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DIGITIZATION OF PHYSICAL MODELS OF RURAL ARCHITECTURE

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ABSTRACT

Working with objects in digital spatial form is gradually becoming a standard in many fields. In addition to the advantage of easier object manipulation, digital representation can also be used for presentation purposes or better cataloguing. In the case of objects from museum collections, it can serve as a basis for restoration or for conducting deeper research into detailed structures. The method of photogrammetry allows 3D modelling of real objects without physical contact with them, while at the same time making use of affordable equipment. However, the disadvantage of this method is the size of the output data (even hundreds of megabytes), which can be a barrier to easy web sharing. This paper presents an efficient workflow for the 3D digitization of smaller physical objects and the subsequent process of generalizing the resulting triangular model to reduce the data volume. Finally, the model generalization is utilized when publishing the model in a web environment to make it available to the widest possible range of users. The whole procedure is applied to a physical model of a cottage from the village of Orlová (Karviná district, Czechia) from the collection of the Czech National Museum (scale reduction of a vernacular building at a scale of approximately 1:20).

KEYWORDS

3D modeling, Photogrammetry, Cultural heritage, Vectorization, Generalization, Web presentation, SketchUp

INTRODUCTION

With the gradual development of technology, the requirements for the creation of documents in digital 3D form arise. This applies both to the planned form of future objects and products (plans in construction or robotic production in industry) and to existing objects. One of the frequent applications of digital copies of existing objects is heritage conservation, that is, the management of historical buildings and smaller items [1], [2], [3]. For such objects, detailed spatial documentation is used for possible reconstruction or restoration [4]. However, it can also serve a promotional [5] and marketing purpose – it can make the work (and the institution) more visible or present objects that are not exhibited and not accessible to the public. Promotion using 3D models for marketing purposes is common, for example, in the retail sector. Examples of commercial use can be the offers of online stores[1] or even web models of shopping centers[2]. Finally, digital models are also used in

1 https://www.nike.com/cz/u/custom-nike-metcon-8-by-you-10001328/8164255504

2 https://thedubaimall.com/en/map

healthcare, education, industry, culture, and many other sectors. Thus, the presentation of objects using 3D models is commonly used among industries. The purpose of this paper is to build on the knowledge of 3D modelling of smaller objects for heritage purposes and further connect it with the experience of sharing 3D content for promotion purposes.

The main disadvantage of modelling 3D physical objects in the past was the complexity of the workflow, which until now required the work of specialists with expensive equipment. In some cases, it was possible to use other methods to help – for example, if good quality printed documentation in the form of drawings and other technical documents was available, a model could be created using these sources [6]. However, the rapid development of computer technology has brought about the possibility of generating spatial data from photographs and thus expanded the application of the field of photogrammetry.

Photogrammetry, specifically the Structure-from-Motion (SfM) method, allows the creation of 3D digital models of physical objects using a camera and powerful hardware [4]. A specialized program calculates the position of each point in space from images that capture the object from as many directions as possible (Figure 1). In recent years, sophisticated programs and rapidly evolving computing technology have made this method more accessible than ever [2]. Even for a large number of appropriately captured images, the image alignment process is reliable and often fully automatic. The method also benefits from decreasing cost of acquiring high-quality digital cameras. Due to these advantages, the technique is gaining in popularity, thus overtaking other methods such as terrestrial laser scanning or geodetic surveying. The product of the photogrammetric method is a highly detailed textured 3D triangular model (mesh) containing millions of points. The accuracy and detail of the model has one drawback, namely, the large volume of output data (hundreds of megabytes or more).

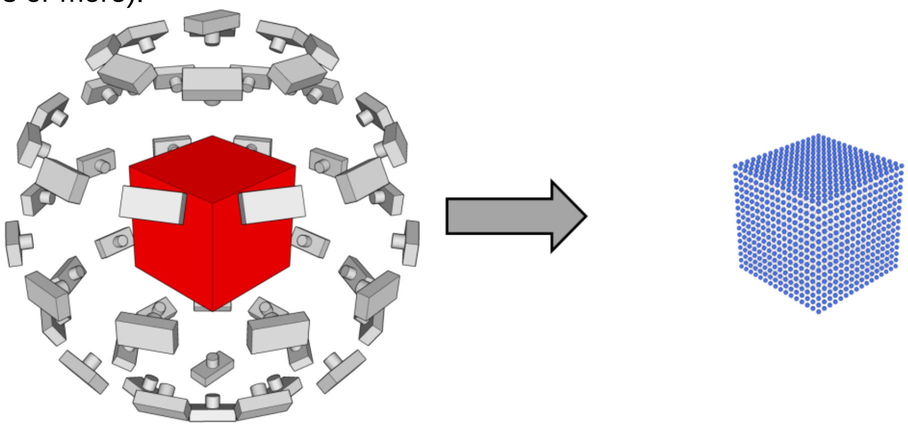


Fig. 1 – Structure-from-Motion method, optimal layout of imaging positions (from all directions to the object)

Today, the Internet is the primary medium for sharing digital content, where a high-quality user experience depends on fast loading and smooth operation. This depends on the speed of data transfer and the volume of data transferred [3]. Therefore, part of the project involved generalizing the detailed triangular model into a form that kept the resulting file size around 10 MB while not significantly reducing the quality of the geometry and textures. The data volume limit was empirically determined with respect to the normal data connection speed in our conditions. It can be assumed that this limit will increase rapidly.

The developed technological procedure was applied to the photogrammetric digitization of a physical model of a vernacular house (with dimensions of approximately 60×100×70 cm, Figure 2) and the subsequent modification of the model (generalization) so that the file complies with the size condition mentioned. All this is done with an emphasis on simplicity and automation of the workflow, which can then be easily applied when digitizing other models with similar parameters. The digitized model has a detachable roof, under which the interior with four rooms and furniture is hidden.

Fig. 2 – Model of a vernacular building from the village of Orlová, Karviná district, Czechia

RELATED WORK

Current research on photogrammetric documentation of historical objects is mostly devoted to building objects of real size (tens of meters). Separately, attention is paid to the digitization of smaller objects. However, the work on the model of a scaled-down building combines the specifics common to both of these fields. In addition, current research hardly focuses on the digitization of the interiors of such physical models, which, due to the high granularity and overall inaccessibility of the small space, represent a challenging environment for the method used.

Karachaliou et al. [1] used the UAV photogrammetry method to create a 3D representation of the "Averof's Museum of Neohellenic Art" building in Metsovo, Greece. In the next step, they converted the model to the HBIM (Historic Building Information Modelling) system to create an effective visualization with a high level of detail for efficient building management and at the same time a high-quality documentation for reconstruction purposes [1], [7]. They highlight the use of photogrammetry as an inexpensive means of producing accurate and detailed 3D documentation of physical objects. They also highlight the importance of HBIM in terms of the increasing frequency of research in this field in recent years.

Moreover, Jeong et al. [7] performed a 3D photogrammetric documentation of a building (traditional timber building), this time to evaluate the reliability of this method. They agree with the advantage of non-contact data acquisition, and their procedure goes on to discuss basic CAD vectorization using cut planes at regular intervals.

Poloprutský et al. [6] present a procedure for creating a 3D building model by combining multiple data types. In addition to the 3D photogrammetric data itself, they also present modelling possibilities using old building plans. This method is quite inexpensive, but it is redeemed by the amount of time spent searching the archives and subsequent manual modelling (adding the third dimension). In addition, the plans for old buildings are often different from reality due to various reconstructions [4]. The resource also stresses that this procedure should be used in cases where a historic building is partially or completely destroyed.

Photogrammetric imaging of 3D objects is often done manually (manual determination of camera position). However, a certain degree of automation can be used to save time and improve the quality of acquired data [3]. Tannús J. [2] proposed a low-cost semi-automated photogrammetric solution containing a camera, tripod, motorized turntable, softbox, and photographic background. This device captures smaller objects using a turntable and a static camera (with an angle of 11° between each frame) to produce image data with regular angular spacing. According to this research, switching from manual scanning to this new procedure saved 20% of the total time. In addition, part of the process (imaging) was performed automatically without the need for human supervision. Furthermore, Marshall et al. [3] designed and built a device for automated image data collection. With it, they tested the relationship between the degree of image overlap and the quality of the output or the duration of the process to find a compromise in the choice of these parameters (finding this compromise is a common dilemma in photogrammetry) [2]. They also took care of the software design and implementation of safety features to prevent object-camera collisions. The commercial project CultArm3D [8] is very far along in this area of research. It uses a robotic arm for 3D digitization, providing a fixed attachment of the camera while allowing its arbitrary positioning in space.

The software used also plays an important role in 3D modelling, both in terms of the quality of the results, the speed of processing, and the user-friendliness of the interface. In his research, Kingsland K. [9] paid attention to comparing the capabilities of three main programs for 3D modelling from image data. The research shows that although Agisoft Metashape did not achieve the lowest processing time, it was evaluated as the most versatile, both in terms of alignment quality, noise filtering, variability of settings during processing, integration of a robust 3D editor, and finally a more favorable pricing policy. Basically, it can be said that the longer time required for (automatic) processing is compensated for the lower time spent on manual editing of the outputs. Also, Vacca G. [10] tested the data processing software of the Structure-from-Motion method, specifically open-source licensed programs. However, since these two groups of programs are compared separately, it is not possible to reliably compare the results between them.

The final stage of the work is the presentation of the outputs. To distribute the product to as many users as possible, it is best to publish it on the web. In this case, the user only needs basic equipment such as a PC and an internet connection to view the product. Other options to present 3D data include 3D printing [3], [11] (cannot be distributed over the Internet) or VR/AR [5] (requiring expensive hardware). Nishanbaev I. [12] linked existing web technologies to create a web archive for digital 3D models tailored to cultural heritage objects. In his research, he discusses, among others, the available web-based 3D frameworks and libraries (CesiumJS, Three.js, Babylon.js) or file formats suitable for sharing 3D data. Furthermore, Rahaman et al. [5] set out a workflow for non-expert users to create image-based 3D models (photo acquisition, 3D reconstruction), share online and visualize in VR/AR. They highlight specifically the focus on non-expert users (e.g., museums and hobby institutions), for whom digitization and content sharing can help both the preservation of cultural heritage objects and their promotion. For users without code-writing skills, using one of the commercial web repositories with 3D models (Sketchfab [13], 3D Warehouse [14], etc.) is also a good solution. Champion et al. [15] provide a clear comparison of these commercial services and their features, including controls, supported formats, and upload file size limits.

METHODS

The 3D modelling process used is based on the Structure-from-Motion method, which uses calculations to create a 3D model from 2D photographs. For proper functioning, high-quality images with sufficient overlap and clearly identifiable ground control points with precisely known positions (points determine the position and size of the model and characterize its accuracy) are a prerequisite. The calculations (alignment of the images and calculation of the detailed triangular model) were performed in Agisoft Metashape [1], [2], [16], evaluated as the ideal choice of one of the sources [9]. The following sections (Measurement and Computation sections) are devoted to this initial processing. The generalization of the detailed triangular model was performed manually in Trimble SketchUp [17] and is the subject of the third section, Modelling.

Measurement part

According to the research of Hruška et al. [18], who tested the identifiability of six targets (ground control points) of different size, coulor, reflectivity, and pattern, under different conditions, the best recognizable target is in the form of a black and white checkerboard array of 2×2 squares with the center at the intersection of four coloured segments. They also stated that the detectability of a target depends mainly on its size and reflectivity. Therefore, the recommended pattern was chosen and then printed on hard matte paper in a size of 50×50 mm, which sufficiently exceeds the requirement of six times the pixel size established by the source [18]. Numbers were added in the corners to facilitate identification (Figure 3). Eight targets were mounted on a flat imaging board (Figure 4), and the relative position of each was calculated by planar adjustment from 28 distance measurements (all combinations of distances between points were measured with an empirically determined standard deviation of 0.5 mm). The standard deviation of the resulting coordinates did not exceed 0.2 mm (the least squares method in GNU Gama [19] software was used to calculate the adjusted coordinates).

Agisoft Metashape allows printing of special coding targets with automatic center position detection. This feature can save a lot of time during the process, but its reliability is not verified under various conditions. Therefore, two test targets with automatically detectable patterns were placed near the targets described above (Figure 3). These points were used only to test automatic detection, not as ground control points.

Fig. 3 – Manual detection target (left), automatic detection target

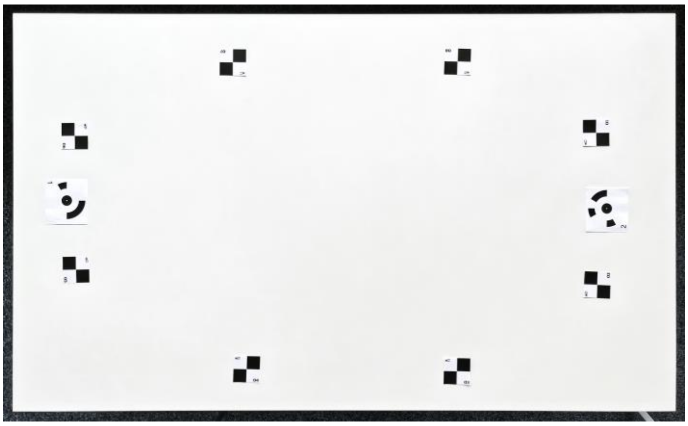


Fig. 4 – Distribution of ground control points on the imaging board (object placed in the center)

Images can be taken handheld, but this approach has many pitfalls (risk of blurring the image with longer exposure times, difficult lighting, etc.). It is therefore preferable to shoot using a tripod and to move the subject between shots by placing it on a turntable. The shooting scene was therefore arranged in this way, with the camera at such a distance from the subject that it was entirely in the frame (the lens used, with a focal length of 40 mm, corresponded to approximately 2 m distance). Illumination was provided by a pair of 50 W LED spotlights with a light color of 4000 K (neutral white) directed at the subject from the same direction as the camera (Figure 5). The subject was rotated at a constant 10° during the imaging, which ensured sufficient image overlap. Thus, rotating the object horizontally produced 36 images (for one elevation setup, see below). This layout of the imaging scene has the great advantage (in contrast to handheld imaging) of simplicity of workflow and therefore ease of reproducibility. Another advantage is the constant position of the lighting (elimination of shadows) or the choice of any exposure time without affecting the sharpness of the image. The disadvantage is the necessary manipulation with the subject, which is therefore exposed to a certain risk of damage. A comparison of the two scene schemes is given below (Figure 5).

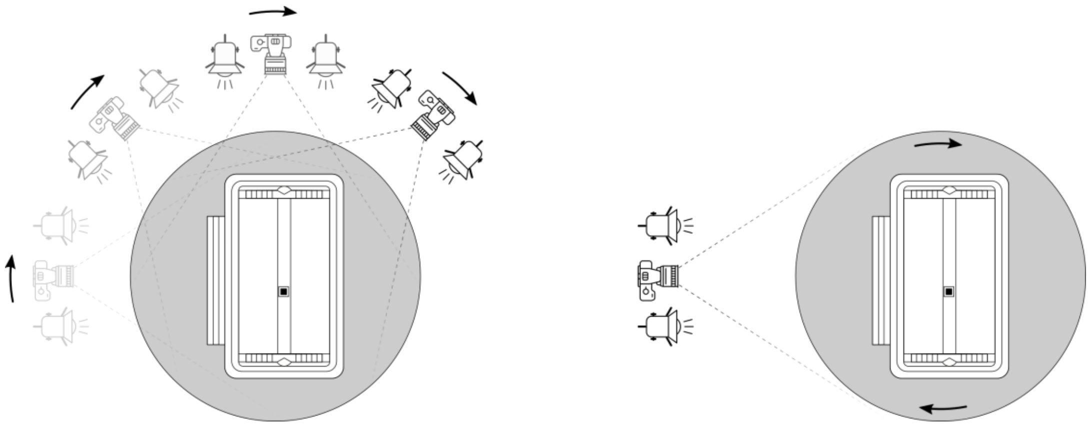


Fig. 5 – Plan view of the shooting scene – handheld (left) and tripod shooting

To precisely capture the object's structure in the vertical direction, the camera was placed in two additional height levels, each time performing one additional horizontal rotation. Finally, additional images were taken covering areas that were difficult to reach (the bottom of the object was not captured [3]). This was followed by imaging of the interior, a difficult environment for the photogrammetry method, with very limited visibility (the necessary view is often obstructed by walls and furniture) and many small details. Only one set of 36 images (horizontal rotation) was captured for each room and the missing vertical dimension was added by a single vertical distance measurement in each room. In total, 121 images for the exterior and 144 images for the interior of the building were taken and used to calculate a detailed triangular model.

Computation part

Today, a variety of programs can be used to process photogrammetric images. Agisoft Metashape is a popular software for image-based modelling. A good quality image set and an appropriate setting of computational parameters are essential for successful model processing. The procedure consists of several steps: initial alignment of the images (sparse cloud), then identification of the ground control points, calculation of the dense point cloud, and finally calculation of the triangular model (mesh) with texture. During the identification of the ground control points, automatic detection was performed for two test points. The results of this function were successful in only 47% of the cases. Examination of the unsuccessfully detected cases showed that failure occurs when the target is not visible in its entirety or is captured from a too sharp angle.

During the processing, it is advisable to clean the model from noise and other objects (base, surrounding environment). The result is a textured, highly detailed 3D model of the object. Individual sets of images (exterior and 4 rooms of the interior) were processed separately, and then the models were aligned in a unified coordinate system (cloud-to-cloud method) and merged. Some of the interior locations were not visually accessible (covered by furniture) and the image coverage at these locations was not sufficient to generate the model. At these locations, the calculation failed, and the triangular model does not contain geometry.

Although the triangular model in this form is sufficient as a good 3D documentation, it would be difficult to present it in a web environment due to its file size. Therefore, the next stage was to create a compact generalized model. Although the model loses detail, it is much more economical in terms of data volume.

Modelling part

Agisoft Metashape features a tool for uniform model generalization. In this process, it reduces the point density but does not consider the logical subdivision of the model. It does not preserve important edges and leaves flat parts too dense (Figure 6), which is not an optimal solution.

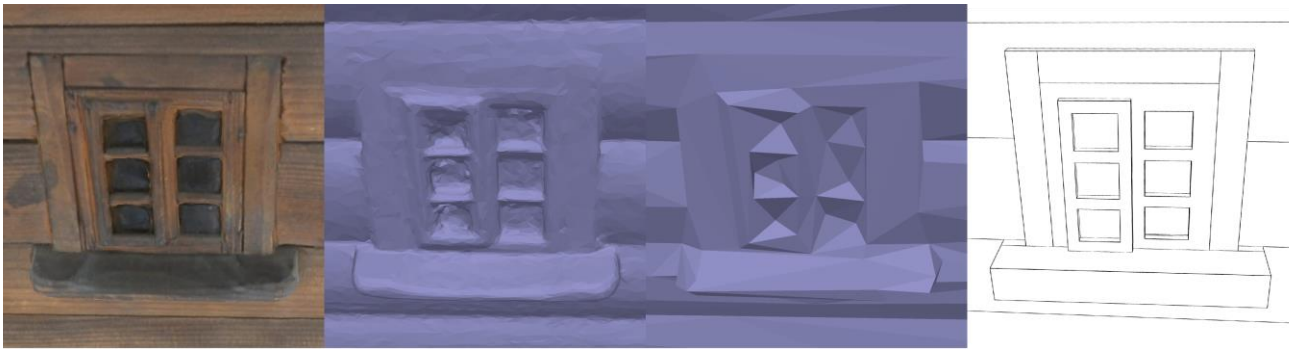


Fig. 6 – Types of geometry generalization

For these reasons, the Trimble SketchUp modelling program with the Scan Essentials plugin was used. Geometry was manually modelled directly into the point cloud. During the modelling process, generalization techniques were used to replace flat parts with planes (the reduction of the number of points was in this case in a ratio of up to 10^6:1), as well as alignment of surfaces along the axes (orthogonality), geometry simplification of some elements (elimination of detailed structures) or regularization of the dimensions of elements (e.g. constant stair spacing). A special approach was given to the thatched part of the roof, where the generalization techniques described above were ineffective due to the irregular structure. Therefore, this part was generalized by uniformly reducing the number of points of the original triangular model to a point spacing of 10 mm. Although all above-mentioned generalization techniques degraded the accuracy of the model in some areas, they contributed significantly to the overall clarity and topological correctness of the model. Due to the reduction in geometry, the resulting generalized model saved 663.9 MB (99.7%) compared to the original triangular model from Agisoft Metashape; the comparison of the parameters of the two models is shown below (Table 1). Data volumes refer to files in DAE text format.

Tab. 1 - Comparison of model data volumes (exterior + interior)

	No. of points	No. of faces	File size [MB]
Detailed triangular model	4 691 084	9 343 001	666,0
Generalized model	11 411	23 639	2,1

Fig. 7 – Orthogonal projections of textures onto the generalized model

Orthogonal projections from the four horizontal directions and from below were used to texture the generalized model (Figure 7). This method can be used if the model has an orthogonal shape (the main walls are perpendicular to each other). Since the triangular model is the basis for both the generalized model and the projected textures, the position of the modelled elements corresponds to the projected textures. These can therefore be applied to all geometry of the selected wall after initial alignment.

Visually inaccessible parts of the interior could not be covered with texture (Figure 8). However, given the purpose of the generalized model, it was not appropriate to leave these areas blank. Therefore, these parts were covered using graphics editor tools (Affinity Photo software was used). Copies of sections from other suitable parts of the image were used to replace larger areas. Smaller elements such as colour differences and other poorly rendered parts were smoothed out with the retouching functions. All interior textures (20 textures in total, 4 walls, and the floor in each room) were refined in this way, giving the model a better look for presentation purposes.

Fig. 8 – Corrections to the orthogonal projection of one of the walls, "before" (left) and "after"

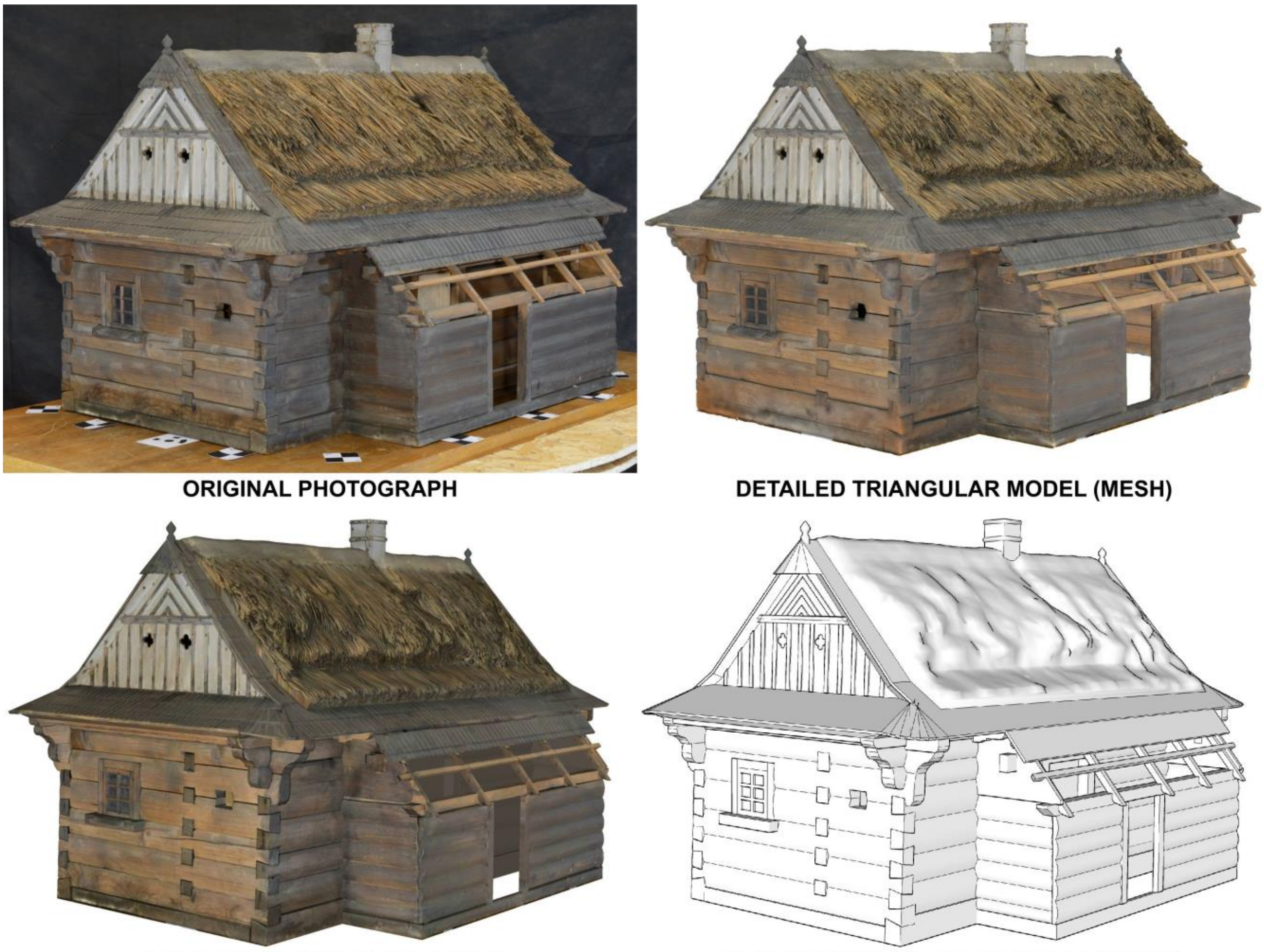
Another weakness of textures was their size (data volume). To maintain the final size of the model specified, it was necessary to reduce it. Raster image files can be effectively compressed by using a suitable format, reducing resolution, reducing colour depth, or increasing compression (for some formats). The effect of changing each factor on the overall file size was tested (tested on the texture in Figure 8); the results are summarized in the table below (Table 2). As can be seen in Figure 9, reducing the resolution and increasing the compression rate have different impacts on the visual quality of the image file. Although the two compared texture sections were extracted from a file of similar size (approximately 600 kB), the sample located on the right shows significantly worse visual quality. Reducing the colour depth had a negligible impact on the file size. Therefore, to reduce the volume of texture data, the resolution was preserved and the JPG compression value was set to 30.

Tab. 2 - Dependence of texture file size on resolution and compression intensity (texture data from Figure 8, each file was modified from the original, IrfanView program used)

		Resolution [px]				
		5000×2949	4000×2359	3000×1770	2000×1180	1000×590
Quality (JPG)	100	5151 kB	3604 kB	2386 kB	1290 kB	377 kB
	85	2243 kB	1567 kB	1022 kB	539 kB	156 kB
	70	1516 kB	1075 kB	701 kB	360 kB	100 kB
	55	1157 kB	818 kB	532 kB	268 kB	73 kB
	40	927 kB	649 kB	420 kB	210 kB	56 kB
	25	658 kB	459 kB	293 kB	145 kB	39 kB

5000×2949 px, quality 25 2000×1180 px, quality 85

Fig. 9 – Texture detail for different compression parameters (detail of Figure 8)



GENERALIZED TEXTURED MODEL GENERALIZED MODEL (GEOMETRY ONLY)

Fig. 10 – Views of the model at different stages of the work process

In total, 5 textures were created for the exterior and 20 for the interior. Each of them required editing with retouching tools due to incompleteness. In total, the image files for the model included 6.1 MB of data (JPG format). The total size of the textures in their original form (full resolution, low compression) was 193.5 MB, so 97% of the data was saved by graphical processing of the files. After adding the vector geometry of the model (DAE format), the total size of the generalized model was 11.4 MB. In this form, it meets the size and texture quality criteria (the quality can be visually compared in Figure 10).

The main objective of the described technological procedure was the presentation of the 3D model in a web environment. For this purpose, the JavaScript library Three.js [20] and its ColladaLoader function were used. This function loads 3D data in Collada format (DAE extension) into the web browser window [6]. Since the model contains an interior that is initially covered by the roof, it was necessary to add controls to the loaded page, allowing the model to be displayed both in its complete form and in its uncovered form (interior revealed by removing the roof). The resulting output is an HTML file executable in a web browser in the form of a web page containing a generalized textured 3D model. In the upper right corner, the page contains checkboxes with a label for each layer (part of the model), each of which can be clicked to change the visibility of the layer (Figure 11). The content of the web page takes approximately 3 seconds to load with a normal internet connection speed. There is no need to include user instructions, as the interface is simple and intuitive.

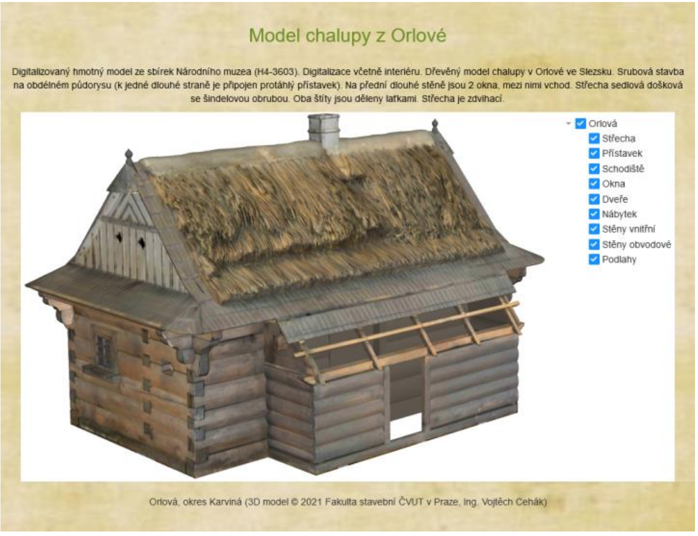


Fig. 11 – Presentation of the generalized model in a web environment

RESULTS AND CONCLUSION

The paper presents the methodology of the technical procedure for digitizing a physical model of approximately 1:20 scale of a building using photogrammetry (exterior and interior). Furthermore, the generalization of the resulting triangular model is carried out in both the form of geometry reduction and the reduction of the texture data volume. The use of photogrammetry ensures high accuracy and detail of the output, as well as the efficiency of the workflow.

The generalization process was performed by manual modelling using a detailed point cloud in Trimble SketchUp. The generalization saved 99% of the data volume compared to the original triangular model (the size of the resulting textured model was 11.4 MB). The resulting model could thus be published and presented as a lightweight web application based on the features of the Three.js library, including a user-friendly environment for switching layer visibility.

The developed procedure from digitization to presentation is applicable to physical models of buildings or other objects of similar dimensions. Thanks to the use of a turntable and a static camera position, it can be performed even by a person with no knowledge of photogrammetry. In future work, it is planned to further improve the procedure technologically – for example, by testing a light diffusion device (softening the shadows in the image) or using a green screen to mask the background to speed up the calculation [2]. It is also worth exploring technological improvements to the generalization process. The latter involves difficult decisions about which elements to keep and which to omit, depending on the structure and subdivision of the digitized object. It requires an individual approach and is, therefore, time-consuming and difficult to automate.

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REFERENCE

[1] KARACHALIOU, E., GEORGIOU, E., PSALTIS, D. and STYLIANIDIS, E. UAV for Mapping Historic Buildings: From 3D Modelling to BIM. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Online. 31 January 2019. Vol. XLII-2/W9, p. 397–402. DOI 10.5194/isprs-archives-XLII-2-W9-397-2019.

[2] TANNUS, Julia. Optimizing and Automating Computerized Photogrammetry for 360° 3D Reconstruction. In : 2020 22nd Symposium on Virtual and Augmented Reality (SVR). Online. Porto de Galinhas, Brazil : IEEE, November 2020. p. 267–271. ISBN 9781728192314. DOI 10.1109/SVR51698.2020.00048.

[3] MARSHALL, M. E., JOHNSON, A. A., SUMMERSKILL, S. J., BAIRD, Q. and ESTEBAN, E. Automating Photogrammetry for the 3D Digitisation of Small Artefact Collections. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Online. 23 August 2019. Vol. XLII-2/W15, p. 751–757. DOI 10.5194/isprs-archives-XLII-2-W15-751-2019.

[4] PAVLOVSKIS, Miroslavas, MIGILINSKAS, Darius, KUTUT, Vladislavas and ANTUCHEVICIENE, Jurgita. Initial data preparation for 3D modelling of heritage building. In : Online. Vilnius Gediminas Technical University, 3 December 2019. DOI 10.3846/mbmst.2019.049.

[5] RAHAMAN, Hafizur, CHAMPION, Erik and BEKELE, Mafkereseb. From photo to 3D to mixed reality: A complete workflow for cultural heritage visualisation and experience. Digital Applications in Archaeology and Cultural Heritage. Online. June 2019. Vol. 13, p. e00102. DOI 10.1016/j.daach.2019.e00102.

[6] POLOPRUTSKÝ, Zdeněk, FROMMELTOVÁ, Eva, MÜNZBERGER, Josef and SEDLICKÁ, Kateřina. 3D Digital Reconstruction of Defunct Rural Buildings Based on Archival Sources. Stavební obzor - Civil Engineering Journal. Online. 30 April 2022. Vol. 31, no. 1, p. 196–210. DOI 10.14311/CEJ.2022.01.0015.

[7] JEONG, Gi Young, NGUYEN, Tan No, TRAN, Dang Khai and HOANG, Thi Bich Huyen. Applying unmanned aerial vehicle photogrammetry for measuring dimension of structural elements in traditional timber building. Measurement. Online. March 2020. Vol. 153, p. 107386. DOI 10.1016/j.measurement.2019.107386.

[8] CULTLAB3D. Digitization made easy. CultArm3D. Online. 2022. Available from: https://www.cultarm3d.de/

[9] KINGSLAND, Kaitlyn. Comparative analysis of digital photogrammetry software for cultural heritage. Digital Applications in Archaeology and Cultural Heritage. Online. September 2020. Vol. 18, p. e00157. DOI 10.1016/j.daach.2020.e00157.

[10] VACCA, G. Overview of Open Source Software for Close Range Photogrammetry. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Online. 23 August 2019. Vol. XLII-4/W14, p. 239–245. DOI 10.5194/isprs-archives-XLII-4-W14-239-2019.

[11] BALLETTI, Caterina, BALLARIN, Martina and GUERRA, Francesco. 3D printing: State of the art and future perspectives. Journal of Cultural Heritage. Online. July 2017. Vol. 26, p. 172–182. DOI 10.1016/j.culher.2017.02.010.

[12] NISHANBAEV, Ikrom. A web repository for geo-located 3D digital cultural heritage models. Digital Applications in Archaeology and Cultural Heritage. Online. March 2020. Vol. 16, p. e00139. DOI 10.1016/j.daach.2020.e00139.
[13] SKETCHFAB. Sketchfab. Online. 2022. Available from: https://sketchfab.com/
[14] TRIMBLE INC. 3D Warehouse. Online. 2022. Available from: https://3dwarehouse.sketchup.com/
[15] CHAMPION, Erik and RAHAMAN, Hafizur. Survey of 3D digital heritage repositories and platforms. Virtual Archaeology Review. Online. 8 July 2020. Vol. 11, no. 23, p. 1. DOI 10.4995/var.2020.13226.
[16] AGISOFT. Agisoft Metashape. Discover intelligent photogrammetry with Metashape. Online. 2022. Available from: https://www.agisoft.com
[17] TRIMBLE INC. SketchUp. 3D Design Software, 3D Modeling on the Web. Online. 2022. Available from: https://www.sketchup.com/
[18] HRUSKA, Jonas, PADUA, Luis, ADAO, Telmo, PERES, Emanuel, MARTINHO, Jose and SOUSA, Joaquim J. Target Influence on Ground Control Points (GCPs) Identification in Aerial Images. In : IGARSS 2020 - 2020 IEEE International Geoscience and Remote Sensing Symposium. Online. Waikoloa, HI, USA : IEEE, 26 September 2020. p. 6487–6490. ISBN 9781728163741. DOI 10.1109/IGARSS39084.2020.9324222.
[19] GNU Operating System. GNU Gama. Online. 2022. Available from: https://www.gnu.org/software/gama/
[20] Three.js – JavaScript 3D Library. Online. 2022. Available from: https://threejs.org/