurement, with the laser pulse, and with phase modulation. In both methods, the laser pulse is emitted to an object from which it is reflected back to the scanner. Pulse scanners calculate a distance of the point by measuring the time needed for the pulse to reflect back to the scanner. In phase scanners, the emitted beam has a specific frequency modulation, and a phase shift is measured in the reflected beam which determines the distance to the point, /10/.

Scanning of a selected surface, or area, is performed by an automatic unit in the scanner, which guides the beam through a rotating mirror at radial horizontal and vertical trajectories and in certain steps, so a huge number of points are collected at surfaces visible from the scanner direction. All scanner models can cover 360° of the horizontal axis, but vertical angles of scanning are varying, Fig. 1. The density of scans, or the resolution, depends on the beam guiding step, i.e. rotation of the movable mirror. Many factors affect scanning precision (surface roughness and the material of the scanned object, atmospheric conditions, laser beam diameter, noise level, etc.), and for many models, the manufacturer declares that the precision is in the range of 2-6 mm. Generally, it is accepted that phase shifting scanners are more suitable for architecture scanning, where the rate of data collecting and the density of scans is important, /11/.

The scanner collects information about the area and the surfaces around one point, usually the centre of the rotating mirror, so the primal product is point cloud in a spherical coordinate system, where each point is defined with a vector of distance and angles to base planes. The cloud point represents an aggregation of collected points inside the scanned area, in the scanner's range, that are mutually spaced by a dimension of angle movement (step) of the rotating mirror, and whose arrangement is affected by the noise level. With simple translation, point coordinates are translated into Cartesian coordinates (x, y, z), what is the first step in the preparation of the point cloud for further computer editing. Usually, a surface's triangular mesh is generated from this format which is more convenient for analysis.

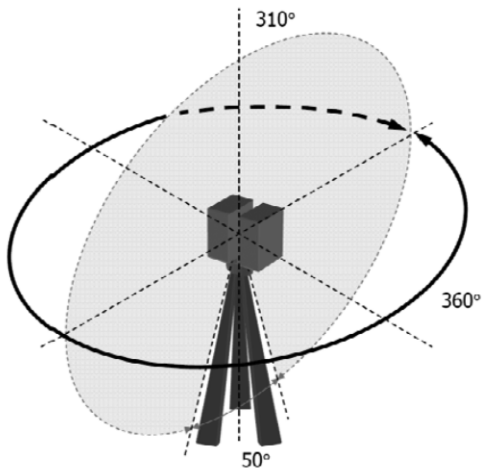

Figure 1. Scanning range of laser scanners.

The intensity of the reflected beam is also measured, which means that the quality of the scan is affected by the angle of scanned surfaces, i.e. incident angle of the laser beam. The biggest reflection is achieved at perpendicular surfaces with regards to the emitted laser beam. Metallic surfaces are difficult to scan, because the beam is not reflected back to the scanner, and very diffuse surfaces reflect back a very small intensity of the emitted beam, /12/.

Table 1. Characteristics of FARO Focus3D 120S scanner.

Unambiguity interval	153.49 m
Range	0.6-120 m, with normal angle and 90% reflectivity
Max. measurement speed	976,000 dots per sec
Ranging error	±2 mm at 10 m; 25 m at 90% and 10% reflectivity
Ranging noise	0.6 mm at 10 m and 0.95 mm at 25 m, with 90% reflectivity
Resolution of integrated camera	70 Mpix
Field of view	360° horizontal, 300° vertical
Minimal rotation step	0.009° (40,960 3D pixels inside 360°)
Max. rotation speed of mirror	5,820 rpm
Laser power	20 mW
Wavelength	905 nm
Beam divergence	cca 0.011°
Beam diameter	cca 3.0 mm, round

Until recently, 3D scans were colourised by overlapping with independently created colour photographs, but new models of scanners have integrated cameras, making the process of colorization automatic, and points inside the point cloud possess, beside spatial coordinates, also RGB parameters (in range from 0 to 255).

Surfaces not visible from the scanning direction, create missing parts, holes or shadows in the scan. For full 3D scanning, some objects are needed to be scanned from all sides, or from all necessary positions, so to be sure that all surfaces are included. Various types of referent points are used for aligning 3D scans (referent spheres, targets, or total station georeferenced points), but it is also possible to connect the scans with special software, without the use of any additional equipment.

Characteristics of the device used for scanning the Old Ironworks complex are given, according to the specification from the manufacturer, /13/, in Table 1.

3D field survey

The surveying location is rather demanding hence to the neglected and poorly maintained facilities over the years. Historical buildings are scattered in an area of approximately 300×300 m within the industrial complex of a larger surface and mixed with structures of a recent date. However, a linear path could have been formed connecting the old warehouse of coal, power plant, steel mill and power plant with gas generators, while the smiting workshop, as the largest facility, is spatially separated by production facilities. An additional problem while scanning is a very limited time for survey since the owners allowed two-day presence of heritage protection experts.

Based on the assessment, it is decided to undertake prompt and coordinated 3D scanning, Fig. 2. The selected scanning resolution was 11.1 Mpts with an angular network of 0.07°/pts and two minutes average time of a single scan. It was also decided, as the emphasis was on documenting the form and appearance of objects, not to perform colour scanning, but only basic infrared, while subsequently if necessary, the 3D scans could be colourised by independently made photographs.

As the plan for documenting also included metric survey, 3D scanning was used to get an overview of the complex and building measures. Furthermore, the 3D scan

Figure 2. Scanning of the workshop interior.

ning of facades, due to the characteristics of industrial buildings having exposed structural systems, enabled to quite accurately reconstruct the structural system even by using partial images of external surfaces. In this manner the warehouse of coal, the power plant and the steel mill were surveyed, while the power plant with gas generators, due to its considerable height could not be accessed without scaffolding or cranes, was scanned inside as well. For each positioning and merging of individual 3D scans, a set of 12 registration spheres with a diameter of 14.5 mm was used. This group of buildings within the complex of the Old Ironworks was scanned in the form of 50 individual scans for a duration of 10 working hours.

The most complex structure, the forge workshop, was scanned in the same way as the power plant with gas generators. The building is square shaped, occupying the area of 100×100 m^2, so its documentation started with outer scanning of all four facades, in order to obtain an accurate external base. Afterwards, the scanning took place inside the building which consisted of several rectangular rooms with different supporting systems. Many of these areas could not be accessed either because they were locked or due to time constraints. Therefore, a series of 3D scans was made diagonally through the facility, including however, all types of structural systems. A total of 34 individual scans were made and the scanning process lasted 5 hours. Scans merged into a group are shown in Fig. 3.

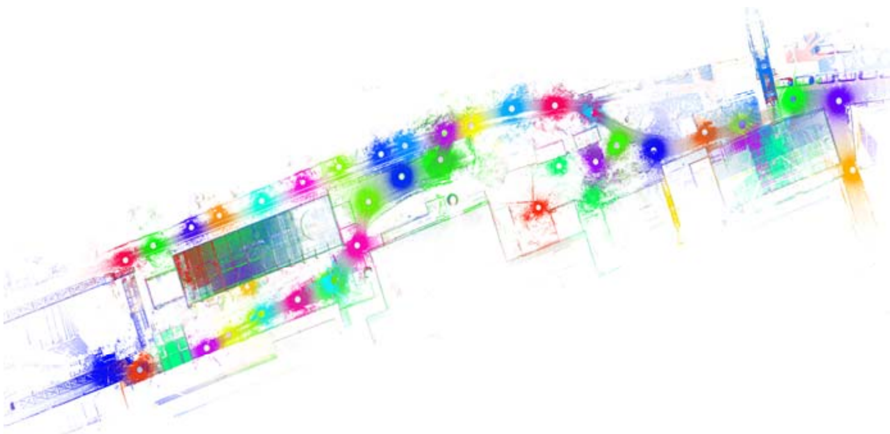

Figure 3. Scans merged into a group

All objects in the scanned area are built in skeleton systems of steel or composite concrete columns, with a variation of steel and wooden bar roof construction covered with steel sheet. Initially there is an opinion that metal surfaces can pose a difficulty, because they can scatter the laser beam. However, the sad fact that the buildings are poorly maintained for years, resulted in a covering layer of surface rust and dirt which can reflect a good intensity of the return laser beam and enabled fast pace scanning without the special preparation of metal surfaces. The biggest problem during the scanning process was the presence of high and medium vegetation around the objects, which had hidden some of the surfaces on the facades (most notably in the northwest facade of the forge workshop).

3D scan processing

Computer processing of 3D scans primarily included their automatic merging using common referent points (registration spheres) with software Scene 5.0. Based on that method, two groups of 3D scans are formed, a linear group composed of the warehouse of coal, power plant, steel mills and power plant with gas generator, and a second group of scans – the smiting workshop, with orthogonal connection error of less than 3 mm and angular error of less than 0.01°. The integrated models consisting of individual point clouds were transferred to specialized software JRC Reconstructor 2.0. In order to compensate the precision that was jeopardized by scanning speed, overlapping by using automated algorithms performed as an additional check, reduced the error to 2.5 mm.

Processing included the creation of orthophotos (without perspective shortening) of ground floors, facades and the characteristic vertical sections with colour obtained from the measured intensity value of the reflected infrared rays, necessary for obtaining the basis for producing the technical documentation. Orthophotos were made with the resolution of 6 pixels per cm, as shown in Fig. 4. The digital cross sections are made through the whole models, enabling easier drafting with CAD software. Since scans are made with relatively low resolution and are colourless, 3D models were lit by angular light, usually perpendicular to the horizontal plane, thus providing a clearer picture of protrusions and bumps of vertical surfaces. This eased reading and understanding of the structural systems on the orthophotos. Furthermore, the models are made with scalar colour values depending on the distance from the cutting plane in order to obtain a comprehensive perception of depth. Horizontal section through the 3D model of the workshop, with partial reconstruction of element positions, is given in Fig. 5.

From created plans, it is easy to read exact positions of all elements in the structural system of the building. Workshop hall is constructed as a skeleton system with transitional grid at around 7 m and a longitudinal grid at 6.5 m. The area of the hall is distributed at 12×13 fields; therewith the north transitional fields are merged in double raster. Eight different types of columns are scanned, in variation from steel trusses in the southeast segment, up to precast reinforced concrete rectangular columns and composite concrete columns with steel U profiles.

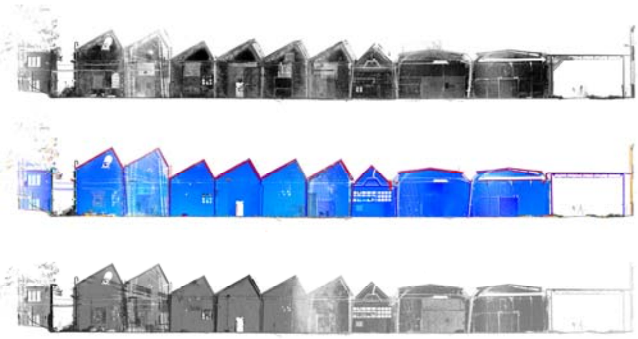

Figure 4. Orthophotos of northeast facade of Forge Workshop – model with infrared texture, range map, and side light.

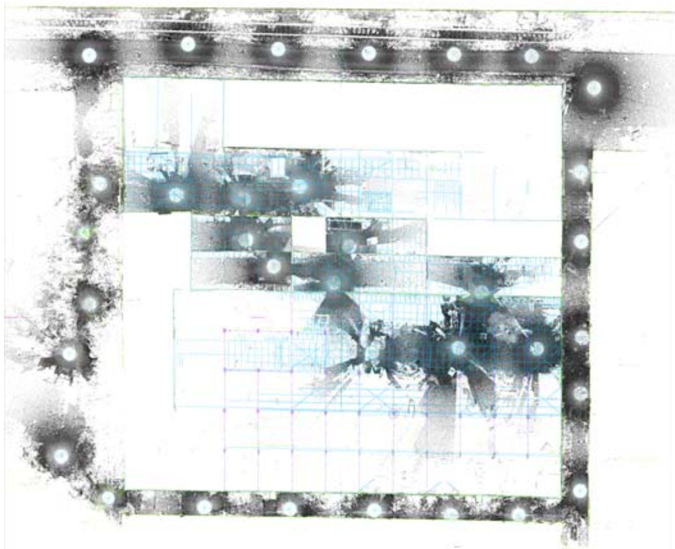

Figure 5. Horizontal section through 3D model of workshop, with a partial reconstruction of element positions.

Columns are designed in 2 heights; the southeast part with truss columns is taller and has larger inner height by 1.6 m. Roof construction is formed with triangle trusses from an L-shaped profile steel sheet. The middle segment is bridged with simple timber structure. Windows are positioned in the roof area, and in the northern part also formed are elevated roof light wells. On steel trusses installed are box section rafters with a span range from 1.1 to 1.5 m. Roof covering is in steel sheets, and dewatering is designed in the longitudinal direction with U shaped profile cladding, positioned at truss joints, above the columns. On roof slabs, in facades and at transversal axes of columns, vertical and horizontal bracings exist, formed from L-shaped profile steel sheet. The presence of bracing has not been observed at partition walls inside the hall, but it is assumed that they exist. On orthophotos and 3D scans an evident lack of longitudinal joint elements for columns is spotted, which implies a question of static equilibrium. It is possible that the columns are connected with the beam positioned above roof flutes, but generated sections show that there is not enough space for beam setting. It is assumed that the columns are connected with trusses trough rigid joints, and that the longitudinal connection is secured with adequate dimensioning of rafters. The only longitudinal connection is presented at the timber roof structure in the middle part. The variety in structural elements implies phase construction, or later adaptations in accordance with new spatial needs. Also, a lack of original build documentation creates a necessity of expert static analyses, which shall also determine and calculate potential risks for the structural system, and imply on weak spots.

APPLICATION

As the most urgent spot, the Forge Workshop 3D model emerged damaged, bended trusses in the middle part of the hall, Fig. 6. Present is a bending in the middle point on the longitudinal axis, and the same pattern (direction) of bending on all trusses is observed, just with different intensity. Deformations or displacements are not spotted on neighbouring vertical elements, and bending of the trusses is only in the horizontal plane, i.e. there is no deformation in relation with the vertical position of trusses' joints. Virtual reconstruction of truss shapes is given in Fig. 7. Thus it could be concluded that damage is not a consequence of disturbed static equilibrium, but it is an effect of outside sufficient force to bend the elements in the most sensitive direction, but not strong enough to disturb connections with columns. In this case, the most relevant cause is the movement of a certain machine, e.g. the crane carrier, which was fixed to middle points on trusses. Nevertheless, just this fact deserves a detailed investigation.

Figure 6. Photograph and 3D scan of bended trusses.

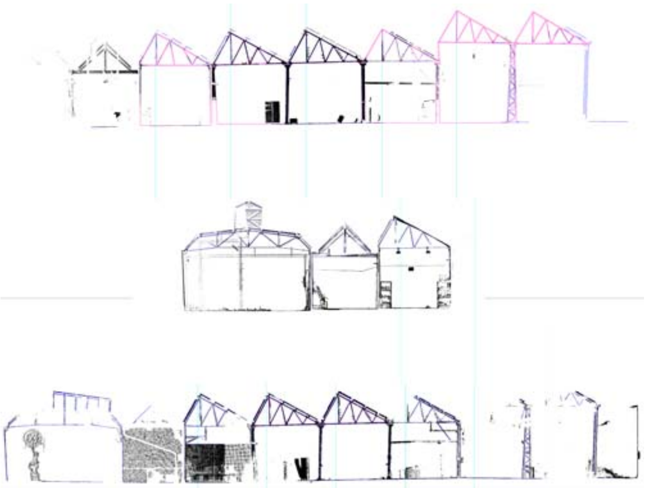

Figure 7. Virtual reconstruction of trusses shapes

Further analyses in the field of static stability of the building should include a recalculation of actual forces. The model geometry can be very easily converted from point cloud format into some more suitable for that job. It is possible to derive a detailed data of surfaces of all scanned structural elements with accordance that the larger part of the building is surveyed, so it is possible to reliably suppose positions of elements which are not scanned completely. Point cloud, as a file format, is not the most proper for static analyses, because it possesses too much information irrelevant for this process, but also because of surfaces in a point that does not have any orientation. All structural elements should be reduced to simple models which are used in static calculations. It is just necessary to identify all edges of elements, which imply a section shape, and guide in determining the central axis. This should result in a full 3D model of the structural system, which can be used for further processing and analyses. With identification of materials used in the building, it is possible to project actual loads that are present in the system. The biggest weakness in this model would be a lack of foundation information, the 3D laser scanning is a surface survey technique and it does not have the ability to penetrate into layers. However, even without this data, it is achievable to create a very realistic digital model of a building.

An important fact is the trustworthiness of the vertical orientation of scans. The used scanner possesses an integrated axis compensator which allows operation reliability in work and investigation. Verticality of the elements is possible to measure on orthophotos, because it is also a regularly oriented product. Setting vertical lines and measuring angles formed with elements, could define eventual eccentricity. At the Smiting workshop, measured angles of columns and ideal vertical lines are mostly small (around 0.02°), that could not be surely claimed to origin in movement of the elements, but are probably imperfections in the construction process.

CONCLUSION

Use of 3D laser scanners in documentation of buildings provides a lot of conveniences. Speed of documenting, achieved in this example, is not feasible with other techniques.

Also, the quantity of collected data additionally improves the quality of this method, because surveying of full environments provides a much more objective image including surfaces which could show their relevance only in detailed analysis, in contrast to the total station survey where documenting is only selected by characteristic points.

Creation of a realistic digital model gives a laboratory dimension to analyses in the field of protection of immovable heritage, it provides an investigation of the building without the presence on-site. The 3D model manipulation in CAD software makes available objective approach and precise analyses, due to the possibility of generating any necessary section, and seeing the model from any direction and angle.

Today we can find a variety of computer software, where it is possible to perform advanced analyses, e.g. static stability analyses in AxisVM software, /14/. It is certain that development of these diagnostic tools will continue, conditioning the input data, as e.g. building geometry in this case, to be more precise and detailed.

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