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Graphical 3D Reconstruction of the Tustan Rock Fortress, Ukraine, in the Study and the Promotion of Architectural Heritage Sites

Trójwymiarowa rekonstrukcja graficzna skalnej twierdzy Tustań w Ukrainie w badaniach i promocji obiektów dziedzictwa architektonicznego

Keywords: rock fortress, Tustan, 3D graphical reconstruction, architectural heritage sites

Słowa kluczowe: skalna twierdza, Tustań, graficzna rekonstrukcja 3D, dziedzictwo architektoniczne

Introduction

Graphical reconstruction, as a method of reproducing the original hypothetical appearance of an architectural monument, is not something fundamentally new. It originated in the Renaissance and became a separate type of architectural activity. The graphical reconstruction of architectural monuments became a completely independent direction at the end of the eighteenth and in the nineteenth centuries when large-scale studies of the monuments of the ancient worldbegan. 3D reconstructions of architectural monuments have a much shorter history and are associated with the development of software and hardware technical capabilities. It can be assumed that the original foundations were laid in the United States in the 1960s when Ivan Edward Sutherland developed the Sketchpad program at the Massachusetts Institute of Technology (MIT) in Cambridge, MA. With the help of the program, it became possible to transform two-dimensional objects into three-dimensional ones using a keyboard and the so-called "light pen" and "interactive light terminal" [Heike 2016]. The 1980s marked a turning point in the use of computer technology in archaeology. In 1985, Bernhard Frischer drafted a report on the use of 3D technology at the Computer Applications in Archaeology (CAA) conference. The possibility of the widespread use of digital technologies for performing

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Fig. 1. Location of the Tustan rock fortress, 2021; by M. Yasinskyi.
Ryc. 1. Lokalizacja skalnej twierdzy Tustań, 2021; oprac. M. Jasiński.

three-dimensional reconstructions was justified by the British archaeologist Paul Reilly [Reilly 1991]. Since 2000, three-dimensional reconstructions of ancient Roman monuments have been appearing [Johanson 2009], those of objects of Byzantine heritage [Bayliss 2003], virtual reconstructions of Shikki and Sazadeo in Japan [Pasko et al. 2001], and many others. There are publications devoted to the use of architectural heritage objects and the use of virtual reconstructions in games [Kargas et al. 2019]. Augmented reality (AR) technologies have been developing in recent years and they are implemented in projects for the reconstruction of architectural monuments. The introduction of systems such as the VITA (Visual Interaction Tool for Archaeology) allows viewers to immediately imagine how excavation sites look like [Dähne and Karigiannis 2002].

Ukraine has also accumulated its own experience in the 3D graphical reconstruction of historical heritage sites. In this paper, we aim to demonstrate this using the example of the Tustan rock fortress, which is located near the village of Urych in the Lviv region in Ukraine.

Tustan is an archaeological monument from between the ninth and sixteenth centuries and is of national significance in Ukraine. Its study also employed the graphical reconstruction method, which is usually used among Ukrainian researchers for the graphical reconstruction of completely or partially lost historical structures such as earthen fortifications [Yasinskyi and Vasylyuk 2016], fortifications of historic cities [Cherkes and Lytvynchuk 2020; Rybchynskyi 2020], castles, or religious buildings [Bevz 2019]. However, the problem of wooden building reconstruction from the period of the Kyivan Rus and Galician-Volhynian Principality is not covered, because of a lack of information. That is why Tustan fortress is a unique example of medieval rock fortifications and residential development in the Carpathians. Traces on the rocks from wooden buildings from between the ninth and the thirteenth centuries put Tustan among unique monuments not only in Ukraine but also throughout Europe, since today there are no preserved wooden fortresses from this period.

The purpose of this paper is to present the history of studying the monument as an example of an integrated approach to the study of a unique object of architectural heritage, as well as to demonstrate the importance of modern methods of graphical reconstruction for studying and promoting an architectural monument on the example of the Tustan rock fortress.

Methodological approach

The methodology of this article is based on the generalization and systematization of existing information about the process of graphical reconstruction of the Tustan rock fortress and the use of its results in the research and promotion of historical heritage monuments.

By graphical reconstruction, we mean the entire complex of works (or part of it): from collecting materials, field research and fixing the monument to modelling options for lost wooden buildings and verifying them. The result of the graphical reconstruction is a model of the wooden rock architecture of the Tustan complex [Rozhko 2013].

History of Tustan research

According to research, the fortress city of Tustan existed on the Uritsky rocks during the period between the ninth and sixteenth centuries. In historical sources, Tustan was first mentioned in the chronicle (1333–1384) of the sub-chancellor of King Casimir Janko of Czarnków and by the Polish historian Jan Długosz in 1340. Afterwards, the fortress was captured by the Polish King Casimir the Great and rebuilt. The trade route from the Drohobych saltworks through the Carpathian passes to Western Europe passed through Tustan [Parkhuts 2012]. The fortress of Tustan lasted until the sixteenth century, and then began to decline. Since the eighteenth century, the ruins of the Tustan castle-fortress

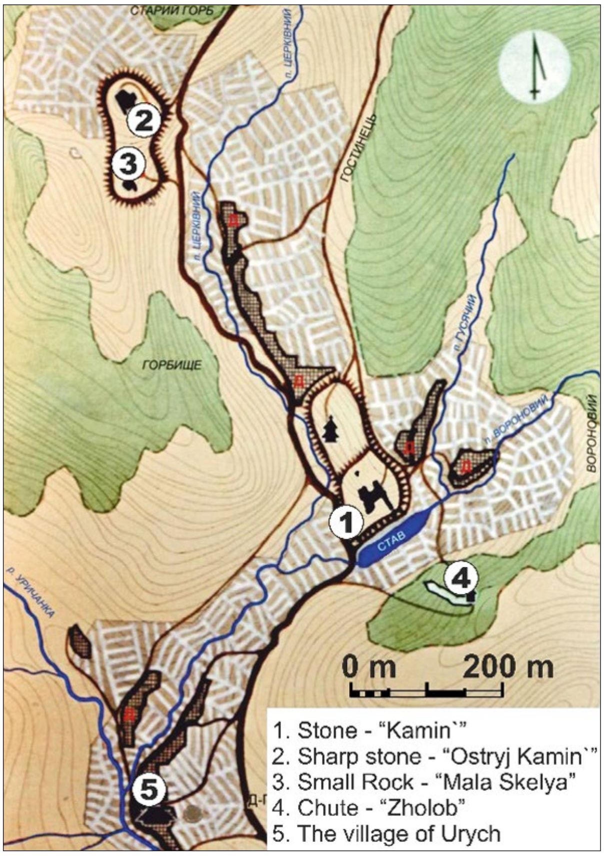

Fig. 2. Scheme of the Tustan rock fortress, 2021; by M. Yasinskyi
Ryc. 2. Schemat skalnej twierdzy Tustań, 2021; oprac. M. Jasiński.

Fig. 3. Fragments of the rock group "Stone" with traces of fastening wooden structures, 1996; photo by M. Rozhko.
Ryc. 3. Fragmenty skalnej grupy „Skała" ze śladami kotwienia drewnianych obiektów, 1996; fot. M. Rożko.

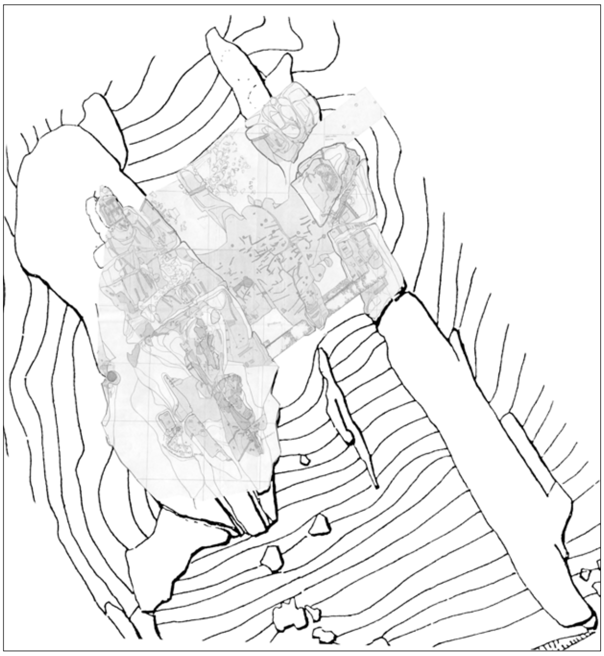

Fig. 4. The scheme of the locations with traces of fastening wooden structures on the rock group "Stone" according to the results of an archaeological expedition led by M. Rozhko, 2012; by M. Yasinskyi.
Ryc. 4. Schemat lokalizacji ze śladami zakotwienia obiektów drewnianych w obrębie skalnej grupy „Skała" według wyników badań ekspedycji archeologicznej pod kierunkiem M. Rożki, 2012; oprac. M. Jasiński.

began to attract the attention of travellers, tourists, ethnographers and historians.

One of the first researchers of Tustan was a member of the "Rus Trinity," I. Vagilevich, who began the process of popularizing monuments of rock architecture. After visiting the site, he described his impressions of the trip in the article *Berda in Urych* (1843) (Wagilewicz 1843), where he summarized the materials collected and systematized folk legends. In 1861, I. Sharanevych also mentioned Tustan in his book *Ancient Lviv* [Sharanevych 1861]. Subsequently, the Polish researcher A. Kirkor turned to the topic of idolatry in pre-Christian times in Galicia [Kirkor 1879]. A certain generalization of previous publications was the material published by A. Czołowski [Czołowski 1892]. Analyzing the material devoted to the study of Tustan, we should recall the publications of the Ukrainian writer and poet I. Franko (Franko 1894) and research by the Polish archaeologist W. Demetrykiewicz [Demetrykiewicz 1903]. The last publication of the pre-war period was the article by Ya. Pasternak, whose title can be translated as *Old Tustan Castle* (Pasternak 1938).

In the Soviet era, in the 1950s and 1960s, Tustan once again attracted interest. One of the first riddles about Tustan, which, was only of a referential nature, belongs to O. Ratich [1957]. Among the first researchers of Tustan was P. Rappaport, who surveyed many old and ancient settlements in the western regions of Ukraine in 1962 [Rappaport and Malevskaya 1963].

However, knowledge of rock monuments (not just Tustan) was mostly superficial. In 1978, Mykhailo

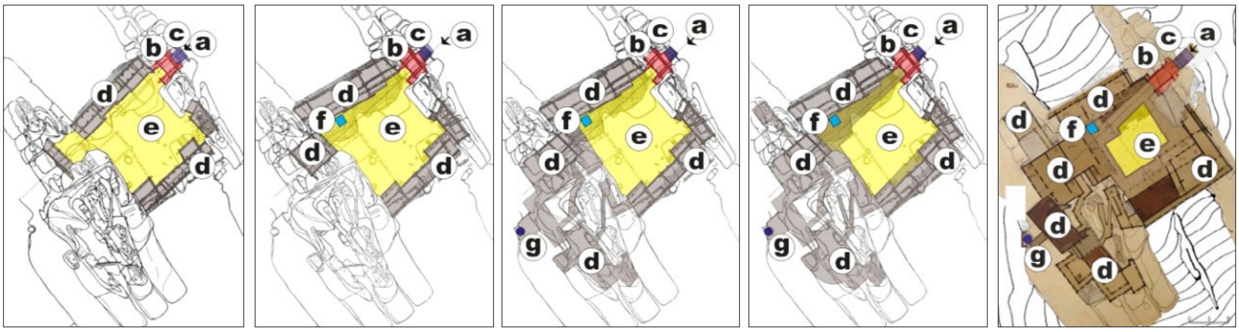

Fig. 5. Five stages of the Tustan fortress wooden construction, legend: a—entrance, b—gateway, c—bridge, d—wooden buildings, e—courtyard (dytynets'), f— water tank, g—well; prepared by M. Rozhko, drawn by M. Yasinskyi.
Ryc. 5. Pięć etapów wznoszenia drewnianej twierdzy Tustań; legenda: a – wejście, b – brama, c – most, d – drewniane budynki, e – dziedziniec, f – zbiornik na wodę, g – studnia; oprac. M. Rożko, rys. M. Jasiński.

Rozhko began field archaeological studies of Tustan. The "Tustan" state historical and cultural reserve was established by a resolution of the Cabinet of Ministers of Ukraine in 1994 to preserve and rationally use the unique Tustan rock fortress city. Since 1999, it has been a natural monument of national significance, and in 2001 it was included in the State Register of Archaeological Immovable Monuments of National Significance [Постанова Кабінету Міністрів України від 5 жовтня1994 р. 687 «Про державний історико-культурний заповідник «Тустань» (Львівська область)»].

The rock-fortress city of Tustan includes three rock complexes with traces of wooden buildings, the remains of masonry, three cisterns, a well, three caves, petroglyphs, the remains of a salt road, earthen fortifications and a dam.

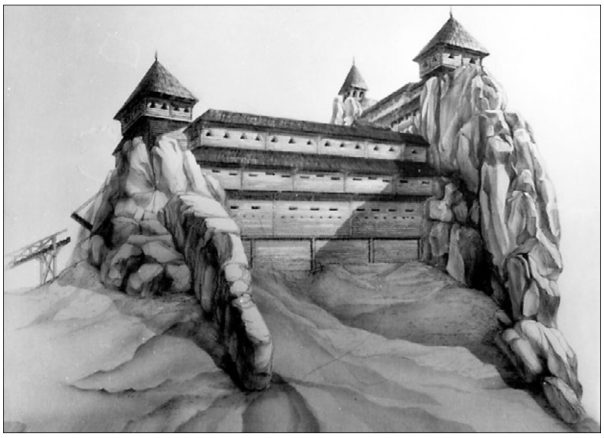

Fig. 6. Perspective of the Tustan rock fortress from the northeast, 1996; by M. Rozhko.
Ryc. 6. Rysunek perspektywiczny skalnej twierdzy Tustań od strony północno-wschodniej, 1996; rys. M. Rożko.

First stage: 2D graphical reconstruction

The heritage of Tustan is, first of all, a complex of rocks with log cabins and grooves, which are traces of the former fortress. Most of the archaeological remains of wooden structures are the remains of walls with a small height (planning structure), general descriptions, and later analogues. The reliability of graphical reconstruction of such objects is low.

Wooden rock architecture was a special method of medieval construction using rocks. The wooden structures themselves have not survived. However, rock carvings and grooves allow for recreating the former appearance of medieval buildings with a certain degree of authenticity, including their height characteristics. Due to this, as well as due to the lack of well-known analogues in construction technology abroad, this type of monument is unique in the world history of architecture.

It is difficult to apply traditional methods of research and fixation to rock monuments, in particular, due to the complex terrain, large size, and significant height (up to 90 m), irregular geometric shapes of rocks, and complex spatial placement of traces in different planes. The only known method of research and graphical reconstruction of monuments of wooden rock architecture today is the complex method by M. Rozhko, developed while studying Tustan and tested on other objects. This system is complex, covers the necessary stages and sequence of research, but it is quite generalized and is formulated more as a process of studying a specific object (Tustan). M. Rozhko's fixation on monuments of wooden rock architecture, reflected in his methodology, mainly coincided with the 1970s and 80s. M. Rozhko processed graphical images of the probable five stages of the wooden development of the fortress (about 4000 traces of development were identified), where it grew and transformed. However, many questions about the construction of the fortress remained open, since the methods of graphical reconstruction available at that time did not allow us to answer them.

Second stage: 3D graphical reconstruction

New opportunities opened up with the development of digital technologies. Although conceptually the basic principles of M. Rozhko's methodology remained the same, the accuracy of measurements and recording technology increased due to the development of geodesy and surveying. At the same time, it was necessary to learn how to use modern information technologies

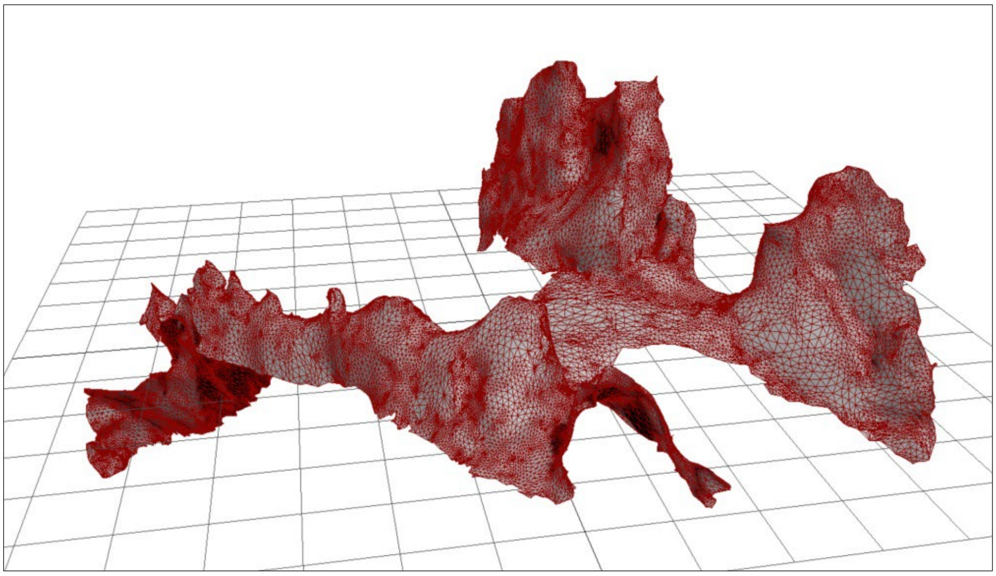

Fig. 7. The first results of laser scanning and photogrammetry of the rock group "Stone" 2021; by M. Yasinskyi.
Ryc. 7. Ostateczne wyniki skanu laserowego i pomiarów fotogrametrycznych skalnej grupy „Skała", 2021; oprac. M. Jasiński.

to store, organize, and display all research materials, as well as to work effectively with them. It became necessary to develop a comprehensive, complete, modern methodology for the graphical reconstruction of lost wooden rock structures. This technique was developed by Vasyl Rozhko, the son of M. Rozhko.

Among the rock traces, the origin of which can be different, according to V. Rozhko the most important thing was the identified traces of devices or architecture: grooves, log cabins and sub-scaffolding for anchoring wooden structures, stone steps, benches, ditches for water drainage, caves, cisterns, masonry, traces of fire, etc. For graphical reconstruction, the primary task is to study rock traces of fixing wooden structures. To do this, they are identified and differentiated from natural formations and deformations of the rock surface. First, the characteristics of the original rock surface, its properties, destruction factors, and natural deformations are determined. After that, anthropogenic changes are determined, the technology of rock processing, their adaptation, rock images and destruction are investigated.

Laser scanning and photogrammetry methods were used to accurately and thoroughly correlate the surface of rocks with traces of buildings. The approach to creating a 3D model of rocks with traces of rock development involved the following steps: creating a geodetic network on the ground in the selected coordinate system; placing stamps to integrate survey fragments into a single model; determining the coordinates of scanning stations and brands; performing laser scanning; photographing an object from different angles with overlap; aerial photography or laser scanning of the object; on-site processing of ground and air scanning and photography results, integration of fragments into a single model, simplification and generalization, binding to the coordinate system; texturing a model by superimposing photographic images of an object onto it.

At the turn of 2004 and 2005, the first 3D model of the rocks and relief of the rock group "Stone" complex was built (Fig. 7). With this attempt came the realization of the complexity of such an object as rocks with traces of development, and therefore the inappropriateness of transferring points to the electronic version according to their three-dimensional coordinates from measurement plans (x, y) and steps z: the process was excessively laborious, and there was a high risk of error in manual measurement from drawings. Entering points manually was untenable.

In 2007, the creation of a three-dimensional model of the rock group "Stone" (Kamin') was started using an improved technique. Ground-based laser scanning (Mensi GS200 scanner) was chosen as the main method of 3D rock modelling. This made it possible to describe the overall shape of the rocks, as well as small important details to recreate the original appearance of the rock fortress city. However, problems arose again: due to the very difficult terrain, it was not possible to place the scanner at the necessary points, a significant part of the rocks was covered by trees, and it was also not possible to scan the upper part. The team tried to finish this on their own using photogrammetric methods, photographing (ground-based) rocks from all sides [Dashlyk and Markov 2009].

However, a complete model of rocks was created only in 2015. The next stage of reconstruction provided for the "landing" of the fortress on a rock. The sequence of reconstruction of the lost wooden rock architecture was proposed to be divided into four stages: reconstruction of the original appearance of the rock complex; reconstruction of certain elements of the rock complex; recreating its structure; detailing the model of a wooden rock complex.

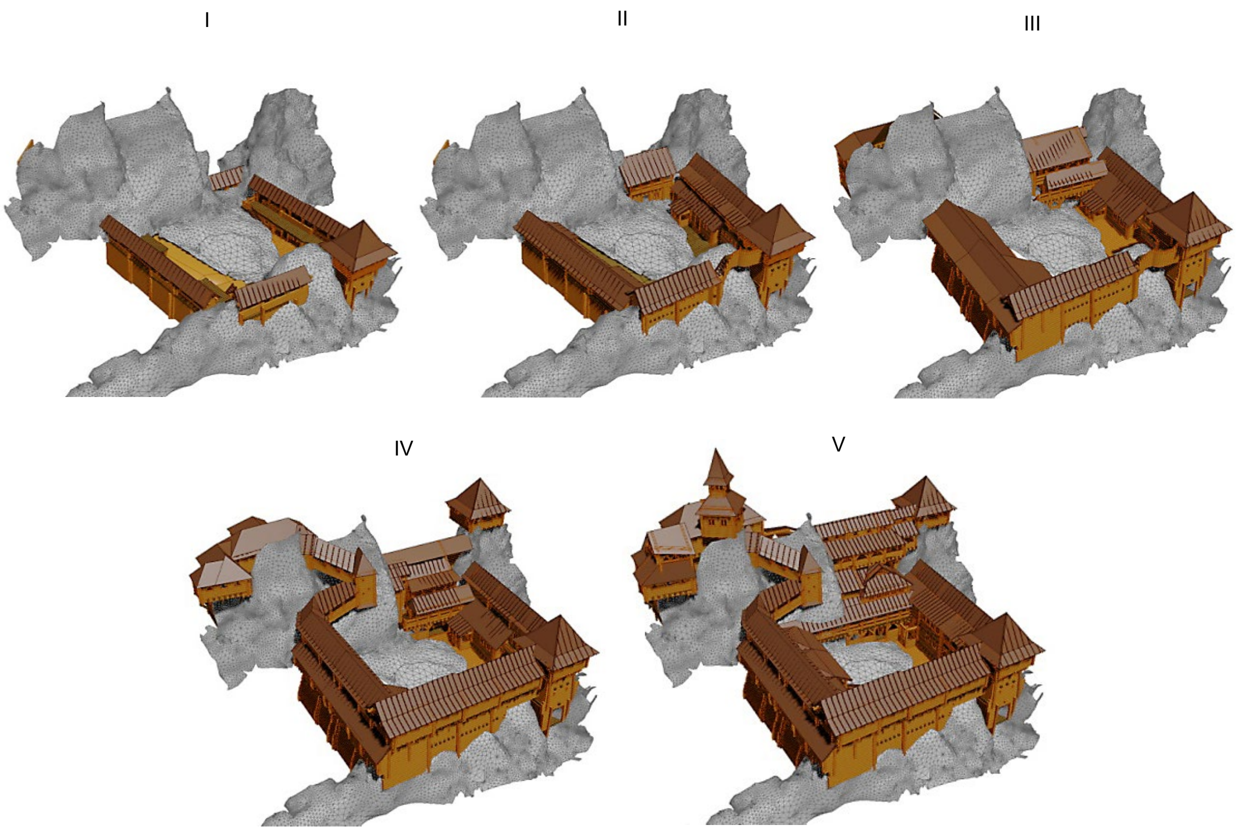

Fig. 8. 3D model of the five stages of wooden construction development of the Tustan fortress, based on research by M. Rozhko; by M. Yasinskyi.
Ryc. 8. Model trójwymiarowy pięciu etapów rozwoju zabudowy drewnianej twierdzy Tustań, na podstawie badań M. Rożki; oprac. M. Jasiński.

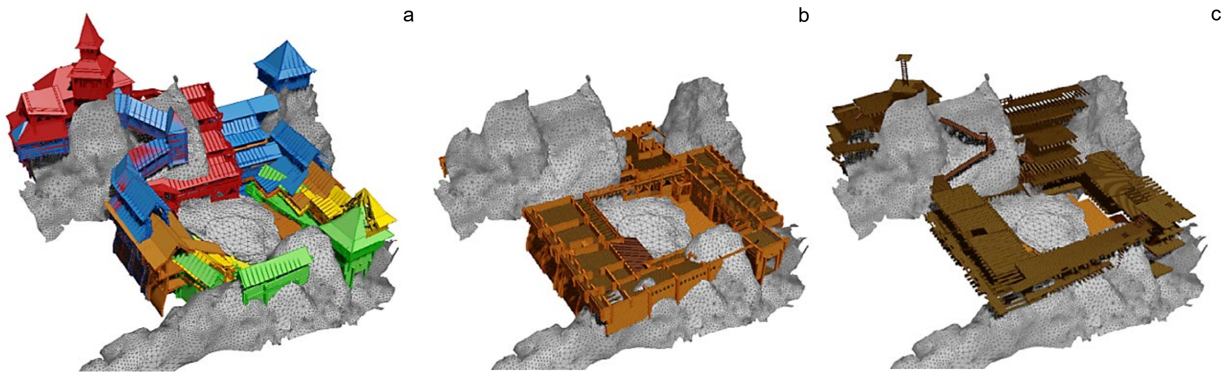

Fig. 9. Selected examples of the modelling process, f—combined sections of all stages of wooden building development, b—perspective image of the second level of the fifth stage, c—scheme of floor levels and vertical circulation paths of the fifth stage; by M. Yasinskyi.
Ryc. 9. Wybrane przykłady procesu modelowania, f – połączone przekroje wszystkich etapów rozwoju zabudowy drewnianej, b – obraz perspektywiczny poziomu drugiego etapu piątego, c – schemat poziomów kondygnacji oraz komunikacja pionowa etapu piątego; oprac. M. Jasiński.

The modelling process looked much more complicated than the steps listed above. Designer Vasyl Dmytruk started modelling the rock complex based on a topo-geodetic survey, the results of 3D scanning and photogrammetric modelling of rocks. Already at this stage of 3D modelling, there was an awareness of the complexity of the virtual reconstruction of both rocks and structures. Firstly, because of the complexity of the object: it was rock with traces of development, which has an irregular geometric shape, large size and limited accessibility. Secondly, even when the existing state of the rocks was scanned and modelled, the placement of the fortress on them was still problematic, since a significant part of it had been destroyed for a long time. Therefore, it was necessary to create a 3D model of the rock complex for the period of existence of the wooden building. For this purpose, the lost parts of the rock surface and its volumes that collapsed in the last peri-

Fig. 10. Selected examples of the modelling process of the 3D reconstruction of the Tustan rock fortress, 2014; by M. Yasinskyi.
Ryc. 10. Wybrane przykłady procesu modelowania rekonstrukcji trójwymiarowej skalnej twierdzy Tustań, 2014; oprac. M. Jasiński.

od were modelled, focusing on iconographic materials and photo recordings of the mid-twentieth century.

During the next stage, an attempt was made to hypothetically reproduce the spatial structure of the complex (in masses), using the results of previous studies to model the architecture with volumes: building sites; transitions, vertical circulation; blocking access between rocks; entrance area; functional features; later masonry as a convenient place for development; the location of wooden buildings that burned. A detailed comparison of the available graphical reconstructions revealed a significant number of places that needed to be finalized and clarified.

There was a need for architectural development, after which each of the five periods of the fortress would become an building, coordinated with the rocks and with a clear design solution, stairs and levels. This was achieved only after the systematization and architectural analysis of all available graphical reconstructions, topographic surveys and the results of 3D scanning of rocks performed by architect Maksym Yasinskyi [Yasinskyi 2012], with the scientific consultant being Prof., D.Sc., Ph.D. Eng. Architecture Oleh Rybchynskyi from Lviv Polytechnic National University. At this stage, historical materials of a descriptive nature also played an important role, covering those places or components of the fortress that were not presented in any drawings of hypothetical graphical 2D reconstructions by M. Rozhko.

Architectural 3D modelling of the stages of fortress development was performed in Autodesk 3dsMax. This approach made it possible to create models of the five stages of fortress development, argue and correct its design features. The main scientific value was that in the process of creating 3D models, with a deep analysis of previous materials, most of the controversial issues regarding the number of stories of the building, its configuration, vertical communications, and the three-dimensional composition of the complex at different stages of development were justified and resolved.

At the final stage, the model was detailed, in particular, its functional elements and features, engineering support, structural elements and details, architectural elements (small fragments of buildings that were not reproduced in previous stages), interiors, details, material, and the surrounding area (including vegetation) were recreated. In the process of graphical reconstruction, the construction traditions of the region were taken into account, they dictate the architectural and stylistic features of the structure: from structural (cuts, releases, fasteners), architectural (galleries, roofs) elements to details (window openings, embrasures, profiles).

The graphical model has been presented to the public online at the "Tustan" website [Tustan n.d.], which is also designed to become an information platform for the intellectual management of a real attraction.

3D promotional products

In addition to the obvious academic result, the question arose as to how to demonstrate these developments to visitors of the complex? In 2014, at the public presentation of the Tustan 3D model, the possibility of the spatial study of Tustan's architecture from different periods was presented through a browser, through a PDF file, with transparency modes and the ability to measure distances, as well as virtual travel around and inside using Lumion, and the parallel (past–present) 3D panoramas of five points. However, the completed products were two short videos with a voiceover: it was a photorealistic review of the fifth period of construction of the fortress and a story about the evolution of all five periods of Tustan on the rock complex "Stone."

The next step was the development of an augmented reality (AR) application for Android by graduates of the Lviv Polytechnic National University in 2015 [Voloshyn et al. 2009]. Thus, being among the rocks, it was possible to virtually "reconstruct" an old castle. When developing the app, the following tasks were successfully completed: adapting a 3D model for mobile devices and apps; object recognition by mobile apps; the app worked on all devices.

The launch of the app allowed every visitor to see the fortress by downloading the app from Google Play onto their mobile device. The disadvantage was that the program did not work on iOS at the time and had a high dependence on the weather: it did not work in direct sunlight and snowfall, the image "hooked" and "took off" (the application was built based on a 3D point map, the so-called point cloud, which relies on weather conditions to be reliable).

At the end of 2016, the research division of SoftServe R&D took up the creation of the application [Frish 2009]. The specialists chose Vuforia technology, which is currently considered the most widely used augmented reality platform in the world. This platform works with predefined markers with a known location, similar to QR codes on paper or the screen of electronic devices. The next step was to correlate the real landscape with the 3D model. The task was not easy, because the camera and model have many parameters, in particular, the focal length and physical size of the sensor, lens distortion, zoom, rotation. All these parameters must be coordinated with each other, which is not possible to do quickly and accurately. Therefore, SoftServe R&D specialists used several algorithms for the mathematical modelling of the reconstruction. In particular, BLAM, an application for Blender, was used to reconstruct the camera parameters. Then we used built-in Blender tools to determine the camera settings. After additional analysis, technologies such as OpenCV for reconstructing camera parameters, the LASTools laser scanning package, and MeshLab photogrammetry techniques were selected for further work. 6-8 iterations were performed (the last one lasted five days) and another two days were dedicated to calculations, on which 25 GB of intermediate data was generated and used. The algorithms for obtaining structure from motion SfM (structure from motion) and MVS (multi-view stereo) were used, on which the Photo and Google Street View project is based, to get a digital model that shows the camera parameters, the photographer's position in space and the transformation of the 3D model.

Tustan AR, which is now available for free for different versions of both platforms (Android and iOS). For further development of this non-commercial product, the application's software code has been made publicly available on Github. A useful bonus was that the app recognizes not only rocks in nature but also their images—photos. This is convenient to use for promotional materials to showcase anywhere.

SoftServe continued to help Tustan and created a prototype of a virtual reality station, publicly presented at the "Tu Stan 2018" festival. This combination of software and hardware with an environment allows you to view the fortress from above, from the sides, and even its courtyard during a realistic controlled hang glider flight. Thus, visitors had the opportunity to virtually fly over the fortress and view it from different angles.

At present, the rock fortress city of Tustan has one of the best digital platforms in the virtual reconstruction sector. This shows the significant achievements of Ukrainian researchers and programmers in the field of the digitization of cultural heritage, as well as the huge potential of Ukrainian experience, which should be embodied in the unique digital platform "Ukrainian national intelligence," which is designed to provide access to the digitized cultural heritage of Ukraine [Ukrayins'kyy kul'turnyy fond 2018].

Conclusions

The Tustan rock fortress is a unique cultural and natural phenomenon, the detailed study of which has lasted for around half a century. Today, we have accumulated a unique trove of experience of both architectural-archaeological research and graphical reconstruction, which allow us to better understand the history of the construction of the rock fortress, the stages of its development and transformation, and its structural, architectural and planning features. The history of Tustan research very clearly shows us the history of the development of methods and technologies for studying rock complexes: from traditional measurements and hand-made hypothetical reconstructions to digital modelling and augmented reality.

We can interpret innovative technologies not only as a logical continuation of the evolution of methods of archaeological and architectural research but also as an important stage in verifying and detailing the results of previous research work. Using the example of constructing a three-dimensional model of the Tustan rock fortress, it became possible to significantly clarify the results of previous graphical reconstructions of five periods of fortress development, which were determined 50 years ago by M. Rozhko. A 3D model of the rocks and fortress is the basis for planning emergency, conservation and restoration works and museumification of the monument. The 3D model made it possible to study the technical condition of rock complexes, their load-bearing capacity, and the dynamics of destruction. An integrated 3D model, database, and geographic information system enable multiple researchers to work comprehensively and efficiently with large amounts of heterogeneous information at the same time.

An important aspect of innovative technologies is the possibility of using the results of their application to promote cultural heritage. Using the example of Tustan, it is shown that it was the three-dimensional graphical model that formed the basis of its public presentation, and later became the basis for creating the augmented reality application Tustan AR. The use of the app significantly increases the tourist attractiveness of the object and contributes to its popularization in the regional and international context.

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Legal acts / Akty prawne

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Abstract

The Tustan state historical and cultural reserve was established in 1994 with the stated aim to preserve and rationally use the unique rock fortress city of Tustan, situated near the rural community of Urych in Lviv Oblast, Ukraine. Research into Tustan was initiated around four decades ago by architect and archaeologist M. Rozhko. This research resulted in the discovery of previously unknown stone fortifications. The researcher developed his own method of graphical 2D reconstruction and identified the main stages of the fortress's development and growth. V. Rozhko created 3D graphical reconstructions of the fortress, which opened up new perspectives in the study of the structure. This paper shows how the use of modern 3D modelling methods for reconstructing the stages of the fortress's construction helped to solve issues that could not be previously clarified with the help of traditional research methods. It was proved that contemporary 3D reconstructions are not only a new method of investigating and studying heritage sites, but also a new means of promoting them at regional and international levels.

Streszczenie

Narodowy rezerwat historyczno-kulturalny „Tustań" utworzony został w roku 1994 w celu zachowania i racjonalnego wykorzystania unikatowego skalnego miasta-twierdzy Tustań znajdującego się w pobliżu wsi Urycz w obwodzie lwowskim (Ukraina). Czterdzieści lat temu archeolog M. Rożko rozpoczął w Tustaniu badania, których wynikiem było odkrycie skalnych fortyfikacji. Badaczowi udało się opracować własną metodę graficznej rekonstrukcji 2D oraz ustalić podstawowe etapy budowy twierdzy. Architekt V. Rożko wykonał graficzny model 3D przedstawiający rekonstrukcję twierdzy, co otworzyło nowe możliwości prowadzenia badań obiektu. W artykule przedstawiono sposób wykorzystania nowoczesnych technik modelowania 3D przy rekonstrukcji etapów budowy twierdzy, co pomogło uporać się z problemami, których nie udało się wyjaśnić przy użyciu tradycyjnych metod badawczych. Udowodniono, że współczesne rekonstrukcje 3D są nie tylko nową metodą badań zabytków, lecz także nowym sposobem ich promocji na poziomie regionalnym i międzynarodowym.