Virtual 3D reconstruction of historical vehicles: Columbia electric car and Kulibin's pedal carriage

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***Abstract*—Historical vehicles are a part of technical heritage. Some of them are still exist as museum exhibits, while others are lost and we can investigate them only by drawings and descriptions. Virtual 3D reconstruction of such vehicles provides an opportunity to restore their historical appearance, visualize and check hypothesis about their construction and interaction of mechanical elements, and prepare for physical reconstruction. In the article, we analyze two projects of virtual 3D reconstruction of historical vehicles, their methods and results: Columbia electric car of 1901 year that exhibits in the Moscow Polytechnic Museum, and the lost Kulibin's pedal carriage of the late 18th century.**

***Keywords*—historical vehicle, laser scanning, 3D model, 3D document, virtual reconstruction, virtual animation, virtual heritage**

INTRODUCTION

Historic vehicles are one of the interesting types of technology heritage. Some of them have been preserved in nature, completely or in part, with restoration or not; information about others is only available in drawings and descriptions. The historical reconstruction of such objects is a complex and multifaceted task that requires the involvement of a wide range of methods.

Physical reconstruction is expensive and has several disadvantages. The physical model (no matter, replica or reconstructed original) allows you to show only one version of the design of the object, while in reality there may be various hypotheses about its structure; or it is known that the object existed in several modifications. With physical prototyping, the possibilities of demonstrating the internal structure of an object are limited, especially for valuable objects. In addition, for a physically reconstructed artifact of technology, the possibilities of object animation and interactive demonstration of its action are limited.

In this regard, the task of virtual 3D reconstruction of historical vehicles becomes highly relevant. Virtual 3D reconstruction means that the object is recreated in the form of a three-dimensional digital computer model. Virtual reconstruction overcomes the limitations of physical prototyping mentioned above, and allows you:

- To present several versions of the object design. This is relevant, for example, in the case of competing hypotheses about its structure, when the choice cannot be made at present due to lack of data; or in the case when the object existed in several modifications.
- To demonstrate the internal structure of the object. In a traditional museum exhibit, the internal structure is demonstrated through dissection (eg, by cutting out "windows" in the case to display the interior). For valuable exhibits, dissection is not performed - thus, their internal structure remains inaccessible for viewing. The virtual model allows you to turn on and off the visibility of any elements of the model (for example, the body).
- To animate an object and interactively demonstrate its action. For example, based on a virtual model, you can show the operation of the mechanical systems of a car, visualize the operation of electrical circuits, etc.

Virtual reconstruction also allows solving a number of problems directly related to the preservation and study of artifacts of technology:

- To save information about the existing state of the exhibit (geometry, structure, color and texture of surfaces) in the format of a 3D document - the most up-to-date format of scientific and technical documentation [1]. To create a metrically accurate and visually realistic virtual 3D model of the exhibit or its preserved original parts.
- To carry out a detailed historical and technical study of the structure, including its individual subsystems (mechanical, electrical, etc.); to systematize the information about the elements (both existing and to be restored); compare the construction of the object with similar exhibits and historical documentation.
- To restore lost structural elements in a virtual form, to test hypotheses about their spatial location and structure. To reconstruct the lost details, one can use the preserved drawings and descriptions, as well as photographs and measurements of similar exhibits in other museums.
- To prepare for the physical restoration of the exhibit: to check the spatial layout of the object, taking into account the reconstructed elements, to simulate the interaction of parts in a three-dimensional virtual space, to identify the lack of data to restore any elements or the discrepancy between the documentation and the actual geometry of the object.
- After the physical restoration of the exhibit, its virtual model can be used to control the quality of the restoration.

In addition, the created 3D model can be used as a virtual exhibit for demonstration to the public. The virtual model can be presented in the form of a multimedia presentation within a museum exhibition (for example, a video or

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interactive 3D model on a touch screen), or in the form of a public Internet application on the museum website.

In this article, we will discuss two examples of virtual 3D modeling of historic vehicles. The first of them is the 1901 Columbia electric car, which has been preserved in a restored form in the Moscow Polytechnic Museum. The second is Kulibin's pedal carriage of the late 18th century, information about which has been preserved only in the form of drawings. We will consider the applied approaches and modeling techniques, show and analyze the results obtained.

COLUMBIA ELECTRIC CAR

The 1901 Columbia electric car is a unique exhibit of the Polytechnic Museum in Moscow [2], Fig. 1. It belonged to Empress Maria Feodorovna, mother of the last Russian emperor Nicholas II. A similar car also belonged to her older sister, Alexandra of Denmark, Queen of Great Britain and Ireland; it is currently stored in the National Automobile Museum (Bewley, England). Of the 20 thousand electric vehicles produced by Columbia, according to some information, only 24 have survived to date [3], of which only two, described above, were equipped for imperial persons.

Fig. 1. Columbia electric car (1901) from the collection of the Polytechnic Museum (restored in 2007).

The project on virtual 3D modeling and virtual reconstruction of the Columbia electric car was carried out in 2015 in the framework of cooperation between the Polytechnic Museum and the S. I. Vavilov Institute of the History of Science and Technology of the Russian Academy of Sciences (IHST RAS) [4], [5]. The goal of the project was to restore the historical appearance of the electric vehicle in the form of a visually realistic digital 3D model.

A. Description of the exhibit and historical documentation

The exhibit of an electric car in the Polytechnic Museum is partially intact: the engine, mechanical rods (steering, differential speed control, hand brake), a significant part of the electrical wiring, lighting lamps and other details are lost. In addition, some of the elements are remakes, recreated during the 2007 restoration: fenders, a steering lever, a folding roof over the passenger seat, etc. According to experts from the Polytechnic Museum, most of the remakes were made unsuccessfully. Re-restoration of the exhibit is planned, however, additional funding is required to complete the restoration work in full, the search for which has not yet been crowned with success.

No drawings or historical photographs of this exhibit have survived. The only surviving image of Alexandra of Denmark's electric car, which is similar in design, is represented by an engraving based on a photograph taken by her daughter Princess Victoria [6, frontispiece]. In the meantime, historical articles on the construction of various models of Columbia electric vehicles are available, including photographs, mechanical and electrical diagrams [7-9], Fig. 2, courtesy of Bruce Duffie, publicly available at https://www.kcstudio.com/colindex.html.

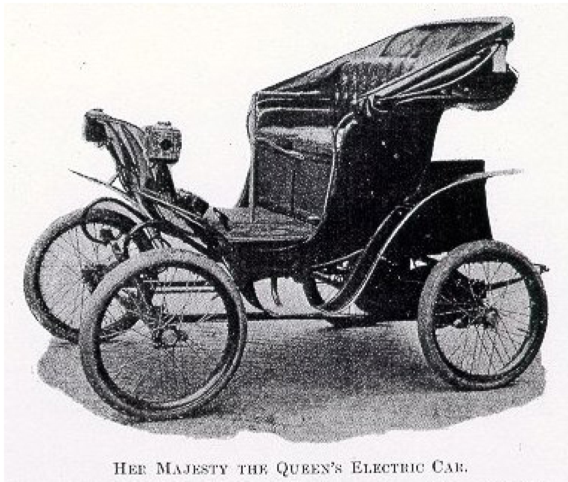

Fig. 2. An example of a historical image of a Columbia electric car.

The available documentation does not give a complete picture of the car's structure. Drawings and diagrams of the particular model in the collection of the Polytechnic Museum are missing.

B. Fieldwork and preliminary results

The first stage of the field work was photographing the electric vehicle. A series of shots were taken on a Canon 450D camera with a 50 mm focal length lens. The shooting was carried out in several stages:

- Photographing from a long distance to obtain the lowest possible perspective distortion; the photos were subsequently used to create orthophotography and 3D modeling.
- Circular photographing of the object. Initially, it was intended to create a car model using photogrammetry methods. Later, these images were used in 3D modeling as a reference, as well as to create textures for the model.
- Detailed photography for subsequent polygonal modeling of small elements using photogrammetric methods.

Due to the uneven illumination of the pavilion with the car, the images from each point were taken with different shutter speeds to store as much information as possible in different areas of the photographs. Images taken from one point were subsequently converted into one frame with high dynamic range [10] in Adobe Photoshop.

When processing the photos, it became clear that it is impossible to obtain a model of the entire car by the photogrammetric methods due to the large number of small parts, often overlapping each other. It also turned out that taking measurements manually with so many small parts is impractical. In this regard, we decided to apply laser scanning to obtain a three-dimensional point model of the exhibit. This point cloud was used later for polygonal modeling to control geometric parameters.

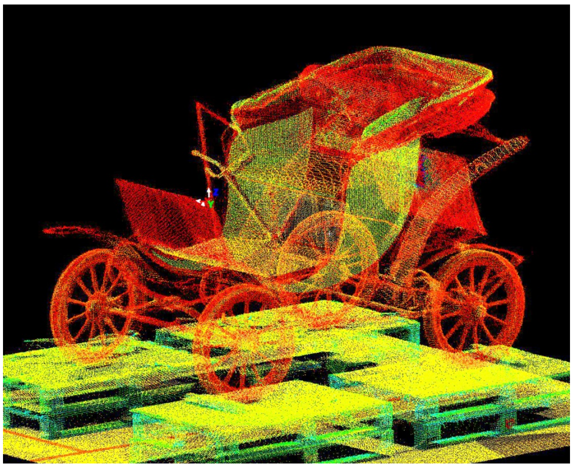

Fig. 3. Laser scan result: 3D point model of an electric car (point cloud).

The survey was carried out using a Leica P20 scanner, the primary data processing was performed using the Leica Cyclone software, Fig. 3. To access the bottom of the electric vehicle, podiums of wooden pallets were built, which made it possible to photograph the parts under the car. The car was scanned in two versions: with the roof up and with the roof down. Several authentic spare parts of the car were scanned separately (voltmeter and brake components), since they are currently stored outside the vehicle.

C. 3D modeling technique

When processing the results of laser scanning, it became clear that the geometric characteristics of the exhibit are not stable and change when it is moved from place to place (which was repeatedly made in the process of photographing and laser scanning). Moreover, the geometric characteristics of the exhibit do not correspond to its original state, due to dilapidation and the last restoration.

In this regard, we decided to abandon the creation of a metrically accurate model of the entire car. We developed metrically accurate models of individual elements of the car, but in preparation of a complete model, the emphasis was on creating a visually realistic model of the car and an accurate reconstruction of the operation of its mechanical systems.

Therefore, based on the first stage of fieldwork and preliminary processing of the results obtained, we suggested the following method for modeling the object:

- Creation of a metrically accurate 3D model of the preserved historical part of the object and individual elements using a combination of automated methods (laser scanning and photogrammetry) and manual modeling with the priority of geometric accuracy;
- Visually realistic reconstruction of the entire car (including the internal structure) using the preserved documentation and manual modeling with the priority of reconstructing the historically accurate appearance of the object, including mechanically correct reconstruction of moving parts.

D. Results of the 3D modeling

As a result of modeling, a full polygonal 3D model of the electric car was created, with the exception of the elements of the electrical circuit, Fig. 4.

Fig. 4. Textured 3D model of the Columbia electric car.

In the course of the work, the missing control elements were also virtually recreated: the main steering rod and the brakes of the rear wheels. We used archival photographs, photographs of a similar car from the Bewley Museum, as well as 3D models of the surviving parts of the brake mechanism. These elements were modeled and positioned on a 3D model of the car, taking into account the possibility of their mechanical interaction, Fig. 5.

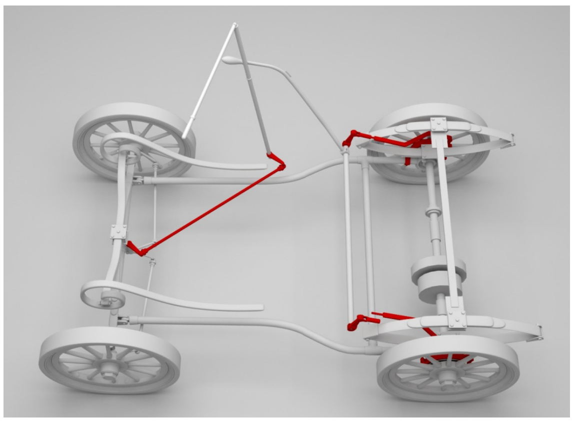

Fig. 5. Missing elements recreated virtually in 3D model: main steering rod and rear wheel brakes.

At this stage, we identified inconsistencies between the construction of the restored car and its original design. For example, during the 2007 restoration, the brake lever was wrongly attached from the outside of the axle bracket. In the 3D model, the real design was reconstructed: the right link of the rear brakes was attached from the outside of the axle bracket, while the brake lever was attached from the inside of the axle bracket, Fig. 6.

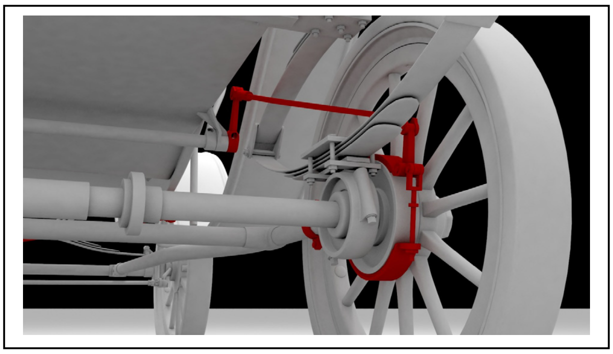

Fig. 6. Brake mechanism rebuilt using 3D modeling of existing dismantled parts and photos of a similar car from the Bewley Museum.

All parts of the virtual model are modeled taking into account their interaction, which allows the model to be used to demonstrate the principles of the car's mechanisms. For example, we created 3D animation of turning the front wheels of the car by controlling the steering lever.

E. Interactive web application

In addition to the 3D model, we have developed an interactive application that provides an interactive demonstration of the created 3D model, Fig. 7. The application allows you to view a 3D model of a car from any angle of view, enable or disable the visibility of various elements of the car to study its device, view the animation of the steering system, and display information about the elements of the car.

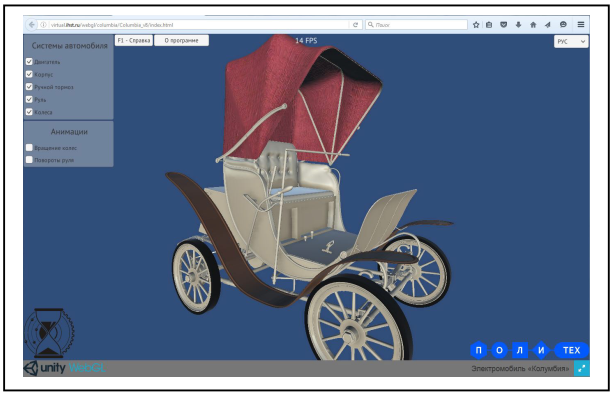

Fig. 7. Interface of the web application. Control panel is on the top left.

The ability to turn on and off the display of various elements of the car can be used to study the design of the exhibit. Using the buttons on the keyboard, you can control the rotation of the wheels and turn the steering mechanism of the car. The application interface is available in Russian and English. The Internet version of the application is available at the link: http://virtual.ihst.ru/columbia.html.

The application is based on the Unity 3D engine and integrated into the web site using the WebGL technology (that is, without using a plugin). The application is launched when a web page is opened in a browser; no software installation is required by the user.

KULIBIN'S PEDAL CARRIAGE

Some historic vehicles have not survived in their original form and can only be reconstructed according to drawings. This narrows the possibilities of modeling (in comparison with those described above), and poses a slightly different set of tasks for the researcher and the developer of the virtual 3D model. Russian self-propelled carriages of the 18th century are one example of such vehicles.

Self-propelled carriages that use human muscle power to spin wheels have been known since ancient times. In the 18th century, self-propelled carriages were invented in all leading European countries. Numerous drawings have been preserved that allow us to reconstruct their appearance and principles of operation [11].

Mechanisms of Russian inventors of the 18th century - Leonty Shamshurenkov (1687-1758) and Ivan Kulibin (1735-1818) - also take a worthy place in this row. The inventions of the Kulibin are described in more detail, which allows an attempt to be made to reconstruct them.

A. Description of historical documentation

Ivan Petrovich Kulibin worked as the head of the mechanical workshop of the St. Petersburg Academy of Sciences since 1769. He began developing pedal carriages in the 1780s, a prototype was created in 1791. The carriages were designed to amuse noble people. Despite the fact that Kulibin's mechanisms were not widespread, they had a great influence on the further development of mechanics in Russia.

The personal fund of Kulibin in the St. Petersburg branch of the Archive of the Russian Academy of Sciences contains 1036 storage units [12], including drawings of pedal carriages on 8 sheets, relating to the period 1780–1790s. The surviving drawings show 3 models of carriages: one four-wheeled and two three-wheeled (with and without a flywheel). The three-wheel carriage with flywheel is available in two versions.

There is also a description of the principle of operation of a three-wheeled carriage with a flywheel, which was given by Semyon Kulibin (son of Ivan Petrovich Kulibin): "The servant stood on the heels in attached shoes, raised and lowered his legs alternately, without almost any effort, and the vehicle rolled pretty quickly" [13].

Thus, based on the analysis of the surviving drawings and descriptions, it can be concluded that in Kulibin's pedal carriages, the muscular force of the legs was converted into rotation of the flywheel and wheels using two rods that connected the pedals and flywheel.

None of Kulibin's self-propelled carriages has survived. Various researchers have repeatedly attempted a three-dimensional reconstruction of Kulibin's carriages from the surviving drawings [14].

The exact reconstruction of Kulibin's mechanisms according to the surviving drawings is a difficult task due to their incompleteness and ambiguity. Almost no drawings show dimensions, scales, legends and specifications. The text placed directly in the drawings is partially lost.

The work with the drawings is additionally complicated by the incompleteness and inaccuracy of fixing the structural parts (running gear, brakes, and wheels).

A drawing of a three-wheeled carriage without a flywheel and a drawing of a four-wheeled carriage have survived only in one projection, which makes it almost impossible to reconstruct them reliably. Therefore, almost all researchers tried to reconstruct a three-wheeled carriage with a flywheel that is shown in several surviving drawings in different projections.

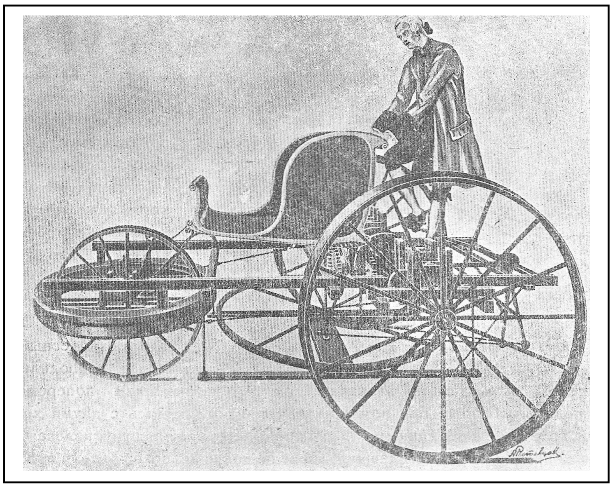

Fig. 8. Reconstruction by I. A. and A. A. Rostovtsev (1935), drawing [15].

In 1935-2015 several different reconstructions of Kulibin's three-wheeled carriage with a flywheel were carried out, both in the form of drawings [15-17], Fig. 8, and in the form of full-scale models (replicas) of various scales [18-20], Fig. 9. They all differ slightly from each other, due to different interpretations of the surviving drawings by different researchers.

Fig. 9. Reconstruction by A. S. Isayev (1955), replica 1:5 [18].

For example, the design of the seat is different for all authors, as well as the fastening of the body to the chassis. A common feature of all reconstructions in the form of drawings in axonometric projection is the absence of a steering wheel, while it is present on the surviving historical drawings (albeit fragmentarily).

We have studied all these reconstructions, and made our own attempt to reconstruct Kulibin's carriage in the form of a virtual 3D model [14].

B. 3D modeling technique

We made our own attempt to reconstruct a three-wheeled pedal carriage with a flywheel. During the modeling process, the existing drawings in two projections were aligned with each other in three-dimensional space.

After that, we modeled the individual elements according to the dimensions of the drawing; the 3D model of each element was compared with both drawings, Fig. 10. This made it possible to maintain the relative scales of the parts, even without knowing their exact dimensions.

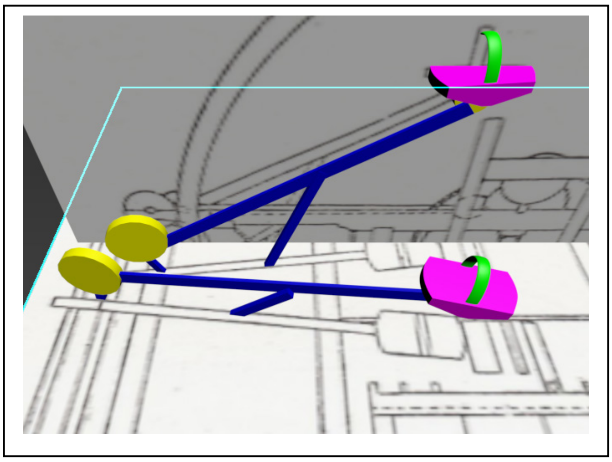

Fig. 10. Pedals 3D model attached to two drawings.

C. Results of the 3D modeling

A general view of the full 3D model of a three-wheeled pedal carriage with a flywheel is shown on Fig. 11. Different elements of the model are painted in different colors. The textured version of the 3D model is shown on Fig. 12.

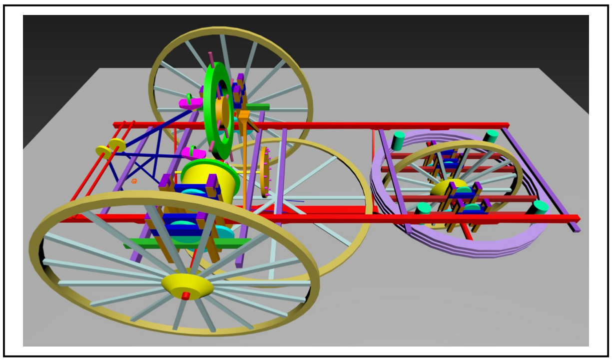

Fig. 11. 3D reconstruction of a three-wheeled pedal carriage.

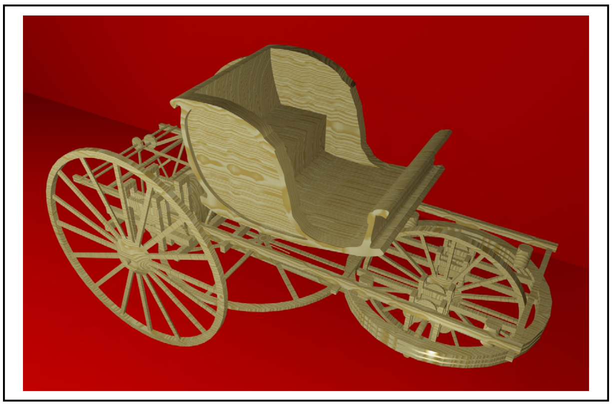

Fig. 12. 3D reconstruction of a three-wheeled pedal carriage with a body (rendering of a model with a wood texture)

CONCLUSIONS

The use of a combination of modern methods of collecting and processing spatial information and virtual 3D modeling allows for a virtual reconstruction of technical artifacts, which is safe for them and is not expensive compared to physical restoration. Virtual reconstruction allows you to restore the historical appearance of the object, to demonstrate its structure and principle of operation.

With a virtual 3D modeling, we can save information about the preserved object (or its parts), perform a detailed historical and technical study of the structure and virtual reconstruction of the lost parts. The virtual 3D model can be used to prepare for the physical restoration of the object (for example, to check the mating of the restored mechanical elements, or to visualize the recreated textures and furniture). In addition, based on a virtual 3D model, a freely accessible interactive web application can be created, which allows you to present a 3D model of a technical artifact to the public.

In the case of the Columbia electric car, we created a visually and historically realistic 3D model of the electric car, including a virtual reconstruction of the lost mechanical elements. We virtually animated the action of the mechanical components of the car and demonstrated the operation of the steering system. The created model reproduces the visually accurate historical appearance of the car, and allows you to demonstrate its structure and principle of operation. This model can be used to plan the subsequent physical restoration of the vehicle, as well as to display this artifact of technology to the public.

In the case of Kulibin's pedal carriage, we have shown that with the help of simple techniques and modeling tools it is possible to "revive" inventions of the past, to visualize drawings in the form of interactive computer 3D models. The toolkit necessary for this is very simple and accessible even to a schoolchild.

Computer 3D modeling has a number of advantages over full-scale prototyping. It is significantly cheaper and easier than creating full-scale models, and is available to a wider range of people, including schoolchildren and students. A virtual 3D model can be easily made in different versions to test different spatial hypotheses and different interpretations of the preserved drawings; it can be animated to show the work of all mechanisms in motion. A virtual 3D model can be made available over the Internet to a large number of people and thus we can widely present the engineering heritage to the public. Finally, the creation of a virtual 3D model can be the first step towards full-scale prototyping, including 3D printing.

Visualization and "revitalization" of historical inventions with the help of modern interactive computer graphics allows attracting a wide range of people who do not have direct access to archival materials to the study of technical heritage, as well as vividly and excitingly present the technical realities of past centuries to the public. Thus, virtual modeling, as well as physical prototyping, provides an important contribution in the study of technical heritage.

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