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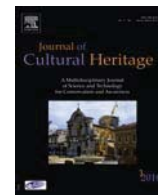
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Original article

Laser scanning and 3D modeling of the Shukhov hyperboloid tower in Moscow



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ABSTRACT

The Shabolovka radio tower in Moscow, also known as the Shukhov tower, is a famous example of the Russian avant-garde style of the early 20th century. With a height of approximately 160 m, it is the highest hyperboloid lattice steel tower ever built by Shukhov and is one of the symbols of Moscow. It is widely recognized as an artifact of modern cultural heritage. Despite being an iconic object of engineering and architectural heritage, it was deprived of technical maintenance for many years. Its technical condition has degraded since the early 1990s and has now reached an alarming level. Several restoration projects are still being discussed by the Russian government, including the full rebuilding of the tower in another place. Therefore, digital preservation of the tower's original geometry and design has become a crucial task. Its under-documentation is also a concern: the initial project and engineering documentation is almost completely lost. To preserve information about the tower, we performed laser scanning and created a precise polygonal 3D model using both the results of the scanning and the existing drawings. The transition from an unstructured point cloud to a highly structured representation included the development of a special methodology to model deformed steel elements of hyperboloid sections. The tower was scanned from seven viewpoints, resulting in a 65 M point cloud. To reproduce the individual shapes of twisted rods and rings, we used > 4 K pre-defined cross-sections. These were precisely positioned in a point cloud. The connection joints of steel elements were modeled using drawings based on measurements that were made in 1947. Non-original design elements such as service platforms and an elevator were also modeled using the point cloud. We also made use of historical drawings and photographs to represent the internal structure of the concrete basement and the non-extant original superstructure. The combination of various methods of 3D modeling for different parts of the tower allowed us to visualize the geometry of the huge steel construction with high accuracy (1 cm or so) and with high level of detail in a reasonable timeframe (300 man-days). Public access to large 3D models and to vast amounts of raw data is a sensitive issue for virtual heritage applications. To provide free access to our results, we created an open-source software application based on Open Scene Graph. It supports stereo visualization of the point cloud and the 3D model, as well as management of the visibility of different layers of the model in accordance with its lifecycle period. A light web-version based on Unity 3D is also being developed to provide Internet access to the model. The software is freely available at our website (<http://virtual.ihst.ru/shukhov-tower.html>). Thus, we created a comprehensive visual representation of a steel lattice radio tower of the early 20th century and shared precise technical documentation with researchers worldwide. The experience that we have gained can be useful for other similar projects that involve precise polygonal modeling of large-scale objects of modern cultural heritage.

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1. Research aims

Lightweight metal structures of the renowned Russian engineer Shukhov are often considered to be the most original constructions in the history of building with iron and steel. It is likely that the most famous of Shukhov's structures is a 160-m lattice hyperboloid tower in Moscow, built in 1919–1922 (Shabolovka tower). At this time, its technical condition is poor, and different methods of reconstruction are being discussed by the Russian government and independent experts.

The tower is under-documented. The original documentation is almost completely lost; the complete measurements and drawings of all of the elements were made in 1947. These do not reflect many later changes and the current condition of the building.

Thus, the digital preservation of the information about this tower has become a crucial task. The aim of our project is to create a precise virtual 3D model of the tower using laser scanning and the existing documentation and to disseminate the resulting data through the development of suitable visualization software. To be useful in a broad variety of scientific and educational applications, the model should not only be accurate and complete enough but also visually realistic and adaptable for interactive rendering.

2. Introduction

The lattice hyperboloid towers are probably the most popular structures of the Russian engineer Shukhov. To date, only approximately 20 of the more than 200 original towers have survived. These include two multisection towers: the 160-m Shabolovka radio tower in Moscow (6 sections) and the 130-m NIGRES tower of the power transmission line near Nizhny Novgorod (5 sections).

The object of our research is the Shabolovka tower, a live symbol of Soviet radio- and TV-broadcasting (Fig. 1). The tower was built in 1919–1922 and was used up to 2001. Despite being out of operation for many years, the tower is still officially regarded as a strategic object of the communication infrastructure, and therefore, free access is not permitted.

The technical condition of the tower has gradually degraded since the early 1990s, when a noticeable level of gap corrosion was first reported. No restoration or conservation was performed until now, and the current state of the tower has alarmed many experts.

2.1. The construction of the tower

The tower consists of 6 hyperboloid sections stacked on top of one another, followed by the superstructure (antenna part). The original superstructure was reconstructed in 1937, and it was dismantled and replaced with a new one in 1991. The height of the superstructure was different at different periods; the total height of the tower is usually cited as 160 m.

Each section has the form of a hyperboloid of rotation and consists of straight metal rods. These are twisted around its axes. Intermediate rigidity rings are riveted to the rods on the inner side of the tower. The lower two sections have 48 pairs of rods each, the middle two sections – 48 rods each, and the upper two sections – 24 rods each. In the lower two sections, each rod is constructed of channel bars, and in the upper four sections, each rod is constructed of angles.

The connection joints of rods of neighboring sections are strengthened with ring lattice girders (Fig. 6). The construction of the joints uses individual designs for each pair of sections.

2.2. Overview of existing documentation

Almost no project or engineering documentation of the Shabolovka tower has survived. The only existing project drawing

(from 1919 [1]) and calculations in Shukhov's diary (from 1919 [2]) have many discrepancies with the real construction. Two sheets of engineering documentation (from 1921 [3]) contain schemes of the substructure and a connection joint between the 2nd and 3rd sections. This last one also has some differences with the real construction.

In 1947, the tower was carefully measured to prepare a set of drawings. This is still the most complete traditional documentation of the tower [4] (Fig. 6). In 1971–1973, several additional rings and service platforms with a ladder were added to the tower. No documentation is available for them or for the elevator that was added in the 1990s.

2.3. Related works

Laser scanning is extensively used for a large variety of virtual heritage applications [5]. It is an effective method for the analysis of the overall object's geometry and deformations, especially for large buildings and constructions [6]. However, precise polygonal 3D modeling of old large-scale steel structures requires much more effort than just scanning the structure. Therefore, this is not a popular task.

Shukhov's engineering heritage is widely recognized and researched [7]. In 2010, a joint project "Konstruktionswissen der frühen Moderne: Šuchovs Strategien des sparsamen Eisenbaus" between four research teams from ETH Zurich, University of Innsbruck and the Technical University of Munich was started with a primary focus on the scientific investigation of Shukhov's lattice towers. Fourteen towers were measured using Total Station and photogrammetric methods, and they were 3D modeled using Rhinoceros3D software. The 5-section NIGRES tower was also included [8,9]. The Shabolovka tower was not measured and modeled for different reasons.

A project with 3D modeling of the Shabolovka tower was performed in 2011 in the Steklov Mathematical Institute of the Russian Academy of Sciences [10]. Its goal was to create an animation movie demonstrating the mathematical principles of the hyperboloid structures and the original technology of assembling the tower (<http://www.etudes.ru/ru/etudes/shukhov/>). Linear measurements were made on different levels of the tower. The metric accuracy of the model is not uniform. High accuracy is reached only for those parts that were measured directly.

Another project with laser scanning and 3D modeling of the Shabolovka tower was performed in 2011 at the request of the tower's owner [11]. A Riegl VZ-400 laser scanner was used to make 7 scan stations at distances of 100–200 m from the tower. A wire-frame 3D model was developed for engineering calculations, and a rough polygonal 3D model was developed to provide a low level of detail. The reported accuracy of scan inter-alignment was 3–4 cm.

In our project, we aimed at precise polygonal 3D modeling of the Shabolovka tower with an accuracy of approximately 1 cm and with a high level of detail to enable photorealistic visualization.

3. Generic methodology

The tower is a huge steel building constructed of 336 rods with lengths from 20 to 27 m and 69 rings with diameters from 40.3 to 3.2 m. It has approximately 3500 connection joints of approximately 200 types, with 2–30 rivets and/or bolts in each joint. Obviously, individual measurement and modeling of each steel element of the construction is practically impossible. Therefore, we decided to individually model only the rods and rings of the hyperboloid sections and to create generic models of joints (including small metal elements, rivets and bolts). These were later multiplied and embedded into the 3D model of the tower. By doing so,



Fig. 1. Shukhov tower in Shabolovka, Moscow, general view.

we limited the modeling work to only several hundred individual elements.

To gather the data about the actual geometry of the elements of the tower, we could choose from among laser scanning, photogrammetry and manual measurements. The latter requires execution of high-rise works that we could not afford. Moreover, manual measurement of the geometry of even a single 27-m rod with a desired accuracy of 1 cm is very difficult. We also thought that our measurements would not add much to the data gathered in 1947.

The application of photogrammetry in our case requires the use of an unmanned aerial vehicle (UAV) to bring a photo camera close to the surface of the tower. Two attempts at using UAV-based photogrammetry for modeling the Shabolovka tower were made by Prof. Gruen from ETH Zurich and Prof. Zheltov from GosNIIAS (Moscow) in 2012. Unfortunately, technical difficulties hindered the completion of this project. At the same time, they reported successful modeling of the 37-m lattice Shukhov tower in Polibino using photogrammetry (the results are still unpublished). Therefore, the feasibility and potential accuracy of UAV-based photogrammetry for modeling of the 160-m Shabolovka lattice tower is still an open question.

Taking into account the considerations mentioned above, we decided to use laser scanning to measure the geometry of the tower.

4. Laser scanning

The tower is surrounded by buildings with height of no more than 30 m (Fig. 1). The only tall building (75 m) is located at a distance of 150 m from the tower. Thus, locating a scanner on top of any neighboring building does not improve the range of scanning of the external surface of the tower. The closest range is achieved



Fig. 2. Laser scanning at the 100-m level.

when the scanner is located on the ground near the tower. However, in this case, the top of the tower is scanned at a steep angle.

At the same time, the tower has a lattice construction and is empty inside. Thus, it is possible to organize scan positions at service platforms on different levels inside the tower.

It was reported that placing scanners at distances of 100–200 m from the tower enables a scan inter-alignment accuracy of 3–4 cm [11]. This accuracy is not sufficient for our tasks. Thus, we decided to place the scanner close to the tower and directly on it to achieve better accuracy of scan inter-alignment, with a probable lack of coverage of the external surface of the top of the tower.

We used four scan positions on the ground, one in the center of the tower and others 5–10 m outside the tower. Three more positions were located on service platforms on levels of 100, 125 and 141 m. We used a Leica ScanStation2 for all scan stations except the upper one where a compact FARO Focus3D scanner was used.

Field work took 6 man-days. Laser scanning was performed on December 1–2, 2011 (Fig. 2). The day before the scanning, we made some preliminary tests.

To combine point clouds from different scan stations, we used temporary magnet marks. Four marks were installed at a level of 100 m and later at a level of 125 m in such a way that they were visible both from the ground and from the scan positions on the service platforms.

Scans were inter-aligned using Leica Cyclone software with an accuracy of 7 mm (Fig. 3). The point cloud of the tower contains approximately 65 M points. The density of the point cloud is not uniform; it is approximately 1 cm for the external surface of the tower's top and better for all other parts.

5. Geo-referencing

The tower has no local geodetic network. During the laser scanning, we created a temporary network of data points using range poles, marks, and existing nail-heads in the tower's basement. Using Total Station, this temporary network was coordinated with the permanent reference points of the Moscow geodetic control grid. Their relative position has a permissible error of 5 cm in plane view. Therefore, the accuracy of the geo-referencing of our model is of the same order.

Obviously, more precise geo-referencing is desirable for comparison of different 3D models and monitoring of the structure over time. However, this requires the building of a local network of permanent data points in the close vicinity of the tower. This task was far beyond the scope of our project.

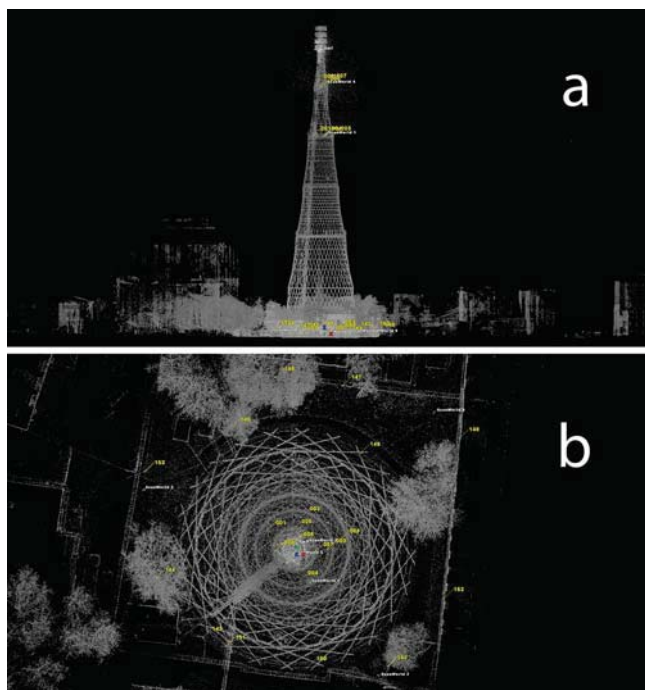


Fig. 3. Point cloud, front view (a) and top view (b).

6. 3D modeling

A peculiarity of the hyperboloid steel lattice structure is that each rod is twisted around its axis. For example, the angle of twist of a rod in the lower section of the tower is approximately 38 degrees. In theory, the axis is straight. However, in real construction, each rod has individual deformations that arose mainly during the installation. The deviation of a central line of a rod from a straight line exceeds 3 cm in some places, as shown by our measurements. The same individual deformations are observed on rings of the tower.

Therefore, a key task for the modeling of rods and rings was the development of a methodology that allows us to represent the

individual shape of each element with the desired accuracy. The general idea consists of the individual adjustment of a generic profile to a point cloud for each element. The step-by-step technology is described below. During a set of experiments, we determined that it is enough to use 10–12 intermediate “adjustment cross-sections” for a 27-m rod to achieve an accuracy of 1 cm or better.

The exact shapes of the iron profiles of the tower were not measured during the field work. Therefore, we used the current standard cross-sections of angles and channel bars in Russia.

The process to move from a point cloud to a highly structured 3D model in our project includes three principal steps:

- alignment of pre-defined cross-sections in a point cloud;
- modeling of rods and rings of the tower using cross-sections;
- modeling of connection joints using existing documentation.

6.1. Alignment of cross-sections

A preliminary set of cross-sections was drafted in AutoCAD and then exported to Leica Cyclone. In the Cyclone software, all of the imported cross-sections were located in the XY plane.

Then, a set of 10–12 cross-sections was manually aligned for each rod of the tower. This procedure consists of several steps. First, an additional object is created: two points are set manually at the ends of the rod, and a straight line is manually drawn between them. This line corresponds approximately with a central line of the rod. A precise correspondence is not needed. Second, we use the LimitBox tool. This is a box that hides most of the point cloud except for the points inside the box. The box (and a local coordinate system connected with it) is set in such way that the Z axis is oriented along the line and the XY plane is perpendicular to the line. Then, we choose a view from the end face (i.e., along the Z axis), select the orthogonal projection (no perspective distortion), set the Z size of the LimitBox to 1...10 cm (this depends on the density of the point cloud for this particular element), and shift the LimitBox to some part of the rod (along the Z axis). By doing these, we create a “slice” of a small part of the rod in a point cloud, and we look at this slice from the end face. Then, we visually choose an appropriate cross-section from a set of pre-defined cross-sections (for example, a channel bar 140 × 60 mm) and manually align this cross-section

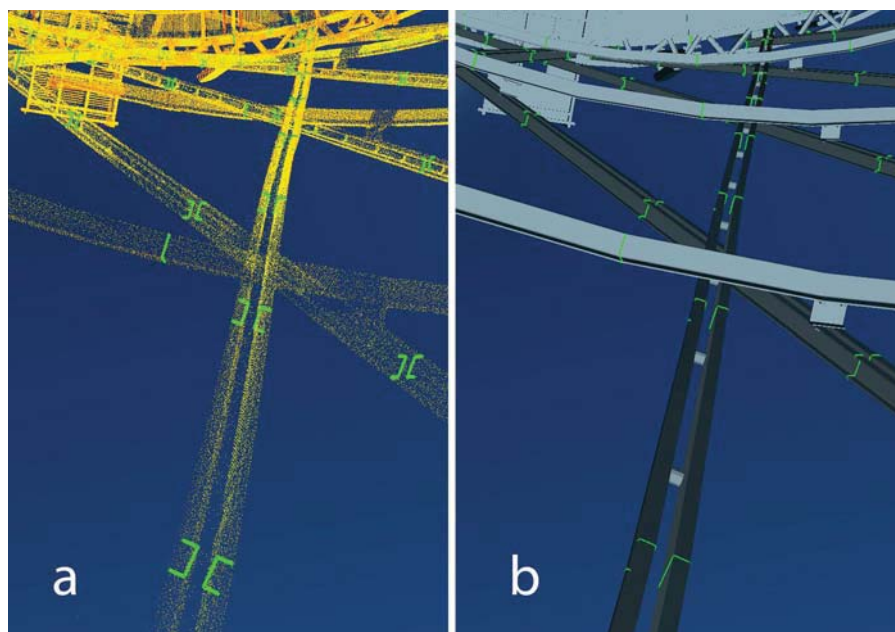


Fig. 4. Placing cross-sections in a point cloud (a) and drawing elements individually based on cross-sections (b).

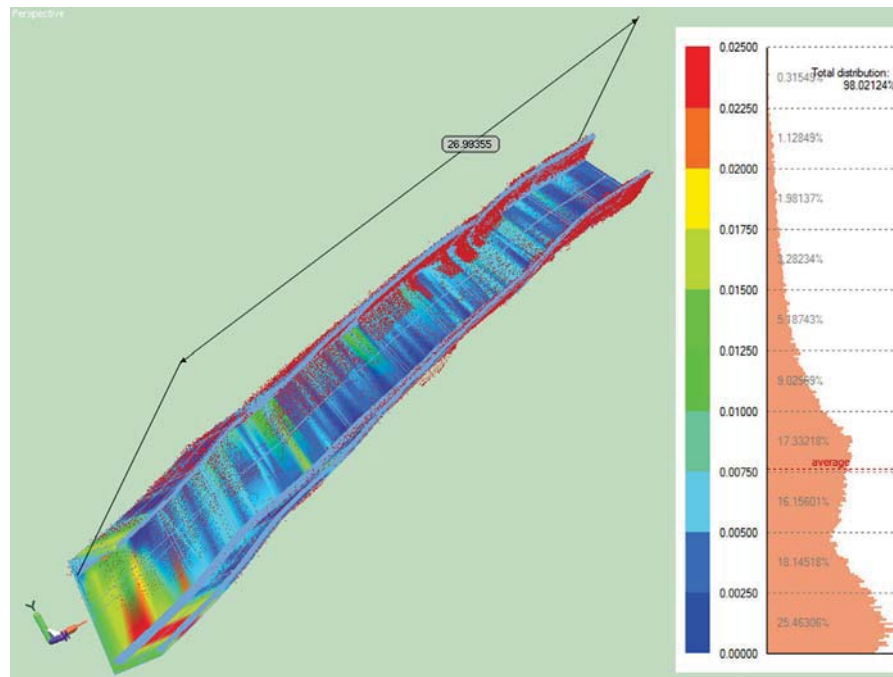


Fig. 5. Deviations of the polygonal model of a rod from the point cloud.

in the XY plane of the current LimitBox (using 3 degrees of freedom: X, Y and rotation). Then, we move the LimitBox to another part of the rod (along the Z axis), with a step of approximately 2–3 m and perform the same operations again. As a result, we create a set of 10–12 cross-sections for the chosen rod. These cross-sections are precisely located in the point cloud (Fig. 4).

The same method was used for the rings. The only difference is that straight lines were drawn for small parts of a ring (2–3 m).

This procedure was performed for each rod and almost every ring of the tower (57 of 69). The tower has 96 pairs of rods, 144 single rods, and 69 rings. Twelve rings are not readable in the point cloud and/or have complex construction.

In total, 4393 cross-sections were manually aligned in a point cloud for 393 elements ($96 \times 2 + 144 + 57$). Thus, the mean number of cross-sections per element is $4393/393 = 11$.

The created set of cross-sections was exported from Leica Cyclone to AutoCAD and then to software used for further modeling (Rhinoceros3D, Blender3D).

Compared with the 1947 documentation, our cross-sections turned out to be different for 8 rings of 57, and also for the top part of rods of the 6th section. We interpret this as an error of our method except for one ring, where a probable error was found in the 1947 documentation.

6.2. Drawing the polygonal 3D model using cross-sections

To draw a 3D model of an element (rod or ring), we connected a set of cross-sections with straight lines. The “Loft” tool was used for this procedure in Rhinoceros3D to create a solid 3D model, and the “Bridge” tool in Blender3D was used to create a meshed 3D model. Solid and meshed 3D models were drawn independently based on the same set of cross-sections.

The accuracy of polygonal modeling can be defined as the mean root square (MRS) deviation of a polygonal surface from the point cloud. An example of the calculation of the modeling accuracy for a rod of the 1st section is shown in Fig. 5. The 27-m rod is shown in orthogonal projection (without perspective distortion); the cross-section is a channel bar of 140×60 mm. The color shows

the deviation of a polygonal surface from a point cloud. This deviation varies from 0 m (blue) to 0.025 m (red) for 98% of the points in the cloud. The average deviation is approximately 0.0075 m (7.5 mm).

We calculated MRS deviations for 3 arbitrary rods in each section. The mean deviations for rods in sections 1–6 are 8, 4, 6, 5, 4 mm, respectively. Taking into account the 7-mm MRS error of the inter-alignment of scans, we estimate that the mean deviation of the polygonal model from the real geometry of the tower is approximately 1 cm ($MRS_{total}^2 = MRS_{alignment}^2 + MRS_{modelling}^2$).

Direct verification of the model's accuracy could be done via linear measurements of distances between specific points of the tower in the model and in the real tower. For example, one could directly measure the distance between central points of rods' crosses on opposite sides of a section using a laser ruler and compare this

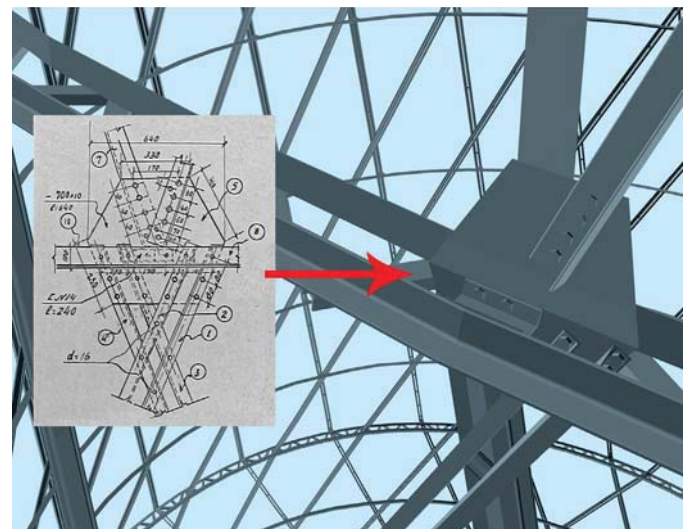


Fig. 6. Modeling of a joint using the 1947 documentation.



Fig. 7. Final 3D model, close view, photorealistic rendering.

value with the same distance in the model. However, this requires high-rise work in the field, and we are not able to do this.

6.3. 3D modeling using existing documentation

More than 200 types of connection joints are used in the tower. We modeled only the main types: between rods of different sections, between crossing rods, and between rods and intermediate rings. For each of these, we created a generic meshed 3D model based on the 1947 documentation. The generic models were multiplied and embedded into the meshed 3D model of the tower with individual adjustments at each location (Fig. 6).

The solid model is intended for use in possible future engineering research. Smooth embedding of solid 3D models of connection joints into a solid 3D model of the tower is a really difficult and impractical task. Therefore, we did not do this in our project.

We also used existing documentation to model the current superstructure (built in 1991) and the internal design of the basement of the tower. The original superstructure (dismantled in 1991) was modeled roughly based on existing photographs.

As a result, a complete and precise 3D model of the tower was created with a high level of detail. The model is visually realistic at all distances and enables both photorealistic non-real-time rendering (Fig. 7), and real-time interactive rendering (Figs. 8–10).

7. Development of a software application

Creating a virtual heritage application means not only exact 3D modeling of an object but also making it available for public use. We used open-source software (OpenSceneGraph) to develop a downloadable application that provides interactive visualization of our results.

The 3D model is shown precisely located on a map or on a virtual globe with the use of osgEarth and OpenStreetMap (Fig. 8). The point cloud and the cross-section can be shown simultaneously with reconstructed 3D. A user can adjust the transparency of the polygonal model and thus visually estimate its accuracy without the use of special engineering software (Fig. 9). Our experience has shown that such “visual verification” of a 3D model plays an important role in its perception by the public.

The structure of the tower has changed over time; the software allows the user to visualize these changes. Six periods were emphasized in the lifecycle of the tower. After the choice of a desired time period, only the appropriate layers of the model are shown. Thus, a simple click allows the user to “travel through time” and see historical views of the tower (Fig. 10).

Interactive shadows on the ground can be added for a more realistic view. The visibility of the ground map and the basement can be switched off to reveal the internal structure of the basement.

The application supports different modes of stereo visualization, including horizontal interlace and quad-buffered stereo. Thus, a virtual tour of the tower can be organized using different 3D systems and monitors. For example, the application was successfully demonstrated on a stereoscopic projection system with a 6-m-wide screen, Barco Galaxy 12000 projector and Infitec 3D glasses. Stereo visualization significantly increases the sense of immersion into the virtual scene and provides a sense of real flight through the lattice tower.

We are also developing an experimental web application based on Unity3D to provide access to the 3D model over the Internet. Here, we are testing some additional features such as a ruler that allows the user to measure the distance between any two points on the model.

Raw data cannot be downloaded or exported in the software because of copyright issues. However, they can be obtained from a state archive [12] or directly from the authors upon request.

Future development of the software would probably include support to annotate the 3D model and to connect it to other types of documentation (photos and drawings). This is an attractive idea because it could lead to creation of a comprehensive information system with access to large amounts of traditional data based on a 3D interface. We believe that such a system could be of great help to experts who are planning the conservation of the tower. However, the copyright issues with both the traditional archive data and the results of modern measurements of the Shabolovka tower impeded the development of such an information system.

8. Results and discussion

We have digitally preserved the geometry of Shukhov’s unique hyperboloid structure using both 65M-point cloud and polygonal 3D models. The individual shape of each rod and almost every ring of the tower was reproduced in a polygonal model with high accuracy. Such accuracy is practically impossible to achieve using traditional methods of documentation.

We also developed a method for precise modeling of twisted rods in lattice structures. The method can be used in other similar projects. The accuracy of the modeling in this method can be adjusted by varying a series of cross-sections.

The construction of the tower was visualized with a high level of detail that can be useful for understanding its design. The results of this project are freely available and can be accessed without the use of proprietary 3D software.

The weak point of this project is a lack of manual measurements on-site. This lack is due to methodological and financial and organizational issues. The lack of data about the actual shapes of the cross-sections of the iron profiles results in uncertainty when the profiles in the point cloud differ from the existing documentation. The lack of control measurements of linear distances did not allow us to perform direct verification of the accuracy of the model.

The resolution of the point cloud was not enough to calculate the thickness of the iron profiles. Nevertheless, we tried to derive the thickness of the profiles from the point cloud. In many cases, this resulted in smaller values than the thickness of the profiles measured in 1947. This difference can be explained as a result of corrosion. However, additional on-site measurements are necessary to make sound conclusions.

The locations of a considerable number of small elements are not visible in the point cloud, including the heads of rivets and bolts, joints of rods and rings, and spacers between doubled rods in the lower two sections. The modeling of joints (including rivets, bolts

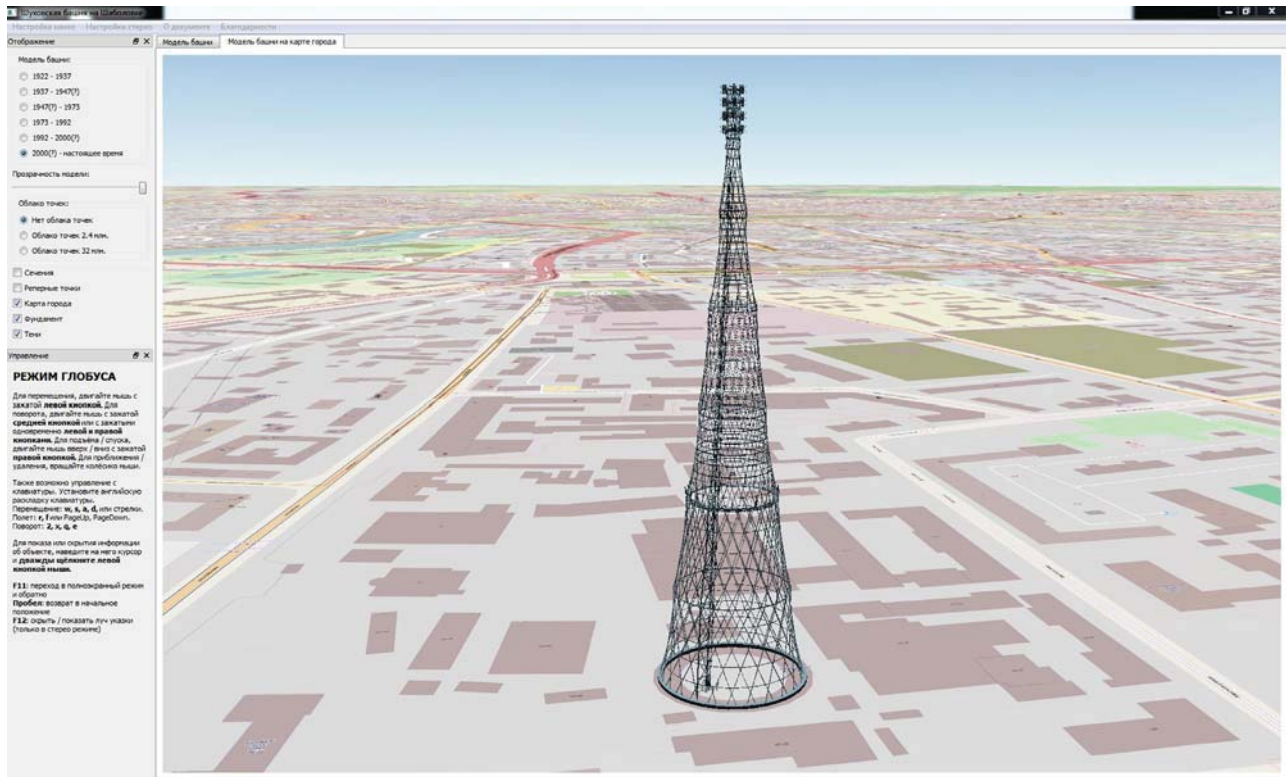


Fig. 8. View of the 3D model in software with interactive rendering.

and gusset plates) was intended primarily to increase the visual realism of the model and for visual representation of the design of the tower. The modeling of joints did not add anything to the existing traditional documents in the sense of preserving information

about the construction. Some types of joints were not modeled (for example, joints of parts of a rod or ring of the same profiles). Spacers between doubled rods were modeled arbitrarily just for visual consistency (Fig. 4b).

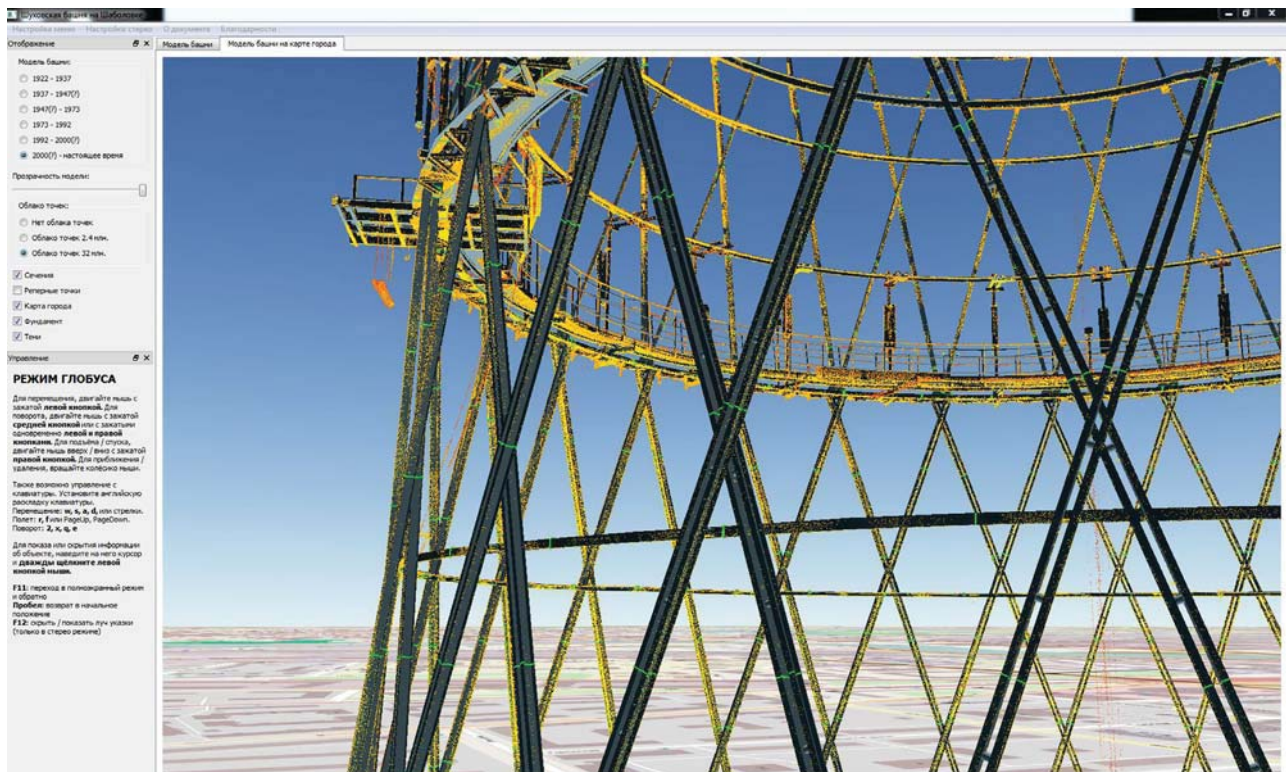


Fig. 9. Point cloud, cross-sections and 3D model are shown simultaneously.

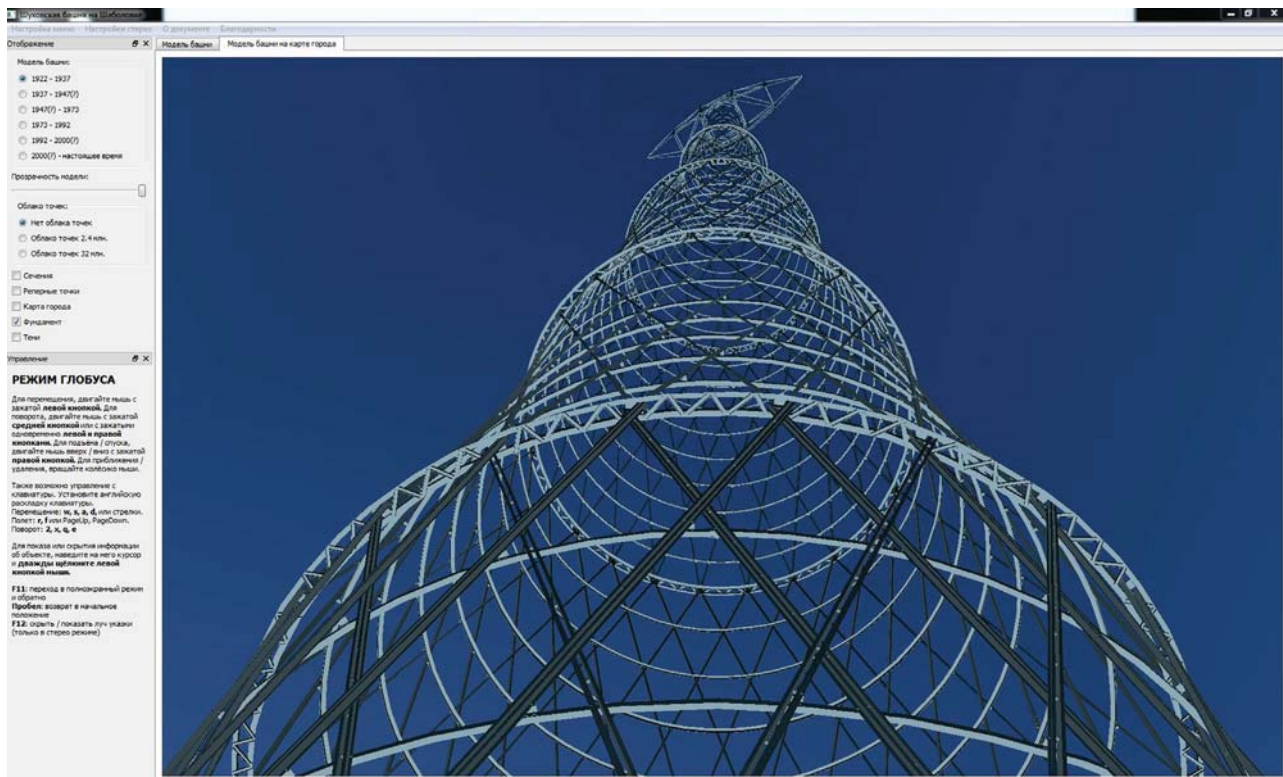


Fig. 10. View of the tower as of 1922 (original superstructure, no platforms).

Probably, the main challenge for polygonal modeling was the shape of the small curved elements, such as the heads of rivets and the curvatures of cross-sections. Such shapes that are below the resolution of the point cloud were a matter of our choice; this choice turned out to be unexpectedly important. We used low-polygonal models for heads and high-polygonal models for curvatures; both choices resulted in undesired consequences.

For example, we used a hexagon to model the head of a rivet, just as a simple approximation to a circle. Later, we realized that this makes the tower look like it is made only with bolts. In reality, both bolts and rivets were used, but our data are insufficient to resolve the type of fastener in most cases. We could not find a way to resolve this issue in our model.

Another example is the shape of the curvatures of the cross-sections. We used smooth curvatures with a large number of vertices to achieve better visualization at close distances. This turned to be a drawback in a web application where the volume of the downloadable data is crucial. The use of rough curvatures would probably decrease the volume of the model several times without significant loss in visual realism but with great gain in speed of download. However, we cannot easily resolve this issue. Manual remodeling is not possible in the scope of this project, and automatic simplification does not provide appropriate results for such a complex model.

In general, we can conclude that the limits of 3D reconstruction in our project were determined mainly by a variation of the scale of modeled elements and by the huge amount of small elements. The rivet head radius is 10^4 times smaller than the tower height; the need of the reconstruction of curvatures in cross-sections and rivet heads for visual purposes increases the difference in scale to 10^5 . An attempt to simultaneously achieve high overall accuracy, high level of detail and high visual realism required many compromises during the modeling.

9. Conclusions

Huge technical objects are a special type of cultural heritage. Their virtual modeling requires different approaches than those used for archaeological sites or architectural monuments. In our project, we tried to develop a comprehensive approach for 3D modeling of old steel structures such as towers or bridges using the Shabolovka steel lattice tower as a case study.

We created a visually realistic 3D model of the tower using laser scanning. This can be used as a reference model to monitor the state of the tower or to check the tower's geometry after its possible reconstruction or re-building. Our research is independent, and the results are freely available to provide a foundation for independent expert evaluation in the future. We also developed a software application for visualization of the model and the raw data. The software can be used for virtual travel to the tower and to learn its structure and history of reconstruction.

In late 2013, the 3D model was committed to the Russian State Archive of Scientific and Technical Documentation as a first document of a new type: a 3D document [12]. Thus, the results of the project were recognized at a national level as a precedent. This increases the juridical validity of accurate 3D models based on laser scanning and can stimulate their further development.

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