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INFORMATION MODELING FOR CULTURAL PRESERVATION: PORTICO OF THE NEW HERMITAGE AND ATLAS SCULPTURES. PART 2. METHODS AND ALGORITHMS

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This article presents the results of interaction between SPbPU and the State Hermitage in a promising direction of using the latest achievements in the field of information technology in solving problems of preserving cultural heritage, using the example of information modeling of the Portico of the New Hermitage building and Atlas sculptures based on laser scanning data. This part of the work presents the results of the development of digital technologies for solving urgent problems of preserving cultural heritage objects. One of the main symbols of St. Petersburg, the Portico of the New Hermitage building, was chosen as the object of testing the technique. The authors present the developed methodology for collecting and processing spatial data about the elements of a cultural heritage object to build an adequate digital model of the object based on appropriate digital technologies. The following results of the technique approbation are analyzed: creation of a hybrid points cloud of Portico as the basis for the formation of an information model; creation of high-precision models of Portico Atlas sculptures based on point clouds; creation of a parametric families library of the Portico individual elements; creation of the Portico informational model; creation of a finite element model of the main elements of the Portico for stress analysis. The approbation showed the robustness of the proposed method.

Keywords: digital model, BIM, HBIM, laser scanning, cultural heritage, Historical Building Information Modeling, Hermitage, photogrammetry.

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ИНФОРМАЦИОННОЕ МОДЕЛИРОВАНИЕ ДЛЯ СОХРАНЕНИЯ КУЛЬТУРНОГО НАСЛЕДИЯ: ПОРТИК ЗДАНИЯ НОВОГО ЭРМИТАЖА И СКУЛЬПТУРЫ АТЛАНТОВ. ЧАСТЬ 2. МЕТОДЫ И АЛГОРИТМЫ

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В статье представлены результаты взаимодействия СПбПУ и Государственного Эрмитажа в перспективном направлении использования последних достижений в области информационных технологий при решении задач сохранения культурного наследия, на примере информационного моделирования портика здания Нового Эрмитажа и скульптур атлантов на основе данных лазерного сканирования. В данной части статьи описаны результаты разработки цифровых технологий решения актуальных задач по сохранению объектов культурного наследия. В качестве объекта апробации методики выбран один из главных символов Санкт-Петербурга – портик здания Нового Эрмитажа. Представлена разработанная методика сбора и обработки пространственных данных об элементах объекта культурного наследия для построения адекватной цифровой модели объекта на основе соответствующих цифровых технологий. Проанализированы следующие результаты апробации методики: создание гибридного облака точек портика в качестве основы формирования информационной модели; создание высокоточных моделей скульптур атлантов портика на основе облака точек; создание библиотеки параметрических семейств отдельных элементов портика; создание информационной модели портика; создание конечно-элементной модели основных элементов портика для проведения анализа напряжений. Апробация показала робастность предложенной методики.

Ключевые слова: цифровые модели, BIM, HBIM, лазерное сканирование, культурное наследие, информационное моделирование, Эрмитаж, фотограмметрия.

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Introduction

The application of BIM technology to historical buildings and cultural heritage sites in the world is called HBIM (from the English Historical / Heritage Building Information Modeling) [1]. Information modeling of existing buildings, structures and other objects of historical and cultural value begins with obtaining high-precision non-destructive remote sensing geometry of the object [2, 3]. When choosing adequate survey methods, it is the accuracy that plays a decisive role, since the reliability of the model and the degree of its applicability depend on it [4, 5]. In practice, the following shooting methods have successfully proven themselves: laser scanning, digital photogrammetry technology and high-precision 3D scanning [6]. Each method has its own indicators of accuracy, features and limits of applicability [7]. Laser scanning (LS) is the most modern and actively developing type of remote sensing (RS) [8]. The drug belongs to the active remote sensing method [9]. The principle of operation of laser scanners, regardless of their type and purpose, is based on measuring the distance from a laser pulse source to an object [10]. The laser beam leaving the emitter is reflected from the surface of the examined object. The reflected signal enters the scanner's receiver, where the required distance is determined by the time delay (pulse method) or phase shift (phase method) between the emitted and reflected signal [11]. Typically, the laser scan results in a point cloud containing 3D coordinates of the points and the intensity of reflected signal. Currently, modern technologies allow points in this cloud to store information about the color, we will call such clouds hybrid [5]. Point clouds can be obtained not only using direct measurements, but also by calculating distances from images using special algorithms. This technique is called digital photogrammetry, which uses overlapping 2D images to create a 3D point cloud. Combining images and converting them to the cloud takes place automatically. Shooting can be carried out with a hand-held camera or from an unmanned aerial vehicle (UAV). On the basis of hand-held images, high-precision reconstruction of the full-size texture of the surfaces of interior rooms [12], complete reconstruction of the internal geometry of rooms [13, 14], as well as small three-dimensional objects outside the scanner's field of view [15] is possible. UAV photographs are used to photograph the roofs and facades of relatively tall buildings, where a person cannot go with cameras or scanners [16]. Most often, photogrammetric point clouds are used in conjunction with the results of laser scanning [17]. In addition, high-precision 3D scanners based on laser triangulation technology are used for small architectural forms and sculptures, which a ground laser scanner is not capable of capturing in high resolution and full volume [18].

HBIM serves as a universal platform for storing and sharing information about the current state of a structure. Defects that are inherent in any cultural heritage object are included in the model by adaptive components that are linked to the corresponding elements. An adaptive component has a value parameter representing what it is: mold, destruction, crack, etc. Further, the component has its own color, depending on what it is, and the legend gives a decoding of the color designation [19]. Most defects, such as discoloration, a loose element, or a crack, are easy to detect visually. However, there are defects that require special instruments and algorithms to be detected. For example, the following methods are used to determine the moisture content of a material:

- Contact method: a high-precision moisture meter is applied to the object evaluating the moisture content in it. The readings are recorded and a map of the distribution of moisture values over the surface is built. The map is superimposed on the corresponding surface to obtain a visual picture of potentially hazardous areas where the water content in the material exceeds the average permissible value [20].
- Non-contact method: the intensity value of the cloud points obtained as a result of laser scanning is processed according to an algorithm that shifts the values with respect to the histogram, and as a result a moisture parameter is assigned to each point [21].

Remote sensing and room modeling techniques are proving to be extremely useful in surveying and reconstructing buildings after natural disasters [22]. HBIM is also the basis for all kinds of simulations: finite element analysis of structures, determination of the risk of collapse under conditions of an earthquake, deformations and other influences [23], heat engineering calculation and verification of insolation norms. In addition, HBIM can act as a basis for the development of a project for the reconstruction of an object and a repository of all historical and up-to-date documentation in all possible forms: from written sketches to drawings [24]. Designing utility systems in historic buildings is a particularly complex task that requires a modern approach. Digital information modeling technologies allow capturing the current state of networks and designing new ones, avoiding collisions [25]. Over the past decade, virtual and augmented reality technologies have become very popular and widely available, and specialists around the world have learned to apply them in their fields. In the field of preserving cultural heritage, technology allows not only to service buildings more efficiently, but also to provide tourists with expanded opportunities for visiting and studying monuments [26]. HBIM can be used to organize virtual tours through the VR platform. The user has the ability to move around the model, inspect it, interact with its elements, receive relevant and historical information [27] and enter rooms that are physically closed to visitors. VR even helps engineers in building maintenance, as it makes it possible to accurately understand the situation without leaving the office and to plan work as efficiently as possible [28]. This technology can be used in the field of education of specialists, historians and restorers [29].

This paper explores the possibilities of using modern digital technologies in relation to the preservation of a cultural heritage site, one of the main symbols of St. Petersburg: the Portico of the New Hermitage building.

This study has the following objectives:

- to develop a methodology for collecting and processing spatial data for cultural heritage sites using digital technologies;
- to create a resulting hybrid points cloud of Portico to preserve the object of cultural heritage;
- to create high-precision models of Atlas sculptures based on the data obtained;
- to create a library of parametric families of individual elements of the Portico;
- to create an information model of the Portico;
- to create a finite element model of the main elements of the Portico;
- to analyze the deformations of the main elements of the Portico caused by their own weight.

Materials and methods

In general, the developed methodology for cultural heritage objects (Fig. 1) includes a collection of spatial data reflecting the up-to-date geometry of the Portico elements (1), their processing (2), creation of an information model based on the processed data (3) and modeling of processes and phenomena at the facility, including finite element analysis of the elements (4).

Depending on the type of analysis carried out, different requirements are imposed on the level of elaboration of the HBIM and its individual elements. For example, when calculating insolation, there is no need for full compliance of the model geometry with its real state, and an assessment of the cultural heritage object VAT, on the contrary, requires an accurate model of the object. Taking into account the fact that HBIM is created from elements obtained on the basis of point clouds, it is possible to formulate certain quantitative requirements for the data obtained in the course of the study (Table 1).

Table 1

Quantitative requirements

Data Type	Element	Quantitative requirements
Point clouds	Complex architectural forms	Density $\geq 10^6$ dots/ m^2, % blind spots $\leq$ 10 %
	Metal constructions	Density $\geq 10^4$ dots/ m^2, % blind spots $\leq$ 70 %
	Reinforced concrete structures	Density $\geq 10^2$ dots/ m^2, % blind spots $\leq$ 50 %
	Basic dimensional elements (walls, floors)	Density $\geq$ 5 dots/ m^2, % blind spots $\leq$ 50 %
NURBS surfaces	Basic dimensional elements (walls, floors)	Number of splines $\geq$ 5, spline density $\geq$ 1 vertices/ m^2
Meshes	Complex architectural forms	Number of polygons ~ 1/3 on the number of points
Revit families	Replicated elements (windows, doors)	Number of parameters $\geq$ 2
HBIM	Model granularity	LOD100 – LOD500

In addition to the listed requirements, there may also be additional requirements for the semantic classification of point clouds and for the geographic referencing of data. Polygonal models can be subject to requirements for the absence of topology artifacts (double vertices, incorrectly oriented polygons, missing polygons) and for topology optimization (retopology).

Data collection. Depending on the requirements for the initial data, data collection can be carried out using terrestrial, mobile or aerial LiDAR systems. Individual elements can be captured using close range photogrammetry, or high-resolution 3D scanning systems based on LiDAR or stereo cameras. To improve accuracy and data binding, GCPs are surveyed with a total station or GNSS receiver.

Data processing. After completing all field measurements, independent datasets of laser scanning, photogrammetric surveys and additional control measurements are formed. They are then converted to point clouds and control point coordinates. As a result of this conversion, irregular data arrays with different spatial density are obtained, containing hundreds of millions of laser reflection points, including the so-called “false” reflections resulting from the reflection of a laser beam from the surface of water, mirrors, etc., as well as unwanted points reflected from foreign objects in the scanning area. To simplify further work with such clouds, as well as to ensure fast data transfer between all project participants, it is necessary to reduce the number and density of points and eliminate unwanted points. Therefore, various algorithms for filtering and thinning point clouds are used based on the open PCL library [30]. Each dataset is processed

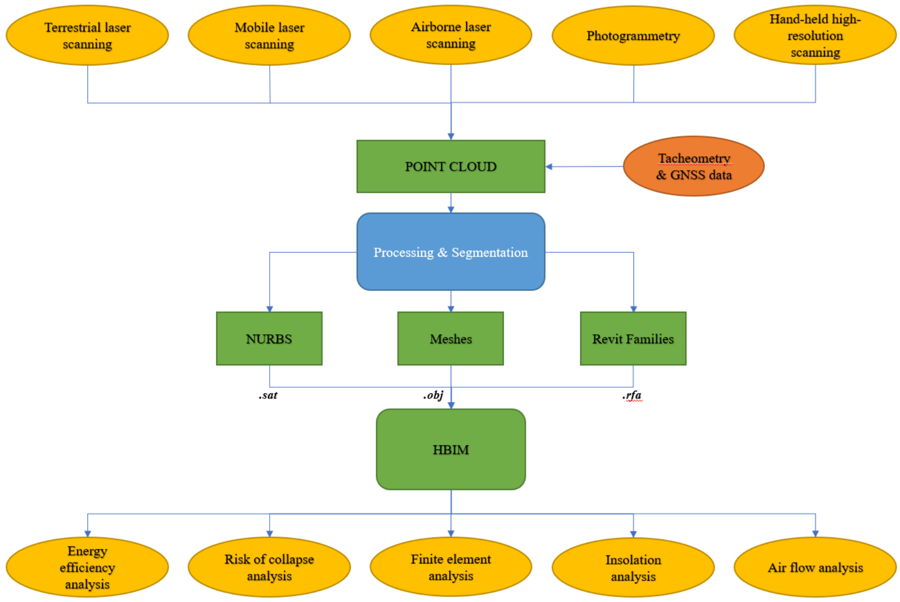

Fig. 1. Block diagram of the developed technique

independently of each other, then the resulting point cloud is formed to reduce blind spots. For the convenience of further work, segmentation of individual elements from the cloud is performed.

BIM. The most common cultural heritage information modeling (HBIM) software is Autodesk Revit [31]. Information Modeling in Revit uses system and user-defined families. System families create features such as walls and floors and cannot be modified, but you can customize the layer structure and settings. Their main disadvantage in a BIM context is regular geometry. However, this disadvantage can be partially eliminated due to the possibility of creating system families based on NURBS surfaces. Custom families create elements such as columns, beams, facade decorative elements, etc. Despite the greater flexibility of modeling compared to system families, their main disadvantage is also the regularity of the geometry. However, this problem also has a solution: for elements of complex shapes, it is possible to create families based on imported polygonal models. Thus, using the basic principles of Revit, a model is created that reflects the actual geometry of the object under study. HBIM includes not only geometry, but also information about materials obtained by instrumental methods, as well as the necessary documentation, results of energy efficiency calculations, structural analysis, etc. Documentation and the formation of the results of various calculations are performed using standard Revit tools, depending on the requirements for a specific project. The resulting model is a database of the object, containing all the available information and is the basis for planning and carrying out future work, as well as for creating a digital twin of the object.

Analysis. On the basis of the resulting information model of the cultural heritage object, various types of analysis are carried out, including analysis of the energy efficiency of a building, analysis of the stress-strain state of an object, modeling of air flows, calculation of insolation, and so on. The use of the information model as a basis for certain calculations is ensured due to the compatibility of the computational software systems with the three-dimensional geometry of which HBIM consists.

Results

To obtain accurate results, fully reflecting the actual geometry of the Portico elements, we performed laser scanning of the object and digital photogrammetric photography of its individual sections. Terrestrial laser scanning was carried out using a Leica BLK 360 laser scanner, which was controlled using an iPad Pro tablet. The scanning accuracy was 4 mm.

The survey was carried out in 2 stages. At the first stage, the main elements of the Portico were scanned, but as a result of the analysis of the data obtained, blind spots were identified in the narrow spaces between the columns and sculptures, as well as in the upper parts of the sculptures. To eliminate the identified blind spots, an additional stage of surveys was carried out using digital photogrammetric photography. Photogrammetric shooting was carried out using Nikon D610.

The processing of the received data begins with bringing individual scans to a common coordinate system. Registration was performed in the local coordinate system using paper stamps in Cyclone Register 360 software. The number of points after registration was about 200 million. For further processing, it is necessary to optimize the number of laser reflection points. In doing so, it is also necessary to maintain a high density of points related to the sculptures. For this, the points related to the Atlas sculptures were segmented from a common cloud. Then, the rest of the cloud was optimized, so that the distance between adjacent points was 5 mm. Then the points were filtered to improve their decoding properties and reduce noise. The data was filtered using the SOR algorithm. Next, the remaining noise was removed based on the TLO roughness parameter. To automate data preprocessing, the command line mode of the CloudCompare software was used. Due to different data density requirements, the points describing the surfaces of the sculptures were processed separately.

Photogrammetric surveys were processed automatically using Metashape software. Optimization of the alignment of images was carried out using the coordinates of paper stamps obtained on the basis of a cloud of laser scanning points. The dense cloud was built automatically. Then all non-sculpture points were removed. A dense point cloud, like a raw laser scan point cloud, is too dense and therefore requires preprocessing. Its preliminary processing was carried out in the same way as processing the cloud of laser scanning points. After independent processing, the resulting clouds were combined into a resulting point cloud based on the common coordinates (Fig. 2).

Thus, the collection and processing of data can be summarized as follows:

- first of all, data are collected using laser scanning and digital photogrammetry methods, it is necessary to provide for the survey of areas between sculptures and columns, and also for the visibility of at least 3 paper stamps at each scanning station to improve the registration accuracy;
- preliminary processing of points related to sculptures must be performed independently of other points;
- preprocessing (registration, optimization and filtering) can be automated using the CloudCompare command line mode;
- combining data into the resulting point cloud should be based on the shared coordinates.

To create an information model of the New Hermitage Portico, Autodesk Revit software was used. First of all, the cloud was segmented into separate parts, and then, using Revit tools, 12 parametric families of elements of a historical object were formed based on point clouds: windows, columns, pilasters, capitals, pedestals, Atlantean statues, etc. The families of Atlas sculptures were created based on their triangulation models. Model elements such as walls with significant deviations from the plane were modeled with Revit tools based on NURBS surfaces, which in turn were generated automatically from the point cloud in Rhinoceros software. The resulting information model reflects the actual state of the Portico with accuracy of 1 cm (Fig. 3).

Thanks to modern software systems, it is possible to obtain a finite element model based on the geometry obtained from the information model. In this case, ANSYS software was used to solve this problem, for it supports the import of models saved in the ACIS geometric modeling format. The export of information model components from the Revit environment for their finite element analysis in ANSYS was performed in the .sat format. The finite element mesh was generated automatically based on the geometry of the information model. After setting the boundary conditions and loads, we carried out an analysis of the deformations of the Portico elements, including the Atlas sculptures. The analysis result is shown in Fig. 4.

Fig. 2. The resulting point cloud

Fig. 3. Information model

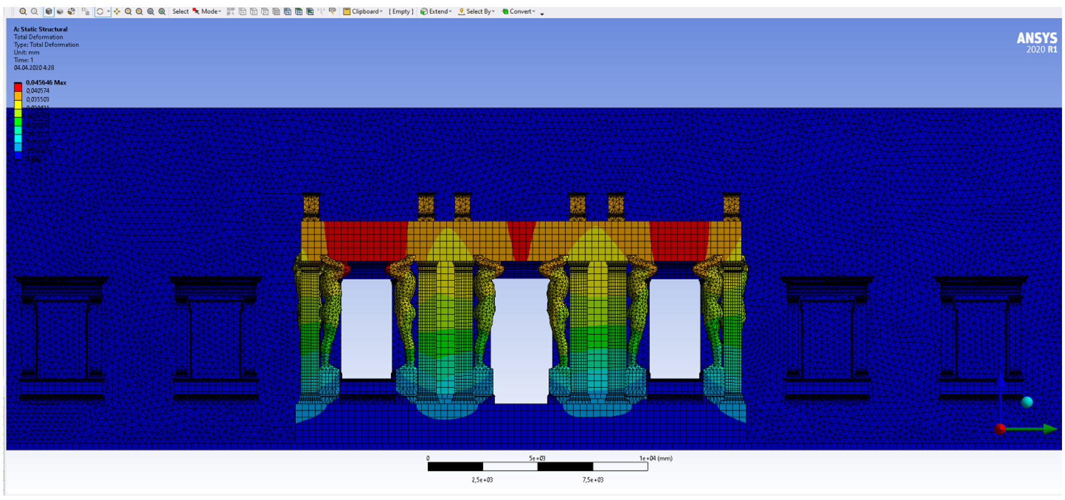

Fig. 4. Analysis result

As a result of the finite element analysis based on HBIM, the maximum deformation values of the Portico elements were calculated to be 0.04 mm. Taking into account the main assumptions within the framework of which the calculation was performed, it can be concluded that the local maxima of the deformation diagrams of the longitudinal beams of the Portico are of the greatest interest. According to the analysis results, their location coincides with the location of the sculptures cracks during field observation. This suggests that the formation of cracks in the sculptures could have occurred as a result of deformations of the structural elements of the Portico and the transfer of load to the sculptures themselves.

Conclusion

This work is the second part of [32], which presents the results of the development of digital technologies for information support for the preservation of cultural heritage sites. One of the main symbols of St. Petersburg, the Portico of the New Hermitage building, was used as an object of approbation. The following results of method approbation are analyzed:

- creation of a hybrid points cloud of Portico as the basis for the formation of a digital model;
- creation of high-precision models of Portico Atlas sculptures based on point clouds;
- creation of a library of parametric families of individual elements of the Portico;
- creation of an information model of the Portico.

The results of the finite element analysis of the deformations of the elements of the Portico of the New Hermitage building are presented on the basis of the information model of the cultural heritage object (HBIM) obtained from the laser scanning results. The main advantage of the proposed technique in comparison with traditional methods of object inspection and corresponding finite element analysis is the completeness and speed of measurements, as well as increased adequacy and accuracy of the results.

Numerical comparison of the proposed methods with the traditional approach based on the use of tacheometric measurements allows us to draw the following conclusions. Thus, the accuracy of the tacheometric survey of the individual points coordinates is approximately 0.5 mm. In turn, the accuracy of the individual points coordinates measuring by laser scanning is 4 mm. However, it should be noted that the density of tacheometric measurements is hundreds of thousands of times inferior to the proposed methods; therefore, when using only discrete measurements, most of the information on the object elements geometry under study is absent, which inevitably leads to a decrease in the processed results absolute accuracy. Thus, based on the expert judgment, it can be concluded that the absolute accuracy of the simulation results based on the proposed methods is several times higher (depending on the scanned surfaces geometry homogeneity) compared to the simulation results based on tacheometric measurements. For a complete capture of the scanned scene using the proposed methods, it will take about 2-3 times less time compared to using tacheometric survey. This is achieved due to a high degree of measurement automation by the proposed laser scanning methods. In addition, it should be noted that, due to the complex geometry, shooting the Atlas sculptures using the tacheometric method is impossible in principle. A similar comparison can be made with the photogrammetric survey approach. The result of such surveys is also a point cloud. However, in the case of laser scanning, the coordinates of the points are obtained by direct measurements, while in case of photogrammetry, the coordinates of the points are obtained by calculating distances based on two overlapping images. Therefore, this method of calculating coordinates is subject to distortion which negatively affects the final accuracy, which, among other things, depends on many factors (illumination, surface material, equipment, shooting mode, processing parameters). Thus, the final accuracy of the proposed methods in comparison with the use of photogrammetry is 5-10 times higher. According to expert estimates, the speed of photogrammetric surveys is also at least 2 times inferior to the proposed methods. This is due to the fact that for a complete photogrammetric shooting of an object, it is necessary to make about 5 thousand images with the required overlap, and also to provide the absence of strangers in the frame. It should be noted that the existing experience, for example, of obtaining a high-precision digital model of the sculpture of David Michelangelo and others, is usually associated with the transfer of objects to special rooms and / or the installation of devices to strengthen scanning cameras [33–36]. In our case, the survey was carried out in real "field" conditions. It should also be noted that the proposed method includes all the advantages of the traditional methods that are used for additional shooting of the necessary elements. For example, tacheometric survey of control points is used for more accurate registration of point clouds, and photogrammetric survey is used for partial survey of blind spots.

In addition, an information model with the up-to-date state of elements can become the basis for creating a digital twin of an object. The main difference between the proposed data processing methods lies in the significant automation of the preliminary processing of point clouds, as well as in the increase in the decoding properties of laser reflection points. The proposed methods for creating an information model based on point clouds, including the use of NURBS surfaces, increase the degree of model adequacy in comparison with traditional modeling methods.

As a result of the work we obtained:

- a point cloud to preserve the object of cultural heritage,
- informational model of the Portico, reflecting its up-to-date state at the time of shooting,
- results of finite element analysis in the ANSYS software package.

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