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June 23th - 26th, Belgrade, Serbia

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THE POSSIBILITIES OF APPLICATION OF 3D DIGITAL MODELS IN CULTURAL HERITAGE OBJECT PROTECTION AND RECONSTRUCTION

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ABSTRACT

Contemporary cultural heritage protection relies on precise technical documentation obtained by new technology accomplishments in the domain of 3D digital models. Both 3D models of the existing state of object and virtual ones are equally important in reconstruction and renewal processes. Accurate, textured and detailed 3D point cloud models of various objects, i.e. cultural heritage monuments, are outcomes of contemporary photogrammetric and laser scanning method application, aided by adequate software solutions. The authors presented procedures and results of terrestrial laser scanning and 3D modelling of a cultural heritage monument – the monastery church of the complex Kastaljan, located in the mountain region Kosmaj in Serbia.

The first part of presented research, concerning data acquisition, carried out using laser scanner and adequate software processing, resulted in 3D dense point cloud model and further 2D plan view along with characteristic cross sections. The possibilities of 3D model presentation, measurements and additional graphic operations were explored, through various software solutions aided by adequate technical support.

The second part of research elaborated on the reconstruction of the entire 3D model of the church in the complex Kastaljan, dated back to the 13th century, according to its architectural style characteristics.

Keywords: 3D digital documentation; laser scanning; 3D modelling; point cloud; cultural heritage monument; geometric analyses; 3D model visualisation

SUBJECT CODE: Applied Geometry and Graphics - Modelling of objects and processes

1. INTRODUCTION

Contemporary digital 3D models vary due to modelling techniques. According to one's needs and potentials the adequate technique should be chosen. Applications of 3D models are numerous and actual in different branches, e.g. industry, geodesy, civil engineering, architecture, cultural heritage protection, medicine, etc. During the last decade the development of laser scanning technology and photogrammetric software solutions turned the focus onto 3D point cloud models (Quattrini and Baleani, 2015, Srećković et al., 2015a, Bijelić and Krasić, 2012, Alonso and Choi, 2014). The outcomes of 3D point cloud modelling became significant source for design, construction, operations and maintenance, marketing and proposals, forensics, security planning, education and entertainment, civil infrastructure, plant and industrial applications, cultural heritage protection and archaeology. This research aims are in the area of cultural heritage protection and reconstruction, concerning the application of 3D point cloud models and additional 3D geometric models created in various software.

1.1. The importance of 3D documentation in cultural heritage protection

Three-dimensional digital model of an existing building plays several important roles in cultural heritage protection and reconstruction. The importance of cultural heritage documentation is unquestionable. Cultural heritage documentation has a short definition as follows: "recording of the existent state and surroundings of the building by reports, drawings and photographs" (Yilmaz et al., 2007). Although this definition implies all kind of documents concerning cultural heritage object, it can be said that contemporary digital 3D model is a source of such defined tasks. After 3D model analyses, the reports on building phases (layers of the building visible in 3D model), evaluation of deformation or destruction of the building or its parts can be made; characteristic views of 3D model can be transformed into 2D drawings (elevations, facades and sections); various 2D images can be obtained from the same source. Historical goals are also included through transfer of information to the future generations by historical media presentations, virtual museums and 3D model libraries (Polić Radovanović et al., 2010, Horošavin, 2010). Most of the goals share cultural heritage monuments planned for reconstruction process and the ones already being reconstructed (Boeykens et al., 2008, Dragović et al., 2015).

1.2. The methodologies for obtaining 3D point cloud model

Nowadays various surveying methods like tacheometry, photogrammetry and laser scanning can be used to obtain data necessary for 3D modelling of complex structures (Pejić, 2013). Depending on the nature of the engineering task, i.e. structure characteristics, sometimes several methods have to be combined for proper data acquisition (Obidowski, 2003, Altuntas et al., 2014). In comparison with tacheometric surveying, photogrammetric method and laser scanning result not only in pure geometric data (point coordinates), but also in RGB values (colours) of object points. In the case of laser scanning these values allocated to points are obtained using a digital camera integrated in a laser scanner system. The combination of geometric data and colours makes photogrammetry and laser scanning particularly suitable for deriving realistic 3D models of various structures and thus for use in the area of cultural heritage protection and reconstruction (Yastikli, 2007, Obidowski, 2003, Altuntas et al., 2014). In this case terrestrial (close-range) photogrammetry and terrestrial laser scanning (TLS) are used although both of these methods have their airborne variants as well: aerial photogrammetry and airborne laser scanning (Lasaponara et al., 2011, Srećković et al., 2015b). And while photogrammetry means obtaining point coordinates from photos of a structure, laser scanning features a procedure for obtaining point coordinates similar to that of tacheometric surveying (measuring angles and distances) but much faster. Nevertheless, both photogrammetry and laser scanning result in point clouds of similar density (Pejić, 2013). Data post-processing in both cases is quite time-consuming compared with field work and requires computers with high performances and specialized software. Workflow for getting everything out of nothing involves data collecting in the field (obtaining photos or laser scans), data post-processing (e.g. filtering, registration, etc.), 3D modelling using adequate software and finally geometric analysis of a structure (Entwistle et al., 2009).

In this paper the procedure of obtaining architectural documentation from terrestrial laser scanning data aided by photographs is presented. The case study was the monastery church of the complex Kastaljan near Belgrade.

2. TERRESTRIAL LASER SCANNING PROCEDURE

Terrestrial laser scanning as a method for mass data acquisition collects geometric information on an object by measuring angles and distances towards object points. The result of terrestrial laser scanning is a point cloud consisting of a huge number of points. For each individual point in a point cloud its coordinates (X, Y and Z) and the intensity of the reflected laser beam are stored in the instruments' memory. More sophisticated scanning systems record mentioned RGB values of points using an integrated digital camera. Modern scanners enable gathering millions of points in just a few minutes. This means that a powerful computer with specialized software is needed in order to process the obtained data.

Complex structure such as cultural heritage complex can never be scanned from one station point due to its geometry (shape and dimensions). This means that during scanning of one such structure several point clouds are obtained and they have to be registered, i.e. transformed to a common coordinate system. Registration is followed by various manipulations with point clouds, depending on the type of required deliverables. Sometimes the whole process ends with a point cloud, while in other cases a mesh (triangulated irregular network – TIN) model or a 3D model based on geometric primitives and/or parametric surfaces is created. But often different 2D drawings like plan view, cross-sections or facades are created as well, especially when quality architectural documentation is supposed to be the final result of a structure scanning.

3. THE FIELD WORK

3.1. Historical background of the monastery complex Kastaljan

During medieval period on Serbian territory (from the 7th to the 14th century) numerous sacral complexes were built being cultural, political, educational and spiritual centres of the country. Those were monasteries whose characteristic architectural concepts implied space bounded with walls, where the central building was the church. The other buildings (living quarters and refectory) leaned up against the outer walls. Often the building process was divided into phases through the time. One such complex was built on the eastern slope of the mountain Kosmaj in the village Nemenikuće. The complex on the site Kastaljan represents a cultural heritage of the exceptional worth, especially regarding studies concerning the lifestyle in medieval Serbia during Stefan Lazarević's ruling (Marjanović-Vujović, 1969). Archaeological diggings from 1968 to 1970 have shown three characteristic parts of the complex: the church dedicated to St. George (dated back in the 13th century), living quarters for the monks (built in the 15th century) and a residential part (summer residence) of the dynasty ruler Stefan Lazarević (Fig. 1).

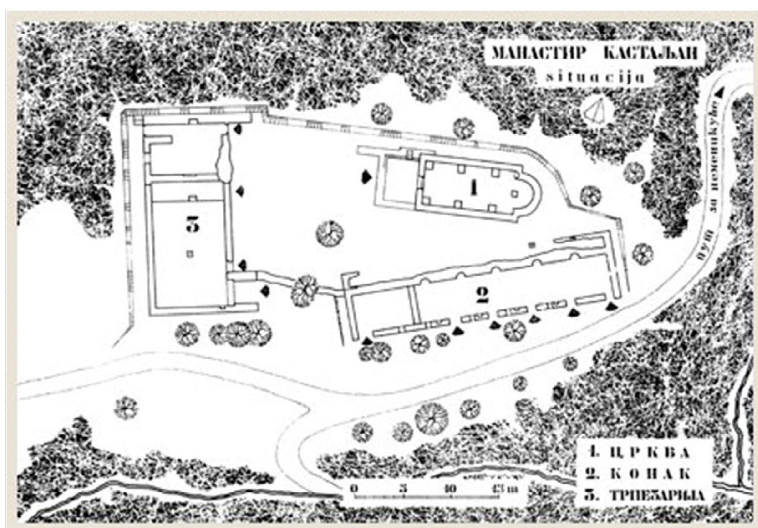


Figure 1: Site plan of the monastery complex Kastaljan: 1-church, 2-living quarters, 3-summer residence (Source: http://beogradskonasledje.rs/kd/zavod/sopot/manastir-kastaljan.html, accessed: 10th March 2016)

The church was probably built in the 13th century, during the ruling time of the king Dragutin, on the foundations of the ancient Roman castrum (2nd or 3rd century). It was renewed by Stefan Lazarević in the 15th century when the dome was added. After the Ottoman invasion on the Serbian territory in the 17th century, the complex was severely damaged. The remains of the church, whose dimensions are 12.5 m × 6 m, were analyzed and sorted in the Rasian (orig. Raška) architectural style group (Marjanović-Vujović, 1969).

Unfortunately the monastery complex is in the state of ruins waiting to be renewed. Since the people in the surroundings and Serbian church organization have intention of rebuilding the monument, some activities were started around 1980 in the direction of providing adequate documentation of the current state of the monument (geodetic surveying, architectural drawings, etc.).

3.2. Terrestrial laser scanning of the monastery church of the complex Kastaljan

The church of the monastery complex Kastaljan was scanned in December 2015 by the team of professors and students of the Faculty of Civil Engineering in Belgrade. Previous documentation on this site was available in the form of architectural drawings with measurements obtained manually in the field by the experts of the Cultural Heritage Protection Institute of the City of Belgrade.

Many terrestrial laser scanners significantly varying in characteristics are available on the market today, Riegl VZ-400i, FARO Focus3D X 330 HDR, Trimble TX8, Leica ScanStation P40, just to mention a few. In the case of Kastaljan scanning was conducted using the terrestrial laser scanner Leica ScanStation P20 which features a scan rate of up to one million points per second (Leica Geosystems, 2013). The accuracy of 3D position of a single point in a point cloud is 3 mm at the distance of 50 m. Leica ScanStation P20 field of view is 360° × 270° in the horizontal and vertical plane respectively, while it operates in the range from 0.4 m to 120 m. This scanner has an integrated 5 Mp digital camera which enables collecting 17° × 17° colour images of a scanned object for its better visualization. In this experiment the 20.2 Mp digital camera Canon EOS 6D with the lens Canon EF 24-105mm f/4L was also used since it gives more realistic images regarding colours than the scanner camera.

Because of the terrain configuration and church geometry, scanning from six different station points was needed in order to fully cover all parts of the church. Two station points were inside the church and others were outside (Fig. 2).

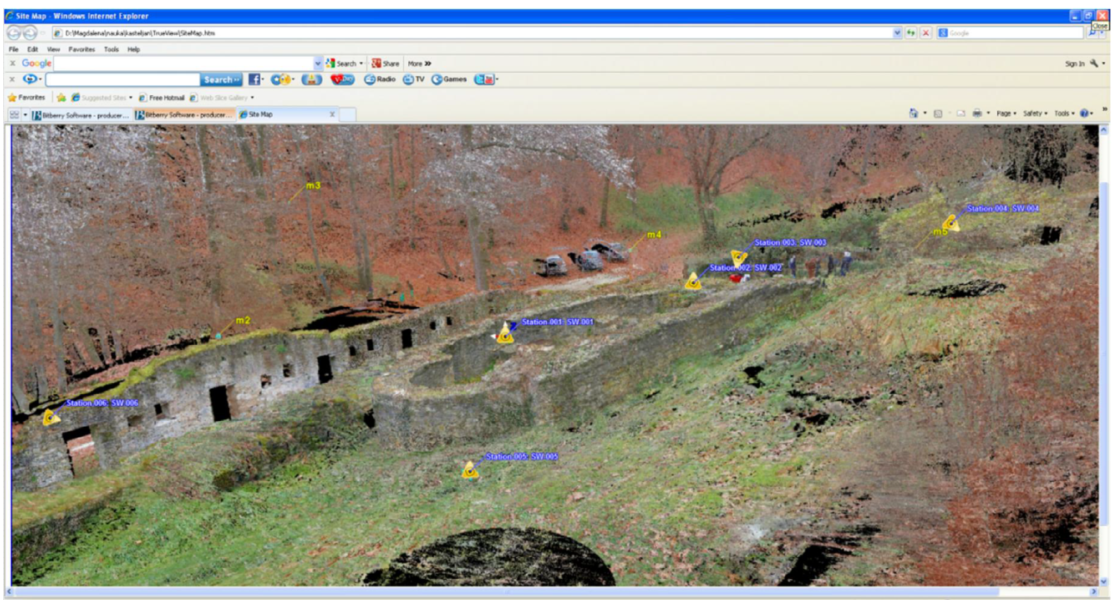


Figure 2: Site map – disposition of scan station points and targets in the field – yellow triangles represent station points, m2-m5 represent targets (targets m1 and m6 are not visible here). Point cloud presentation in Leica TruView via Internet Explorer

Additionally, six targets were placed in the church surroundings (Fig. 2). These targets were used in transforming different point clouds to a common coordinate system through the process of point cloud registration. Although two targets present in two point clouds are theoretically sufficient for their successful registration when the scanner is equipped with a dual axis compensator, more targets were used in this case in order to achieve better spatial coverage of the scene and consequently better registration results.

In this project the point cloud of the monastery church was used for extracting various geometric pieces of information necessary for its 3D architectural modelling. Since scanning was done from six different station points and consequently six point clouds of different parts of the church were obtained, point cloud unification and resampling had to be done in order to obtain uniform point spacing. After unifying six point clouds into one and resampling the resulting point cloud to point spacing of 3 cm, a slightly more than two million points were maintained.

4. MODELLING OF THE MONASTERY CHURCH

3D digital models presenting both current state of the monument and its future design are tightly connected and mutually dependant. However, these models demand almost opposite approach, meaning various modelling methods and procedures. The first one, concerning current state of a monument, relies on collecting of geometric information about existing parts of a devastated historical object carried out by TLS procedure. The other one, which is a matter of creative (reconstruction) designing process in engineering software, relies on previous knowledge, i.e. studies of similar cases from the references and the assumption of non existing parts of the hole.

4.1. Processing and visualization of the scan data

Leica Cyclone software package possesses tools for point cloud registration and filtering, creating meshes and 3D models of objects (Leica Geosystems, 2016a), etc. But in this case it was used only for scan registration. Namely, point clouds obtained from six different station points were imported into Leica Cyclone and registered using targets placed throughout the scene. Leica also delivers plug-in software for AutoCAD called Leica CloudWorx for AutoCAD. It provides users with the opportunity to efficiently visualize and process large point cloud data sets within the familiar AutoCAD environment (Leica Geosystems, 2016b). Point clouds registered in Cyclone were imported into CloudWorx where the plan view of the church was created, as well as the series of its cross-sectional views. These views enabled creating 2D drawings from which the geometric data necessary for further 3D modelling of the church were collected (dimensions in the first place).

One of the possible solutions for the efficient visualization of scan data is Leica TruView software. This is free software that operates within an internet browser. It uses high resolution images and true colour point clouds to give a user the impression as if he/she was standing in exactly the same place where the laser scanner was stationed (Leica Geosystems, 2014). This panoramic point cloud viewer enables gathering instant geometric pieces of information through various measurements and markups made within the point cloud. One such panoramic presentation of a part of the church with the acquired measurements is shown in Fig. 3.

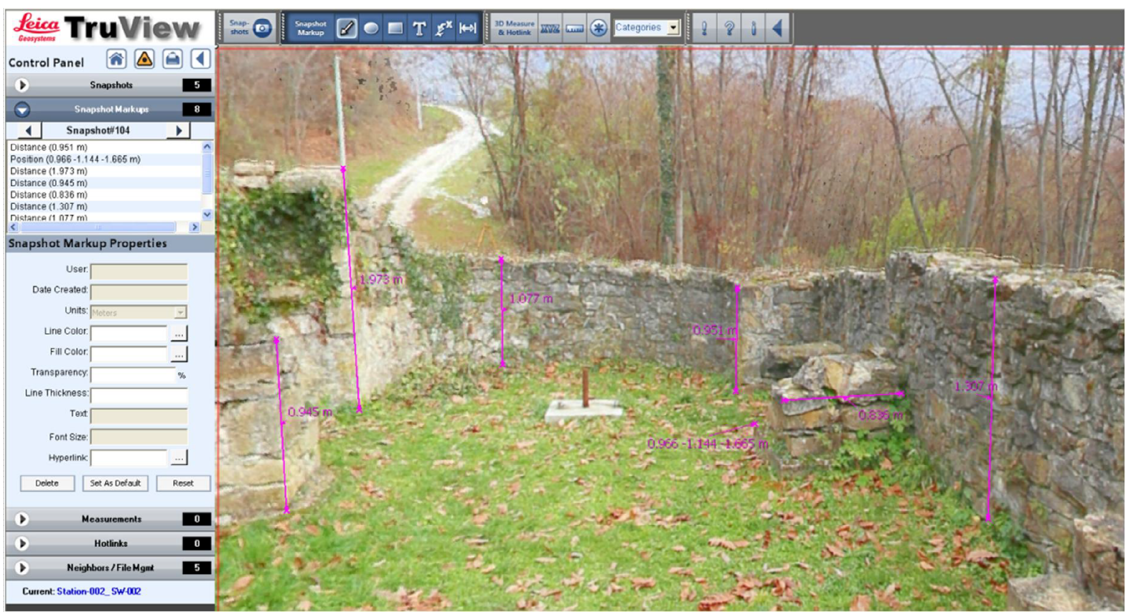


Figure 3: Panoramic point cloud 3D presentation with measurements of the interior of the monastery church

4.2. 3D digital model of the monastery church – architectural concept

Post-processing of the point cloud enabled further steps in creating of an architectural concept for the monument revival. 2D image of the plan view, imported in AutoCAD software, served for precise dimensioning of 2D floor plan drawing (Fig. 4). The results of some manual measurements provided *in situ* were confirmed by the dimensions obtained from point cloud deliverables.

Present architectural one-nave concept of the church is "inscribed cross" shaped with six accented pilasters, which have a supporting role. Severely ruined narthex leaned on the cross shaped church nave. Longitudinal direction was probably spanned by cylindrical vault, while the central dome, with tambour above the regular quadrilateral central space, leaned on four central pilasters. Semicircular big apse is a logical extension of the nave.

Deviations of the outer walls from the orthogonal concept are not significant (up to 2^o), as well as the ones of the semicircular apse. Such regularity is rare regarding building techniques of the medieval monuments (Nenadović, 2003).

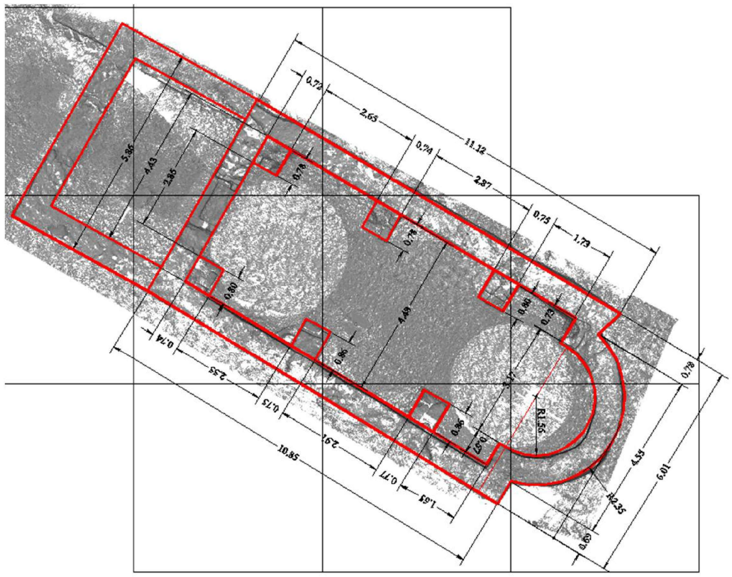


Figure 4: Auto CAD drawing of the floor plan of the church with dimensions

Solid model geometry of the church emerged from the point cloud data in 3D environment of ARCHICAD software (Fig. 5). The authors chose the methodology where 3D architectural conceptual model should be obtained as a result of interaction between interior and exterior models of the church building.

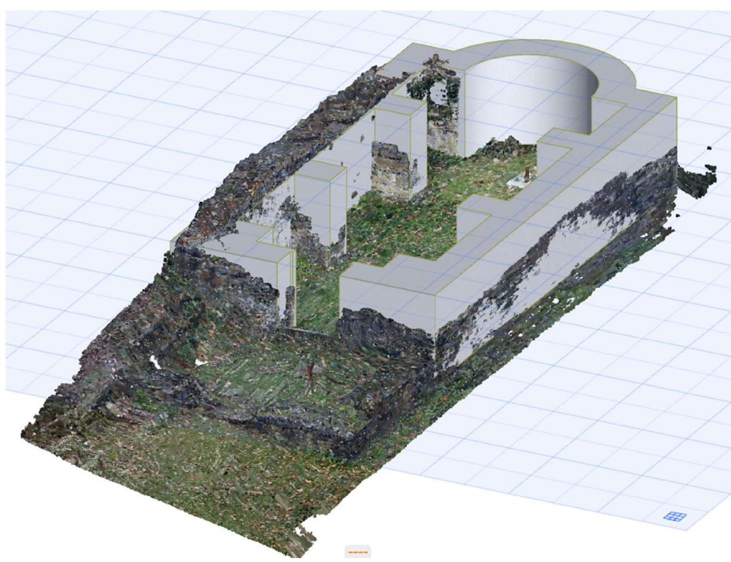


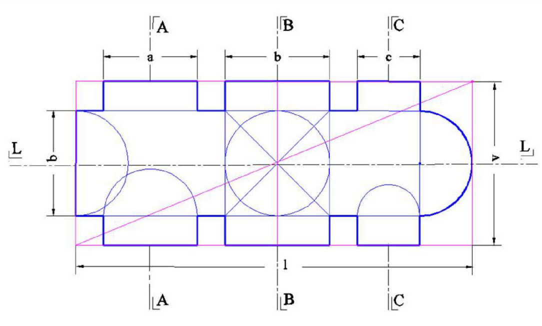
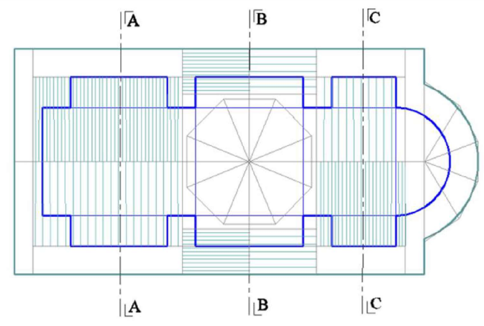
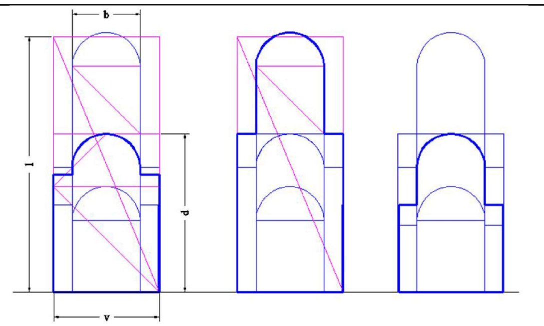
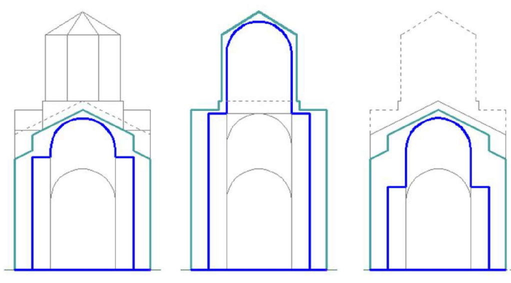
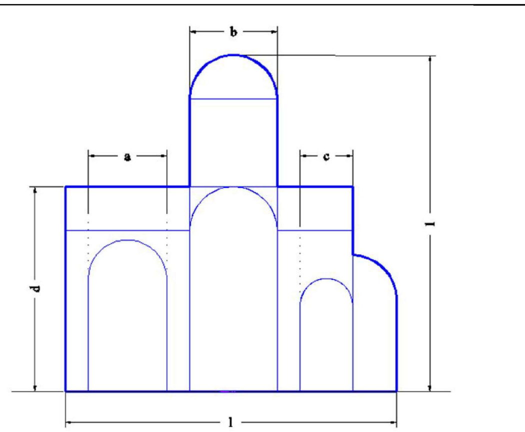
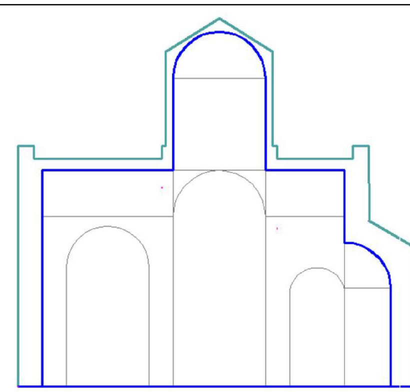
Figure 5: Virtual 3D object arisen from 3D point cloud

Prior investigations on architectural style group and adoption of geometric criteria for the architectural object concept were necessary for the creation of its 3D interior space model (Vasov et al., 2014). Mutual relations of geometric elements in Serbian medieval architecture where thoroughly studied by Nenadović (2003) and Radujko (2006) where valuable information on proportions for the monument's revitalization and restoration purposes were found. 3D point cloud model of the church remains offered clear and reliable information on the geometry of the floor plan, considering the wall remains, while the corpus of the building was a matter of discussion and assumptions regarding the architectural style group and building period characteristics.

4.2.1. Prior analysis of the architectural interior and exterior concept

Before proportional analysis the floor plan of the church was adjusted to the idealized horizontal rectangular grid (Vasov et al., 2014). The narthex, a common element in architectural concept of a church, often added in postponed building phase, was intentionally left out of consideration (e.g. monasteries Pavlovac, Trška, Davidovica, etc.). In order to achieve the integrity of the architectural concept, the authors brought such decision. The proportional scheme revealed mutual relations of three aisles a:b:c=3:3.3:2 and width/length v:l=1:2.43 of the interior space. The assumed proportions of the idealized vertical plan (cross sections A-A, B-B, C-C) were conducted by the l, v, b - values taken over from the horizontal plan. Hence, d=1.5v was chosen (Table 1).

Table 1: Parallel overview of two architectural concepts – interior and exterior

	a) INTERIOR CONCEPT OF THE CHURCH	b) EXTERIOR CONCEPT OF THE CHURCH
PLAN VIEW		
TRANSVERSE SECTIONS		
LONGITUDINAL SECTION		

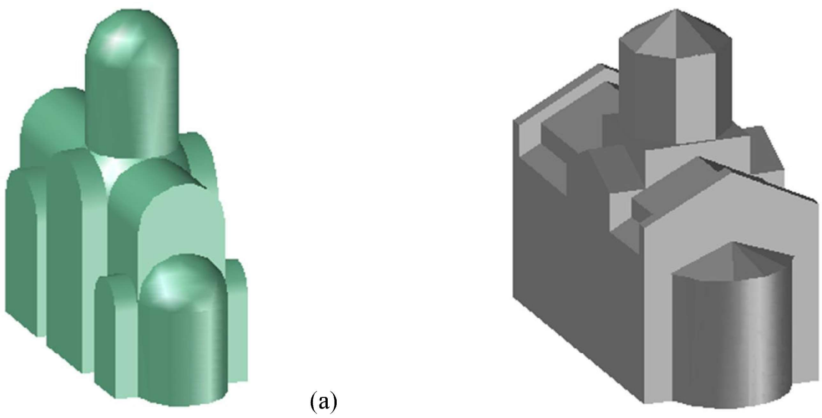
The exterior concept of the church was composed in compliance to its interior. Gable roofing above two aisles of the church nave and transept, cubical pedestal and octagonal tambour above the central dome arose from the floor plan, chosen geometry of cross sections and medieval geometric standards (Nenadović, 2003).

4.2.2 Modelling procedures for conceptual 3D model creation

The main characteristic of medieval architectural forms is that dominant geometric shapes of the interior structure are cylindrical and spherical (Fig. 6(a)), while the most of the elements which exterior structure consists of are prismatic (Fig. 6(b)). Particular elements of both complex structures are separately modelled as solid models and positioned on adequate elevation. The union of partial elements resulted in two characteristic models: interior and exterior 3D models of the church.

Three vaulted alcoves varying in dimensions lean on the dominant central vaulted space. Semi-spherical element above central isle, cut with four vertical planes, represents the substructure for final pendentives. Cylindrical tambour with calotte above it, reaches the highest point of the central inner space. Half cylindrical apse is the ending element along the major axis of the interior model. The modelling procedures rely on extruding of characteristic profiles (in vertical planes) or creation of geometric primitives cut with adequate planes (Fig. 6(a)).

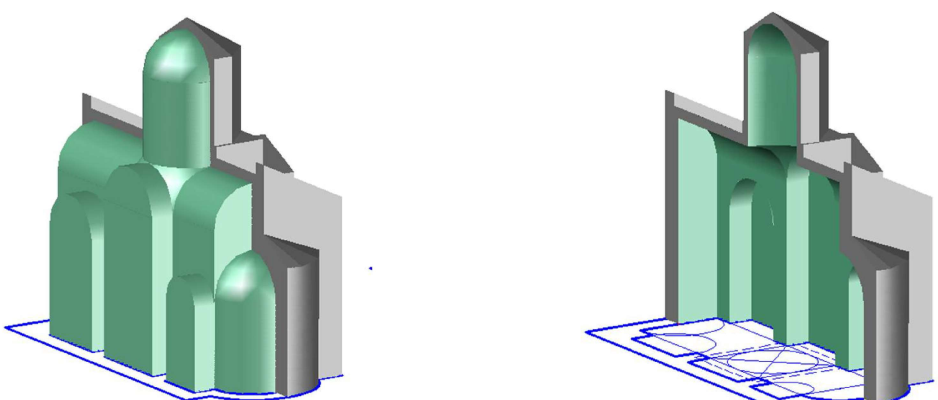
The main corpus of the exterior 3D model is defined by its transverse cross sections of the first and third isle (sections A-A and C-C). The east and west facade walls have simplified version of this geometry. The same logic is followed concerning the transept creation (the central extension of the side facades). The cubical pedestal and dome structure are designed as regular prismatic shapes (four and eight sided) with pyramidal ending (Fig. 6(b)).



(a) (b)

Figure 6: The two conceptual 3D models of the church - interior model (a) and exterior model (b)

The final – conceptual 3D model of the church was obtained by subtracting the interior space model from the exterior model. For the presentation purposes of the final modelling results, longitudinal cutting plane was set along the major axis of the church (Fig. 7).



(a) (b)

Figure 7: Final phases of conceptual 3D church model: two models interfering (a) and subtracted model (b)

5. CONCLUSION

This research merged some of the consecutive phases in the workflow of cultural heritage monument protection and revitalization which characterize 3D digital modelling. The first phase is collecting of 3D data by terrestrial laser scanning, while the second phase involves creating architectural documentation of the existing state of the monument and 3D virtual model (architectural concept proposal) of the renewed monument based on the collected 3D data. Although it is not rare nowadays for a point cloud itself to be considered a final TLS product, in this project it served as a basis for extracting various geometric pieces of information necessary for 3D architectural modelling of the monastery church.

The result of TLS was detailed 3D point cloud (with its deliverables) of the monastery church of the complex Kastaljan. 3D virtual model of the renewed church inside the complex Kastaljan based on this point cloud consists of two conceptual geometric models representing interior and exterior architectural forms.

Here applied methodology for creation of 3D models, where two complex structures of the church exterior and interior mutually interact, has shown time efficiency and reliability in prior analyses for architectural design proposal. The possibility of fitting the 3D virtual model into 3D point cloud model in compatible software solutions enabled one more check point in defining the final design proposal of the restored monument.

Further investigations may consider possible variations of the exterior model: designing of the roof surfaces (e.g. curved shapes), tambour (e.g. cylindrical surface), or gable (e.g. curved ending of the wall), which strongly depend on authors' experience in reconstruction and revitalization of medieval Serbian monuments, reliable historical information and knowledge.

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