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POINT CLOUD SPATIAL EXPANSION METHOD IN HBIM APPLICATIONS – STATE OF THE ART AND CURRENT CHALLENGES

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Abstract. Digitalization of historical objects constitutes an important element in the preservation of cultural heritage. Laser scanning technology enables rapid and detailed acquisition of information about the shape of measured objects. The resulting point clouds are widely used for inventory and numerical modeling of historical structures. After processing, these data become part of Historical Building Information Modeling (HBIM) models. The scope of attributes and features contained in these databases is diverse, as this technology has not yet been standardized in a manner analogous to BIM models. The present study describes the current state of knowledge about the Point Cloud Spatial Expansion (PCSE) method, which enables the determination of symmetry and deformation parameters of historical structures that are significant from the HBIM perspective. Furthermore, the study presents current directions of development of the PCSE method as well as potential areas for its further application.

Keywords: PCSE, HBIM, deformations, symmetry.

1. Introduction

The term Historical Building Information Modeling (HBIM) was introduced in 2009 as a system of modeling historic structures (Murphy et al., 2009). HBIM constitutes an extension to historical objects of Building Information Modeling (BIM) systems that have been developed since the 1970s (Eastman, 1974). The extension of the BIM data scope to HBIM involves the introduction of parametric modeling and the integration of geometric data with other data specifying the history, construction material, and degradation of the historical object. In summary, HBIM is a library of parametric objects based on archival data that documents the life cycle of historical buildings (Arayici et al., 2017; Penjor et al., 2024). The transition from static BIM models to dynamic HBIM conservation tools has occurred gradually (Lovell et al., 2023). Phase 1, lasting from 1992 to 2012, established the foundations of digital documentation. Phase 2, covering the years from 2013 to 2017, focused on the consolidation of existing inventory methods. The latest Phase 3, ongoing since 2018, is associated with the rapid growth of artificial intelligence techniques (Cui & Wu, 2025).

Geometrical data defining historical objects are acquired using various methods. The most popular solutions are Terrestrial Laser Scanning (TLS) and Airborne Laser Scanning (ALS) technologies (Vosselman & Maas, 2009). Additionally, for smaller objects, Close-Range Photogrammetry (CRP) is commonly applied (Moyano et al., 2020). It should also be noted that the use of Unmanned Airborne Vehicles (UAVs) equipped with optical and multispectral cameras is becoming increasingly popular (Santoro et al., 2023). In some studies, multisensor datasets are utilized which, due to different coordinate systems and sometimes varying scale factors, are transformed into a single global coordinate system by means of the seven-parameter Helmert affine transformation (Klapa et al., 2022). A weak point of the above methods is the inability to acquire data beyond the field of view of the measuring device. The resulting occlusions limit the possibilities of interpretation and processing of three-dimensional data models. Prior field reconnaissance and proper planning of the placement of measurement stations or the drone flight path minimize the occurrence of occlusions in the resulting dataset.

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Numerical representation of an object's shape is used to define parameters and attributes in HBIM. The applied approaches include, among others, parametric segmentation (Abbate et al., 2022) or semantic segmentation (Quattrini et al., 2015). The level of detail and fidelity of the geometry of historical objects is determined by the adopted Level of Detail (LoD) parameter, which defines hierarchical levels of architectural accuracy of the created model (Heok & Daman, 2004). In defining geometric parameters of subsequent components of the numerical model, Principal Component Analysis (PCA) (Abdi & Williams, 2010) and Random Sample Consensus (RANSAC) (Bolles & Fischler, 1981) are commonly used. Furthermore, the enrichment of HBIM models in terms of geometric parameters can be achieved by adding information about the symmetry and deformations of the historical object's surfaces using the Point Cloud Spatial Expansion (PCSE) method (Dabrowski & Specht, 2019). Additionally, approaches utilizing Machine Learning (ML) for automating segmentation are becoming increasingly popular, such as PointNet (Haznedar et al., 2023) or Mix Pooling Dynamic Graph Convolutional Neural Network (MP-DGCNN) (Zhou et al., 2024). The non-geometric attributes of HBIM include, among others, information about the history and reconstructions of the object, construction materials and building process, state of preservation and structural degradation, as well as conservation data.

Efficient use of BIM and HBIM models is closely related to their interoperability. In the case of BIM models, standards are applied regarding the structure of BIM models – ISO 16739 standard (International Organization for Standardization [IOS], 2024) and regarding BIM management – ISO 19650 standard (IOS, 2018). The Industry Foundation Classes (IFC) format defined in the first standard constitutes a universal and widely used tool for recording and exchanging information in BIM models. A related format is CityGML, which serves to store digital 3D models of cities and landscapes; the CityGML format was adopted in 2008 by the Open Geospatial Consortium (OGC). However, conversion between the two formats is not unambiguous or fully specified and leads to partial data loss (Colucci et al., 2020). The interoperability problem, beyond the issue of formats, is also related to the harmonization of data coming from different sensors (da Silva Ruiz et al., 2023). It is worth noting that the recording and exchange of data in HBIM models do not yet possess the widely recognized and established standards that exist for conventional BIM models.

The practical application of information from HBIM models currently focuses on documentation (Themistocleous et al., 2018), damage diagnostics (Silva et al., 2022), conservation (Bruno & Roncella, 2019), renovation (Bolognesi et al., 2025), and facility management (Parente et al., 2025). Furthermore, HBIM models provide data for the analysis of symmetry in historical structures for conservation purposes (Dąbrowski et al., 2025), earthquake risk simulations (Sammartano et al., 2023), life-cycle predictions of historical buildings (Mol et al., 2020), and sustainable renovation applications (Svytytė et al., 2025). An unconventional application of HBIM models is energy retrofitting simulation (Piselli et al., 2020). The range of practical uses of HBIM models continues to expand, which may contribute in the future to the development of standardized formats and procedures for processing data about historical structures. The main challenges in the development of this technology include the high cost of measurement equipment such as laser scanners or multispectral cameras, as well as the occasional ambiguity of HBIM products generated by artificial intelligence. On the other hand, forecasts for the development of the full automation of the scan-to-BIM process (Abreu et al., 2023) and the use of HBIM digital twins for monitoring with the application of Augmented Reality (AR) and Virtual Reality (VR) (Lagüela et al., 2024).

In light of the above information, the study presents the application of the PCSE method in the context of HBIM models. The PCSE method is a universal tool for assessing the symmetry and deformation parameters of historical objects, the majority of which lack detailed archival technical plans. Algorithms for estimating reference solids within point clouds enable the determination of a reliable reference for evaluating surface shape, particularly taking into account the symmetry characteristic present in most symmetrical historical structures.

2. Point Cloud Spatial Expansion (PCSE) method – current state

The PCSE method features numerous variants tailored to symmetrical objects of various shapes. All variants share a uniform algorithm consisting of: (1) identification of a symmetry element within the point cloud (e.g. a point or a line), (2) determination of the size and spatial orientation of the reference solid using estimation theory, (3) reparameterization of the points from the cloud with respect to the determined reference, (4) calculation of geometric parameters describing deformations and symmetry of the structure that are not directly available in the original unprocessed point cloud, (5) performing additional spatial analyses in the expanded cloud according to user-defined requirements. The classification of the existing and literature-described variants of the PCSE method is presented in Figure 1.

The determination of symmetry elements in historical objects is carried out using estimation theory. Apart from partially automated approaches such as RANSAC (Bolles & Fischler, 1981), the parameterization of symmetry axes is frequently performed through the analysis of a series of orthogonal cross-sections of the point cloud. This approach is particularly justified in the case of objects with complex architectural structures featuring numerous decorations and additions. In automated

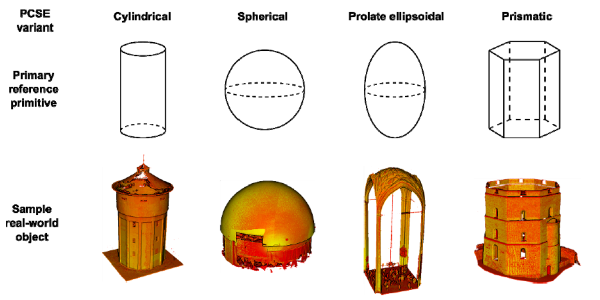

Figure 1. Current variants of the PCSE method

methods, the presence of a large number of outlier points causes significant difficulties in identifying and determining solids that approximate the main shape of the object. By generating a set of cross-sections at a specified interval along the height coordinate, data are obtained for extracting points representing the base surface of the analyzed historical structure (Figure 2a). The sample tower is a prism in the lower part and cylinder in the upper part (Figure 2b and 2c).

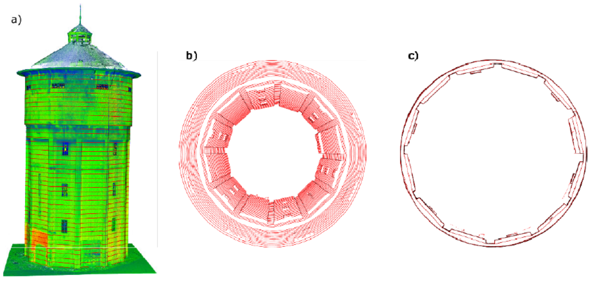

Figure 2. Polygonal and circular cross-sections of the point cloud of a symmetrical historical object shown in: a) oblique view; b) top perspective view; c) top orthogonal view (Dąbrowski, 2024)

Within the cross-sections of point clouds of slender symmetrical objects, the centers of the cross-sections are determined, and their complete set forms a discrete approximation of the course of the structure's symmetry axis. This set consists of three-dimensional points which, after fitting, yield the parameters of the object's axis. Here, either the Errors-In-Variables estimation method (Snow & Schaffrin, 2016) or Principal Component Analysis (PCA) is used (Abdi & Williams 2010), which employs Singular Value Decomposition (SVD) to determine eigenvectors in the data sample, from which the one with the highest significance representing the linear character of the data sample is selected. Once the parameters of the symmetry axis have been determined, in order to perform the PCSE point cloud expanding, it is necessary to define the shape and size of the reference solid (e.g. cylinder or prism). The determination of these parameters is carried out, depending on the spatial arrangement of the analyzed object, either in the coordinate space of the entire point cloud or within individual cross-sections. Ultimately, the calculated dimensions and angular orientation of the reference solid's axis complement the set of required parameters needed to expand the measured point cloud representing the actual current scan of a symmetrical historical object.

The reparameterization of the original coordinates from the point cloud into the transformed unfolding form is performed using appropriate projection functions specific to the given variant of the PCSE method. These functions have been described in the literature for the cylindrical variant (Dąbrowski & Specht, 2019), spherical and ellipsoidal variants (Dąbrowski, 2024), as well as the prismatic variant (Dąbrowski et al., 2023). The computed expansions constitute an alternative representation of the object's shape, referenced to the determined symmetry elements and the adopted reference base solid. The depth parameter of the expansion illustrates the deformation of the object's surface relative to the chosen reference in a single spatial view. The range of the PCSE depth parameter is related to the shape of the analyzed object and represents the distance of surface points from the symmetry axis in the case of cylindrical objects or from the central point of the sphere in the case of spherical objects. The prismatic PCSE expansion for the medieval church tower in Delft (The Netherlands) is presented in Figure 3.

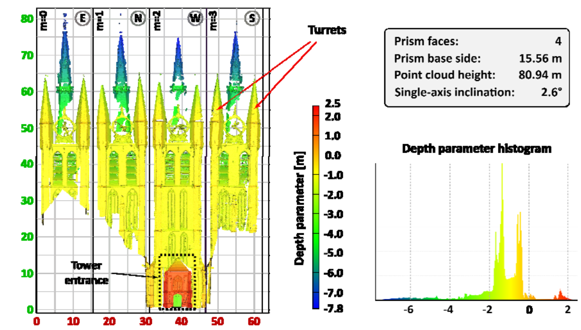

Figure 3. Prismatic PCSE expansion of the church tower in Delft (the Netherlands) (Dabrowski et al., 2023)

In contrast to the cylindrical variant of PCSE, in the prismatic variant the assessment of deformations is performed based on the lateral faces of the reference prism. The values of the PCSE depth parameter indicate, for each side, the position of the measured points on the surface of the historical structure. This enables a systematic parameterization of the shape of all walls while taking into account the dimensions of the adopted reference solid. In detailed analyses of wall surface deformations, it is justified to select specific portions of the PCSE expansion, which results in narrowing the range of the depth parameter. An example of the application of this approach is presented for the Leaning Tower of Pisa, where two segments with different cross-sectional radii exist (Figure 4). The use of separate depth parameter ranges allows for an effective evaluation of the shape, symmetry, and deformation of the surfaces of the entire historical structure. It is worth noting that the PCSE methodology required accounting for the non-vertical course of the structure's symmetry axis in order to obtain reliable numerical data concerning HBIM attributes.

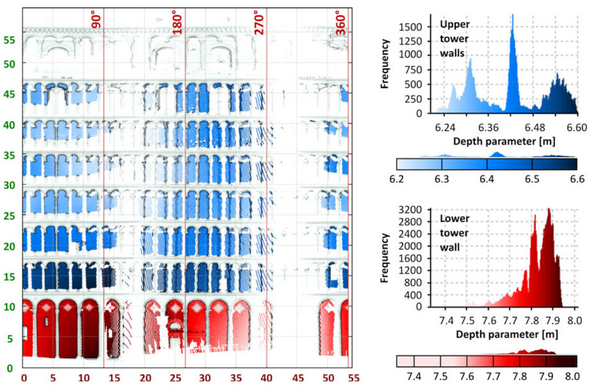

Figure 4. Deformations of the surface of the Leaning Tower of Pisa (Italy) after taking into account the range of the PCSE depth parameter (Dąbrowski et al., 2023)

A significant advantage of the spherical and ellipsoidal variants of the PCSE method is the possibility of adapting various classical cartographic projections in the point cloud transformation functions, such as Lambert, Mercator, Gauss-Krüger, Cassini-Soldner, or Sanson projections. As a result, depending on the user's needs, PCSE transformation functions are employed that preserve, in the two-dimensional plane, the distortion characteristics of the selected cartographic projection, for example, the conformality condition in the Gauss-Krüger projection. It should be noted that the expansion constitutes a three-dimensional set, which extends the applicability of classical cartographic projections by introducing the depth parameter, thereby increasing the dimensionality of the data. Figure 5 presents example adaptations of two cartographic projections used in the assessment of deformations of a planetarium. It should be emphasized that both PCSE expansions represent the same geometric information, yet it is presented in two different ways, each taking advantage of the specific strengths of the applied cartographic projections.

A significant step forward in the application of the PCSE method within HBIM was the formulation of a methodology for assessing asymmetry and deformation (Dąbrowski et al., 2025). The algorithm introduced in that study is applicable to a broad range of symmetrical historical structures. The proposed approach was verified using two independent point clouds acquired by means of terrestrial (TLS) and airborne (UAV) laser scanning technologies. The solution employs the parameters of the prismatic PCSE expansion but significantly advances the post-processing stage of the data, enabling the determination of parameters valuable for HBIM that describe the symmetry characteristics of the historical structure. This area of geometric evaluation of buildings had not been sufficiently described in the literature prior to this study. The proposed parameters present, in a unified manner, the symmetry features of the axis, edges, and walls of the structure (Figure 6).

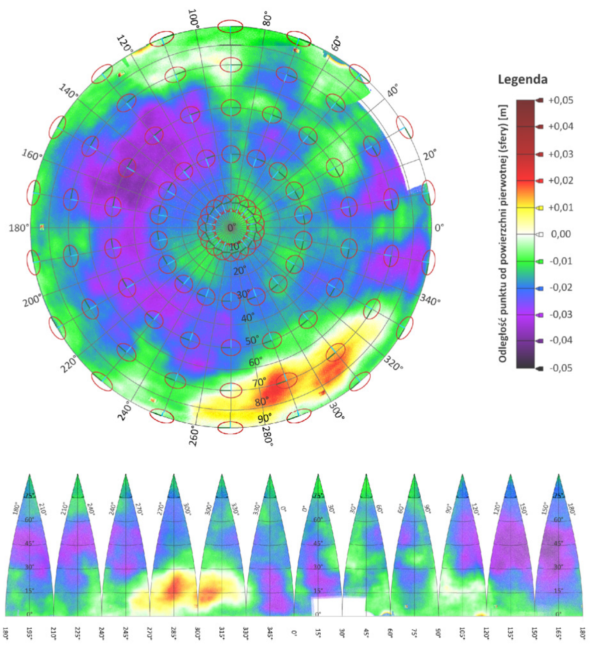

Figure 5. Deformations of the spherical surface of the planetarium determined using the spherical variant of PCSE with adaptations of the azimuthal Lambert projection (top) and the cylindrical Gauss-Krüger projection (bottom) (Dąbrowski et al., 2023)

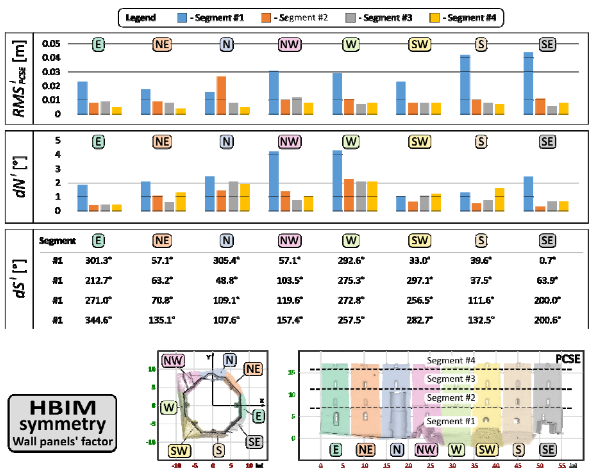

Figure 6. Parametrization of the symmetry of the walls of Gediminas Tower in Vilnius (Lithuania) for the purposes of an HBIM model (Dąbrowski et al. 2025)

The current state of knowledge regarding the PCSE method enables the numerical processing of symmetrical historical objects and, on this basis, the determination of descriptive and geometric parameters that are significant for HBIM models.

3. Point Cloud Spatial Expansion (PCSE) method – challenges and future plans

The universality of the PCSE method lies in the possibility of adapting the generalized algorithm to individual historical building objects. Currently, study is underway to develop hybrid variant of the PCSE method. The object of study is the bell tower of the Archcathedral Basilica of St. Stanislaus and St. Ladislaus in Vilnius (Lithuania). An interesting feature of the structure is the uncommon form of the bell tower's solid, consisting of segments with a circular cross-section in the lower part and a regular octagonal cross-section in the upper part (Figure 7). The cylindrical and prismatic variants differ significantly in terms of the data processing algorithms and the PCSE transformation functions.

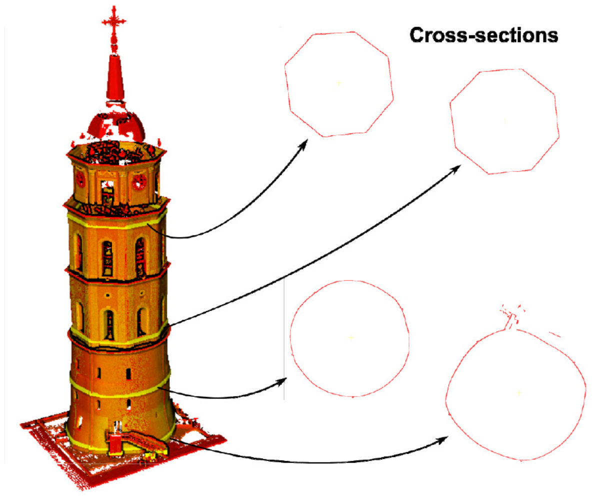

Figure 7. Selected cross-sections of the point cloud of the bell tower of the Archcathedral Basilica in Vilnius (Lithuania)

Additional research material for the analysis includes the technical report on the structural stability of the bell tower from 2004. The study will encompass an evaluation of the feasibility of applying previous cylindrical and prismatic PCSE variant solutions, processing and elaboration of data from the technical report, development of a hybrid methodology for expansion the point cloud, as well as verification of the developed approach through comparison with archival data concerning the bell tower of the Archcathedral in Vilnius.

The second area of development of the PCSE method for HBIM purposes is the assessment of the shape of Gothic vaults. Selected churches in Gdańsk and its surroundings possess technical plans from the 17th century prepared by Bartel Ranisch (1695). As a result of hundreds of years of transformations and historical events in the territory of Poland, many of the objects presented in the book have been damaged or destroyed. The destructions caused by World War II particularly contributed to the loss of numerous historical buildings. During the post-war reconstruction period, architects and monument conservators obtained information from the few surviving archival documents for the reconstruction of destroyed buildings (Figure 8).

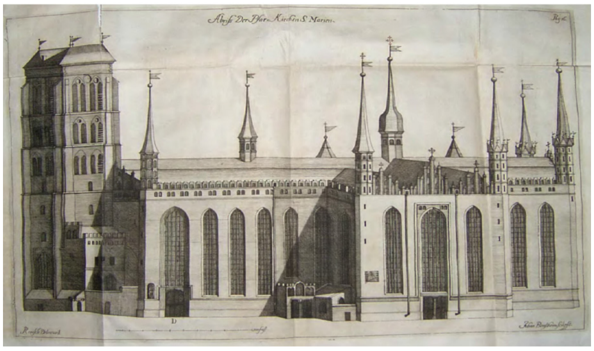

Figure 8. Figure of the façade of the Basilica of the Assumption of the Blessed Virgin Mary in Gdańsk (Ranisch, 1695)

From the perspective of applying the PCSE method, Ranisch's work contains detailed sketches depicting complex Gothic vaults, which can be compared with point clouds representing the current state of the vaults. The vault inventory procedure employed by Ranisch (1695) requires skills in interpreting perspective sketches (Figure 9). Additional difficulties associated with the analysis of archival materials include the non-uniform scale of the drawings caused by paper deformations as well as the determination of an appropriate linear scale corresponding to the currently used units of the SI system.

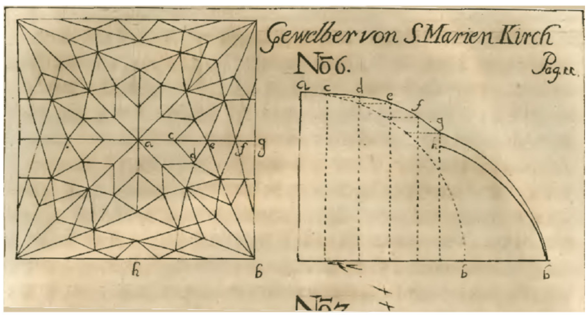

Figure 9. Orthogonal flat projection (left) and schematic diagram of the vault rib connections (right) in an exemplary Gothic vault (Ranisch, 1695)

Another direction in the development of PCSE application solutions for HBIM models is the methodology for mapping the complex geometry of Gothic vaults in order to achieve a unified parameterization of their shape. Particularly important in this context is the symmetry feature characteristic of the regular arrangement of vault ribs (Figure 10). Future estimation procedures must take into account the variable curvature present in vaults. A significant research issue is to demonstrate the fidelity of the 17th-century sketches in relation to the current vaults, which have often undergone multiple reconstructions.

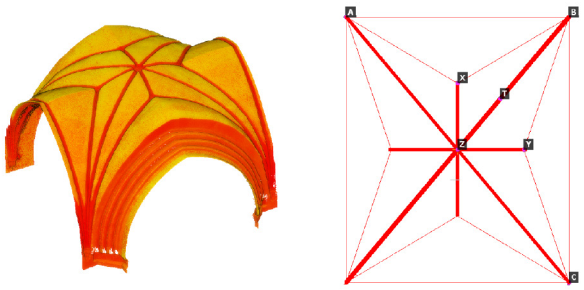

Figure 10. Point cloud of a Gothic vault (left) with the theoretical reference shape recreated based on Ranisch‘s archival documentation (right)

After determining the course of the curvilinear edges connecting the vault cells and ribs of the Gothic vault, it is necessary to approximate the vault cells with numerical surfaces. An appropriate solution is the application of B-spline theory along with the associated Non-uniform rational basis spline (NURBS) (Piegl & Tiller, 2012). By combining data on the edges and the concave surfaces of the vaults, a reference model will be obtained for parameterizing the point cloud of the vault. The task requires knowledge from the fields of geodesy and geoinformatics, as well as architecture and art history. It is worth noting that the subject of Ranisch's 17th-century plans of Gothic vaults remains an important research issue addressed by numerous scholars (de Andrés, 2011, 2017; Kulig & Romaniak, 2008).

4. Conclusions

The issue of creating and developing HBIM models constitutes an important element in the advancement of interdisciplinary knowledge, used among others in construction, cultural heritage preservation, architecture, and building engineering. Among the many methods of acquiring source data for creating models of historical structures, laser scanning technology occupies a special place. Point clouds represent an accurate, detailed, and efficient method of mass acquisition of spatial data that numerically describe the shape of buildings. The main weakness of this technology is the very large size of the data, which makes their processing and real-time transmission difficult. Nevertheless, knowledge in this field continues to advance, and new solutions are constantly emerging that improve data processing efficiency.

The Point Cloud Spatial Expansion (PCSE) method is a universal tool for assessing the symmetry and deformation of historical structures. The determined parameters become part of the descriptive attributes of the building and can be implemented in individual HBIM models. At present, the multi-variant feature of the PCSE method enables the processing of point clouds of cylindrical, spherical, ellipsoidal, and prismatic objects. Nevertheless, the universality of the methodology is not limited to this set of objects and allows for the introduction of further variants tailored to additional types of symmetrical historical structures.

The paper presents the current areas of application of the method and indicates specific application examples described in separate scientific works. The current directions of development of the PCSE method include the creation of hybrid variant that make use of the advantages of individual existing solutions as well as the development of a new variant addressing the problem of parameterizing the shape of complex Gothic vaults.

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