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Managing the accuracy and speed of processes for automated monitoring of construction works in the context of new technologies

Artem O. Rada*, **Aleksandr D. Kuznetsov**, **Anatoly O. Akulov**, **Nikolay Yu. Kon'kov**
Kemerovo State University, Kemerovo, Russia
* Corresponding author: e-mail: rada.ao@kemsu.ru

ABSTRACT: Introduction. Existing automated construction inspection technologies do not allow the user to select the level of detail. At the same time, in the context of the use of nanotechnology, there is a growing need to expand the capabilities of monitoring and control of construction projects. The aim of the research is to develop, implement software, and validate a technology for controlling the speed and accuracy of constructing three-dimensional models from dense point clouds for automated monitoring of construction works. **Materials and methods.** The research is based on the methodology of non-binary data trees, including the method of constructing octant trees. An unmanned aerial vehicle with an aerial laser scanner, a ground-based scanning total station, and specialized software were used, including the web application "Management System for Monitoring Construction Works on Objects that have undergone state expertise" developed with the participation of the authors. **Results and discussion.** In the course of the study, a technology was developed and implemented in software that allows the user to select the required balance between accuracy, degree of detail of monitoring and control data for construction work and time costs and computing power requirements. The comparison is made between a construction project, presented in the form of a building information model, and a three-dimensional model of a real object, obtained from a dense point cloud. The degree of comparison accuracy is set by choosing the level of octrees used. By default, the web application uses level eight. However, in the early stages of construction, when the geometric parameters of a dense point cloud deviate significantly from the design boundaries, the ninth, tenth and other levels can be used. In this case, the accuracy and degree of detail increases. Positive and negative deviations are visualized in red and blue colors, respectively, which allows the user to monitor and control the progress of work at the site. **Conclusions.** The developed technology can be used by customers and other decision makers to control and monitor work.

KEYWORDS: nanotechnology, nanomaterials, monitoring of construction works, construction control, digital technologies, building information model, laser scanning, dense point clouds.

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INTRODUCTION

In modern construction, nanotechnologies, new materials with unique properties, and new methods of physical and chemical transformation of traditional materials are being actively introduced. This allows you to create buildings and structures with unique characteristics, significantly reduce work time, and also reduce costs at all stages of the facility's life cycle. However, it is obvious that the use of nanotechnology is associated with higher risks, like any technological innovation, due to the lack of experience and less predictability of processes. Therefore, the use of nanotechnology in construction requires the development of automated monitoring and control capabilities to assess the situation and make decisions. This can only be achieved using digital technology.

Comprehensive digitalization of processes, equipment, control objects, and human activities is the most important global trend in the technological development of the economy [1, 2]. The advantages of digital technologies (for example, unmanned vehicles, the Internet of things, thermal, laser scanning of objects, etc.) are well known and have been repeatedly described in the literature, such as high speed [3], greater accuracy [4], independence from the qualifications and conscientiousness of performers [5], significant improvement in the quality of information support for management decisions [6], etc.

A central place in the process of digitalization of various sectors of material production is the creation of “digital twins” of control objects – models in the information environment that almost completely reproduce reality online [7, 8]. The use of such doubles for control and monitoring of the situation not only provides decision makers with comprehensive information (which was previously unavailable), but also ensures the choice of optimal management influences, rational planning, and the possibility of proactive actions (not waiting for obvious manifestations of problems) [9, 10].

Although the construction industry is often characterized as “conservative” [11], digital technologies are quite actively penetrating it. The review [12] highlights the main areas of construction digitalization, which include building information modeling using BIM models, augmented and virtual reality, laser scanning, robotics, three-dimensional printing, Internet of things, specialized software, digital twins, and blockchain. Another review article [13] examines the use of computer vision, the Internet of things, BIM models for quality management in construction and reducing the number of defects caused by insufficient qualifications, low motivation of personnel and other reasons.

A review of works on the benefits of digital technologies in construction highlights such advantages as improving the quality of visualization, improving data exchange between participants, increasing productivity, and reducing construction waste [14]. In particular, under certain conditions, the use of digital technologies can contribute to the implementation of the ESG agenda and increased sustainability of the construction economy [15].

The introduction of digital technologies in construction faces certain problems associated with barriers to control and competence [16]. The lag of construction from other types of economic activity in digitalization also led to the slow growth of labor productivity. However, the COVID-19 pandemic has served as a powerful stimulus for the widespread adoption of digital technologies [17]. Experts support the opinion that digitalization is becoming the “new normal” for the construction industry [18, 19]. Russian authors also note both the importance of introducing digital technologies in construction and the problems associated with the need for significant investments and the shortage of qualified specialists [20, 21, 22].

One of the main digital technologies most important for the development of construction is the creation and operation of digital twins of construction projects in the form of BIM models. A significant number of works have been published that discuss the use of BIM models for the design of buildings, structures, and control of construction works. They are considered a technology that significantly speeds up construction, ensures cost reduction and a high level of quality of work performed in accordance with the project [23]. The construction information modeling market is valued at $7.9 billion in 2023, with the potential to grow to $15 billion in 2028[1]. It should be noted that in a number of countries around the world, the use of BIM has been mandatory for quite a long time in construction at the expense of the state budget [24].

To build BIM models, information about the state of the construction site is used, obtained using various technologies – laser scanning, Internet of things, thermal imaging, etc. [25] in order to have a complete and accurate picture of the real world for decision-making. These models cover all stages of the life cycle of buildings, including planning, design, construction itself, operation, and disposal [26]. An important advantage of building information modeling is the wide possibilities for visualization, including three-dimensional visualization, as well as the accuracy of measurements [27].

These features of BIM models allow solving a wide range of technical problems. For example, in [28] an information model of a medical complex is described, created to reduce the spread of nosocomial infections. The authors of the study [29] consider the case of using a BIM model for designing the most energy-efficient buildings, as well as minimizing waste.

One of the main problems in the development and operation of a BIM model is the rational organization of collecting and processing a large amount of information characterizing a construction project. After the completion of design and the start of construction works, constant monitoring and control of the construction site is necessary. In a limited period of time, the BIM model receives large amounts of information that must be processed with acceptable speed and accuracy [30].

This information affects changes in the geometric parameters of a building or structure under construction, the volume of materials used for construction over certain

[1] Building Information Modeling Market. 2028. URL: https://www.marketsandmarkets.com/Market-Reports/building-information-modeling-market-95037387.html (accessed 10/20/2023).

periods of time, on certain dates, as well as the strength of structures, their thermal conductivity, etc. [31]. Quite often, laser scanning data is used to control and monitor construction works with BIM models [32]. When using laser scanners, dense point clouds are created, which are then converted into three-dimensional models of a real construction site using special software [33].

This approach to creating digital twins of buildings can already be considered classic, traditional. However, it is most often used, as an analysis of a number of scientific works shows, for one-time construction of digital models of fairly large objects [34, 35]. The use of laser scanning for operational automated monitoring and control of construction works is discussed less frequently [36]. This is due to the fact that existing technologies do not allow users to fully choose the relationship between the quality (accuracy) of model construction, on the one hand, and the costs of laser scanning and data processing (time and financial costs) on the other hand. At the same time, in practical problems it is advisable to use different levels of detail of information contained in dense point clouds depending on the stage of construction and other factors.

In other words, it is advisable to allow users to independently determine the level of detail and accuracy of 3D models built on the basis of dense point clouds, without being limited by the default parameters of the software. This will expand the number of user options and make it possible to make the most productive use of the computing power of existing computer equipment. In accordance with the above, the purpose of the study is the development, software implementation and testing of technology for controlling the speed and accuracy of constructing three-dimensional models using dense point clouds for automated monitoring of construction work.

METHODS AND MATERIALS

When conducting the research, the following technical means were used for aerial and ground laser scanning of construction sites:

1. Commercial class unmanned aircraft (UAV) "DJI Matrice Pro" made in the People's Republic of China, hexacopter type, flight speed up to 65 km/h, maximum take-off weight 15.5 kg, maximum flight altitude 2.5 km, communication range 5 km, longest flight duration 18 minutes, intended for operation at wind speeds up to 8 m/sec. The UAV has an onboard satellite navigation system receiver (GNSS receiver).

2. Airborne laser scanner, designed for placement on an UAV "AGM-MS3.200", manufactured in the Russian Federation, scanning frequency 600 kHz, maximum scanning distance 150 m, review – 360 degrees, range determination accuracy – 3 cm, coordinate determination accuracy – 5 cm, weight – 1.3 kg.

3. Trimble scanning tachometer "Trimble SX10", manufactured in the United States of America, scanning speed up to 26,000 points per second in a range of up to 600 m, laser beam size 14 mm per 100 m, reflectorless mode up to 800 m, prism measurement range up to 5500 m, angular accuracy 1'', minimum measured distance 1 m.

To process dense point clouds and construct three-dimensional models, the "Credo Scan 3D" program was used (developed by Credo-Dialog Company LLC, Moscow, Russian Federation). The software implementation of the author's developments was carried out in a specialized web application "Management System for Monitoring Construction Works on Objects that have undergone state expertise" (the application was developed by the Institute of Digital Science at Kemerovo State University, Kemerovo region – Kuzbass, Russian Federation with the participation of some of the authors of this study[2]).

The study used the methodology of non-binary data trees and the method of constructing octant trees. The objects of work were several non-residential buildings and structures under construction in the city of Kemerovo (Kemerovo region – Kuzbass, Russian Federation) in 2022-2023.

RESULTS AND DISCUSSION

The study included the following stages:

1. Obtaining laser scanning data as individual stages of construction are completed for comparison with the project presented in the BIM model.

2. Construction of octrees for faster search of coordinates of points obtained from laser scanning results.

3. Search for the nearest starting point (reference) for calculating deviations of the actual state of the construction project from the planned state using the algorithm for searching for the nearest points.

4. Calculation of distances for each point and subsequent visualization of the results using a color scale.

Based on the results of laser scanning, dense clouds with billions of points are formed, so processing, storing and using the relevant information requires large computing power and (or) significant time costs. To reduce them, the methodology of non-binary data trees can be used, in particular, the construction of octrees. This makes it possible to speed up the search for the coordinates of each

[2] Certificate of state registration of a computer program Certificate number: RU 2023663552. Application number: 2023662975 Registration date: 06/24/2023. Publication date: 06/24/2023. Authors: Rada A.O., Kuznetsov A.D., Snezhkov A.M., Zverev R.E., Nepomnischev I.L., Chernykh G.S., Timofeev A.E., Popov P.S., Kon'kov N.Yu., Tyutikov A.A., Nikitina O.I., copyright holder – Federal state budgetary educational institution of higher education "Kemerovo State University". URL: https://www.elibrary.ru/download/elibrary_54198120_50908639.PDF (access date 10/15/2023).

point and groupings of closely located points, reduce the need for computing power and (or) reduce the time of work.

An octree is designed to recursively and regularly partition three-dimensional space in the shape of a cube into a bounding region. Each subsequent level of division divides the top level cube (parent) into 8 child cubes (lower level). Thus, at the first level, the original cube (null cube) is divided into 8 child cubes of the first level (see Figure 1). Then the cubes of the first level are divided into 8 child cubes of the second level, etc.

At the same time, the number of cubes by level of detail increases in accordance with the following proportion: at the first level the detail is $8^2 = 64$, at the second level – $8^3 = 512$ cubes, etc. The construction of octrees (recursion) stops either when there are no points in the cube, or when the maximum level of detail specified by the user is reached. The construction of octrees makes it possible to quickly determine which points obtained from laser scanning results lie in specific cubes. Accordingly, the search for point coordinates, finding nearest neighbors and solving similar problems of processing dense point clouds are accelerated.

The tree structure of the octree makes it possible to use a coding scheme in which for each point a long code of $3n$ bits is defined, where n is the maximum subdivision level of the octree. To encode the zero-level cube, numbers from 1 to 7 are used. For example, in Figure 1, the number "3" corresponds to the zero-level cube (also called a cell) in which a certain point is located. Each bit corresponds to the position of the cell relative to the parent cube in one dimension. These numbers are combined for all successive levels to construct the cell code. The encoding process is fast, since the algorithmic complexity of encoding is linear in nature, depending only on the number of points and the level of the cube (the complexity class of the algorithm is "linear time", type $O(n)$).

Next, the codes were sorted to make the octree structure more convenient for quick calculations. This makes it possible to quickly find the codes of dense cloud points, as well as all points laying in a cell of a given level I. An increase in search speed is achieved due to the fact that only the first 3 I bits of codes are considered. The time complexity of the algorithm is minimal, since it corresponds to the complexity class "linear-logarithmic time" ($O(n \log n)$). The octree structure is easy to maintain because it is highly flexible, allowing you to easily add or remove points.

At the next stage of the study, it was necessary to place the initial BIM model (building design) and dense point clouds in a single coordinate system. Since the BIM model was created taking into account the geodetic reference and coordinate system, and the real object is built in accordance with this model, monitoring and control of construction works are carried out in the same reference system. If the original BIM model (project) and dense point clouds (result of work monitoring) are in a single coordinate system, then the same method of constructing octrees should be applied to them.

Each octree structure is computed starting from the same source cube, which is the smallest cube that contains all the clouds. Therefore, similar cells in all octrees

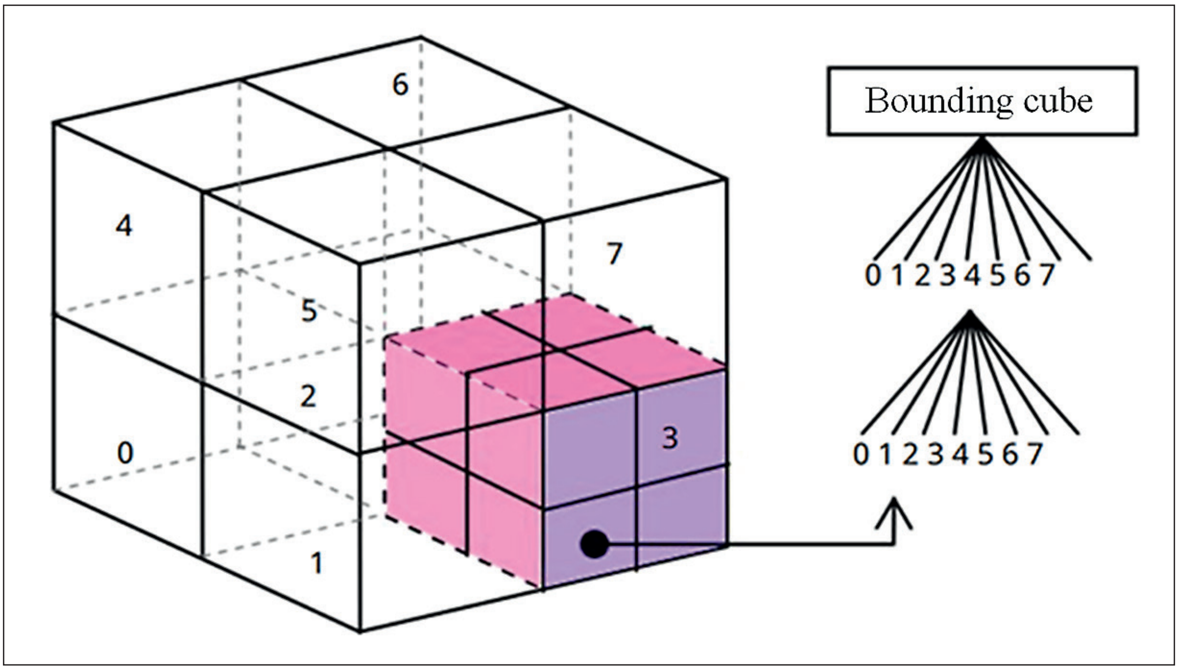

Fig. 1. **General scheme for dividing three-dimensional space using octrees**

are spatially equivalent. Therefore, the subsets of points located in these cells are also comparable; to find the nearest points and calculate the distances between points, it is necessary and sufficient to select cubes with the same code, that is, take cells of different clouds located in the same spatial coordinates.

A distinctive feature of the technology developed in the study is the ability to select the level of detail when comparing dense point clouds with a BIM model. Thus, the user has the option to prioritize greater accuracy or greater speed of calculations, depending on specific needs and the type of tasks being solved. For this purpose, different levels of octrees are used on which calculations are carried out. The lower the level of octrees, the higher the accuracy of the calculations and the higher the costs and vice versa.

By default, the web application “Management System for Monitoring Construction Works on Objects that have undergone state expertise” uses the eighth level of detail. It was determined experimentally based on quantitative data on the density and size of point clouds. If the dense cloud points are far enough from the BIM model (early stage of construction, when a relatively small part of the building is built), then lower levels of octrees (ninth, tenth, etc.) with a higher degree of detail should be used. At later stages, lower levels of detail can be used, which reduces calculation time and/or computing power requirements.

As a result of processing dense point clouds and comparing them with the original BIM model, the web application “Management system for monitoring construction work at sites that have passed the state examination” displays a heat map. It shows deviations of the actual state of the construction project from the BIM model (building design, structure). An example of the program interface is shown in Figure 2.

It should be noted that when comparing dense point clouds with a BIM model, it is necessary to take into account the normals of the latter’s polygonal mesh. The normal reflects the outside of the polygon mesh surface. Accordingly, all points that are located beyond the plane of the current triangle of the polygonal mesh show a positive deviation from the BIM model (and are colored red).

If the point is on the side opposite to the direction of the normal, then this means a negative deviation, which is visualized in blue. When analyzing deviations, you need to take into account that in some cases the direction of the normals may be distorted. The direction of the normals may depend on the characteristics of the polygonal mesh, the specifics of the applied computational algorithms and other factors. It is most rational to set the normals in a certain way when designing a construction project, that is, to standardize them at the initial stage of work.

The web application “Management System for Monitoring Construction Works on Objects that have undergone state expertise” allows the user to configure a heat map with fixed tolerances. An example is shown in Figure 3. Thus, the part of the image highlighted in red means a positive deviation of the actual state of the construction project from the project (BIM model) by more than 5 cm upward. These may be temporary structures, stocks of materials and tools located on site,

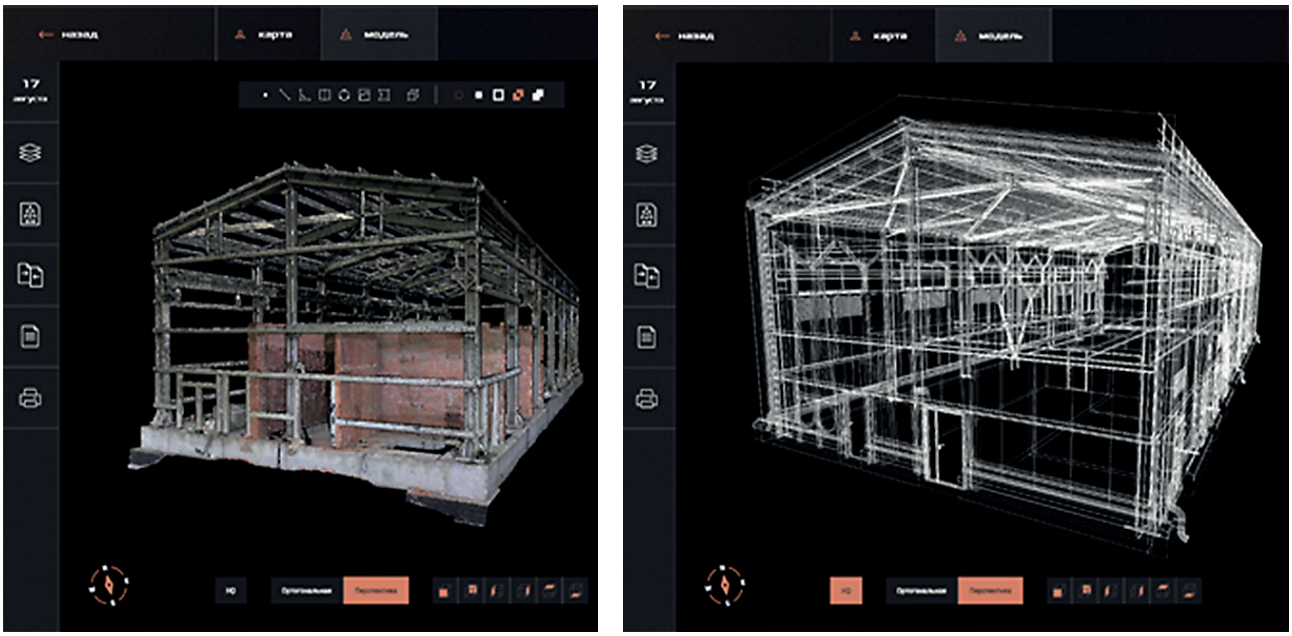

Fig. 2. **An example of the interface of the web application “Management System for Monitoring Construction Works on Objects that have undergone state expertise” (on the left is a dense point cloud, on the right is a BIM model)**

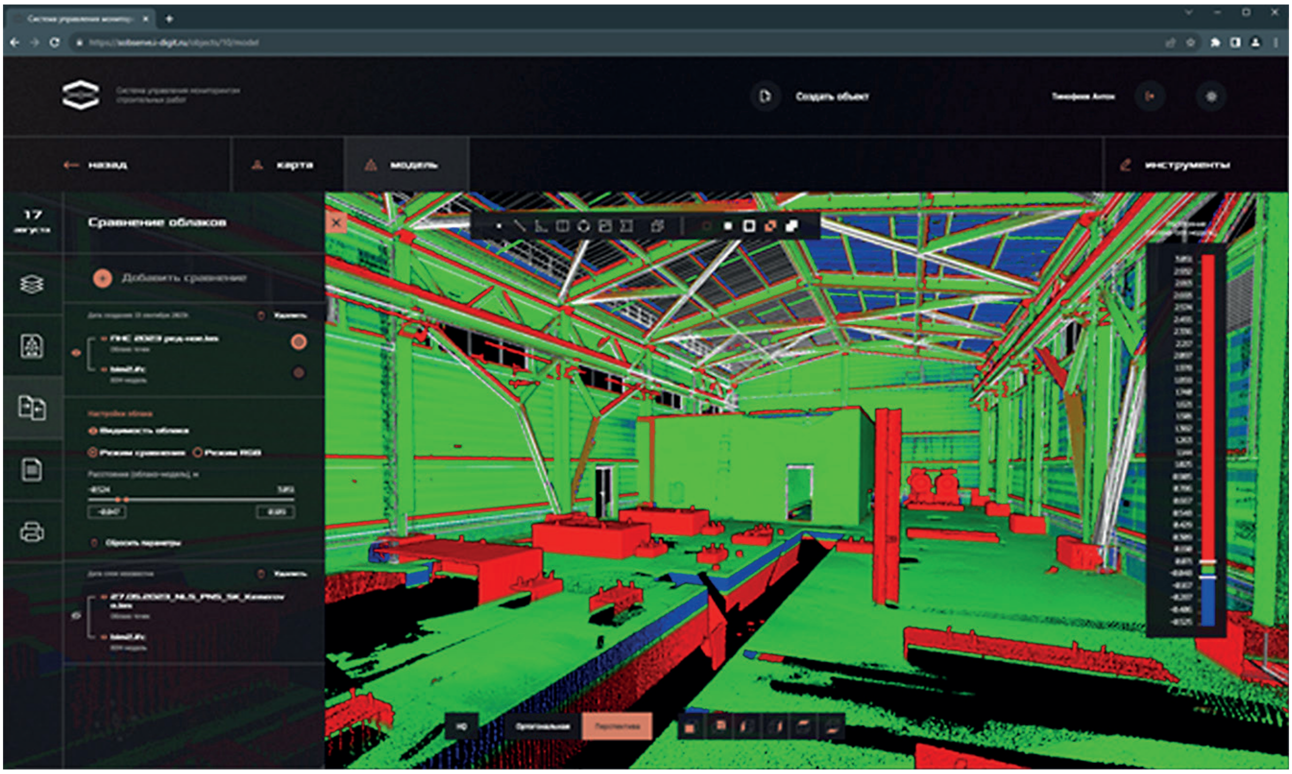

Fig. 3. **An example of visualization of the results of comparing a dense point cloud with a BIM model in the web application "Management System for Monitoring Construction Works on Objects that have undergone state expertise"**

as well as deviations of geometric parameters from the design during construction (for example, a large height or thickness of walls, which indicates an overconsumption of material).

Blue fill in fig. 3 denotes a downward deviation of actual parameters from the design ones, when the geometric parameters of the real object have not yet reached the design values. Thus, the developed web application makes it possible to visualize deviations from design values with the required degree of detail and rational use of computing power.

CONCLUSION

Currently, BIM models are being quite widely introduced into the construction industry as digital twins of buildings and structures, which make it possible to monitor work automatically and identify deviations. This technology has great production and economic advantages, but its use is to a certain extent hampered by the need to collect and process large volumes of information (billions of points based on the results of a single laser scan), which requires large computing power and (or) a long time. Therefore, it is necessary to develop software solutions that allow the user to choose a rational balance between speed and accuracy of monitoring construction work, depending on specific tasks.

The study used data from both terrestrial and laser scanning of a number of construction sites, which made it possible to obtain dense point clouds as an empirical basis for the development and testing of technology for monitoring and control of construction work with the ability to select the level of detail.

For the purpose of information processing, the octree methodology was used, which allows reducing the need for computing resources, because tree structures speed up the search for coordinates of points through the use of algorithms of the "linear time" and "linear-logarithmic time" complexity classes. Spatial similarity of the project in the BIM model and dense point clouds obtained during monitoring and control of construction work has also been implemented. In this case, you can consider 2 cubes (cells) from the BIM model and a dense point cloud, which are presented in the same coordinates.

The developed web application "Management System for Monitoring Construction Works on Objects that have undergone state expertise" implements the option to select the accuracy of detail, which depends on the number of octree levels used. By default, the eighth level is set, but if necessary, at earlier stages of construction with large differences in geometric parameters from the design ones, you can select the ninth, tenth and lower levels. Then the number of levels can be rationally reduced, which saves time and computing resources.

The study identified and analyzed the risk of incorrect interpretation of information when comparing a dense point cloud with a BIM model due to distortion of the direction of normals. Therefore, it is advisable to recommend standardizing the directions of normals when developing a construction project, that is, at the initial stage.

After processing dense point clouds in the web application "Management System for Monitoring Construction Works on Objects that have undergone state expertise" positive and negative deviations of the geometric parameters of the work from the design parameters are visualized in color. Red color means positive deviations, geometric parameters exceeding the design values. Negative deviations are visualized in blue. This allows users to conduct automated operational monitoring of the progress of construction work, the condition of construction objects with the choice of the required level of accuracy and rational use of computing resources.

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AUTHORS INFORMATION

Artem O. Rada – Cand. Sci. (Eng.), Director of the Institute of Digitalization, Kemerovo State University, Kemerovo, Russia, rada.ao@kemsu.ru, https://orcid.org/0000-0001-7678-8402

Aleksandr D. Kuznetsov – Director of the Center for Geodesy, Aerial Survey and Cadastral Works of the Institute of Digitalization, Kemerovo State University, Kemerovo, Russia, adkuz@inbox.ru, https://orcid.org/0000-0002-1986-3039

Anatoly O. Akulov – Cand. Sci. (Eng.), Associate Professor of the Department of Management named in honor I.P. Povarich, Institute of Economics and Management, Kemerovo State University, Kemerovo, Russia, akuanatolij@yandex.ru, https://orcid.org/0000-0002-2301-7943

Nikolay Yu. Kon'kov – leading programmer of the development department of the Institute of Digitalization, Kemerovo State University, Kemerovo, Russia, n.konkov@i-digit.ru, https://orcid.org/0000-0003-3817-4893

CONTRIBUTION OF THE AUTHORS

Artem O. Rada – writing sections "Introduction", "Conclusion", and general scientific guidance.

Aleksandr D. Kuznetsov – writing the "Results and Discussion" section, organizing work on ground and airborne laser scanning.

Anatoly O. Akulov – writing the "Methods and Materials" section, preparing a list of sources.

Nikolay Yu. Kon'kov – carrying out the experimental part of the study, development and software implementation of computational algorithms.

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