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ENGINEERING CAD TOOLS IN DIGITAL ARCHAEOLOGY

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ABSTRACT

This paper presents an original approach in the virtual reconstruction of destroyed ancient monument types which have no similarities to other standing monuments, or documentation about the design of these constructions. In this case the virtual reconstruction is a challenging act, which can be done using a large variety of designs. These designs must be validated not just from an archaeological or historical, but also from an engineering point of view, to create valid virtual models from the construction's point of view. For this reason the authors chose to create the virtual reconstructions in Computer Aided Design (CAD) environment, in the detriment of design software's, because it's easier to create the virtual models and to do the simulations in the same software environment.

Also in this paper are presented different reconstruction methods (photogrammetry using profile drawings and knowledge database creation) that can be achieved with the use of CAD software. The authors used different levels of details (LOD), which can be helpful in the validation process, where can be observed the structure of the monuments very detailed, and for renderings for dissemination.

The case study was conducted on a destroyed Dacian watch tower by an interdisciplinary team composed of archaeologists, historians and engineers. The reconstruction of the watch tower was carried out in CATIA V5, and was disseminated through a video render, an virtual reality website and was imported into an augmented reality application.

KEYWORDS: 3D reconstruction, 3D model, ancient destroyed monument.

1. INTRODUCTION

Since technology progresses very fast and computers become more powerful, they are used in various fields of science. A new trend, digital archaeology, also uses these technologies of computer graphics, computer aided design and digital imaging.

A number of three-dimensional reconstructions and models of monuments and landscapes have been created in the context of culture and archaeology. The quality of such models is always questionable in terms of their resolution and detailed information they contain, as well as the concepts, references and background information that they are based upon (Theodoropoulos, Moullou et al. 2009). In addition, cultural heritage can benefit from high accuracy three-dimensional digital imaging for conservation, study and restoration of works (Berndt and Carlos 2000). Apart from being easier to interpret than two-dimensional drawings, these models facilitate data necessary for reconstruction projects, preservation or rehabilitation of the architectural or archaeological heritage (Amparo Núñez, Felipe Buill et al. 2012).

Within this context, any action of digitization and virtual reconstruction of monuments to enrich the digital cultural heritage is welcome.

Some virtual restorations of ancient monuments have been already made with different software solutions (see Table 2).

Table 2 Reconstructions and software solutions.

Virtually restored monument	Software used	Reference
Abbey of Pomposanear Ferrara, Italy	Polyworks	(El-Hakim, Beraldin et al. 2002)
Amra palace, Jordan	Polyworks	(Al-kheder, Al-shawabkeh et al. 2009)
Bam citadel, Iran	3DS Max	(Futragoon, Kitamoto et al. 2011)
Roman villa of Casal de Freiria, Portugal	AutoCAD	(Rua and Alvito 2011)

In the case of the above mentioned reconstructions, the monuments were intact or just partially damaged, so the process of reconstruction is easier because the design of the buildings is well known.

In the case where there is little information (ancient descriptions or hand drawings) available about the destroyed monuments and there are no intact similar monuments after which to create the reconstruction, the process of virtual rebuilding is difficult and can have various outcomes with many different designs. The authors chose to create the reconstructions in a user-based CAD environment, CATIA V5, because can offer assistance in several stages of the reconstruction like: creating standardized construction elements and finite element analysis to validate the structure of the monument.

The presented methodology includes steps such as monument digitization, processing and optimization of three-dimensional model, simulation and dissemination of the virtual reconstructed monument using virtual reality and augmented reality technologies. In this methodology the CAD software is used especially to validate the design of the virtually reconstructed monument, but also to create the three-dimensional model, because it's easier to create and simulate a model in the same software environment.

2. HISTORICAL CONTEXT

Poiana lui Mihu watch tower (near Orăştioara de Sus village, Hunedoara County, Romania) is part of the Dacian fortification system from Orăştie Mountains included on the UNESCO heritage list. From archaeological sources it appears that, in the mid first century BC, the Dacian people built the first fortification structures of limestone blocks, according to Hellenistic influence techniques.

Archaeological research has shown that this is a quadrilateral tower, which has medium dimensions compared to the other towers within Orăştie Mountains. Its outer side measures 11.75 meters, its inner side

6.15 meters and its wall thickness it's about 2.8 meters.

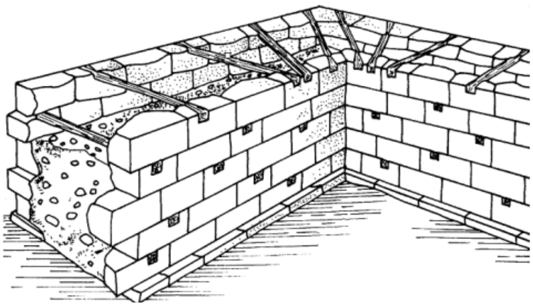

Figure 1 Illustration of a Hellenistic type of wall.

According to (Gelu 2012) the lower part of the tower consists of strings of limestone blocks (four rows in most of the segments, three rows of blocks on some portions of the wall), but the upper part, which consisted of a structure made of wood and very compacted clay, was affected by the passing of time. During the archaeological excavations were found several fragments of tiles, fallen especially outside of the tower's walls.

3. METHODOLOGY

For virtual reconstruction of destroyed historical monuments the authors propose the use of computer aided design software solutions instead of the computer graphics software solutions. CAD software solutions can provide support on several stages of the virtual reconstruction of a monument. In the case where there is little archaeological information or it is missing, different simulation modules or finite element analyses can be used to verify various hypotheses.

The methodology set up by the authors for the development of valid virtual three-dimensional reconstructions of monuments can be seen in Figure 5.

In the authors methodology the virtual reconstruction of a destroyed historical monument should be done by interdisciplinary teams to ensure the credibility and the accuracy of the virtual reconstruction. Depending on the nature of the reconstructed items the team can consist of: historians and archaeologists, engineers and architects, specialists in related fields, like chemistry, materials science, virtual reality.

Since the archaeological data can be very difficult to understand and to interpret by non-specialists, the team setup

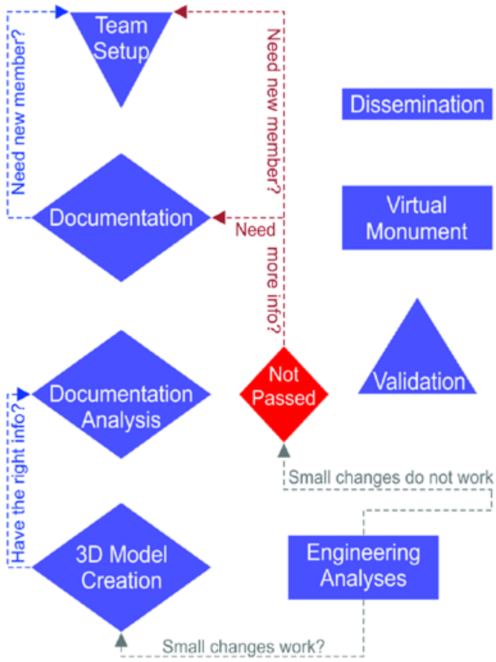

Figure 5 Virtual reconstruction algorithm using CAD software solutions for destroyed monuments.

is the first and the most important phase of this methodology. In this phase are gathered the team members who have different areas of expertise, and whom will help in the gathering and interpretation of the information, which is needed for the virtual reconstruction.

The next phase is the documentation, where all the information is gathered from archives and from the fields. This information consists of ancient descriptions about the monument, hand drawings, older and recent archaeological finds. All of this information is systematized for further use by the team.

In the next phase the engineers or those who will create the three-dimensional models will check if they have enough information to complete the task of virtual reconstruction. If the virtual reconstruction is not possible with the current information the team has to gather more information or the team needs to be extended with specialists from related fields.

In the next phase are created the virtual three-dimensional models using all the information collected in the previous phase. In this step the engineers, the archaeologists and the historians are working together to ensure the historical rigor of the virtually reconstructed models. Using CAD software several model creation techniques are available, like general three-dimensional modeling, modeling using photogrammetry or with creating a knowledge database with parameterized construction elements. The creation of parameterized elements starts with the creation of a base model which contains all the possible features that an element can have (gauges, cut-outs, holes, etc.), which are parameterized for further use in the knowledge database. Parameterizing a model means that for the base model's dimension or angles are assigned standard dimensions or angles (which are average usual dimensions or angles found by the archaeologists during excavations), which later can be modified using the user interface of the database by the user. Also for different features are assigned Boolean operations, in general "false", in this way is generated the simplest model (because for *false* Boolean operator the element is not shown), but also the user can change all the features (selecting *true* for the Boolean operator) using the interface of the database to his or her likings. Another method is used for generating three-dimensional models, which is similar to photogrammetry techniques, using a detailed hand drawing on paper, done by the archaeologists on the dig site. This drawing is digitized using a paper scanner for further use in the CAD software. Using this method a fairly accurate reconstruction of the watch tower's wall can be created, but only on two axis: X and Z, on the Y axis due to the wall's construction the dimensions cannot be measured without destroying the monument, therefore are selected randomly, knowing the usual dimensions of these limestone blocks from previous archaeological finds.

Archaeological wall drawings also help in the creation of a database, because the limestone blocks can be measured on the drawings, also different types of blocks can be identified and categorized.

To ensure the scientific rigor and to validate on a scientific level the virtual reconstruction a series of engineering analyses will be conducted on the created three-dimensional models.

If the created three-dimensional models pass the analyses they are presented for other scientists from related fields (other archaeologists, historians, architects, engineers, etc.), who will validate the virtual reconstructions. In this phase it's important to have validation from other scientists, because they can see the created reconstruction from another point of view and can raise new questions or problems, which were overlooked by the initial team.

If the validation is a success, the archaeologists and the historians can create the metadata, in text, video, sound and picture formats, for the three-dimensional model, which will be used in the dissemination process.

In order to import the generated three-dimensional models into augmented reality or virtual reality applications the raw models have to be optimized to reduce their sizes and shape complexity. The authors propose the internet as the primary channel for dissemination, in virtual reality applications, because it is an accessible technology available for the general public.

4. CASE STUDY

The methodology described above has been already validated by the authors in various applications regarding virtual reconstructions of destroyed ancient monuments belonging to the Dacian civilization from the Orăştie Mountains.

The proposed methodology above has been used as follows.

Team setup - In the case of the Dacian watch tower's virtual reconstruction the interdisciplinary team consisted of experts from the National History Museum of Transylvania and the Technical University of Cluj-Napoca, Romania.

Documentation – At this stage all the published books, articles, archaeological surveys, drawings, pictures regarding the Greek, Roman and Dacian watch towers were gathered by the archaeologists, curators and historians.

Documentation analysis – In this stage the engineers analyse the information package created in the previous step. They decide if the virtual reconstruction of the Dacian watch tower is possible with the given information.

3D model creation - The authors used CATIA™ V5 engineering CAD software solution, developed by *Dassault Systèmes*, to create the detailed three-dimensional model of the Dacian watch tower. The authors used different levels of detail in the virtual reconstruction of the tower to show that different levels of detail can be achieved using engineering computer aided design software platforms.

A portion of the tower's wall was virtually reconstructed with the help of photogrammetry (see Figure 6).

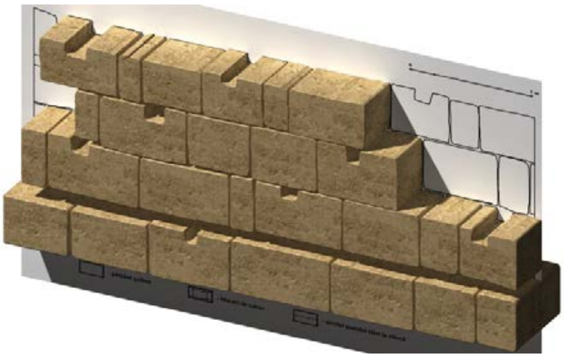

Figure 6 Virtual reconstruction of a portion of the tower's wall using a profile drawing.

Another portion of the tower's wall (see Figure 7), the wooden wall and the roof structure was reconstructed using a knowledge database (see Figure 8), which contains parameterized construction elements, such as limestone blocks, connection beams, beams with special cut-outs and heat threated ceramic tiles. Using a database to construct the three-dimensional virtual monument speeds up the process and provides a very detailed reconstruction.

Figure 7 Virtual reconstruction of a portion of the tower's wall using the database.

These elements are generated the same way as standard assembly elements (bolts, screws, etc.) from the software's built-in database.

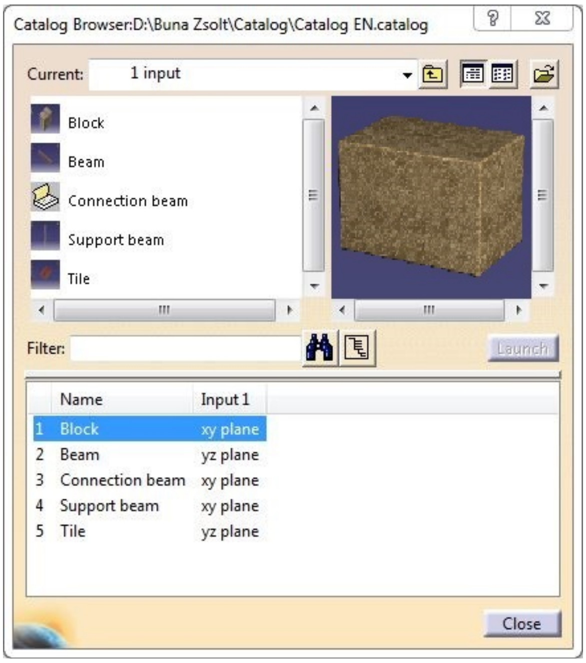

Figure 8 Knowledge database of parameterized construction elements.

In Figure 9 is shown the dialog box which contains the parameters for the limestone blocks, in the same way are defined the rest of the construction elements within the database.

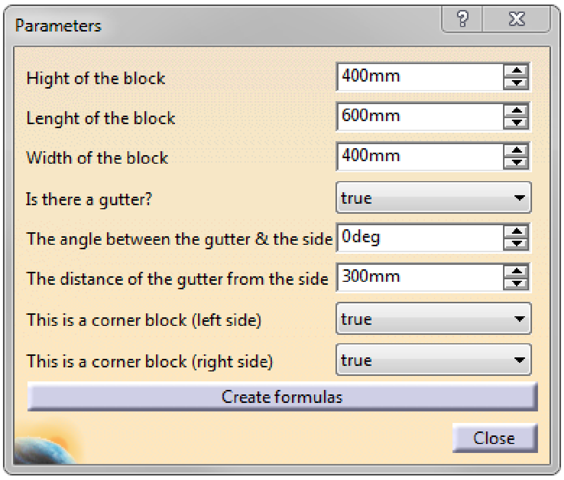

Figure 9 Parameters of the limestone blocks.

Using different input parameters different dimensions, angles and specific characteristics can be generated a variety of limestone blocks, like the ones in Figure 10.

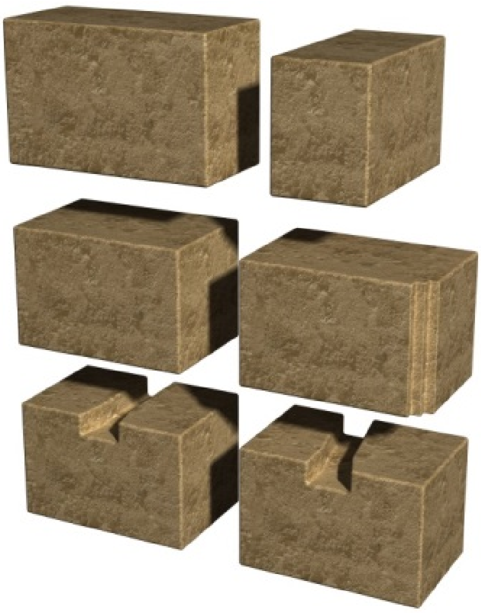

Figure 10 Generated limestone blocks from the knowledge database.

Since during the archaeological excavations the archaeologists did not found any metal fastening elements, the engineers had to design such joints that allow the assembly of the wooden elements of the roof in such manner to support the idea that metal fastening elements were not used in the construction of this watch tower. Such joints can be seen in Figure 11.

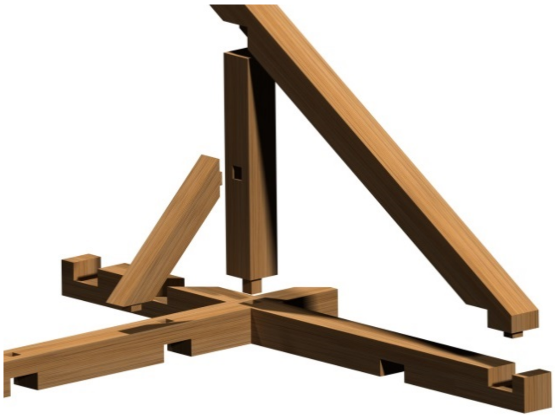

Figure 11 Components of the wooden roof structure.

Using these methods the process of the virtual reconstruction is speeded up and in this way a very high detailed reconstitution can be created, which gives the possibility to use highly accurate engineering analyses on the created virtual models.

Engineering analyses – During the excavations the archaeological data showed traces of ceramic roof tiles, and the archaeologists considered that the roof of the watch tower was covered with heat treated ceramic tiles. In order to validate the structure that can hold the roof covered with tiles the engineers had to run finite element analysis on the structure.

Also because of its position on the south-eastern portion of the European continent, Romania has a temperate climate, which means at winter the precipitation is in form of snow. The authors had to take this in consideration by adding the extra weight of the snow on the roof while doing the finite element analysis. In Table 3 is shown the data used in the analysis.

Table 3 Data used in the finite element analysis.

Data used	Value	Units
Weight of the tiles	26,262.5	kg
Force generated by the tiles	257,372.5	N/m^2
Weight of the tiles on one side	6,565.63	kg
Force generated by the tiles on one side	64,343.13	N/m^2
Weight of 300 mm snow	30,784	kg
Force generated by the snow	301,683.2	N/m^2
Weight of 300 mm snow on one side	7,696	kg

Force generated by the snow on one side	75,420.8	N/m^2
Total weight	**57,046.5**	**kg**
Total force	**559,055.7**	**N/m^2**
Total weight on one side	**14,261.63**	**kg**
Total force on one side	**139,763.9**	**N/m^2**

After running the finite element analysis with the information above, the translational displacement and the Von Mises stress values were identified. These values are showing where in the structure of the three-dimensional model might appear problems in a real life scenario. The translational displacement shows the displacement in centimetres which occurs under the action of forces (see Figure 12, where the roof can be seen from above).

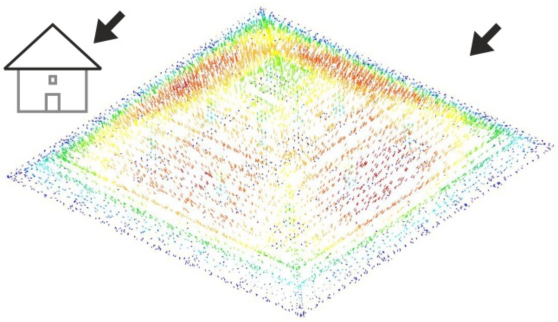

Figure 12 Display of translational displacement.

The Von Mises stress shows how forces act on a structure by using different colours for different values as can be seen in Figure 13, where the structure of the roof is seen from above and where the vertical beams have to support the highest value of stress.

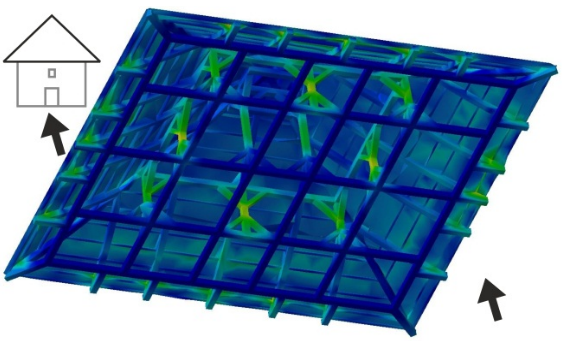

Figure 13 Display of Von Mises stress.

Since the resulted values from the finite element analysis are within the limits of safety, the validation process was a success.

In Table 4 can be seen the values for the translational displacement and for the Von Mises stress.

Table 4 Values obtained within the FEA.

	Translational displacement [cm]	Von Mises stress [N/m^2]
	0.469	5.83E+05
	0.422	5.24E+05
	0.375	4.66E+05
	0.328	4.08E+05
	0.281	3.50E+05
	0.234	2.91E+05
	0.188	2.33E+05
	0.141	1.75E+05
	0.093	1.17E+05
	0.049	5.84E+04
	0	1.25E+02

Validation – In the process of validation the virtually reconstructed Dacian watch tower was presented to the archaeologists and historians from the Babeș-Bolyai University, where the specialists have appreciated the methodology and were very pleased by the results.

Virtual monument - After the process of validation the authors used CATIA™ V5 software platform's built in optimization module to reduce the number of triangles which build the three-dimensional model. The raw model has 1,546,188 polygons and 629 MB in the software's native file formats (*.CATPart, *.CATProduct). After the optimization process the model reached 58,286 polygons and 4.43 MB as an *.obj file format. In this phase were also created the additional metadata, which contain images, sound recordings, video files and text files to enrich the experience of the persons who are interested of this monument.

Dissemination - After creating the virtual monument the resulted three-dimensional model was introduced into an online virtual reality application (see Figure 14), where with the use of an avatar everybody can take a virtual tour in the Dacian watch tower over the internet. For the online virtual reality application the authors chose a free hosting engine created by the same developers that created the CAD software, *Dassault Systèmes*, which can be accessed from *www.3dvia.com.* The upload of the three-dimensional models on the online platform is very intuitive and can be uploaded the native file formats from the CAD software.

Figure 14 The Dacian watch tower in VR.

Additional metadata was added to the existent model to enrich the experience of the visitors. The optimized model was uploaded into an augmented reality application, and also a video rendering was created featuring the virtual construction of the Dacian watch tower, where its structural composition can be seen.

All these materials were presented several times for the public on different occasions, like Long Night at Museum, and archaeological sessions and the feedback of the visitors and the archaeologists was very positive.

The authors recommend for VR and AR applications that the complex three-dimensional models to be remodeled using the detail level that is needed for these applications, in this manner more simpler models can be created, which automatically have lower numbers of polygons and file sizes.

In many cases in these environments using a simpler geometrical model with the right textures can give the same feeling as a more complex one.

5. CONCLUSIONS

Using CAD software solutions in the case of destroyed ancient monuments virtual restorations, which have no documentation available about the design of the monuments, is a viable solution that can be successfully used. CAD solutions allow the use of photogrammetry, reverse engineering methods to virtually restore damaged monuments. Also a knowledge database of parameterized construction elements can be created achieving different levels of details in the restoration process. Using CAD software platforms the structure of the restored monuments can be validated using finite element analyses, creating scientifically more accurate virtual reconstructions. The achieved three-dimensional models can be optimized and introduced in different augmented reality or virtual reality applications in order to be disseminated to the general public.

Depending on the level of detail that is needed for a reconstruction, the models can be crated or imported in computer graphics software, which has a more advanced renderer, and the CAD solution can be used just to validate the structure of the monument.

The proposed methodology in this paper can be used by interdisciplinary teams and can be used to virtually reconstruct other types of monuments as well, due to its general character.

6. ACKNOWLEDGMENTS

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