ISSN 2307-2539 (Print)
ISSN 2712-8202 (Online)

Том 35 № 3 • 2023

ТЕОРИЯ И ПРАКТИКА АРХЕОЛОГИЧЕСКИХ ИССЛЕДОВАНИЙ

Барнаул

Издательство
Алтайского государственного
университета
2023

Журнал основан в 2005 г., с 2016 г. выходит 4 раза в год.

Учредителем издания является ФГБОУ ВО «Алтайский государственный университет».

Адрес издателя и редакции:
656049, Алтайский край, Барнаул, пр-т Ленина, 61, каб. 211,
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Утвержден к печати Объединенным научно-техническим советом АГУ.

Зарегистрировано Федеральной службой по надзору в сфере связи, информационных технологий и массовых коммуникаций:
регистрационный номер
ПИ № ФС77-80671
от 07 апреля 2021 г.

ISSN 2307–2539 (Print)
ISSN 2712–8202 (Online)

Vol. 35 (3) • 2023

THEORY AND PRACTICE OF ARCHAEOLOGICAL RESEARCH

Barnaul

Publishing house
of Altai State
University
2023

The journal was founded in 2005.
Since 2016 the journal has been published 4 times a year.

The founder of the journal is Altai State University.

The address of the publisher and the publishing house: office 211, Lenina av., 61, Barnaul, Altai region, 656049, Russia, tel.: (3852) 291-256.
E-mail: tishkin210@mail.ru

Approved for publication by the Joint Scientific and Technical Council of Altai State University

Registered by the Federal Service for Supervision in the Sphere of Communication, Information Technologies and Mass Communications:
PI Registration number No. FS 77-80671
dated April 7, 2021

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УДК 902, 004.925.83
https://doi.org/10.14258/tpai(2023)35(3).-01
EDN: YVRHEG

TECHNOLOGY OF COMPUTER RECONSTRUCTION OF ARCHAEOLOGICAL FINDS, SIMILAR TO OBJECTS OF ROTATION (ON THE EXAMPLE OF A CERAMIC VESSEL)

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Abstract. The article proposes the technology of computer reconstruction of the most probable form of archaeological finds, if their shape is similar to objects of rotation. Reconstruction is carried out on a virtual 3D model — a digital copy of a real object obtained by photogrammetry. For reconstruction, it is enough to have a small area of a real object with well-defined radii of curvature. The smaller the plot, the more variants of the restored forms will be and the more they will differ from each other. The restored parts can be printed on a 3D printer and complement the existing object.

This technology can help the researcher in reconstruction and in assessing the adequacy and geometric correctness of the products, he is restoring. This is especially important when a large volume of the reconstruction object is lost, when the restorer does not see the full geometry of the object.

The proposed method is a special case of the method of mathematical modeling, the purpose of which is not to replace the experience of a specialist, but to provide him with a tool that allows him to delve more deeply into the essence of the studied phenomena.

Keywords: computer reconstruction of vessels, photogrammetry, mathematical modeling

Acknowledgements: the work was carried out with the financial support of the Russian Academy of Sciences (project No. 22-18-00470 "The World of Ancient Nomads of Inner Asia: Interdisciplinary Studies of Material Culture, Sculptures and Economy").

For citation: Bondarenko S.Yu. Technology of Computer Reconstruction of Archaeological Finds, Similar to Objects of Rotation (on the Example of a Ceramic Vessel). *Teoriya i praktika arheologicheskih issledovanij = Theory and Practice of Archaeological Research.* 2023;35(3):9–22. (*In English*). https://doi.org/10.14258/tpai(2023)35(3).-01

ТЕХНОЛОГИЯ КОМПЬЮТЕРНОЙ РЕКОНСТРУКЦИИ АРХЕОЛОГИЧЕСКИХ НАХОДОК, ПОДОБНЫХ ОБЪЕКТАМ ВРАЩЕНИЯ (НА ПРИМЕРЕ КЕРАМИЧЕСКОГО СОСУДА)

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Резюме. В статье предложена технология компьютерной реконструкции наиболее вероятной формы археологических находок, если их форма подобна объектам вращения. Реконструкция проводится на виртуальной 3D-модели — цифровой копии реального объекта, полученной методом фотограмметрии. Для реставрации достаточно иметь небольшой участок реального объекта с хорошо определяемыми радиусами кривизны. Чем меньше участок, тем больше будет вариантов реконструируемых форм и тем более они будут отличаться друг от друга. Реконструируемые части можно распечатать на 3D-принтере и дополнить существующий объект.

Данная технология может помочь исследователю в оценке адекватности и геометрической правильности реставрируемых им изделий. Это особенно актуально при утрате большого объема объекта реставрации, когда реставратору не видна полная геометрия объекта.

Предлагаемый метод является частным случаем метода математического моделирования, цель которого не заменить опыт специалиста, а дать в его распоряжение инструмент, позволяющий более глубоко вникнуть в суть исследуемых явлений.

Ключевые слова: компьютерная реконструкция сосудов, фотограмметрия, математическое моделирование

Благодарности: работа выполнена при финансовой поддержке РНФ (проект №22-18-00470 «Мир древних кочевников Внутренней Азии: междисциплинарные исследования материальной культуры, изваяний и хозяйства»).

Для цитирования: Бондаренко С.Ю. Технология компьютерной реконструкции археологических находок, подобных объектам вращения (на примере керамического сосуда) // Теория и практика археологических исследований. 2023. Т. 35, №3. С. 9–22. https://doi.org/: 10.14258/tpai(2023)35(3).-01.

Introduction

The development of research methods is currently impossible without the use of information technology. These technologies play a special role in areas related to experimental research. In archaeology, special attention is paid to the study of material objects. However, there is a limited possibility of access to the most interesting and unique finds, as well as, often, the impossibility of studying and removing many parameters, due to the complexity of measurements or even the need for complete or partial destruction of the object of study.

One of the ways to solve this problem can be the technology of digitizing a real object — creating a digital copy, which will allow, at reasonable material costs, to ensure high quality compliance of the digital model with the real object. And also, it will allow to conduct a wide range of its study, to obtain many characteristics without direct contact with the object of study.

A number of researchers are engaged in the problem of documenting and researching archaeological finds using three-dimensional modeling (see, for example: Avdeev, Svoysky, Romanenko, 2019, pp. 135–152; Svoysky et al., 2020, pp. 8–24; Svoysky et al, 2021, pp. 131–136; Zaitsev et al, 2021, pp. 42–43). The relevance of this approach is also confirmed by the fact that in many cases, researchers use both modeling systems and direct measurement systems, which is often economically unjustified or simply impossible in cases where, for example, the object of study has a large size and mass.

For the most part, computer modeling makes it possible not to replace, but to expand the possibilities of full-scale study of an object, which are impossible or very difficult to obtain directly during "live" study. The main requirements are that all simulated objects must be brought into strict compliance with the original!

Currently, the possibilities of professional three-dimensional graphics are actively used to create a relevant mathematical model. Creating such a model is not an easy task and one of the ways to solve it can be called photogrammetry — a way to obtain a 3D model through the process of recording, measuring and interpreting photographic images (Singatulin, 2013, pp. 148–152; Sapirstein, Murray, 2017, pp. 337–350). This technology is a development and the next generation of 3D scanning, but it is not limited to the size of the object and allows you to digitize both very small and huge objects.

The advantages of photogrammetry include high measurement accuracy, the degree of automation of the measurement process, high objectivity of the results, the possibility of remote measurements, etc.

As a result of photogrammetry, a highly polygonal 3D object is created, consisting, it happens, of more than 100 million polygons — with the size of one polygon about 0.5 mm, which allows us to judge the high reliability and details of the model. After building a mathematical 3D model, it becomes possible to download it into professional software for subsequent work.

How can such a model help the researcher, except that he may not have access to the original? There are several areas of work and many tasks that can be solved, or at least, the solution of which can be simplified with the help of computer analysis.

One of the problems can be considered the human factor, and the fact that from a subjective description, as a rule, it is difficult to understand the basic assumptions under which the hypothesis expressed by the researcher remains valid. As a consequence, a characteristic feature of researchers is constant discussions, sometimes becoming more significant than the discussion of the subject of research itself. A subjective description of an object is based on a chain of more or less logical statements, often based on personal experience, and may not lead to clear and unambiguous conclusions. Mathematical formalisms, on the other hand, make it possible to reveal hidden potentially contained information, since they make it possible to calculate the parameters and quantities being tested and obtain new data. The introduction of models provides a strict formulation of both the concepts used and the logic of the study, leads to a clearer statement of the problem and acts, in the future, as an information technology tool for dispute resolution.

Problem statement

In this article, we would like to consider one of the problems that we began to consider earlier (Tishkin, Bondarenko, Mu, 2021, pp. 54–61) and which can be solved using computer modeling and mathematical methods of construction — this is the task of restoring archaeological finds.

Very often archaeological finds come to archaeologists in a destroyed or even ruined form. Many of them fall into the cultural layer already in a broken state-having split into fragments, parts of which may not exist at all; besides, objects can deform, losing their original geometry.

Solving the problem of computer modeling of the reconstruction process of archaeological finds and at least partial automation of scrupulous work with the excavation material, which restorers are patiently engaged in, is an urgent direction of automation of archaeological research.

I would like to note that there is no standard software with which it would be possible to perform a recovery with the determination of the level of reliability of the result. It took us more than two years of hard work to develop our algorithm described in this article and allowing us to find at least a partial solution to this problem, during which a simultaneous synchronous analysis of several dozen digital copies was carried out. As a result, software was created using MAXScript and Python, running under Autodesk 3ds Max and allowing you to automate and visualize this process.

When developing a technique for restoring the geometric shape of objects, our ultimate goal was to build mathematical models of the geometry of these objects. These models should help the restorer in conducting research, mainly for making decisions based on preliminary computer visualization, and also make it possible to study many physical properties of an object by setting up numerical experiments.

Only a restored model with a fully restored geometry will allow these studies to be carried out — to determine the mass-centering characteristics of the object, to perform measurements, to set up a numerical experiment to determine the stress-strain state, stability, thermal, optical and other properties of the object. Undoubtedly, in order to do this, it will still be necessary to supplement the geometric model with the necessary physical properties and a model of the conditions for its use.

According to the geometric model, it is possible to calculate the manufacturing technology and mechanical processing of the object, check the very possibility of manufacturing the object in this way and the quality of this manufacture. In addition, a graphical simulation of the manufacturing process is possible. But in order to do this, in addition to geometric information, you need information about the proposed technological process, equipment and much more related to production.

The problem of solving such problems, especially in which physical laws are used, leads to differential and integral dependencies, finding solutions to which is an extremely difficult task.

In this article, we will not touch on calculations related to physical processes and consider the reconstruction of purely geometric characteristics of objects that do not require additional information.

Object Analysis

As an example of an object of reconstruction, we will give a ceramic vessel with partially lost elements that make up 57% of the volume of the vessel's material. The complexity of the reconstruction process is that the main percentage of losses falls on a single area, and is not divided into many small ones, the reconstruction of which is obvious and does not cause large errors (Malkov, Kharinsky, 2018, pp. 109–114) (Fig. 1).

To set the process of computer reconstruction, it is necessary to develop a certain logic, according to which the process itself will take place. Of course, given that the ceramic vessel is purely handmade and its geometry is slightly limited by some technology, it seems that it is impossible to accurately develop a logic for restoring such a large percentage of a single lost area. Because, theoretically, the lost part of the vessel can represent anything or vary within limits that will not allow us to assert that the reconstruction process restores the actual shape of the vessel.

Fig. 1. Glued ceramic vessel

Рис. 1. Склеенный керамический сосуд

The restorer, carrying out this work, relies on his experience, which is based, however, not only on a large number of objects restored by him, but also on an understanding of the manufacturing process and on an idea of what the product should be in a hypothetically ideal case, taking into account the technology and quality of the work of this master. That is, to understand the author's idea and take into account his real capabilities. It is the last statement that can be used to set the logic of the computer method of reconstruction, which needs a clearly defined task and a clear execution scheme.

Taking this into account, for the computer reconstruction, we assume that each of the cross-sections of the vessel is a geometric place of points tending to a circle. But, since it never reaches a circle due to the manufacturing error, and the impossibility with this technology, we will try to determine the maximum deviation from roundness for the entire vessel. To do this, we determine the greatest distance from the points of the real profile of the vessel to the adjacent circle.

Since it is possible to draw an arc through any three points, and, consequently, a circle, we will find such points on the preserved section of the corolla of the vessel and build circles. To reduce the number of such circles, take the distance between the points greater than 1 cm. Figure 2 shows two such circles giving the maximum error. In fact, there are much more of them.

We will perform the same operation on all cross-sections of the vessel, in increments of 1 cm, in order to determine the zone of theoretically possible finding of vessel points.

As a result, the task of restoring the lost particles of the vessel will be the task of constructing a surface with well-defined radii of curvature at each point and in each segment.

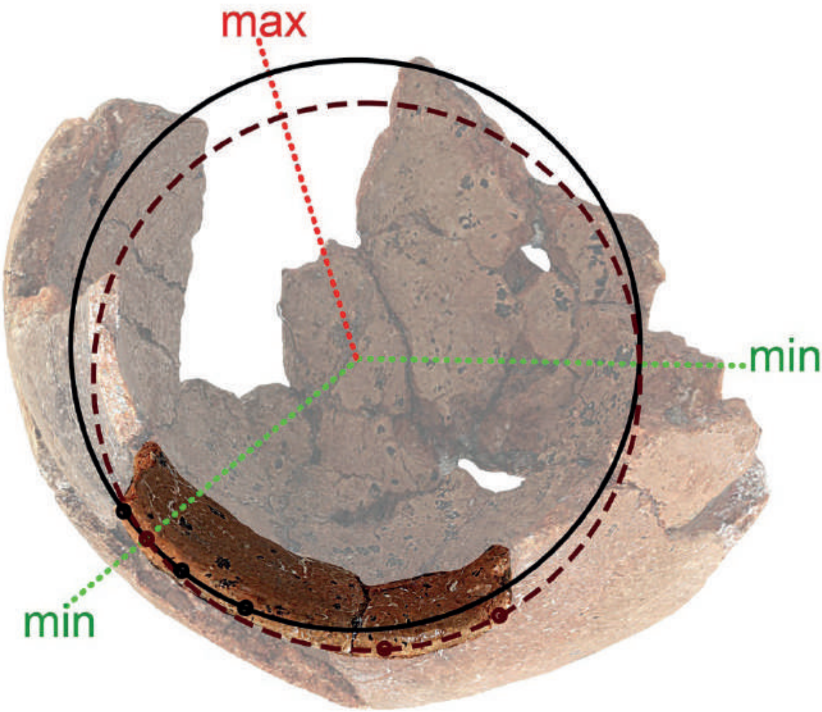

Fig. 2. Overall circles

Рис. 2. Габаритные окружности

Let's analyze the shape of the vessel to determine the maximum deviations that already exist in the shape of the vessel. The analysis will be carried out with the help of orthogonal longitudinal-cross sections passing in the places of reference points, so that these sections most accurately determine the shape of the vessel. Such an algorithm for constructing a surface using cross sections is, in essence, a template method (the method of dependent formation of shapes and sizes of mating elements), and is used to construct complex mathematically indescribable spline surfaces (Samsonov, Tarasov, 2000, pp. 33–38) (Fig. 3). Within a given surface, an infinite number of similar sections can be constructed, differing in the angle of rotation and their number, and the accuracy of the calculation is limited only by computing power and calculation time.

Analysis of these sections shows that, although, yes, of course, the vessel is not a body of rotation and is not made on a potter's wheel, but the manufacturer obviously sought to make it smooth and beautiful, that is, to achieve the geometry of the body of rotation. Let's take this statement as the limit of calculations, taking into account the errors of skill and technology inherent in the geometry of this vessel.

The definition of quality parameters, that is, the "mastery" of manufacturing, consisting of the capabilities of technology and personal characteristics, from the point of view of geometric calculations, is reduced to determining the error from the geometry that the master wanted to achieve. In this vessel, a certain standard deviation in cross sections and conditional centers of rotation for each of the sections vary within 6% of the roundness in all sections.

Fig. 3. Example of vessel template method

Рис. 3. Пример проведения плазирования сосуда

By the way, conducting exactly such an analysis can show this fact. When directly gluing, it is not visible to the eye.

Taking into account this information and assuming that this pattern is clearly preserved in the lost geometry of the vessel, we can build a corridor of maxima and minima coordinates for each point of the vessel and then determine the main curvatures of the surface, which are the maximum and minimum curvatures, respectively.

Building a point cloud

In order to start our constructions, we first need to build a conditional point cloud, that is, to determine an array of coordinates, on the basis of which it will be possible to build a surface later. To construct any point, it is enough to determine its three coordinates and have functions for performing operations on its radius vector. And we will need to classify the point, that is, to determine whether the point belongs to the area of the conditional surface of the vessel, taking into account the established magnitude of errors. To determine whether a point belongs to a two-dimensional surface, it is necessary to find all points belonging to all sections of this surface with the condition that they intersect with the boundaries of the region. This is a very resource-intensive task for a computer, given the potentially huge number of such points and options, so we determined the step of the sections in 1 mm, which allowed us to reduce the number of analyzed sections to a fairly small number, and, further, it is already easy to determine whether the point in question belongs to a given area.

Figure 4 shows the primary cross-section points. In fact, the drawing has already selected the points on which the construction will go. A complete point cloud is not indicative. After constructing the points, an iteration is carried out — a repetition of the mathematical operation of constructing the points, but along another of the possible trajectories. The iteration is repeated many times until all possible trajectories are determined in the specified accuracy.

Of course, the point cloud provides a very wide variety for further construction and generally defines the surface very ambiguously, so we need to introduce criteria for determining the applicability of this point and the possibility of its further use as a surface vertex.

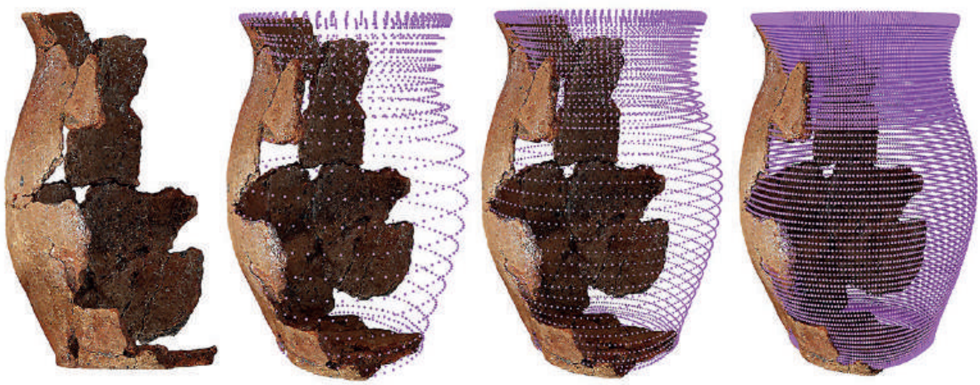

Fig. 4. Point cloud (only the points on which the construction will take place are presented)

Рис. 4. Облако точек (представлены только те точки, по которым будет идти построение)

The construction of a grid of curves

This point cloud defines the surface very ambiguously. In this area of parameter changes, a lot of surfaces can be built, and for the reconstruction of the lost part of the vessel, which is a complex variable shape, it is necessary to first carry out preliminary constructions that simplify the further process and allow you to select only spatial lines and points of practical importance, that is, lying in the area of the specified parameters.

In the subsequent construction of the surface, two families of orthogonal curves are constructed at their intersection point for different values of the maximum and minimum criteria, which form the grid.

Since many different curves can be drawn through the constructed point cloud, and at the same time, the value of the reliability of their construction will have the same value, despite the different shape and curvature, the only selection criterion here can only be that all the radii of curvature of such a curve should be in the interval, maxima and minima the normal cross-section at this point.

For our work, we used NURBS curves (Non-uniform rational basis spline) constructed on a set of non-equidistant nodes. The NURBS curve is a linear combination of piecewise polynomial functions of a given degree and allows you to build curves of a given order of smoothness (Schneider, 2014).

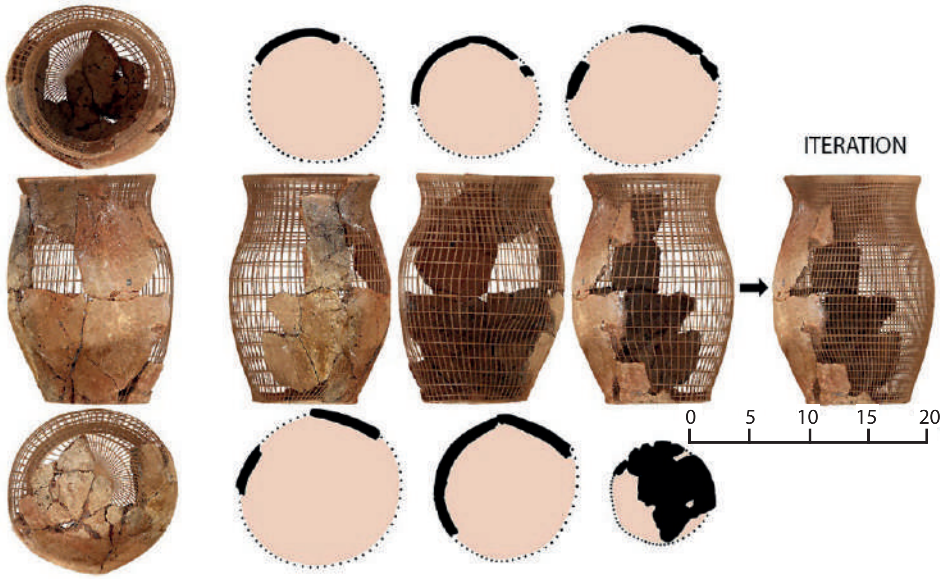

Fig. 5. A family of orthogonal NURBS-curves having the maximum degree of adequacy

Рис. 5. Семейство ортогональных NURBS-кривых, имеющее максимальную степень адекватности

Let us draw a curve by connecting a series of points for this. At the same time, the curvature and shape of this line will vary depending on which points we used as reference points for this curve. A huge number of similar curves can be constructed on the point cloud we have built, from which it is necessary to choose adequate ones.

The following can be taken as the definition of the main criteria for curves: curves for which the curvature of the normal cross-section does not exceed the corridor of maximum and minimum values in the range defined by us can be considered adequate.

Given that the functions of constructing such curves are not independent, and they are interconnected by equations, there will not be so many families of curves that fully satisfy the conditions where the next point of the line should not go beyond the displacement sphere. And the selection of curves with the maximum degree of adequacy is not difficult even in manual mode. Which is preferable, since a computer still cannot completely replace a person in the field of fuzzy logic and can only give him all possible trajectories for consideration (Fig. 5).

The figure shows the displacement of the vessel from the axes of symmetry, which looks strange, but is, oddly enough, the only options for passing networks through all points of the glued vessel while preserving the criteria of radii and points of conjugation of curves. This may be due to both the curvature of the actual vessel and the error of gluing parts by the restorer. In this case, it is necessary to conduct further research in order to find the cause of this unevenness. Computer reconstruction solves issues "as is" and is not able to take into account the fact of imperfection of the source data, without human intervention.

Building a surface

The next stage of reconstruction is the construction of the surface on the resulting grid of orthogonal NURBS curves.

NURBS surfaces interpolate a given shape well and are suitable for generating smooth surfaces, although they are more massive, complex and take longer to visualize. The basis of our NURBS surface will be isoparametric curves that determine the curvature of the surface, the shape of which is determined by the position of the points through which it passes.

The construction of a mathematical model of the surface is similar to the construction of curves. We restrict the surface functions to certain values of its parameters and obtain geometric information about the surface at a point corresponding to these parameter values. If some function of the surface allows the parameter values to go beyond the definition area, then this variant of the surface is discarded and does not participate in further consideration.

This construction is carried out by several iteration levels until the accuracy is sufficient. In our case, the accuracy of the photogrammetry made by us was accepted — 0.32 mm.

These surfaces are limited by the contours of the already existing surface of the vessel and its parameters are allowed to take values only inside the area bounded by these contours.

Since when searching for the parameters of the intersection line, only the overall rectangle of the outer contour of the vessel grid can be used as a boundary, after constructing the intersection lines, the surface was checked for intersection with boundary contours and truncated by these contours, retaining only those parts that lie inside the areas.

After constructing the geometry of the vessel surface, the resulting surface was textured to give a more realistic appearance (Fig. 6), by smoothly filling the selected part of the image with content similar to adjacent texture areas. This technology has been known for a long time and is widely used in graphics packages.

The final result reflects both the full possible appearance of the vessel (Fig. 7) and its cross-sections. It should be noted that computer modeling using this algorithm does not provide a single variant of the shape of the vessel, however, the set of proposed forms does not differ so much. The maximum deviation of the variants of this vessel is ± 6 mm. The RMS value is ± 4mm. This difference is of interest for direct work with the 3D model and further study of the characteristics of the vessel, but it is not essential for visualization.

The reconstruction of the geometric shape made it possible to determine all the characteristics of the vessel (Tab. 1) and detect problems of gluing, which is an indicator for further actions to study this vessel. It also became possible to restore the shape of a real vessel by 3D printing the missing fragments and working directly with a full-scale object.

Reconstruction absolute dimensions of the vessel, mm
Реставрационные абсолютные размеры сосуда, мм

Parameter	Min, мм	Max, мм
Diameter of the corolla	118	126
Diameter at the base of the neck	108	118
The largest diameter on the body	142	149
Diameter on the bottom	87	91
Overall height	207	210*
Neck height	22	25
Shoulder height	83	73
Height of the bottom part	102	112
Wall thickness	5	7
Bottom thickness	9	13

*The size is obtained from the real part of the vessel.

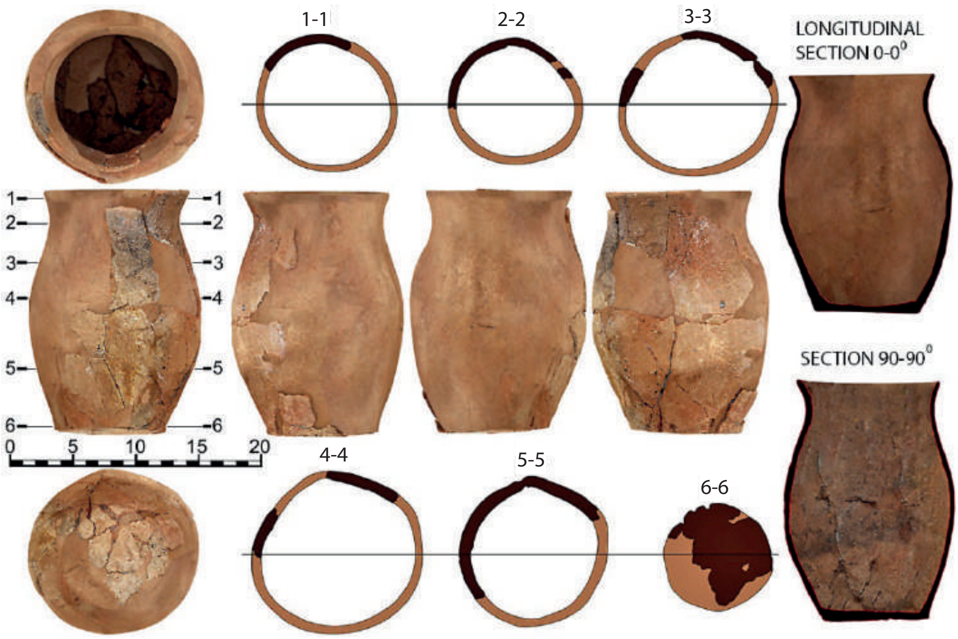

Fig. 6. The final result of the reconstruction of the vessel

Рис. 6. Конечный результат реставрации сосуда

Fig. 7. Isometric view of the vessel

Рис. 7. Изометрический вид сосуда

Conclusion

Computer reconstruction is still a rather laborious and imperfect process with no general methodology and algorithms. And in this article, we wanted to propose a logic from which we can proceed to create mathematical models of reconstruction technology for objects close to objects of rotation. For reconstruction, it is enough to have a small area of a real object with a well-defined radius of curvature. The smaller the plot and the closer the points on the arc, the more variants of the restored forms will be and the more they will differ from each other.

And, although, of course, we understand that reconstruction is nothing more than a variant of predicting and determining the most probable, and not the real form, this technology can help the researcher in restoring and, most importantly, in assessing the adequacy and geometric correctness of the products restored by him. This is especially important when a large volume of the reconstruction object is lost, when the restorer does not see the full geometry of the object.

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The article was submitted 27.05.2023;
approved after reviewing 10.08.2023;
accepted for publication 14.08.2023.
Статья поступила в редакцию 27.05.2023;
одобрена после рецензирования 10.08.2023;
принята к публикации 14.08.2023.

Научное издание
Журнал

ТЕОРИЯ И ПРАКТИКА АРХЕОЛОГИЧЕСКИХ ИССЛЕДОВАНИЙ

Том 35 № 3 2023

Редактор: *Н. Ю. Ляшко*
Перевод и редактирование текстов на английском языке, References: *Е. А. Россинская*
Подготовка оригинал-макета: *Ю. В. Луценко*

Журнал распространяется по подписке через каталог «Урал-Пресс», индекс BH018441
Цена свободная

Подписано в печать 25.09.2023.
Дата выхода издания в свет 27.10.2023.
Формат 70×100 $^{1}/_{16}$. Гарнитура Minion Pro. Бумага офсетная.
Усл. печ. л. 18,16.
Тираж 500 экз. Заказ 631.

Отпечатано в типографии Алтайского государственного университета
656049, Барнаул, ул. Димитрова, 66