3D Virtualisation and Visualisation Technologies for Archiving the Results

András Németh – András Szabó – Ferenc Balog

Technological advances in recent decades have brought about revolutionary changes in all areas of life, which was partly due to the widespread deployment of IT-based and mobile communications solutions. Processes in the semiconductor industry have effectively supported miniaturisation efforts, resulting in smaller and more complex electronic integrated circuits, which made possible the development of IT-based devices with microprocessors of increasing capacity optimised for diverse functions. Due to the rapid increase in computing capacity and the decreasing price of new products, the tools and solutions that were previously available only to professional industrial users became accessible to a wider public, too. This has put an end to the monopoly of multinational companies in the field of IT-based innovation. Due to the spread of the so-called start-up business forms,[1] developments gained a fresh impetus in the field of both hardware and software. Thanks to this, three-dimensional (3D) technologies became an independent factor in the market, and 3D modelling, scanning, and printing started to develop dynamically and spread rapidly. Diverse 3D imaging procedures are now applied in various areas of life (medicine, cartography, architecture, engineering, education, public administration, etc.). They have also been involved in the toolkit of modern archaeology and warfare exploration, complementing the non-invasive investigation procedures and traditional research methods efficiently.

Spatial vision and spatial experience

Without going into details of the physiology and characteristics of human perception of space, it is worth noting here that the natural perception of space is the ability to determine the shape, size and position of the observed objects and their relative position in space based on two images. This is called stereoscopic vision, for which the two images are provided by the right eye and the left eye detecting radiation from the optical range (700–400 nm) of the electromagnetic spectrum. About 80% of all information from the outside world is obtained by man through eyesight. The perception of space within a short distance is based on binocular vision, that is, on measuring the convergence angle of the two eyes

[1] "Generally speaking, a business that has just been started is called a start-up if it has a high growth potential and some kind of innovation is involved in its product and operations." *Márkus* 2016.

https://doi.org/10.36250/00757_13

and the degree of lens accommodation. On the other hand, in the case of long distance, space is perceived on an empirical basis, through analysing perspective, light-shadow effects, coverages and movements.[2] This means that in the case of observation in a greater distance, the perception of space in the optical region is of prognostic, probabilistic nature, resulting in the "deceptability" of our eyes. This phenomenon of optical illusion can be made advantage of when, for instance, something is represented on a flat surface (in 2D) with the aim of creating spatial visual effects (in 3D). Nevertheless, if it can be technically solved that the same object or scene is seen by the two eyes from different angles, the brain is able to reconstruct a kind of spatial experience independently of the observer's intention. This may also be called artificial vision, which can be induced by various active and passive stereoscopic solutions (e.g. stereo slide viewer, polarised filter or anaglyph glasses,[3] VR[4] glasses) and holography.

At the same time, efforts to create a more realistic spatial experience have put 3D visualisation techniques on a new footing in recent decades. Instead of the illusory spatial representation of features (objects, living creatures, natural formations, shapes, and phenomena), today the IT-based design (imaging and making) of their 3D model is now the guiding principle, which can be then freely manipulated or animated against a real background, even in a likewise modelled environment. However, this solution goes far beyond *visualisation,* as it provides the opportunity to create imaginative spaces, locations, objects and scenes that are completely independent of reality. In other words, its application brings us into the world of *virtualisation*. Initially, these technologies emerged in the field of industrial design, video game development and Hollywood studios. Consequently, we could only follow their changes on a monitor or movie screen as passive observers, but they have now become accessible to almost anyone. The various technical solutions offered by the new technology allow us to create, among other things, accurate spatial models of damaged or fragmented artefacts from different historical ages following their 3D scanning. Afterwards, we can digitally complete them on the basis of other available sources (historical descriptions, graphics, etc.) or data. Following the required finishing, texturing and light-shadow effect adjustment, we can reconstruct them in their original state. The finished models can later be freely used for further projects on their own or as a component. They can be manipulated and animated, if necessary, or even reproduced in any number from different materials using some sort of 3D printing solution, to become visible, tactile and rotatable, but they can even be used in their original function.

Using various 3D software applications, we can create highly realistic models of fortresses, castles, palaces, as well as any building or site that existed hundreds of thousands of years ago, which are virtual replica that can be observed in space, but we also have the opportunity to make short films of complete battle scenes in nearly cinema quality. The application of 3D technologies with scientific rigour and historical loyalty, therefore, opens up entirely new perspectives in the field of historical research. It enables

---

2 *Engler:* A térlátás; *Katona* 2012.

3 They are glasses that offer spatial visual effect by separating visual information intended for the right and left eye through the polarisation of light or using a colour filter.

4 Virtual Reality.

us to archive (digitally) and display our historical and cultural heritage in a way that may provide the conditions of an experience-based learning about our past for coming generations for centuries. At the same time, this method also allows us to avoid deliberate[5] or unintentional[6] modification, damage, or total destruction of certain artefacts. This paper presents the above-mentioned technologies, as well as related technical solutions and methods through the example of Zrínyi-Újvár.

3D scanning

There are many methods of 3D imaging – whether in medicine, cartography, architecture, archaeology, or material science – which use various fundamental laws of physics in their operations. 3D scanning is, in effect, a special method for examining a real feature, or the environment, whereby we collect data about its spatial extension, shape, and other properties of its appearance (e.g. colour, texture). The primary purpose of its application is generally to produce a digital 3D model of the scanned feature. The mass of information gathered as a first step is usually nothing more than a spatial point cloud the elements of which are found on the surface under investigation.[7] By fitting the points to a surface with some kind of geometric method, we get the digital spatial form of the observed feature. If we assign colour information to the point cloud during data capture, the texture and pattern of the original feature may also be recorded and displayed.

Although data acquisition can take many physical forms, including traditional measuring techniques, state-of-the-art devices are now represented by cameras mainly based on photoelectric effects (laser or structured light) that are capable of taking digital images of the observed feature from different directions (angles) in a given resolution. Resulting from their principle of operation, scanners have many similar features to digital cameras, so they normally have a cone-like field of vision and can only gather data about uncovered surfaces. On the other hand, their main function is to obtain distance information about the points of the surface of the object in question, with the help of which they can determine its spatial position within their own reference system. The texture and colour of the surface represent only secondary information for 3D modelling. The images produced by scanning and put in a common spatial reference system form a map as a result of a coordinated registration process, which contains a large amount of redundant information due to multiple overlaps. Based on the information stored in each image, a software module creates a spatial point cloud *(Figure 1)* and then reconstructs the 3D model through interpolation *(Figure 2).*

[5] For example, historical sites damaged or completely destroyed by extremists. See https://news.nationalgeographic.com/2015/09/150901-isis-destruction-looting-ancient-sites-iraq-syria-archaeology/ (Accessed: 20 April 2019.)

[6] For example, once the find is removed from its original site (peat bog, clayey soil, salt/sweet water, etc.), the preservative effect of its environment ceases, and therefore the natural decomposition processes begin and accelerate.

[7] *Bernardini–Rushmeier* 2002.

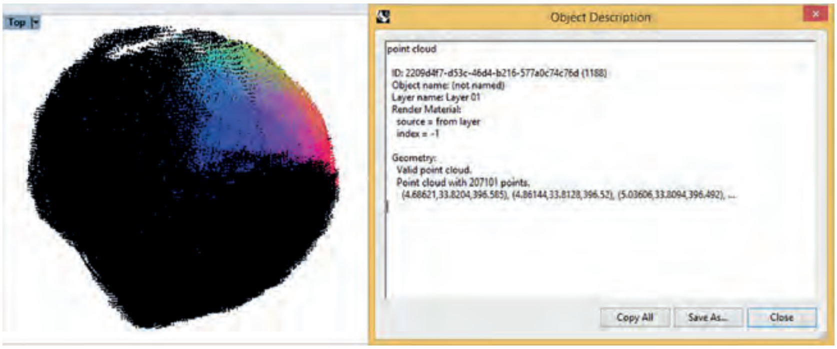


Figure 1.
Scanned 3D model of a musket ball (an unprocessed point cloud with 207,101 points)
Source: compiled by the authors

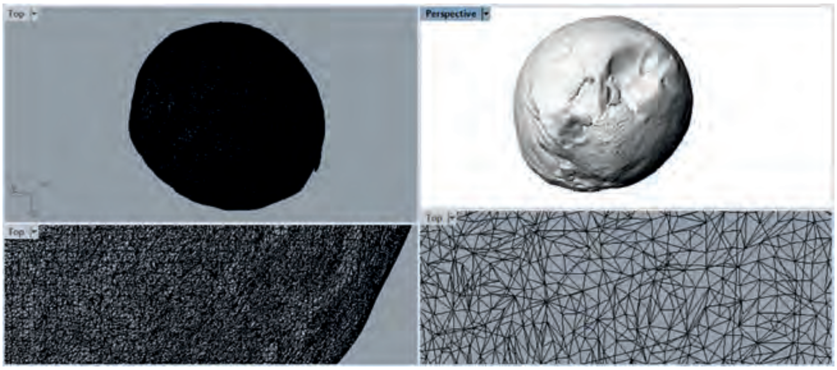


Figure 2.
Scanned 3D model of a musket ball (the polygon mesh of the surface)
Source: compiled by the authors

The features of the mathematical algorithms used in the process affect the quality of the end result to a great extent. The steps required for the reconstruction are summarised in *Figure 3* for scanners that process the distance data of points on the surface and texture information separately and combine them only at the very end of the model creation. Nevertheless, the exchange of information may also be carried out between the steps of the two processes for the sake of increasing accuracy (dashed lines). Although there are several technical solutions for generating point clouds, the most widely used active scanners apply the principle of triangulation to determine distance. The essence of this is that the surface of the object under investigation is illuminated with some source of light and the reflected light is projected through an optical system onto the surface of a photoelectric sensor. The relative position of the light source and the sensor(s) is known (recorded), and after calibration to a plane of reference, the system can detect the depth (ascent or descent) of

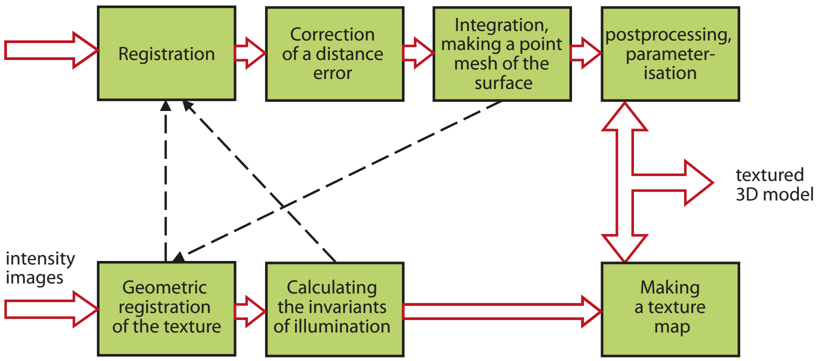


Figure 3.
The required steps for reconstructing a scanned model
Source: compiled by the authors based on *Bernardini–Rushmeier* 2002. 150.

a test point relative to its surface, as after reflection the position (Dz) of the resulting bright spot on the surface of the sensor will change according to the distance (DZ), in proportion to that *(Figure 4).* The software can convert the resulting depth values into a point in the 3D coordinate system of the scanner in knowledge of the calibrated position and orientation of the light source and sensor.[8]

In case of laser scanners, the light source projects a narrow band of light on the surface of the object and the CCD[9] sensor detects the peak of reflected laser light on each scan line, from which the 3D position of each point is calculated by intersecting the scan line with the known plane of laser light *(Figure 5).*[10]

The operation of scanners using a structured light source is slightly different, since such devices project some kind of pattern (preferably a linear one) on the examined surface, and the cameras are used to measure the magnitude of the actual distortion. The displacement of a single line can be transformed into 3D coordinates even directly, but there are also methods that project alternating patterns of band on the surface, resulting in a binary Gray code sequence that can be processed to determine differences in elements of the surface. For example, change in the width of a strip on a given surface will be proportional to the gradient of the examined surface; in other words, it is the first derivative of the depth parameter. The results of frequency and phase measurements with linear sequence can be analysed with a Fourier transformation.[11] Combining the various methods, we get a tool that is suitable for high-precision 3D digital reconstruction of the object concerned. *Figure 6* illustrates the conceptual operation of a dual-camera system, the purpose of which is to reduce errors caused by coverage due to the roughness of the surface during measurements. One of the greatest advantages of this solution is its promptness, as it does not scan the surface by points, but it can survey even the entire field of view. Because such a field-of-view

[8] *Bernardini–Rushmeier* 2002.
[9] Charge-coupled Device (photoelectric detector).
[10] *Bernardini–Rushmeier* 2002.
[11] *Peng–Gupta* 2007.

scanning phase may take place in a fraction of a second, we can scan moving objects in real time if we use the appropriate number and sensitivity of sensors and a high computing capacity processing unit.

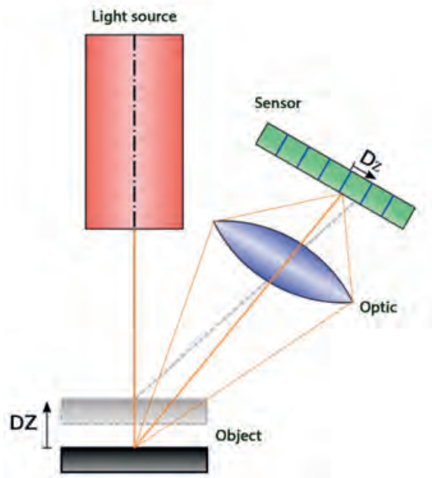


Figure 4.
The method of triangulation in measuring depth
Source: https://upload.wikimedia.org/wikipedia/commons/thumb/2/24/Laserprofilometer_EN.svg/360px-Laserprofilometer_EN.svg.png (Accessed: 20 April 2019.)

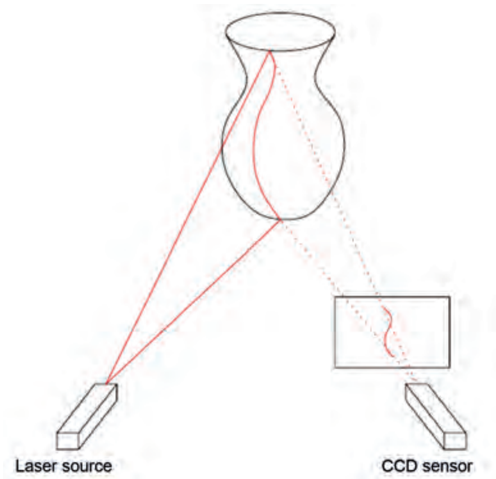


Figure 5.
The principle of laser scanning
Source: Bernardini–Rushmeier 2002. 151.

With both laser and structured light scanners, the main parameters and operational properties of the devices are influenced by a number of factors beyond the circumstances of application. From the part of the hardware, the built-in light source, the sensors, and the quality parameters of the optics have the greatest impact on the resolution and distortion of the point cloud generated by the device, whereas the control and data processing circuits – depending on the methods used – determine primarily the speed of operation. The quality of the created 3D model is determined by the operating principle and additional features of the mathematical algorithms used by the processing software, as well as its error correction capability.

Devices can generate files of different format from the respective direction of measurement. These are normally either files of point set (text files made up of x, y, z coordinates[12]) that can also be opened by other software applications *(Figure 7),* or files of manufacturer-specific formats.[13] If the texture is part of the scanning, then a bitmap can also be created (see *Figure 9*).

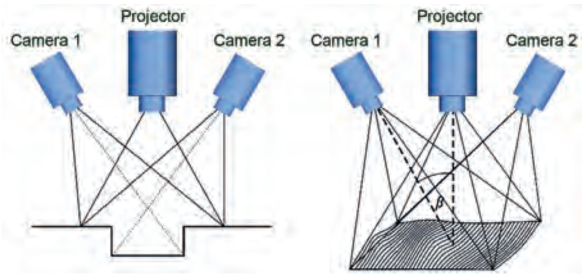
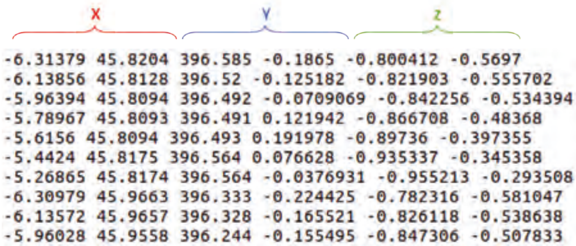


Figure 6.
Scanning with structured light
Source: https://upload.wikimedia.org/wikipedia/commons/a/aa/3-proj2cam.svg (Accessed: 20 April 2019.)




```
-6.31379 45.8204 396.585 -0.1865 -0.800412 -0.5697
-6.13856 45.8128 396.52 -0.125182 -0.821903 -0.555702
-5.96394 45.8094 396.492 -0.0709069 -0.842256 -0.534394
-5.78967 45.8093 396.491 0.121942 -0.866708 -0.48368
-5.6156 45.8094 396.493 0.191978 -0.89736 -0.397355
-5.4424 45.8175 396.564 0.076628 -0.935337 -0.345358
-5.26865 45.8174 396.564 -0.0376931 -0.955213 -0.293508
-6.30979 45.9663 396.333 -0.224425 -0.782316 -0.581047
-6.13572 45.9657 396.328 -0.165521 -0.826118 -0.538638
-5.96028 45.9558 396.244 -0.155495 -0.847306 -0.507833
```

Figure 7.
The structure of a file with .asc extension (the x, y, and z coordinates of the surface points are separated with a space in each line)
Source: compiled by the authors

[12] Generally, in the form of asc, csv, txt, pnt, xyz, and cgo_asci/cgo_ascii extensions.

[13] For example, .RGE (Shining3D), .3DD .RXP .RSP (Reigl), .3PI (ShapeGrabber), .AC (Steinbichler), .BIN .SWL (Perceptron), .BRE .CTR (Breuckmann), .PTS .PTX .PTG (Leica), .CDK .CDM .RGV .RVM .VVD (Konica Minolta).

Sets of points recorded from different angles can be merged into a single file, and (if necessary) gaps in the 3D model caused by measurement errors can be filled in during processing in order to obtain a consistent surface or printable solid shapes, and the redundant/false measurement results can be removed. For scanning smaller objects, we can apply automated object rotation (a rotary table), while for larger objects, vehicles, living creatures, or even buildings, we may use various manual devices. In the case of automated object rotation, the physical size and carrying capacity of the table may represent a limit.[14] Nevertheless, making a full model of small objects is also a challenge, as the base of the target object (the surface resting on the plate), and, in case of concave shapes, further covered parts do not appear in the model *(Figure 8).* This problem can be solved by scanning the object from different directions, followed by software post-processing.

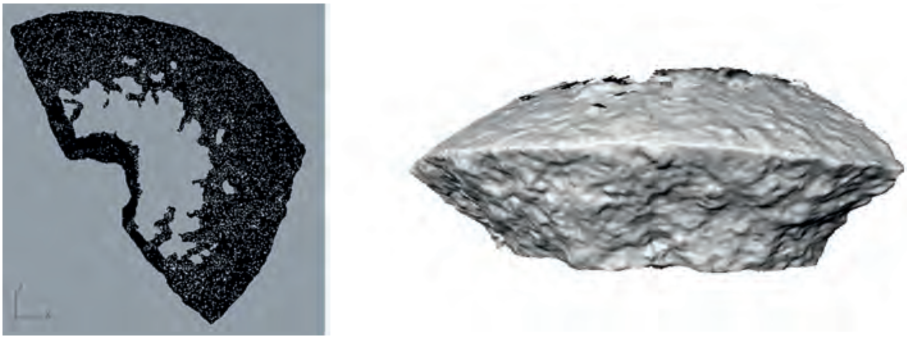


Figure 8.
The 3D model of a bomb fragment discovered at the site of the siege of Zrínyi-Újvár (left side: the polygon mesh from above, right side: a snapshot made from the plane of the cameras of the 3D scanner)
Source: pictures made by the authors

Objects that are dark,[15] shiny, glittering,[16] translucent,[17] or have light and dark details can be problematic from the aspect of scanning, so, for an optimum result, it is advisable to make them "matte" (e.g. using a crack testing aerosol) before beginning the process. With methods using structured light, the intensity and direction of the natural/artificial light sources may also affect the accuracy and outcome of scanning. We need to ensure that evenly diffused light is cast on the object throughout the process, which is relatively easy to guarantee under laboratory conditions, but it may require much more extensive preparation at the site of an archaeological excavation. In these circumstances, it is suggested to use a "light tent" with diffuse illumination – also used in photography – for smaller objects, in order to make error-free models. It is also worth making sure that the objects are not moved while their

[14] The tables are normally suitable for moving objects that are a few centimetres (less than 0.5 m) long and weigh but a few kilograms.
[15] It absorbs light.
[16] It scatters or unevenly reflects light.
[17] It transmits light.

stand is rotated, because this may result in a measurement error. The geometry and material properties of the object determine the fixing methods to be applied, which – in the simplest case – may be a double-sided adhesive or plasticine. If the condition of the find does not allow it, the use of a transparent underlay or support is recommended.

The 3D models[18] produced by scanning usually require post-processing,[19] which can be done with various 3D design/modelling software. Such programs also provide an opportunity to manipulate freely the end result afterwards.

The EinScan-SE device applied by us is suitable for indoor scanning of small-sized objects. It has a 1.3 megapixel camera with a focal length of 290–480 mm, fixed and automatic measurement options. During the scanning of the finds, we gained valuable pieces of information concerning the operation and properties of the device. With the help of its rotating table, the EinScan-SE can automatically take pictures from 8–180 directions, but before measuring, it is advisable to determine the resolution of the model to be made after studying the surface quality and geometric features of the object, and taking into account the measurement accuracy[20] of the device. Staying with the example above, there will be "false" measurement data in the point cloud of an over-sampled model, which is not easy to filter because of the high number of samples. Furthermore, the processing becomes also considerably more difficult due to the multiplied file size.[21]

Concave objects need to be photographed from various directions to minimise the proportion of shady areas. Subsequently, the resulting individual models can be merged with the help of the software. On the basis of practical experience, it can be stated that surveying with multiple object orientations and the merging of the models are both time consuming and rather cumbersome operations. Therefore, it is important to define in advance the orientations that are absolutely necessary for carrying out the task in question, thus minimising the number of scans, which can allow us to save much time, energy and storage space. For instance, if we use a prop or support made of some kind of transparent material, the target object can be raised/tilted to an optimum plane *(Figure 9).* Transparent supports will normally be invisible in the model or will lead to a small number of incorrect measurement points that can be removed with significantly less post-processing work. When using handheld devices, it is advisable to position the object in a way that it can be walked around from as many directions as possible, without interrupting the scanning process (unimpeded) from an optimum distance, because the time required for follow-up work and the size of storage space increases proportionally to the number of necessary measurements. Post-processing work after scanning can be made easier if we select reference points on the object *(Figure 10),* which can be sharp edges and textures, but we may also use patterns and markers in the background or at the base of the target object that do not cover or blend

[18] They are files consisting of spatial point clouds or a polygon mesh generated from them.

[19] For example, filtering "false" measurement results (points or sets of points), generating mesh (polygonal) or NURBS surfaces from a set of points, reducing the number of polygons in meshes, and converting file types (converting to a format used by the software for the purpose of further processing).

[20] The margin of error of the device we used for measuring the distance between the surface points of the studied object was below 0.1 mm.

[21] Although the file size is influenced by many factors, our practical experience shows that it increases in direct proportion to the number of the images made, that is, the disk space required by the model showing the same object from 16 and 32 directions of view gets doubled.

with the target object. In the case of large, and perhaps homogeneous objects, the matching of individual measurements can also be simplified with markings (sticker markers) placed on the surface of the target objects.

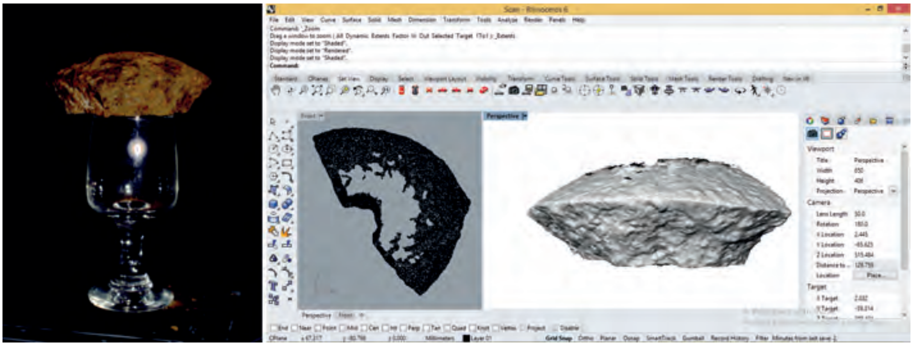


Figure 9.
Target object raised with a glass beaker
(left side: the image is a raw snapshot made by the scanner, right side: the point cloud and the closed surface pulled over it)

Source: pictures made by the authors

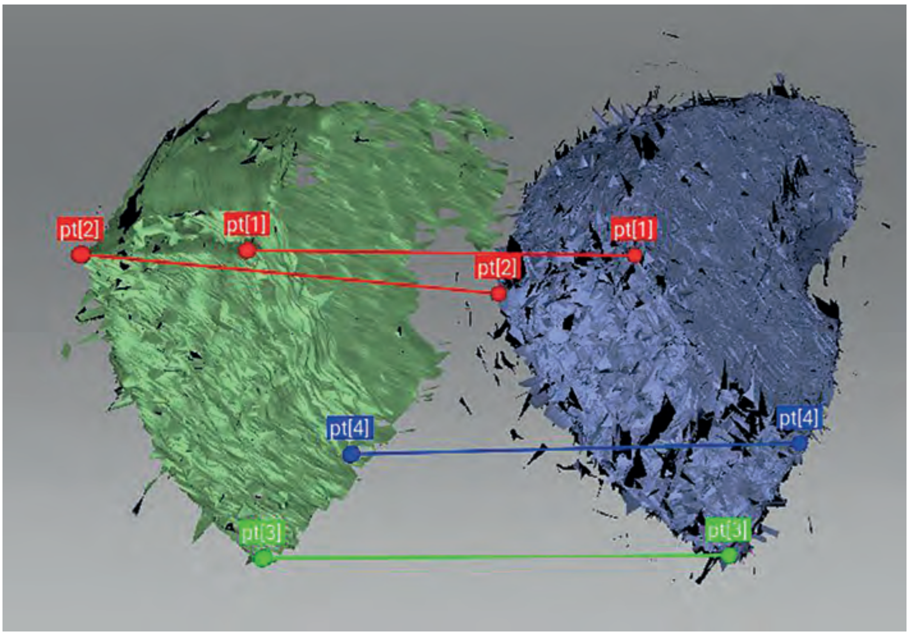


Figure 10.
Using reference points to match models scanned from two different directions

Source: picture made by the authors

The information content of digital models

Similarly to physical objects, the circumstances of making their digital representation (their 3D models) must also be recorded together with their relationship to physical objects. Professionals specialised in 3D scanning often include this information in the filename of the model when saving the file. However, this limits the amount of information to be recorded. Furthermore, ad hoc solutions (the divergent types, formats and the order of the given parameters) increase the likelihood of errors during subsequent processing. The conditions of measurement are not recorded in the files, and they are often not generated digitally by the software of the 3D scanner, either. Therefore, for archaeological applications, it is important to include some meta-information[22] in the descriptions of the files.

The need for these is going to be illustrated through a practical example in the following. *Figure 11* compares two 3D models made by two different devices (a handheld Artec Space Spider and an EinScan-SE scanner equipped with a rotating table). The extent of difference between the models is shown by colour coding in the software, where the parts coloured in red represent the greatest divergence. There are striking, nearly parallel lines at the apex of the spearhead that are visible even at first glance. These probably go back to measurement errors caused by strong lateral light falling on the target object while it is rolled around its longitudinal axis on the rotary table of the scanner. The measurement conditions and the configuration of the devices used during the scanning process could not be determined retrospectively based on the files of the 3D model.

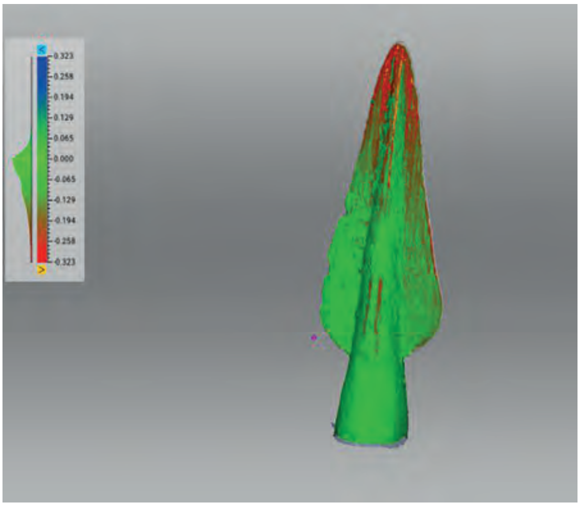


Figure 11.
Comparing the results of measurements made with two different types of scanners
Source: picture made by the authors

[22] Similarly to the "exif" information generated by digital cameras (see in more detail http://owl.phy.queensu.ca/~phil/exiftool/TagNames/EXIF.html [Accessed: 20 April 2019.]).

We can distinguish between metadata describing the circumstances of 3D scanning and recording the techniques used in post-production and data about the object (find) itself. In the former case, the data of the hardware and software used for modelling, their settings, the measurement layout and the modifications carried out during the post-production should be documented. In the latter case, besides the physical parameters (dimensions, weight and composition), the circumstances of the excavation (coordinates of the site, local reference points, etc.) may be relevant. In general, models are used in thematic virtual exhibitions, video presentations, animation and simulation. Therefore, it is worth tagging them (either with NTFS[23] or the tag system of other file systems), and it is advisable to generate a small preview file (to simplify search and management[24]).

3D visualisation and virtualisation

There are many options available today for the visualisation, manipulation and use of completed models in complex environments. Nevertheless, beside the various specialised software applications, it is worth highlighting the solutions that offer anyone an easy management of 3D objects within the most widely used operating system. Advanced 3D display/editing solutions have now been integrated into the Windows 10 software package, which, in addition to editing, are able to show a preview of every supported 3D model format[25] and their own default format (.3mf[26]), as well as to complete them with metadata *(Figure 12).* Unfortunately, these field names are predefined and cannot be modified by the user in the current version. They can only be read by the software applications of the operating system. However, the fact that the built-in applications of the operating systems are capable of displaying and editing 3D models points in the direction that 3D technology – which is still fundamentally used only by professionals – will soon be incorporated into the everyday life and work of large numbers of users, like text, image and video editing.

[23] New Technology File System. A standardised file system for the Microsoft Windows NT operating system and its later versions. Compared to previous file systems, it offers, among other things, access protection, the function of logging, and supports metadata for files.

[24] Files created by scanning objects can range in size from hundreds of MB to several GB, the loading of which may take up resources of the computer system for a long time.

[25] 3D model formats: .fbx, .3mf, .stl and .obj.

[26] https://3mf.io/specification/ (Accessed: 20 April 2019.)

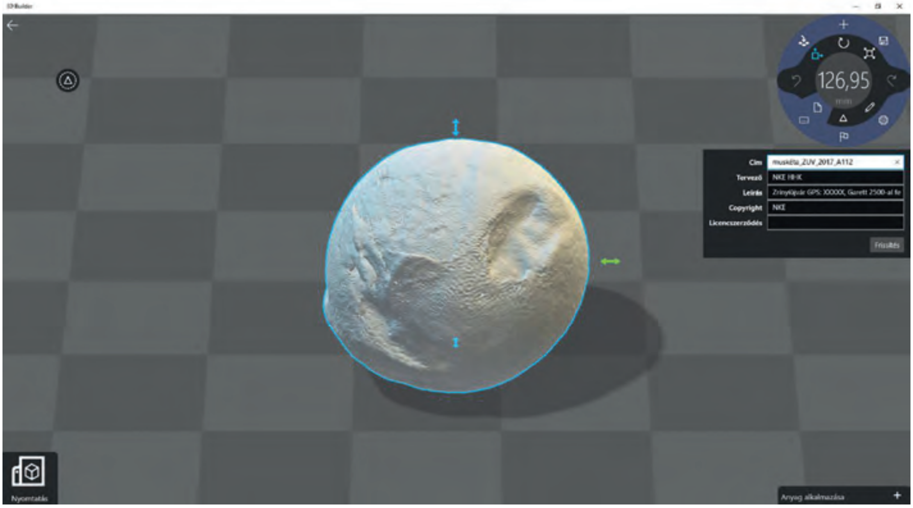


Figure 12.
Metadata fields for the 3D model format used in Windows 10
Source: picture made by the authors

The use of models based on the principle of photogrammetry

During the digitisation of objects, it may occur that the size, weight, or position[27] of the object does not make possible the use of measurement techniques described above, or their application does not demand the accuracy required by laser or structured light technology, or there may be a need for faster processing. In such cases, a 3D modelling method based on photogrammetry comes in useful for users, as illustrated in the case study below.

VR/AR[28] based solutions are useful tools for the interactive teaching of history. When developing the virtual tour of Zrínyi-Újvár, a prototype version was made, in which the user is able to walk around the landscape and the once extant defences, taking up the character of Miklós Zrínyi himself. The gamification[29] of learning can make studying history more attractive, help to envisage different historical events, and allow young people to travel through lost, distant, or inaccessible locations. Information points can be placed on the terrain model, which can be "visited" by students. They can thus learn about the everyday life of medieval people, the various aspects of life in a border fortress, as well as household objects and weapons (in the form of experience-based learning). These information points may comprise the photographs of finds taken of them in their original state, the results of their reconstruction, their 3D models, various written (historical

[27] For example, under water or in a cave.
[28] Virtual Reality/Augmented Reality.
[29] *Damsa* 2016.

sources, publications), visual (copperplates, graphics, photographs, map sheets) and video materials, as well as animations. To enhance the game character, puzzles and exercises can be connected to certain locations and events that must be done by the students during the tour. Of course, traditional teaching methods cannot be fully replaced by VR/AR based solutions, but they can be made more attractive and understandable, and the learning process might be accelerated. In case of augmented reality-based solutions, these games may also involve visiting the different locations,[30] and gathering information about them, for example, during field trips.

When designing the character of the "game" above, instead of using traditional modelling techniques, we applied a photogrammetric method to image Miklós Zrínyi after a bust exhibited in the hall of the Zrínyi Miklós Camp and University Campus housing, among other things, the Faculty of Military Science and Officer Training at the National University of Public Service.

Figure 13.
The model of Zrínyi-Újvár

Source: picture made by the authors

A free smartphone application (Autodesk 123D Design) was used for the photogrammetric processing. The software is no longer available. It has been replaced by the ReCap Pro[31] program. A total of 64 photographs were needed to make the model, which were taken with the built-in camera of the smartphone from two elevation angles – perpendicular to

[30] We may also integrate the principles of popular geocaching for the sake of the game. See www.humankinetics.com/excerpts/excerpts/learn-about-the-benefits-of-geocaching (Accessed: 19 April 2019.)

[31] www.autodesk.com/products/recap/overview (Accessed: 20 April 2019.)

the vertical axis of the statue and at an angle of 30° to that – in a way that the top of the head would be clearly visible. With the two series of 32 photographs, the entire surface of Zrínyi's statue was recorded. After uploading the photos to the application, its processing started and soon a high-resolution, lifelike 3D model appeared on the screen. After copying the raw model into the Autodesk Mudbox software, we first had to reduce its number of polygons and then add texture *(Figure 14).*

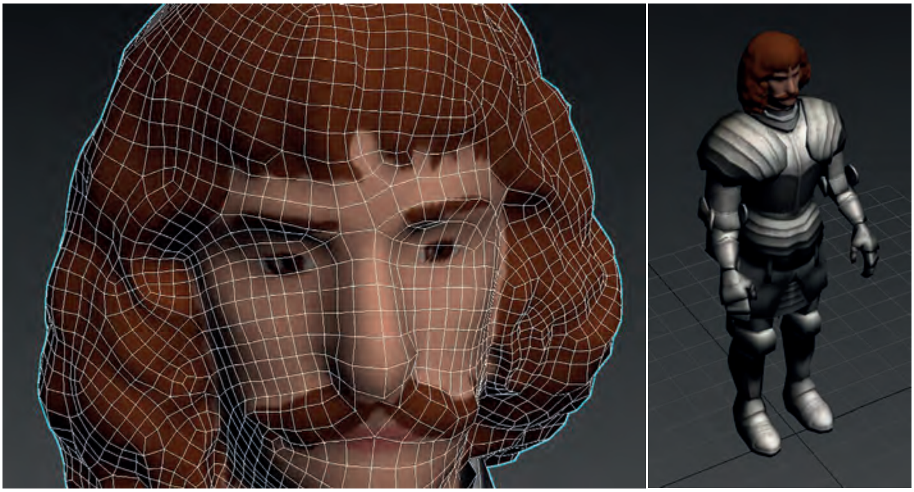


Figure 14.
The 3D model of Zrínyi Miklós

Source: picture made by the authors

The 3D model of the head was then added to a historically correct image of a full body armour suit downloaded from the Internet, creating thus the full figure of Miklós Zrínyi, which had to be subjected to a so-called rigging method[32] before being used. During this, we stretched our model on a skeleton so that during the animation, the polygons would move along with the bones, creating thus a lifelike effect.

The role of virtual and augmented reality in archaeological work

First of all, we need to clarify the meaning of the concepts above. The term virtual reality is an ambiguous term in itself, since the word "virtual" is also used in a sense contrary to (physical) reality. The terms virtual reality (VR) and augmented reality (AR) are often used interchangeably, although they have different meaning contents. VR means full simulation of the perceived/perceptible world, the imaging or artificial reproduction of various sensations

[32] During the rigging, the body and limbs of the 3D model were referenced so that they could move, or be moved, in 3D space in a realistic way.

the way our sensory organs[33] detect them, whereas during the use of AR, our system adds extra information and content to the perceived reality, and therefore the real and virtual space appear simultaneously. This can be the most easily conceived as a second layer of information that does not exist in physical reality.

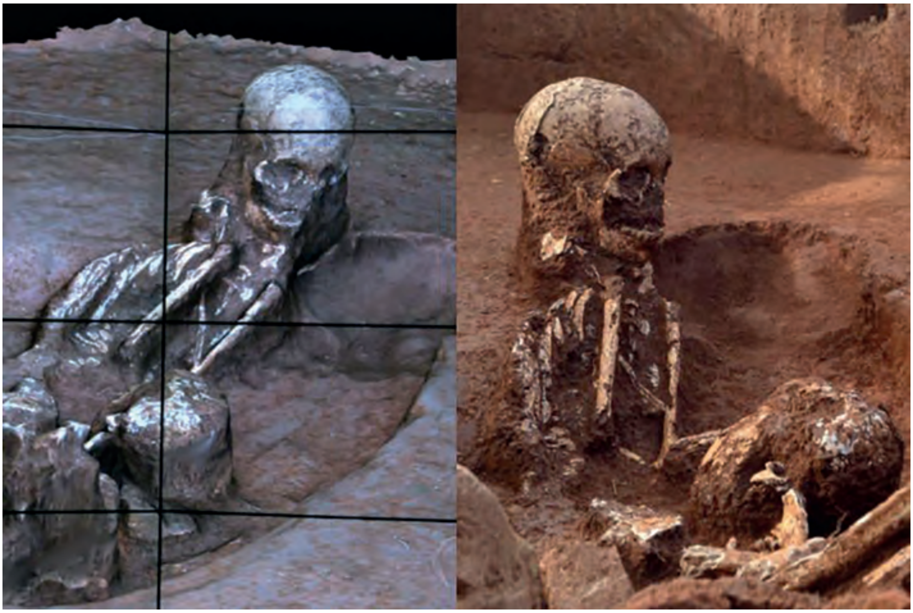


Figure 15.
Comparing a VR image and reality
Source: www.abc.net.au/news/2016-10-18/vr-and-drones-could-unlock-secrets-about-the-plain-of-jars-laos/7938520 (Accessed: 20 April 2019.)

There are many technical solutions for creating a 3D sense of space artificially, but the most widely used ones are the head-mounted displays/goggles, as well as projections[34] that partially or completely fill the field of vision.

In addition to modes of visualisation, solutions used for control (spatial navigation, interaction with the virtual environment) can also be important aspects for choosing a field of application. We can achieve a change of view or location in the environment with controllers, gestures, movements of the hand, but voice control modes are also in development. Physical barriers in space (walls, objects, etc.) may represent a limiting factor for VR solutions unless they are imaged in the virtual space (e.g. we place textures, models on a wall in a room that are visible in the virtual space).

[33] Typically vision and hearing, but attempts have also been made to simulate, among other things, touch and the sense of balance.

[34] This category involves the CAVE (Computer Assisted Virtual Environment) and dome projections.

Archaeological use can be diverse. For example, these solutions open up a possibility for non-invasive surveys. Furthermore, distant, hard-to-access, and intermittently accessible excavation sites can be displayed at any time, making them accessible for professionals taking part in the excavations even on a "daily basis". These models may also come in useful in the field of education and training, as in the event of less professional solutions, the occasional damage of finds can be prevented if the workflows are practiced in a virtual environment prior to the actual excavation. There are many cases when the real environment, physical conditions (size, distances, etc.) cannot be reproduced proportionally by a photograph or video, whereas in virtual space, the observer can get an experience of activities in an environment that is the closest to reality. The use of augmented reality in education is also beneficial as the workflow of an excavation can be recorded by a trained archaeologist at a real site and then the students can experience it in the classroom or at home, and may even take part interactively in the process *(Figure 15).*

Figure 16.
In a VR dome at the Plain of Jars site in South-East Asia (Phonsavan, Laos)
Source: www.youtube.com/watch?v=y9ZHw8T7ECU (Accessed: 19 April 2019.)

The application of 3D technology in archaeological workflows

3D models created during archaeological excavations and surveys can be used for many purposes. The most common ones include the reduction of the cost of expeditionary measurements at remote sites,[35] and the post-processing of the results of surveys made in

[35] *Metcalfe* 2017.

hard-to-reach, dangerous locations.[36] Find reconstruction and “preservation” is another possible use. The historically correct reconstruction of damaged artefacts from written and other sources with digital models is the most cost-effective solution. 3D technology can also facilitate long-term preservation and display, because they can be used to create (even with 3D printing) historically correct props and supports perfectly fitting to the finds. Another possible use is the test and comparison of theories related to the production and application of individual objects. For example, the pressed “bullet with a cylindrical body and globular head” empirically made during the research of Lajos Négyesi[37] could have been produced more simply and faster in the form of a digital model. Based on his research, Zoltán Bereczki[38] creates digital models of various medieval buildings, taking into account the constraints and possibilities of contemporary building methods *(Figure 17).*

Figure 17.
Visualising the steps of the construction of medieval buildings with the help of 3D technology
Source: http://bebop.hu/booklet/arnyekolt_egyben_lo.jpg (Accessed: 19 April 2019.)

In addition to the industrial quality control solutions, the created digital models can be used for controlling measurements of non-invasive surveys and other testing methods without temporal or spatial limitations, without physical touch, and even without the presence of the object. Using appropriate resolution and zooming in the model and maybe even removing the texture, one can see details – surface injuries, engravings, figures and

36 In normal conditions, professionals can concentrate on the archaeological work itself rather than on the circumstances (e.g. monitoring diving equipment and instruments).
37 *Négyesi* 2013.
38 *Bereczki* 2018; *Bereczki* 2017.

inscriptions – that are otherwise invisible to the naked eye. Determining the volume of a musket ball that became irregular or deformed as a result of impact is a good example of such an examination. The result may offer great help in defining the original (production) calibre and, based on additional information, the age and weapon type. *Figure 18* shows a volumetric calculation carried out for the scanned and purified model of a musket ball that could only have been achieved as a result of a lengthy workflow if we had applied conventional measurement procedures and calculations. Importing it into the applied 3D modelling program and running a simple command line resulted in a volume of 2.825 cm,^{3} which is an accuracy of 10^{-9} relative to the actual geometry of the 3D model.

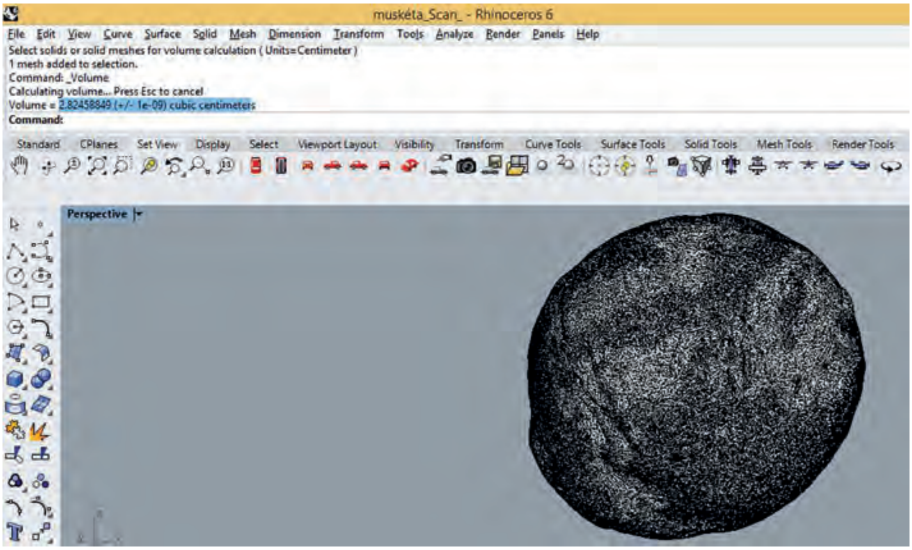


Figure 18.
Volumetric calculation on the model of a musket ball
Source: compiled by the authors

Archaeological excavations can uncover countless finds, the 3D digitisation and saving of which requires considerable storage space. The large size of the files due to recording in unnecessarily great detail and resolution may also cause difficulties in later use. That is why it is worth optimising after scanning, that is, simplifying the point cloud of the model or the number of the polygons to the necessary extent. For example, the open source and freely accessible Instant Meshes[39] software can offer an effective solution for the latter *(Figure 19).*

39 https://github.com/wjakob/instant-meshes (Accessed: 20 April 2019.)

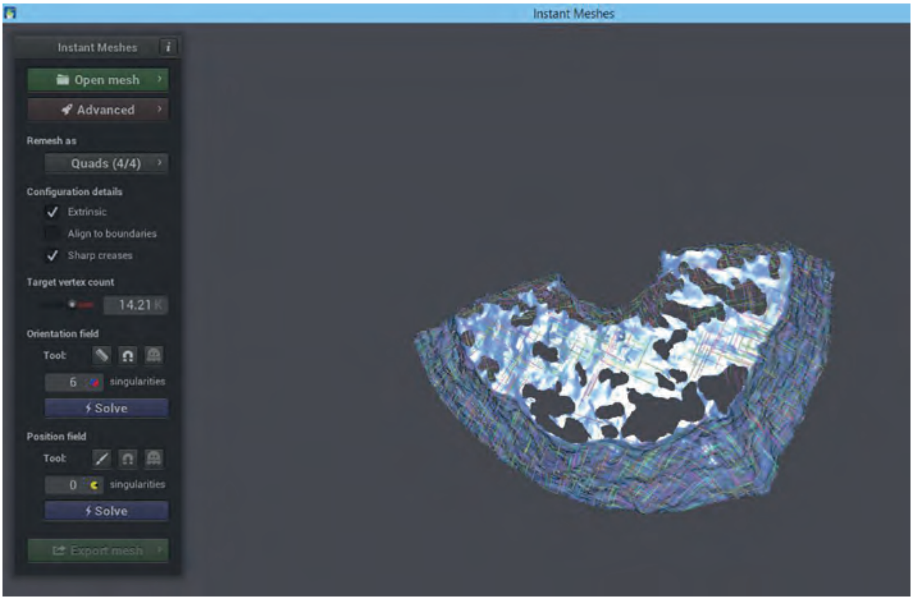


Figure 19.
The starting surface of the Instant Meshes software and the preview of the simplified model
Source: compiled by the authors

3D printing

Digital models of scanned objects and tools, or made with some 3D design software can now not only be displayed on monitors, but they can also be produced in a tangible form in a variety of materials using 3D printers. 3D printing belongs to the group of additive manufacturing techniques, since the desired forms are created by superimposing thin layers on one another instead of shaping prefabrications.[40]

In every case, the process is based on a digital three-dimensional model, which is split into thin horizontal layers using some kind of slicing software. Then we generate the control file that can be read and processed (executed) by the printer. This file contains step-by-step parameters (such as coordinates, speed and timing) for operating the device. After uploading and running the file, the printer starts to execute the instructions encoded in it. The printer constructs the item layer by layer from the selected raw material until it obtains its final form. Although, at first sight, it does not seem to be a complicated process, there are already several techniques for its execution in practice. With these, one can create almost any prototype from hobby use to professional engineering, which can be components and objects in a small or large volume made of almost any base material in a wide variety of

[40] *Husi–Szemes* 2015.

shapes and sizes. These solutions make possible the production of such complex structures that cannot be physically implemented in any other way.[41]

Of the 3D printing processes, the fused filament fabrication (also known as FDM[42]) is the most widely used and cheapest solution today. A common feature of machines operating on the basis of this principle is that the base material (some type of thermoplastic, that is, a plastic polymer material that becomes soft when heated) is available in the form of millimetre-diameter filaments reeled up. This is fed by a stepper motor into the heated extrusion head, where it is melted. The melted material is then squeezed through a nozzle a few tens of millimetres in diameter and cooled after fusing to the previous layer.[43] In a typical FDM system, the extrusion nozzle head is moved horizontally and vertically parallel to the workbench, which vertically moves apart layer by layer.

In stereolithography (also known as SLA[44]), the system works with a liquid polymer (photopolymer) that gets solidified due to light of a certain wavelength. In the process, the product is created on a workbench positioned one layer below the surface of the vat filled with photopolymer. A focused UV beam scans the surface of the liquid according to the geometry of the two-dimensional slices of the model until the polymer solidifies. Subsequently, the build platform lowers one layer deeper and the already solidified layer is recoated with another layer of liquid photopolymer. This method is repeated for each layer of the design until the 3D object reaches its final form. Depending on the geometry of the model, it may be necessary to use mechanical supports that can be removed when the production is completed. The finished products often need to be lit with UV light to achieve their final solidity.[45] This method allows the production of prototypes with significantly higher accuracy, but at a much slower speed than during fused filament fabrication.

In another manufacturing technology based on the principle of photopolymerisation, the liquid surface is illuminated by a projector (DLP[46]). These printers achieve higher speed of printing due to illuminating the entire layer at the same time. On the other hand, the maximum resolution available is limited by the resolution of the projector.[47]

SLS[48] works with a fine powdered material. The essence of its operation is that the device spreads the powered material on the work surface in a layer of desired thickness, and then the laser scans it with a beam directed by a mirror system according to the given slice of the model. The lit powder gets sintered and binds together with the adjacent particles making a solid structure. The powder bed is then lowered by one layer of thickness, and

41 *Gál–Németh* 2019.

42 Fused Deposition Modelling.

43 3D nyomtatás különböző technológiákkal I. – az FDM eljárás [Printing with different technologies I. – The FDM method]. https://3dnyomtato.wordpress.com/2013/07/12/3d-nyomtatas-kulonbozo-technologiakkal-i-az-fdm-eljaras/ (Accessed: 20 April 2019.)

44 Stereolithography Apparatus.

45 Additív technológiák körkép [An overview of additive technologies]. www.cnc.hu/2012/12/additiv-technologiak-korkep/ (Accessed: 20 April 2019.)

46 Digital Light Processing.

47 3D printing Technology Comparison: SLA vs. DLP. https://formlabs.com/blog/3d-printing-technology-comparison-sla-dlp/ (Accessed: 20 April 2019.)

48 Selective Laser Sintering.

another layer of power is applied on top.[49] The greatest advantage of this procedure is that it is capable of printing metal objects, as well. SLM[50] and EBM[51] are similar techniques. The difference between them is that the former uses a high energy laser beam, whereas the latter uses a high energy electron beam to melt the metal powder.[52]

Special mention should be made of 3D printing processes using the "jetting" method. In the case of photopolymer jetting (PJ)[53] technology a liquid photopolymer is dripped onto the workbench, which is solidified with UV light right after it reaches the workbench. Binder jetting (BJ) technology, on the other hand, uses a special binder – pressed through the extrusion head – to bond the powdered material.[54] Both photopolymer and binder jetting procedures make possible very precise additive fabrication and result in a smooth surface, good workmanship and a reasonably long lifetime.

During the production of a laminated object (LOM[55]), a stepper (a system of feed rollers) transfers the sheets or layers of material used as the base material to the build platform. Afterwards, the inner and outer contours of a given section of the object are cut with laser light, which is followed by the binding process with the help of a heated roller. The platform is then lowered one layer deeper, and the system of feed rollers puts on the next layer.[56]

Given that our research team acquired a tool using FDM technique for the reproduction of finds discovered during investigation into the siege of Zrínyi-Újvár and other artefacts used for applicability tests, the printing process and raw materials had to be examined before the experiments began. *Figure 20* demonstrates the operating principle of FDM.

The figure illustrates that in the case of certain geometries, it may be necessary to use supports to avoid distortions. The support can be made of the base material of the printed object, which has to be removed at the end of the process. Subsequently, the superficial defects at the support points have to be smoothed (by polishing). In this case, a single extrusion head is enough, but manual finishing may take quite a long time. Alternatively, we can use two extrusion heads or a dual extruder feed device, so that while one extrusion nozzle builds the model, the other nozzle would fabricate the support from a material soluble in water (or other liquid).

---

49 3D nyomtatás különböző technológiákkal II. – Az SLS eljárás [3D printing with different technologies II. – The SLS method]. https://3dnyomtato.wordpress.com/2013/08/14/3d-nyomtatas-kulonbozo-technologiakkal-ii-az-sls-eljaras/ (Accessed: 20 April 2019.)

50 Selective Laser Melting.

51 Electron Beam Melting.

52 *Palermo* 2013b.

53 Also known as PolyJet.

54 What is 3D Printing? The definitive guide to additive manufacturing. www.3dhubs.com/what-is-3d-printing#technologies (Accessed: 20 April 2019.)

55 Laminated Object Manufacturing.

56 *Palermo* 2013b.

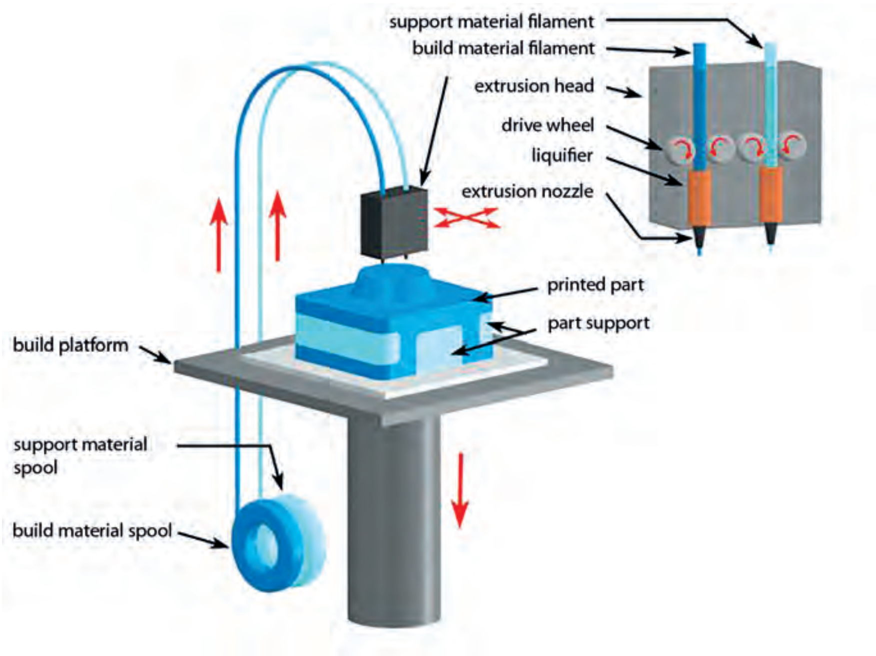


Figure 20.
The operating principle of FDM printers
Source: www.custompartnet.com/wu/fused-deposition-modeling (Accessed: 22 April 2019.)

The long continuous filaments used by the FDM printer (that are called in the same way in the textile industry) are made from a variety of raw materials sold in various packages. They have a wide range of properties due to the growing number of additives mixed to the basic component. Virtually all kinds of plastic polymer can be used as a base material that melts when heated and can be moulded (thermoplastic). They most often contain acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) filaments. The main difference between the two materials is that while ABS is a petroleum derivative, PLA is a biodegradable material that is produced from plants and can therefore be composted. When using ABS for 3D printing, it is worth heating the printer countertop to a temperature of about 110 degrees Celsius, because this material is highly sensitive to heat changes, which can cause deformation to the first layer when printed on a cold surface,[57] which renders it impossible to fabricate the product. Because of the thermal sensitivity, the print area should also be insulated from ambient air in order to minimise the amount of thermal fluctuation caused by air movements during the whole printing process. PLA, on the other hand, is a less sensitive material and can be handled in a much more flexible way, where the desktop does not require a heated environment. ABS is primarily used to manufacture objects designed

[57] 3D nyomtatás különböző technológiákkal I. – az FDM eljárás [Printing with different technologies I. – The FDM method].

for everyday use, such as parts of motor vehicles and plastic toys (including LEGO). In the automotive industry, companies such as BMW, Hyundai and Lamborghini are already using the fused filament fabrication technique, but large companies of other profiles (e.g. Nestlé) also like to use it in the field of product design or directly in production.[58] PLA, on the other hand, is suitable for the production of prototypes and devices subjected to less strain.

One of the benefits of FDM technology is speed. The model can be built quite quickly in a few hours or tens of hours, depending on the material, size and geometry of the fill, while in the case of more complicated techniques, the whole work process may take days for the same size of model. Another advantage is the potential of making larger objects. In the case of non-industrial devices, fabrications with side lengths of up to 50–60 cm can be produced, while with sintering or jetting, the side length is normally limited to 10–20 cm. The price and operating costs of printers using the FDM technology, as well as the relative cost of the basic materials used are considerably lower than in case of other devices, but in terms of the variety of materials, our possibilities are much more limited.[59] In spite of this, in addition to the aforementioned, there are also plastic-based printing filaments of 1.75 and 2.85–3 mm in diameter that can also be used for archaeological purposes.

In addition to filaments available in a wide variety, we can now work with wood-, metal-, and even stone-like materials, and the post-treatment of 3D printed objects offers further opportunities (e.g. cutting, polishing, turning, etching, drilling, reaming, sawing,[60] coating, painting, heat treatment, soaking, sanding and chemical treatment[61]).

The different types of technical filaments include mixtures with special properties that, among other things, change and improve one or more of the basic properties of PLA and ABS materials. These include, for example, heat resistant, impact resistant, flexible, abrasive and conductive/shielding[62] printer filaments.

HIPS[63] is a widely used polymer because of its hardness and heat resistance. In addition to these beneficial properties, it can also be used as a support for ABS filaments since HIPS is soluble in an organic compound, called limonene.

Filaments containing gypsum can be used to reproduce relief map tables, clay-containing objects and ceramics. They are easy to work with, like gypsum, so the end product can be polished, moulded, and the finished model can even be painted with watercolours.

Heat-resistant materials have a higher melting point than PLA, so even objects exposed to direct heat can be made of them. Typically, they also have a relatively high impact and fracture resistance, so objects, tools and show pieces exposed to greater strain should be made from such materials.

58 *Palermo* 2013a.

59 www.cs.cmu.edu/~rapidproto/students.98/susans/project2/pros.html (Accessed: 22 April 2019.)

60 The applicability of these relies greatly on the type of material and the fill geometry of printing, as depending on these, the manufacture gets deformed due to clamping or other forces.

61 For example, in the case of ABS, keeping the item in acetone vapour for a while results in a smooth and shiny surface.

62 In general, materials with antistatic or shielding properties can be used to cover and separate electronic circuits.

63 High Impact Polystyrene.

Elastic filaments can be used, for example, to form props, lids, or supports fitting to archaeological finds. Antistatic conductive materials can be used to make overlay for instruments used in archaeological work (e.g. metal detectors) or devices that are in direct contact with them. Materials reinforced with kevlar and fibreglass have the advantage of being highly heat and wear resistant. Oil and chemical resistant materials, on the other hand, can be used to print structures and containers to store archaeological finds in them, and supports put in them.

In the case of fiberising technology, depending on the material used, but typically for bridges with more than 45 degrees of inclination or for objects without a pedestal ("hanging in the air"), it may be necessary to build supports. These supports can be subsequently removed by breaking or cutting them off the model. However, we might deform objects with thin walls (of a few fibres width) and items rich in detail, or damage them if we try to break off support towers with the same firmness. These destructions can be avoided by using water-soluble filament supports. When using fibres of special components, preparation for printing and the setting of the printer may differ from conventional PLA/ABS printing. We need to set correctly the temperature of the extruder,[64] the optimum printing speed, the rate of retraction,[65] and – in case of elastic and highly wear/impact resistant materials – the configuration of the mechanical elements (rollers)[66] used to transfer the filament (in order to avoid material jamming), and we also have to cope with the effect of thermal expansion. Harder mixtures (e.g. metal powder, kevlar, fibreglass) are likely to lead to the early wear of extruders during use either by themselves or due to the higher temperature required for their melting.

For our research workshop, we purchased a Craftbot3 3D printer[67] designed in Hungary, which has an independent dual extrusion system. Due to its resolution of 50–300 micron/layer, it can be used to reproduce archaeological finds rich in detail or to complete the damaged ones. The printer is equipped with a heated bed, which reduces the likelihood that the bottom layers will roll up or a faulty product is made when the materials used are more sensitive to temperature changes. The two extrusion heads can be freely used to print two objects simultaneously, in synchronicity or mirrored. They can also print an object together with its supports made of soluble filaments, or use two fibres of different colours and/or materials within the same object, offering thus greater freedom to users.

---

[64] 3D Printing Filament Comparison. https://static1.squarespace.com/static/57bafefc15d5dbf599092bd6/t/58a5f3e03e00be425d9b11df/1487270891027/ThreeDotZero+Filament+Comparison.pdf (Accessed: 22 April 2019.)

[65] When printing non-related structures at more than one place on the workbench at the same time, it may be necessary to slightly withdraw the filament when setting the extrusion head between two work-phases to avoid dripping of the material.

[66] For example, elastic filaments may slip from the drive wheels and get rolled up on their pivot, which halts the structure and/or lead to misprints and, on extreme occasions, they may even cause damage to the printer.

[67] https://craftbot.com/category/craftbot-3-3d-printer (Accessed: 22 April 2019.)

Making and editing 3D models

There are several alternative software solutions for making modifications and additions to 3D models. These are generally similar in terms of their basic features and main functions and – focusing on certain dominant areas of use – the developers add further functions (e.g. computer animation, engineering, automotive, medical) to these. In practice, different professionals choose a tool for a particular task based primarily on their own professional knowledge and previous experience, rather than the actual facilities and potential of the software.

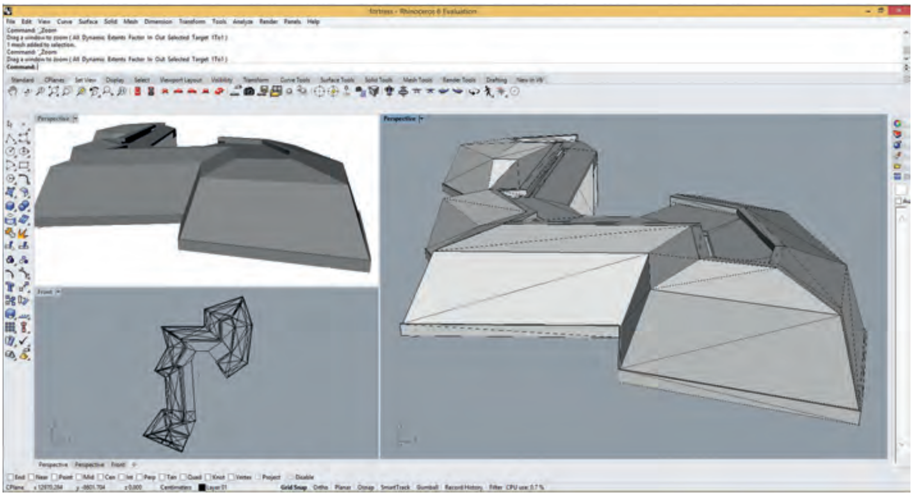


Figure 21.
Different views of the model of Zrínyi-Újvár in the Rhino software
Source: compiled by the authors

Different modelling, CAD[68] and animation software may have different interfaces and features, so switching between programs can either complicate or simplify users' task, depending on their prior knowledge and experience. In order to support the work of our research team, we opted for Rhino(ceros),[69] a professional 3D design software, because it significantly facilitates the tasks of archaeological modelling and find reconstruction due to its freeform design approach and solutions, while integrating many tools needed for parametric design and engineering modelling, and it is also suitable for complex visual designs. The software can open and edit, among other things, major types of files used in the field of 3D modelling and scanning, while different views and calculations support the analysis and processing of models. It is equally suitable for scanning, editing, and post-processing point clouds consisting of a large number of elements, the results of 3D scanning and LIDAR data. Based on 3D models, the reverse engineering[70] toolkit also offers the possibility to produce

68 Computer Aided Design.
69 www.rhino3d.com (Accessed: 22 April 2019.)
70 Remodelling.

models that can be optimised, edited, or manufactured with different technologies. *Figure 21* shows the model of Zrínyi-Újvár in the user environment of the Rhino program, created with a method to be introduced below, after being scanned and visualised in the software.

Graphic design and implementation of the 3D model of Zrínyi-Újvár

The visual environment created in three dimensions with the help of a computer is based on the application of the CGI[71] graphics. One could first encounter with it in cinemas, then in commercials and television programs, but its leading sector has become the development of video games by these days. After the turn of the twentieth and twenty-first centuries, however, the computing power of personal computers (Intel Pentium III,[72] AMD Athlon[73] and Athlon 64[74]) has increased to such an extent that the visualisation of rudimentary 3D graphics created with them has also become available to the wider public both in terms of time and price. Subsequently, due to collaboration of multinational companies producing video cards and operating systems, a simple PC purchased for domestic use has also become capable of displaying much more complex visual representations rich in details (pixel shader,[75] vertex shader[76] and DirectX[77]).

Thanks to hardware manufacturers and system designers, the use of 3D graphics has spread rapidly, so separate development platforms have been designed to develop graphics software. Video game designers have also moved in this direction, as a result of which a number of software 3D engines[78] with different functions have been developed. Today they are used by designers, graphic artists, and even archaeologists and battlefield researchers during their work for creating their artwork or for visualising artefacts.

Employing the currently widely available achievements in 3D graphics, our research team has undertaken to design and build the most accurate 3D model of Zrínyi-Újvár and the visualisation of its immediate environment – based on the information available from our research in the past decades – that can be visited in an interactive way, as well. Our main purpose was to offer an experiential platform for displaying our former and future research results, as the model can be freely modified at any time based on scientifically proven data and information to be acquired in the future.

The complete visualisation of an authentic historical view based on 3D graphics requires a number of input parameters, as many as possible. They can be even redundant

[71] Computer Generated Imagery.

[72] 32-bit edition of 6th Generation Intel Core Processor with an x86 microarchitecture design (1999).

[73] 32-bit edition of 7th Generation AMD Processor with an x86 microarchitecture design (1999).

[74] 62-bit edition of 8th Generation AMD Processor with an AMD64 microarchitecture (2003).

[75] 2D technology, it allows post-processing of individual pixels.

[76] 3D technology, it allows post-processing of certain vertices displayed on the drawn canvas.

[77] It is a Microsoft package for the Windows operating system, which makes possible a faster display of multimedia applications.

[78] The 3D engine is an integrated software development environment designed to develop graphics applications. Each 3D engine is capable of drawing 2D/3D elements, detecting object collision, as well as physical space simulation and model animation.

data, historical notes, parameters, descriptions and survey results, which were fortunately already available to us at the start of the project due to the previous work of our researcher team members.

Baseline

Zrínyi-Újvár was a fortress along the Mura River, in the outskirts of today's Őrtilos in Somogy County, built by a Dutch military engineer commissioned by military leader Miklós Zrínyi[79] to strengthen the defence of Muraköz and his own estates effectively exploiting environmental and terrain conditions. The bridgehead constructed in this way could have served as a base for the recapture of the Fortress of Kanizsa and territories occupied by the Ottomans.

French General Pierre Surirey de Saint-Remy described in his *Mémoires d'artillerie* (1697) how the mortar batteries and cannon stands looked like at that time, and their layout is also presented in this work.[80] A distant view of Zrínyi-Újvár also appears among the sketches of the work *(Figure 22).* Although in this form, it did not provide us with precise information, it helped us begin the process of visualisation.

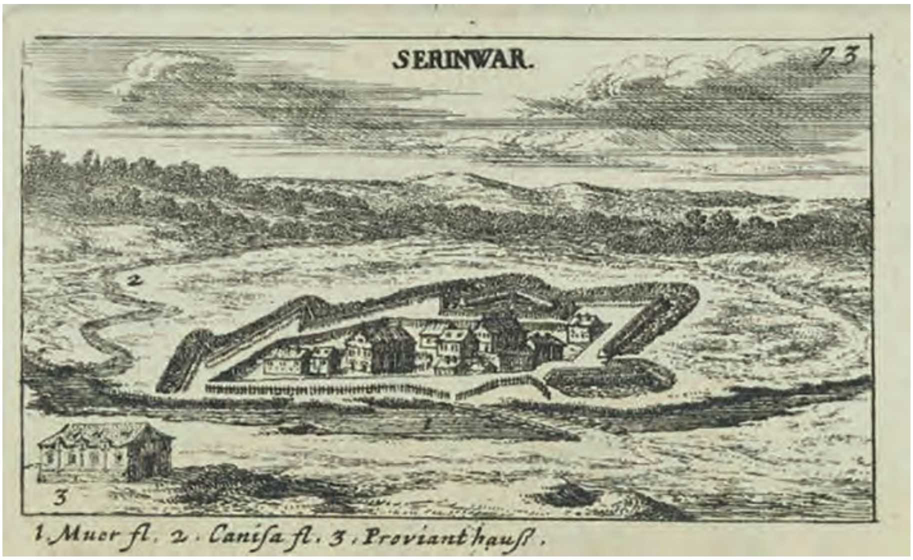


Figure 22.
Panoramic view of Zrínyi-Újvár

Source: Birken 1664.

[79] Zrínyi Miklós (in Croatian: Nikola Zrinski) was a poet, military scientist, commander and politician, who lived in the seventeenth century. He was the Ban of Croatia, Lord Lieutenant of Zala and Somogy Counties, and a high nobleman with large estates.

[80] *Saint-Remy* 1697.

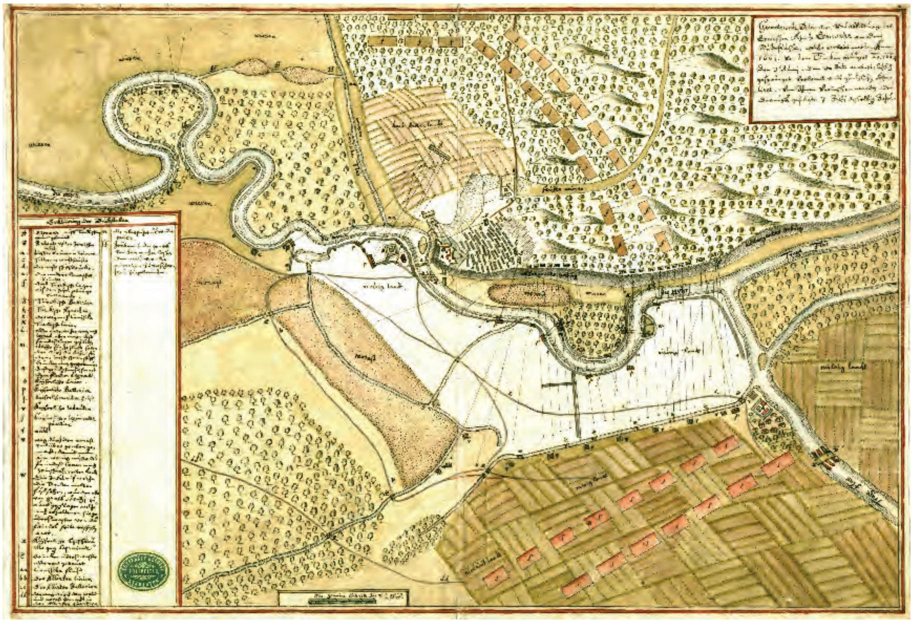


Figure 23.
Map in Pál Esterházy's work, 1664
Source: MNL OL T. 2. XXXII. 1064

Although historical records and descriptions offer us a lot of useful information, the accurate spatial localisation requires the use of maps. When planning orientation, we relied on a contemporary map shown in *Figure 22,* which clearly depicts the position of the fortress and its surroundings, including a nearby lake and the bank of the Mura River. The position of the bridges across the river and the location of the buildings can be clearly seen, and – even if schematically – the relative position of the Ottoman siege trench is also represented.

Perhaps the biggest help in planning was offered by the 2010 model reflecting the state of Zrínyi-Újvár and its surroundings on 14 June 1664, which records the conditions assumed based on the results of the research until then. Therefore, it proved to be a good idea to choose it as a starting point. A detail of this model (top left), its graphic design (right), and a sketch drawing after a contemporary map by Jacob von Holst (bottom left) used as a basis for these two are shown in *Figure 24.*

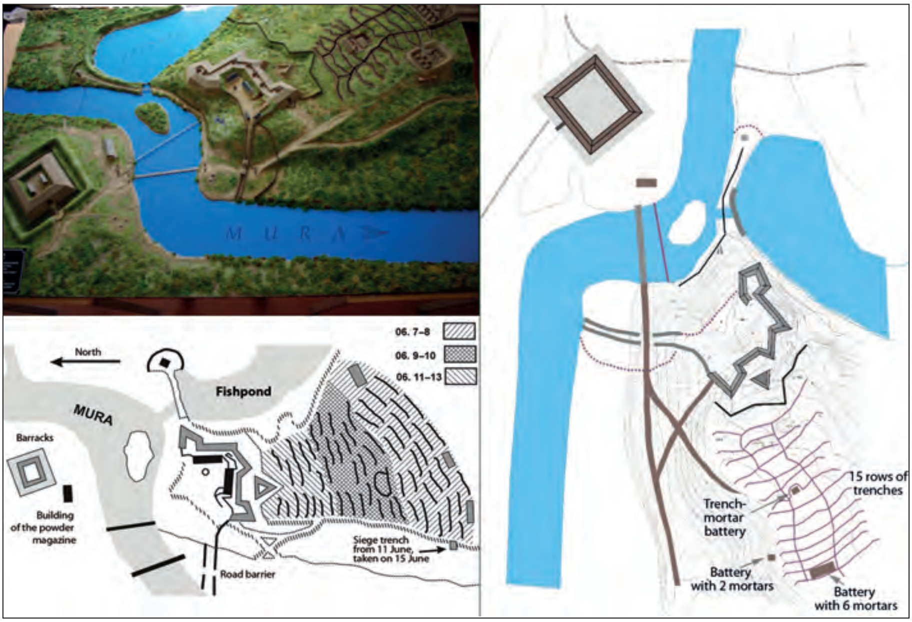


Figure 24.
A model and graphic design of Zrínyi-Újvár, as well as its sketch drawing after a map by Holst[81]
Source: compiled by the authors

Software background

The software that we used for creating the 3D visualisation was chosen on the basis of our already existing professional experience and skills in the field, as well as the potentials and limitations of the application. The Blender Foundation 3D graphic modelling platform is an open source (GNU GPL v3[82]) program and is widely used by 2D-3D graphic designers, modellers and engineers. In addition to creating models, it offers the possibility to perform animation, simulation and rendering.[83] We relied mainly on the Blender version 2.76 when creating the 3D models of some of the elements of Zrínyi-Újvár. Its main advantage is that

81 Based on contemporary sketches and field surveys, the fortress reconstruction was made by the members of the ZMNE Bólyai Scale-Model Club, László Hajba, Imre Kovács, Károly May, Ádám Nagy, Tamás Pénzes, József Réti, Balázs Somogyi, Zoltán Szabó and András Varjasi. The necessary research was conducted by the joint research group of ZMNE and HM HIM, Tibor Bartha, Gábor Hausner, Attila Kállai, Lajos Négyesi, András Németh, József Németh, József Padányi and Ferenc Papp with the assistance of university students, and the support of Belezna and Őrtilos municipalities. Scale: 1/400. The scale-model was handed over on 23 April 2010.

82 GNU General Public License Version 3. https://download.blender.org/release/GPL3-license.txt (Accessed: 25 April 2019.)

83 This is a technical term in computer graphics, which refers to displaying 3D models on the screen.

it is compatible with several 3D engines, including the Unity 3D we use, and it can export the model to a variety of formats. It offers a simple modelling process, for which there is a user's guide along with a number of useful tutorials[84] on the website of the software. The Krita[85] drawing program was a great help for us in texturing. In terms of its look and functionality, it is very similar to Adobe Photoshop professional program, but it is open source and can be accessed by anyone without restriction. We used the software called Materialize[86] for generating the different texture types which allowed us to make complex and precisely calculated bitmaps. The most important part of the technical implementation of the project was the Unity 3D[87] graphics engine, which is the leading software among 2D-3D graphics engines available on the market in the field of amateur use, but it may also be instrumental for projects like Zrínyi-Újvár where appropriate expertise is at hand. Visual Studio,[88] the software development environment of Microsoft supports, interprets and translates countless programming languages into machine code. The 2015 version of Visual Studio Community was used when writing the specific code elements for Unity 3D.

Designing the ground surface

After completing the information acquisition phase of planning, the next step was to design and implement accurately the ground surface. This process was very complicated and complex, and required multiple mappings. In the neighbourhood of Zrínyi-Újvár, the design of the ground surface was based on a recent LiDAR[89] image. Nevertheless, the 3D objects generated from the laser image did not seem to be applicable for visualisation at first attempt. The ground surface generated from the results of aerial laser scanning was available in twelve parts in OBJ[90] format, which first had to be merged in Blender *(Figure 25).* To achieve this, it was enough to create a blank scene, and when importing the tiles in it one by one, those were automatically positioned next to each other, as the coordinates of the vertices of each piece were already well set in relation to the origin. So that the pieces would make a uniform surface, the parts had to be logically merged afterwards.

Generating a height map[91] proved to be a more difficult task, since after merging, it turned out that the model contained 453,960 vertices, most of which formed intersecting planes, thus the computer was unable to display them well. The main problem was caused by the limited capacity of current video cards, as even the most powerful high-end video cards could draw at most one million vertices at a time. In order to overcome this obstacle, it was necessary to optimise the merged ground surface.

84 www.blender.org/support/tutorials/ (Accessed: 25 April 2019.)
85 https://krita.org/en/ (Accessed: 25 April 2019.)
86 http://boundingboxsoftware.com/materialize/index.php (Accessed: 25 April 2019.)
87 https://unity3d.com/ (Accessed: 25 April 2019.)
88 https://visualstudio.microsoft.com/ (Accessed: 25 April 2019.)
89 Light Detection and Ranging.
90 Wavefront Object (This is a simple and widespread 3D model format, which contains the coordinate points of vertices and their relationship in plain text).
91 This is a raster image, the pixels of which correspond to height data. White pixels represent high values, black pixels represent low values.

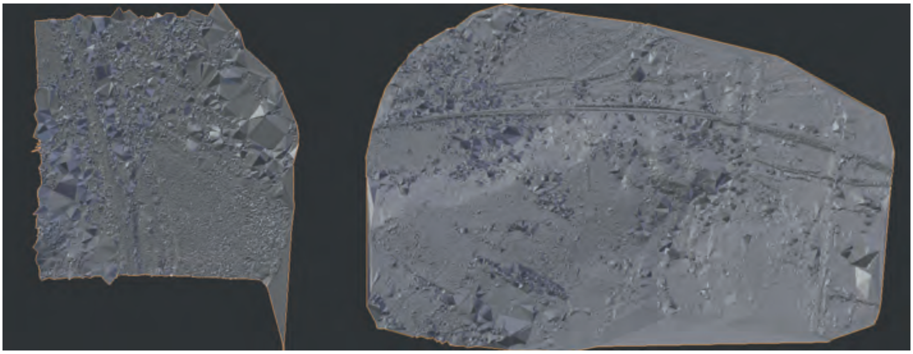


Figure 25.
A piece of the LIDAR image and the model of the whole surface after merging
Source: picture made by the authors

For optimisation, the height value of each vertex parallel to the vertical reference plane had to be taken as a basis and mapped in a 2D matrix, which was a traditional image file in our case. This was rendered possible by the fact that displaying a colour pixel generally requires 3 + 1 channels (RGB[92] and alpha[93] channels), and by their use, we get $256,^4$ that is, 4,294,967,296 different possible height values in the case of 32-bit colour depth. The elevation map made with this procedure is shown in *Figure 26.*

Figure 26.
The finished 2D height map
Source: picture made by the authors

92 RGB corresponds to Red, Green and Blue. The computer mixes the displayed colours from these three colours. Each colour is represented by 8 bits, so the value they take on range between 0 and 255. This is called a 24-bit colour depth.

93 The alpha channel has the same parameters as RGB channels, that is, they also use an 8-bit colour map. This is an additional byte that defines the transparency of an RGB colour. Together they make an RGBA colour, which corresponds to a 32-bit colour depth.

However, because – in addition to the actual terrain – all artificial and natural landscape features are present in the dataset collected by laser remote sensing, they also appear on the height map. In order to eliminate the effects of these, the discrete "clouds" on the map had to be removed before re-mapping, for which we chose the simplest solution, namely image editing. In the Krita software, having selected the individual clouds, we rebuilt their colour using values corresponding to the pixels in their immediate vicinity. The software was able to do this automatically, and we just had to make sure that only those white areas are selected that do not belong to the earth's surface.

After correcting the height map, the surface needed to be created in the engine, next it had to be calibrated and levelled, then the various elevations had to be coloured, finally the riverbed had to be deepened. Since the Unity 3D engine is able to create an elevation surface from a height map, we could simply rely on its capacities. By exporting the height map in RAW[94] format and then importing it into Unity 3D, we achieved the terrain *(Figure 27).*

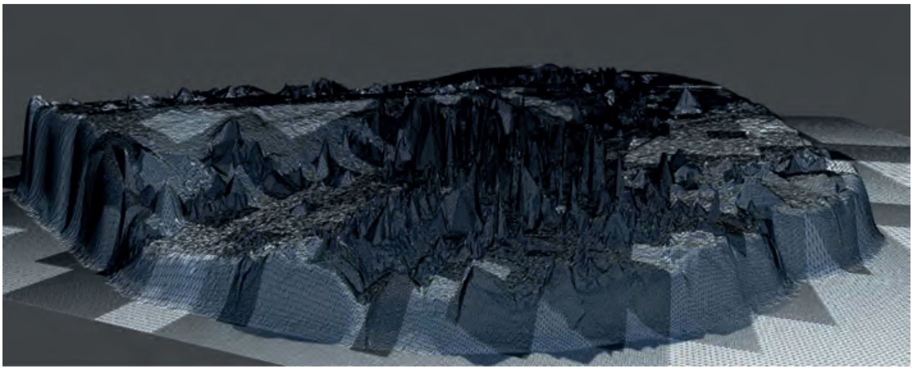


Figure 27.
The relief of the ground surface obtained by generating
Source: picture made by the authors

Unity 3D manages the terrain surfaces in a special way optimising their technical visualisation. It adjusts the vertices to be displayed and the resulting planes in a balanced way. Therefore, it creates only as many vertices as absolutely required by the complexity of the elevation. In other words, in the case of more complex geometries, the grid is denser, while in the case of simpler ones, it is looser.

Over the centuries, the riverbed of the Mura has significantly changed its course. To represent it correctly, the raster image of the model shown in *Figure 24* was superimposed on the designed terrain surface and the various transformations were performed until the two fit nearly perfectly. In this way, not only the river but also the lake next to the castle was replaced by its originally supposed position. Subsequently, we used the terrain deepening tool of Unity 3D to "dig" the riverbed along the outline of the raster, that is, we set the coordinates of the relevant vertices parallel to the vertical plane to zero, as a result

94 Raw file format comprising only bits.

of which they appeared on the horizontal reference plane. Although not every element of the raster fit exactly on the surface, the LIDAR image could be used to draw the course of the river based on the detectable traces of the former riverbed *(Figure 28).*

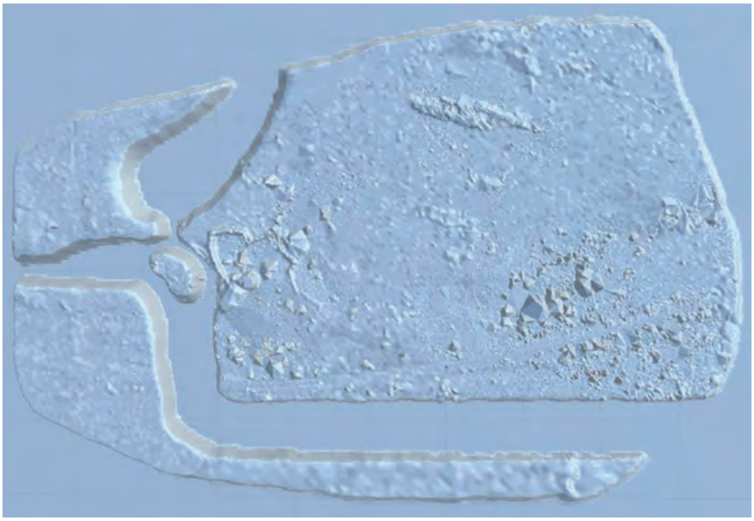


Figure 28.
The relief with the deepened riverbed
Source: picture made by the authors

After the generation, the surface still contained unwanted elements caused by trees and other features recorded during the LIDAR survey (which appear as spikes in the image above) so it was necessary to clean the model. This could be achieved by levelling the surface using the terrain levelling tool of Unity 3D designed specifically for this purpose. The end result is shown in *Figure 29.*

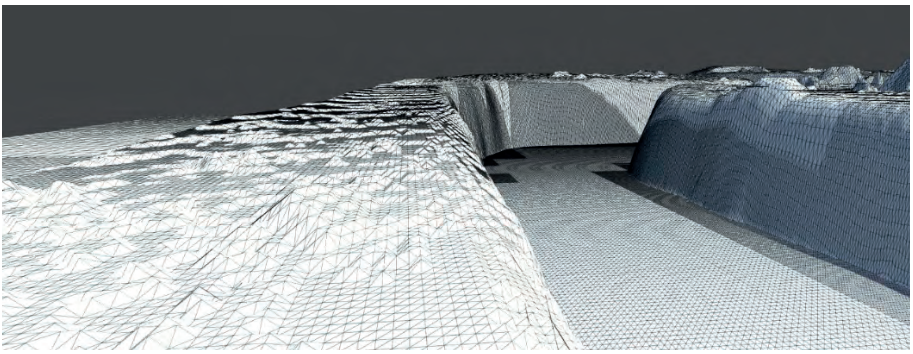


Figure 29.
The relief after levelling
Source: picture made by the authors

Creating features

The creation of the optimum surface gives the possibility for positioning contemporary features and technical establishments, which is why the following stage was the creation of moats, roads, siege trenches and firing positions. The raster image used for designing the river and lake beds served as a reference for this.

The method described above was used to draw the ditch around the barracks. No direct information, no authentic measuring result was available about the depth of the ditch, so we took into account the proportions of sketches shown in *Figure 30.* It can be clearly seen on the image that the depth of the ditch should be the same as the height of the walls around the barracks.

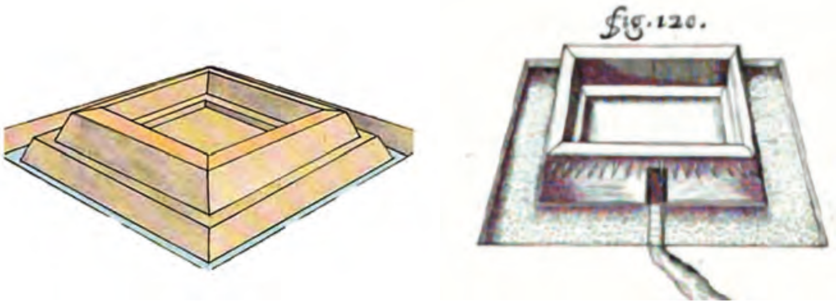


Figure 30.
The possible variations of the barracks
Source: compiled by the authors

Although not included in the sketch, the original structure was presumably also protected by a rampart, so we raised an embankment around the ditch. In its planning, we relied on the proportions of the scale-model. Both the sketches and the scale-model show a bridge leading to the gate of the barracks. This had to be taken into account when designing the embankment and its place had to be left open. The model and the end result projected on the model are shown in *Figure 31.*

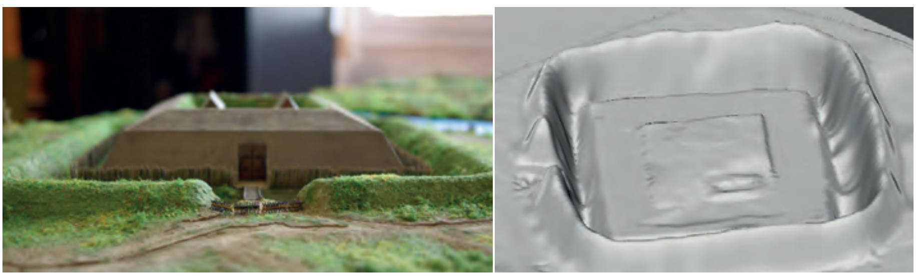


Figure 31.
The building of the barracks in the form of a scale-model (left), as well as its position and defence system in the digital model (right)
Source: pictures made by the authors

The scale-model was also used as a starting point for planning the roads and Ottoman siege trenches. *Figure 32* shows their position and orientation. In order to display these irregular geometries on the relief model, we had to make a template from the image above and project it on the surface. The line of the roads was not deepened. We only levelled its surface so that the model of the road fit properly on the surface and there would be no protrusions and bumps in the model.

During the planning of the siege trenches, their depth was defined relative to the average height of people,[95] while their width had to exceed the average shoulder width of people.[96] These values were used to set the relief deepening tool. Subsequently, the necessary deepening and levelling operations were carried out.

Figure 32.
A detail of the image used as a template
Source: picture made by the authors

The former template was also used to locate the three firing stations, and after the deepening phase, we raised an embankment around them, except for the mortar battery. In addition to the scale-model, sketches were also of great help for us in designing the equipment of the individual stations, which can be seen in *Figure 33,* along with their models.

95 www.averageheight.co/average-male-height-by-country (Accessed: 19 April 2019.)
96 http://antropologia.elte.hu/_vllszlessg1.html (Accessed: 19 April 2019.)

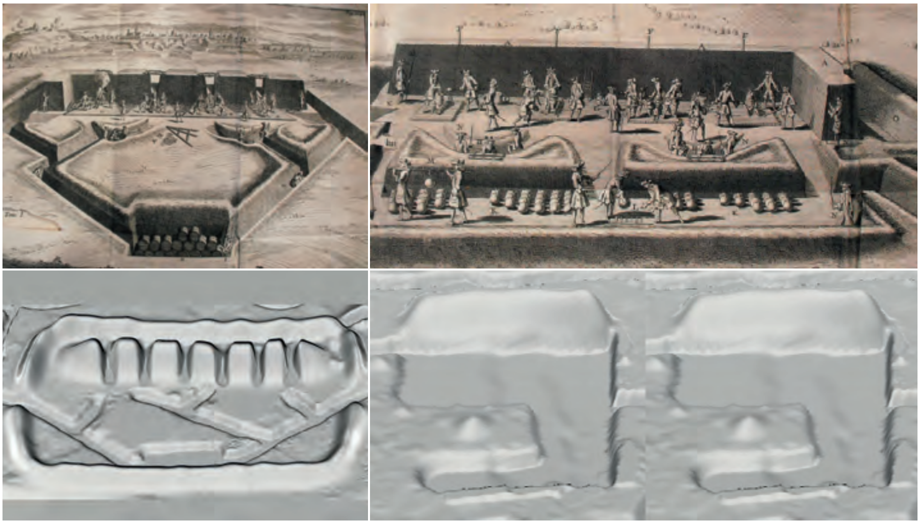


Figure 33.
Cannon (left) and mortar battery (right) stations and their models
Source: compiled by the authors based on *Saint-Remy* 1697

The design of the surface was completed with the creation of the structures above. As a next step, we moved on to modelling the various features of the terrain such as the fortress itself, the barracks, the cannons, the road, the fence, the barrier, guard towers, bridges and buildings.

The modelling of the barracks is illustrated in *Figure 30.* Its size was planned in a way that it would fit in the area delimited by the ditch created previously. For texturing, a mud-earth pattern was used. We projected it on the surface, and the gaps at the joining parts were subsequently refined.

The top view and cross-sectional sketches shown in *Figure 34* were used to create the floor plan of the fortress and to lift it out of the 2D plane. The advanced defensive work was created as a separate model. At first, the advanced defensive work was open from the side of the fortress, but after learning about the new research results we closed it from there, too.

The texture of the advanced defensive work and the fortress is the same as the one we used for the barracks. We faced the same problems when placing the fortification on the surface as in the case of the barracks. Furthermore, it turned out that the relief sloped too steeply towards the river, so the gap caused by the height difference between the base of the fortress and the surface had to be rectified subsequently by fill-up. The completed models are shown in *Figure 35.*

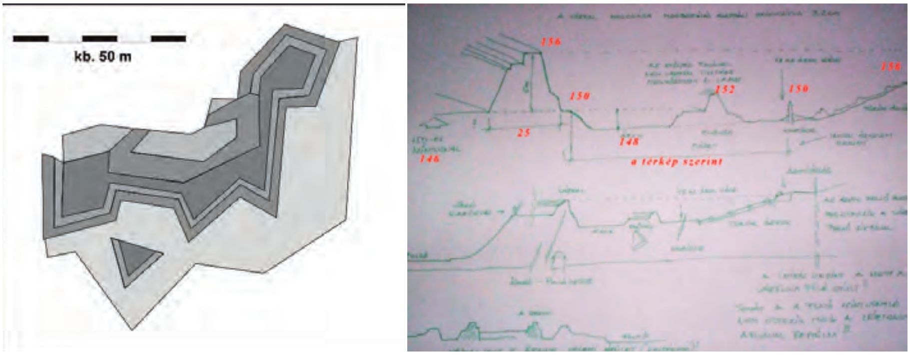


Figure 34.
The sketches of the plan of the fortress and its vertical section
Source: compiled by the authors

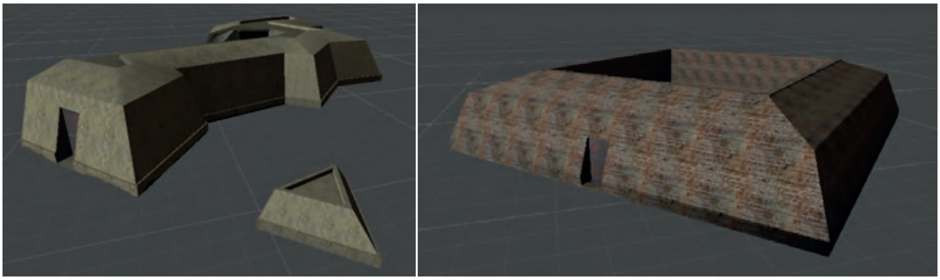


Figure 35.
The models of the fortress (left) and the barracks (right)
Source: picture made by the authors

Unity 3D is capable of generating a road along a line. As we have previously planned the tracks of the roads on the surface, it did not take much time to draw them. Although the software created the individual routes, it was more difficult to match them. In case of intersecting roads – so that their line could be drawn correctly later – one road had to be positioned invisibly higher than the other, as if one path overlapped the other. This was needed to avoid errors in 3D modelling. It also caused a problem with the LIDAR images because video cards are unable to correctly display planes that are in the same place and position. The problem could have been solved more precisely by adding new vertices to the model along the line of intersection and then using logical trimming along the vertices. However, this would have been cumbersome, mainly because the 3D engine used does not support such operations, so the model of the road would have had to be exported, next modified in Blender, and finally re-imported. Another disadvantage of this solution would have been that, in case of need, it would be difficult to modify it later.

When designing the road barrier and roadside watchtowers, we modelled features that could be seen on the scale-model, as no other information was available to us. During the implementation, it was enough to model a single segment of the palisade and multiply it as many times along the raster as necessary to create a continuous technical barrier across the road. In terms of its geometry, the watchtower is a very simple rectangular prism shaped structure, where a wooden plank leads up to the watchtower. The tower is covered with a pyramidal roof resting on four pillars. The watchtower closer to the lake is a stand-alone structure, while the one by the fortress is a bit more complex as it also functions as a crossing point. It consists of two watchtowers, which are connected by a footbridge, under which there is a gate. Both towers can be created from a rectangle and they receive their final form after being textured.

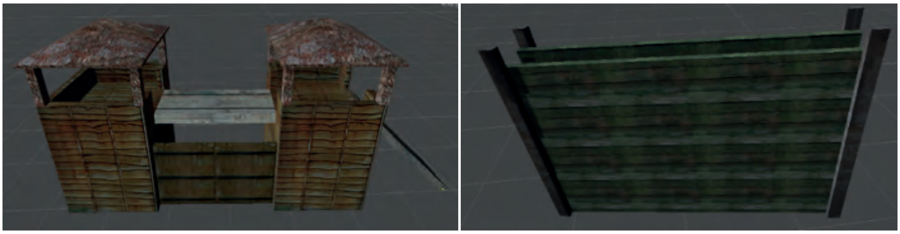


Figure 36.
The models of the crossing point (left) and a segment of the palisade (right)
Source: picture made by the authors

The scale-model also has four bridges and a dam. Two of the bridges span the Mura River, one crosses the dam and another one crosses the trench around the barracks. One of the bridges over the Mura River is a stable stationary engineering structure (i.e. a crossing supported by pillars), and the other one is a temporary pontoon bridge constructed of boats. In practice, the modelling of the permanent bridge meant modelling a multiplied segment. The segment consists of several support pillars joined with a cross bar. We laid beams on the crossbars, and "fixed" the wood boards on those. In practice, this process involved placing rectangles of different sizes on top of each other. The segments were placed side by side along the raster across the Mura River. In case of a pontoon bridge, the methodology was the same, except that the pillars were replaced by boats, which were modelled in advance. With the bridge spanning the ditch of the barracks and the dam, the pillars of the first modelled bridge were replaced with two U-profiles. In case of the dam, we used cylindrical bodies to imitate the logs and applied bark texture to them. The model representing the dam made of logs and the bridge can be seen in *Figure 37.*

Buildings have been digitally designed after the constructions seen in the scale-model. Two of the three taller buildings were placed in the courtyard of the fortress, and the third, which served as a powder magazine, was placed closer to the barracks, on the other side of the Mura River, along the road. The two smaller, one-storey buildings, on the other hand, were positioned in the "funnel" of the linear palisade leading to the river. Because, according to the current state of research, the existence of the buildings shown in the courtyard of the barracks on the scale-model is not proven, they have not been included in the 3D view. In terms of the building material, these were loam houses, so the texture for the models was chosen accordingly. The proportions of the scale-model were taken into account for sizing.

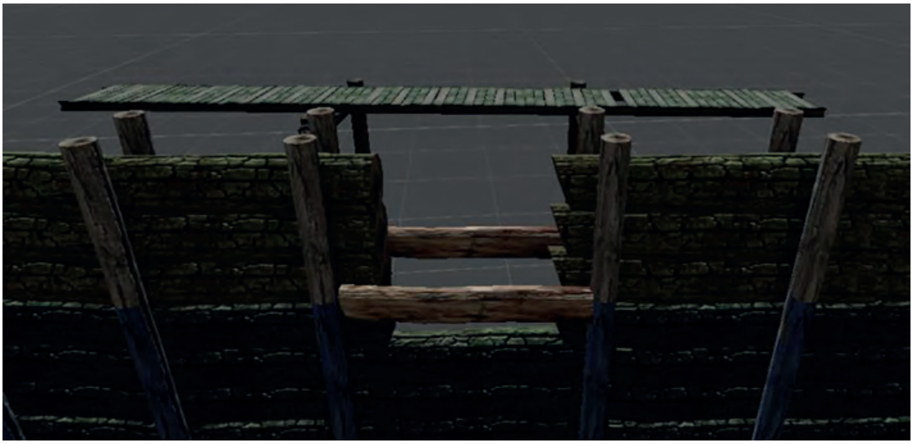


Figure 37.
The model of the dam and the bridge by that
Source: picture made by the authors

For the modelling of the cannon and the mortar, the illustration on the left side of *Figure 38* was taken as a baseline. Since the exact dimensions were not available to us, the illustration was used as a template, and the linear silhouettes of the components of cannons were added to this template in the modelling software. It was then embossed and finished with various solid-state operations. Having put the pieces together, we received the complete model.

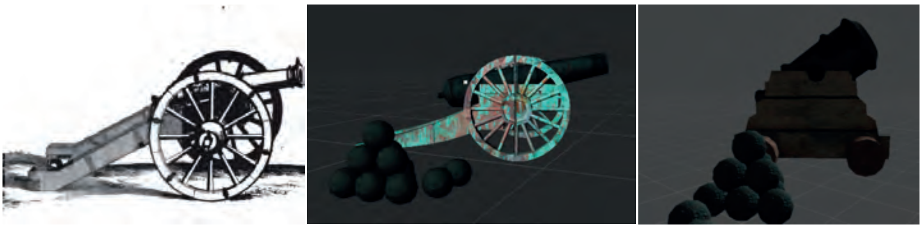


Figure 38.
Representation of a contemporary cannon (left), as well as the models of the cannon (in the middle) and the mortar (right)
Source: Saint-Remy 1697 and picture made by the authors

After the installation of the models, only the landscape features (i.e. trees, the undergrowth, the lake and the river) were missing from the visual appearance of the view *(Figure 39).* For covering the ground surface with vegetation, we could use the built-in surface modifying tool of Unity 3D. The engine contains predefined tree types that can be customised with minor modifications. With the help of these, we finally designed two types of coniferous trees and five types of deciduous trees. “Grassing” was also carried out with the technique above. We designed general grass and a grass tuft version. The foliage was drawn on the surface with a brush, as a result of which at the specified locations between the pre-set limit values trees and lawn appeared at random intervals. The forest around the fortress was previously cut down, so we planted there individually modelled tree stumps.

The water surface was substituted by a simple plane during modelling, because the life-like representation of the water surface – waves, mirroring and reflection – would have demanded high computing capacity from the hardware resources. The plane was scaled in a way that it would cover the entire surface of the lake and then it was raised to the height of the shoreline. The water effects shown in the model were created with shaders[97] built in the graphics engine.

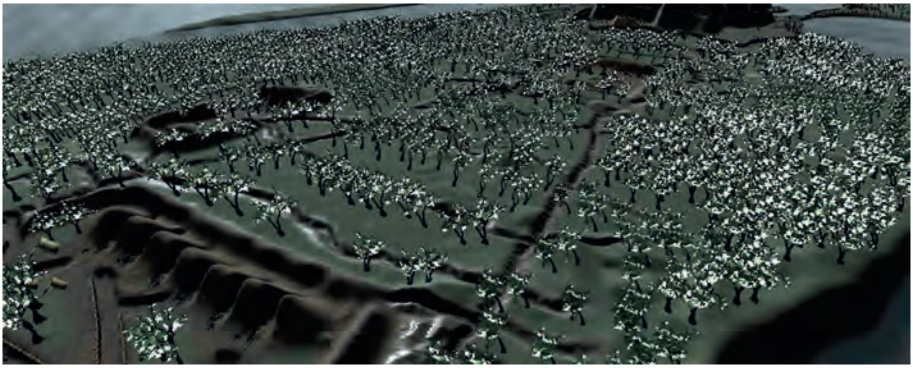


Figure 39.
The visual appearance of the complete model from one perspective
Source: picture made by the authors

We also needed to apply a light source to visualise the view, because without it, we would have only received a dark model. The engine has the potential to imitate global light source, that is, the Sun. For this, we added a so-called directional light to the scene, and applied the sun shader made by Unity 3D developers. The inclination of the light source determines the intensity of the sun. Currently it is 30 degrees, which corresponds to six o'clock in the morning. Although this is adjustable, it is the low angle of the sunlight at sunrise and at sunset that highlights the contours of the fortress and the siege structures the best.

So that we could make a tour within the model, between the locations, we had to plan a kind of "gameplay", which included the ability of rotating the camera, and the possibility of moving and bumping the camera against the landscape features. In order to navigate through space, we needed a point to be moved during control. The actual position of this point also gives the coordinates of the camera, so the camera had to be adjusted to the point when being moved. Unity 3D also allows us to set the focal length, view angle, and even the image quality of the camera. Additionally, there are posterior effects, such as blurring, macro and

[97] This is a sub-programme (algorithm) that modifies the points and/or texture, and colour of a 3D graphic model. Simultaneously to or after drawing, it modifies the drawing mechanism, thus affecting the visual appearance of the final result. It is usually used to visualise complex effects (water, shadow, sun, fire, smoke, fog, etc.). The sub-programme is usually (but not necessarily) interpreted and executed directly by the processor of the video card after its translation to a machine code.

HDR. By default, the drawn image – or more specifically, the focus of the camera – should point in the direction of the cursor. Since, in this case, the focal length is given, it is only necessary to determine the vector connecting the moved point and the focal point of the camera, which can be easily calculated from the starting position and the movement of the cursor. As we want to avoid moving in the global coordinate system – because in that case the image of the camera would not necessarily reflect the expected direction of motion – we need to design the motion of the point in relation to a local coordinate system. This means that the motion is not directed along the XYZ axes, but it is always in relation to the image we see. In other words, the objective is that motion would not be absolute but always relative to the image seen on the camera. For this, we need to use the vector directed to the former focus point; this will be the local X axis, while the normal vector perpendicular to it will be the Y axis, and the product of the two will be the Z axis. In this way, the absolute position of the moved point can be calculated.

All of our models in space are just the combination of planar surfaces bordered by points. Textures can be applied to the planes with different methods, such as stretching and mapping, which gives the colour of the model. Nevertheless, there are no restrictions for crossing these planes. In order to stop movement in space at the boundary of a certain model, a buffer zone must be set around it. This can be the model itself, but in order to avoid complexity, it is worth assigning a relatively simple buffer zone model to a complex model. Because in our case, the majority of the models have a low number of polygons, most of the models in the view are, at the same time, buffer zones. It was only the boundaries of the view where we placed separate planes specifically designed for this purpose so as to set limits to the accessible space.

Like all other software, Unity 3D has a setup interface that allows the user to set the graphics complexity, resolution and keyboard layout of the game before the scene starts.

From our virtual model, we are able to build software that can be executed on numerous processor architectures, devices and platforms. On the other hand, because the code is optimised for Intel architecture processors, the 3D view can only run on desktops and laptops using this resource. However, with minor modifications and at the cost of graphical compromises, it is possible to create a version that can run on ARM architecture, on mobile operating systems. The model itself, the accessible 3D view of Zrínyi-Újvár can be flexibly expanded, and offers users an experience rich in detail. New findings from ongoing archaeological and battlefield investigations can be integrated at any time in the future. Furthermore, the software can be used to investigate different scenarios, questions like "what would have happened if…?" and "what would it be like if…?". All these may provide significant help in the future work of our research team.

Summary

In the beginning, the results of archaeological investigations were recorded mainly in written form and in sketches of drawing, which is a still existing practice today. Afterwards, these were supplemented with analogue, celluloid film-based black and white, and then colour photographs and films, which considerably extended the possibilities of archiving our historical heritage and made data collection during fieldwork easier, but were not yet able to record the properties of finds discovered during excavations in an authentic and comprehensive way. Objects found in our environment have a 3-dimensional expansion in physical space, which cannot be reproduced by 2-dimensional photography without loss of information, even in digital form. In order to bring our material heritage recorded in a digital form closer to real human perception, we need to assign all their properties to a single spatial feature during visualisation.

In this chapter, we presented the archaeological applications of 3D technological innovations and the methods of applying them in different work processes through the example of Zrínyi-Újvár. We reviewed the possibilities of creating, processing and using 3D models. We have demonstrated through practical examples how modern visualisation tools can be combined with different archaeological and battlefield exploration methods. Although the conditions for the application of GIS in archaeological excavations are fully available today, their integration is still limited or have not been undertaken at all in domestic circumstances. Until recent years, the visual archiving of the individual archaeological finds has been limited to taking digital photos of them.

In the course of our research, we investigated the modern methods of archaeological find recording, and the potentials offered by virtual reality (VR), augmented reality (AR) and mixed reality (MR), as well as additive production technology, which can be used to display research results in a spectacular way. During archaeological excavations – as with the forensic investigation of a crime scene – the physical parameters of finds and the circumstances of their discovery must be fully recorded. This is especially important because the changing environmental conditions can greatly worsen the condition of finds after they are found. With MR technology, this information can be recorded within a short period of time and can be used at any time later without loss of information. With 3D printing, missing or damaged elements and details can be fit into place after reproduction, which may help verify various assumptions. Additionally, we are able to make tangible replicas in this way, even for their intended use, with the purposes of illustration or education.

It is also worth mentioning the usability of 3D printing in teaching the visually impaired and in museum education, since, in the case of limited or no vision, touch becomes one of the most important and effective tools for gathering information besides hearing. Thanks to the terrain tables and replicas that can be produced relatively quickly and cost-effectively, the people concerned can have access to many important pieces of information, even through direct experience. Previously, they had no possibility for this, since in most of the cases they could only rely on their imagination in an educational session.

At the same time, in general, the 3D visualisation of research results in the field of archaeology, military archaeology and battlefield investigation improves the process of learning and understanding to a great extent. Consequently, it may not only contribute to the scientific development of professional community but also directly enhance the quality of information available for the interested public. For today's rising generations of information society, solutions based on this – audio-visual or interactive e-learning educational materials, dissemination based on augmented or virtual reality technology – represent significant added values and effectively help them in the fields of their studies and general development through experiential learning.

In addition to general history teaching, this technology can play an increasingly important role in supporting specialised training. Its various methods and technical solutions may significantly increase the quality of practical sessions in archaeologist-technician or restorer-technician training. The leaning and integrating of the work processes of field surveys and excavations can certainly be achieved only through actual pursuit and continuous practice. Nevertheless, their preparation, as well as the transfer and processing of the required theoretical knowledge may become significantly more efficient. This method may save time and energy and thus increase the proportion of resources that can be spent on actual research.

At its current stage of development, technology still allows the design and use of models mainly by technical experts, but as a result of continuous progression, more and more sophisticated solutions and user-friendly IT supported tools are expected to come out. Due to these, the particular techniques will be accessible and usable to anyone. Even students will be able to take notes and prepare learning aids with VR/AR tools. Thus, by the analogy of the web 1.0 and 2.0, the current VR/AR users may turn into content producers in the future.