# Towards an easy-to-implement method of obtaining 3D models of historical wooden churches using a combination of modern techniques

Jacek Kęsik – Marek Miłosz – Jerzy Montusiewicz – Kamil Żyła

PhD Eng. Jacek Kęsik
Lublin University of Technology
Faculty of Electrical Engineering and Computer Science
Department of Computer Science
Nadbystrzycka 36B
PL-20-618 Lublin, Poland
e-mail: j.kesik@pollub.pl
https://orcid.org/0000-0002-2040-8172

Prof. Marek Miłosz
Lublin University of Technology
Faculty of Electrical Engineering and Computer Science
Department of Computer Science
Nadbystrzycka 36B
PL-20-618 Lublin, Poland
e-mail: m.milosz@pollub.pl
https://orcid.org/0000-0002-5898-815X

Prof. Jerzy Montusiewicz
Lublin University of Technology
Faculty of Electrical Engineering and Computer Science
Department of Computer Science
Nadbystrzycka 36B
PL-20-618 Lublin, Poland
e-mail: j.montusiewicz@pollub.pl
https://orcid.org/0000-0002-8571-3354

PhD Eng. Kamil Żyła (corresponding)
Lublin University of Technology
Faculty of Electrical Engineering and Computer Science
Department of Computer Science
Nadbystrzycka 36B
PL-20-618 Lublin, Poland
e-mail: k.zyla@pollub.pl
https://orcid.org/0000-0002-6291-003X

*Muzeológia a kultúrne dedičstvo, 2025,13:1:113–137*
doi: 10.46284/mkd.2025.13.1.6

*Towards an easy-to-implement method of obtaining 3D models of historical wooden churches using a combination of modern techniques*
Modern 3D computer technologies allow for precise documentation of historic architectural objects by building digital 3D models. For this purpose, 3D laser scanning techniques using terrestrial laser scanning (TLS) and photogrammetry are commonly used. This article presents the use of both technologies for the 3D digitisation of historical wooden churches located in the Carpathian Region in Romania. It describes the methodology used to obtain digital mesh 3D models of this type of objects, from the planning stage, through the process of data acquisition in the field, to methods of data processing and integration of data from two different technologies in order to improve the generated digital 3D models.

Particular emphasis was placed on avoiding cost increases and delays resulting from the need to use non-terrestrial data acquisition methods. The article presents the results of generating 3D models on the example of Orthodox churches in the villages of Creaca, Păniceni, Târguşor and Păusa located in the Cluj region in Transylvania. The results indicate that well-performed data integration allows for obtaining digital 3D models that will also be suitable for dissemination.

Keywords: historical wooden churches; 3D model; 3D scanning; TLS; photogrammetry

## 1. Research motivation and aim

Cultural heritage (CH) objects, including architectural ones, are exposed to various types of threats leading to their degradation and loss. An attempt at classifying them is shown in Figure 1. Wooden religious buildings (churches, orthodox churches, bell towers, gates, shrines, synagogues and others) are particularly exposed to natural hazards, such as weather conditions and the passage of time, as well as earthquakes[1] and landslides,[2] tornadoes,[3] pests,[4] moisture,[5] fungus,[6] and fire.[7] There are also threats related to human activity, such as armed conflicts and wars, theft, excessive tourist exploitation, inappropriate management, abandonment[8] and intentional destruction (e.g. for ideological/religious reasons).[9]

In Europe, wooden historic churches are mainly only found in Norway where, of the nearly 2,000 stave churches from the twelfth to fourteenth centuries, only 28 structures have survived. One of them was moved to the city of Karpacz in Poland in 1842.[10] In addition, wooden churches have been preserved in Carpathian Region. These are structures from the fourteenth to the twentieth centuries, built of "solid" wood logs[11]. Other wooden churches have been preserved in Upper and Lower Silesia in Poland. An exceptional example there is the Lutheran Church of Peace in the city of Świdnica. Dating from 1657, it is the largest wooden temple in Europe, serving nearly 7,500 believers. It was built using frame wall technology with clay and

[1] VLAHOULIS, Themistoklis et al. Post-seismic restoration project of basilica churches in Kefallonia Island. In: *Transdisciplinary Multispectral Modeling and Cooperation for the Preservation of Cultural Heritage,* 2019, pp. 131–142.

[2] LIPECKI, Tomasz. Non-contact diagnostics of the geometry of a historic wooden building as an element of periodic safety assessment. In: *Sensors*, 22(4), 2022, pp. 1–23.

[3] HORST, Michael and CLEMONS, Benjamin. Evaluation and repair of tornado damage to a historic church. In: *Forensic Engineering: Performance of the Built Environment – Proceedings of the 7th Congress on Forensic Engineering*, 2015, pp. 387–397.

[4] FRANKL, Jiri. Wood-damaging fungi in truss structures of baroque churches. In: *Journal of Performance of Constructed Facilities*, 29(5), 2015, pp. 1–5.

[5] KLOIBER, Michal et al. Comparative evaluation of acoustic techniques for detection of damages in historical wood. In: *Journal of Cultural Heritage*, 20, 2016, pp. 622–631; LIÑÁN, Carmen Rodríguez et al. Application of non-destructive techniques in the inspection of wooden structures of protected buildings: The case of Nuestra Señora de los Dolores Church (Isla Cristina, Huelva). In: *International Journal of Architectural Heritage*, 9(3), 2014, pp. 324–340.

[6] EL-GAMAL, Rehab et al. The use of chitosan in protecting wooden artifacts from damage by mold fungi. In: *Electronic Journal of Biotechnology*, 24, 2016, pp. 70–78.

[7] MOUADDIB, El Mustapha et al. 2D/3D data fusion for the comparative analysis of the vaults of Notre-Dame de Paris before and after the fire. In: *Journal of Cultural Heritage*, 65, 2024, p. 221–231.

[8] BEDNARZ, Łukasz et al. Analysis of the condition of damaged vaults after a construction disaster in a historic church. In: *Key Engineering Materials*, 817, 2019, p. 613–620.

[9] LAMBERT, Simon and ROCKWELL, Cynthia (Eds.). *Protecting cultural heritage in times of conflict: Contributions from the participants of the International Course on First Aid to Cultural Heritage in Times of Conflict*. ICCROM, Roma, Italy, 2012.

[10] MATTES, Julia. *Die nordischen Stabkirchen*. AV Akademikerverlag, 2011.

[11] BUXTON, David. *Wooden churches of Eastern Europe. An introductory survey.* Cambridge University Press, 2008.

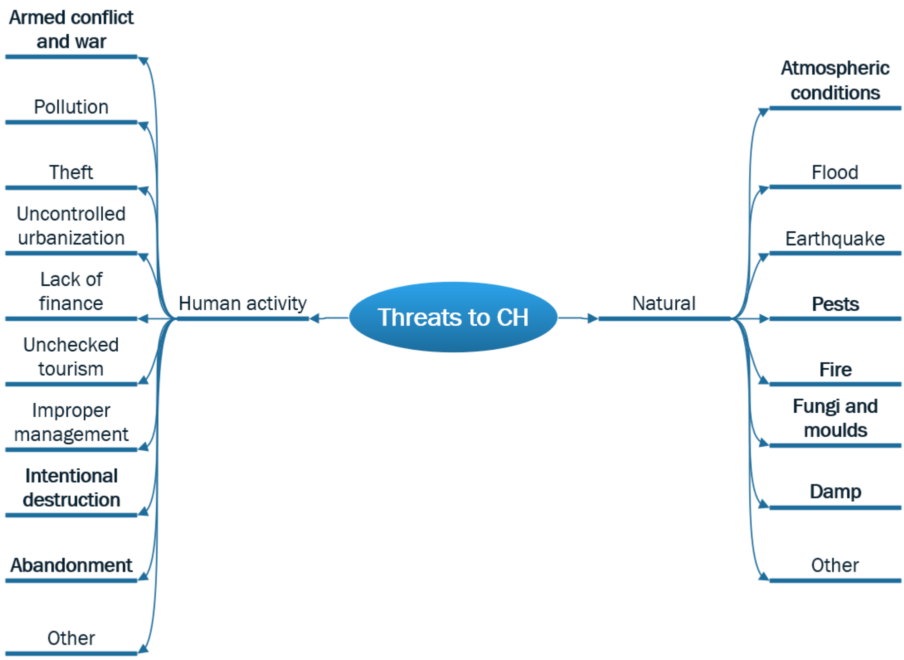


**Fig. 1:** *CH hazard classification. The most important threats in relation to wooden religious buildings are in bold.*

straw filling.[12] Unfortunately, many of the wooden churches were lost as a result of wars (mainly during World War I and II) and under communist rule, when renovations were forbidden and sacred wooden architectural monuments were even intentionally destroyed.[13]

Another significant threat to churches is the depopulation of many areas, which reduces the number of believers and leads to financial problems for many parishes. Contrary to appearance, the opposite trend – that is, a lack of financial problems and dynamically developing parishes – also pose a problem for wooden churches. When new brick church buildings are built, old wooden ones may become unnecessary and are abandoned or used as warehouses. Fires from natural, intentional or accidental causes, exacerbated by the poor technical condition of many such buildings, are also a significant problem. There are two such examples from Poland. The Catholic church of the Nativity of the Blessed Virgin Mary in the village of Libusza, dating from 1513, burned down on the night of 14 February 1986 (the sacristy and part of the walls survived). Rebuilt at the start of the twenty-first century, it burned down again on the night of 1 February 2016. It was subsequently removed from the list of monuments and will no longer be rebuilt.[14] The Orthodox Church of the Protection of Our Lady in the village of Komańcza, dating back to 1802, burned down completely on 13 September 2006 due to the inattention of the faithful lighting prayer candles at the iconostasis. It was rebuilt in 2008–2010.[15]

[12] TRUDYMASON, The largest wooden church in Europe and Książ Castle, Poland, https://trudymason.com/2019/09/07/the-largest-wooden-church-in-europe-and-ksiaz-castle-poland/

[13] MOSOARCA, Marius and GIONCU, Victor. Historical wooden churches from Banat Region, Romania. Damages: Modern consolidation solutions. In: *Journal of Cultural Heritage*, 14, 2013, pp. 45–59.

[14] Medieval heritage, Libusza – Church of the Nativity of the Blessed Virgin Mary, https://medievalheritage.eu/en/main-page/heritage/poland/libusza-church-of-the-nativity/

[15] Komańcza – Cerkiew Opieki Matki Boskiej – Świątynia 3D, https://swiatynia3d.pl/project/komancza-cerkiew/

It is possible to document the dimensions and appearance of these churches using modern 3D IT technologies: laser scanning – terrestrial laser scanning (TLS) and terrestrial short-range photogrammetry (TSRP).[16] Digitisation of these monuments' appearance (and size) facilitates scientific research and dissemination and can also, where necessary, aid reconstruction. It also supports conservation work.

Historical wooden churches are very difficult objects to scan. This is due to their shape (sharp roof angles to cope with heavy snowfall in the mountains), their significant height, and the building materials – old wood which reflects the laser beams poorly, exacerbated by the fact that they are often covered with moss and lichen, which disturbs the geometry of the buildings. Most churches are located in hard-to-reach areas on hills, often without access for ordinary cars or the possibility of using drones or booms.

The aim of the present research was to develop a methodology that combines the use of TLS and TSRP in challenging mountainous conditions, and to verify it during field expeditions to Romania. The article presents a review of the literature on the use of 3D digitisation of CH objects, along with examples of scanned wooden churches in Carpathian Region and details of attempts to document and protect them. It also presents the churches that were scanned as part of a scientific expedition by the Department of Computer Science, Lublin University of Technology in Romania (https://carpatia3d.com/en/pierwsza-karpacka-wyprawa/), problems related to them and a proposal for solving them. The workflow for 3D scanning historical wooden churches is shown in detail, as well as the results of its use, based on the example of the Orthodox church in Creaca.

## 2. Introduction

Wooden religious Christian buildings – including Roman Catholic, Orthodox and Greek Catholic churches – have survived in relatively large numbers throughout Carpathian Region. Despite numerous wars from the fourteenth to the twenty-first century – Tatar invasions in the first half of the eighteenth century; peasant rebellions and national liberation uprisings against the Turkish, Hungarian and Austrian authorities; World Wars I and II – and the destructive activities of the communist authorities in most Carpathian countries, objects of this type have survived to this day, albeit in varying states.[17] The scale of destruction of wooden objects can be traced in the Banat Mountains (southwestern part of modern Romania). In 1891 there were about 200 wooden Orthodox churches, in 1929 only 54, and by 1935 only 48 remained. Today, their number has decreased to 25 buildings.[18]

Wooden religious buildings in the broadly understood Carpathian Region are very diverse in terms of architectural form, and their appearance can be easily assigned to specific regions.

---

[16] ORTIZ, Pedro et al. Experiences about fusioning 3D digitalization techniques for cultural heritage documentation. In: *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences – ISPRS Archives*, 36, 2006, pp. 224–229.

[17] BUXTON, *Wooden churches …*; PASCU, *Monumente Istorice* şi *de Arta Religioasa din Arhiepiscopia Vadului Feleacului* şi *Clujului*. Editata de Arhipiscopia Ortodoxă Română a Vadului, Feleacului şi Clujului, Cluj-Napoca, 1982; BRYKOWSKI, Ryszard. Łemkowska drewniana architektura cerkiewna w Polsce na Słowacji i Rusi Zakarpackiej. Wrocław: Ossolineum, 1986; KOVAČOVIČOVÁ-PUŠKAROVÁ, Blanka and PUŠKAR, Imrich. *Derev'jani cerkvi*. Bratislava: Muzeum ukrajinskiej kultury vo Svidniku, Slovenske Pedagogicke Nakladatelstvo, 1971; BRYKOWSKI, Ryszard. *Drewniana architektura cerkiewna na koronnych ziemiach Rzeczypospolitej*. Towarzystwo Opieki nad Zabytkami, 1995; UNESCO, Wooden Churches of the Slovak part of the Carpathian Mountain Area, https://whc.unesco.org/ru/list/1273

[18] MOSOARCA, Marius and GIONCU, Victor. Historical wooden churches ….

In Transylvania, Romania, the Maramureş-type church has been in use for almost six centuries (the name comes from the region located in the northern part of the country). Orthodox churches of this type are the subject of this article and are presented in Figure 2. What is important is that contemporary Romanian carpenters are successfully building such structures in the twenty-first century, to dimensions much larger than those of their great-grandfathers. The wooden church of the nunnery in the village of Săpânţa has a tower 72 m high.[19]

In Poland, the most famous wooden Orthodox churches are Lemko churches (the Lemko people lived for centuries in the Low Beskids and the eastern part of the Sądecki Beskids until 1947, when they were forcibly deported to western and northern Poland as part of the Operation Vistula). Lemko churches are tripartite with separate roofs over the presbytery and the nave, and a tower with a pillar structure located above the women's gallery.[20] This type of church can also be found in Slovakia, adjacent to the Polish border.[21]

In the Carpathian foothills, tripartite Orthodox churches can be found with separate roofs topped with domes – the highest one above the nave – and a separate bell tower.[22] In modern Ukraine, one can find Boyko churches, which have highly elaborate roofs over the narthex, nave and presbytery, and also Hutsul churches – based on a Greek cross plan with a central dome.[23] Another type of wooden church in the Carpathian Region is the so-called Gothic Hungarian church, which has ridged roofs over the nave and presbytery and a tower with a pole structure added at the front of the body of the church with a characteristic room.[24]

Nowadays, thanks to 3D scanning, it has become possible to effectively transfer real objects representing cultural heritage into the digital world while maintaining information about their dimensions, shapes, existing colours, as well as documenting wear-and-tear or destruction.[25] This type of 3D digitisation can be applied to archaeological sites,[26] architectural objects[27] and

---

[19] BUXTON, David. *Wooden churches* …; PASCU, Ştefan. *Monumente* ….

[20] BRYKOWSKI, Łemkowska drewniana …; BRYKOWSKI, *Drewniana architektura* ….

[21] UNESCO, Wooden Churches …

[22] BUXTON. *Wooden churches* ….

[23] KOVAČOVIČOVÁ-PUŠKAROVÁ and PUŠKAR, *Derev'jani cerkvi* ….

[24] WIERZEJSKA, Anna and MARKOWSKI, Wojciech. Laser scanning of the wooden church of the Assumption of the Blessed Virgin Mary and St Michael the Archangel in Haczów, Poland. In: *Protection of Culture Heritage*, 9, 2020, pp. 141–159.

[25] SILVA, Pinto da Fábio. *Usinagem de espumas de poliuretano e digitalização tridimensional para fabricação de assentos personalizados para pessoas com deficiência. Porto Alegre: Tese Doutorado – Curso de Engenharia, Minas, Metalúrgica e Materiais*. Universidade Federal do Rio Grande do Sul, Porto Alegre, 2011.

[26] LAMBERS, Karsten et al. Combining photogrammetry and laser scanning for the recording and modelling of the late intermediate period site of Pinchango Alto, Palpa, Peru. In: *Journal of Archaeological Science*, 34(10), 2007, pp. 1702–12; BRUNO, Fabio et al. From 3D reconstruction to virtual reality: A complete methodology for digital archaeological exhibition. In: *Journal of Cultural Heritage*, 11, 2010, pp. 42–49; NEAMTU, Calin et al. Methodology to create digital and virtual 3D artefacts in archaeology. In: *Journal of Ancient History and Archaeology*, 3, 2016, pp. 65–74; ARMSTRONG, B. J. et al. Terrestrial laser scanning and photogrammetry techniques for documenting fossil-bearing palaeokarst with an example from the Drimolen Palaeocave System, South Africa. In: *Archaeological Prospection*, 25(1), 2018, pp. 45–58; PEPE, Massimiliano et al. Scan to BIM for the digital management and representation in 3D GIS environment of cultural heritage site. In: *Journal of Cultural Heritage*, 50, 2021, pp. 115–125.

[27] WIERZEJSKA and MARKOWSKI, Laser scanning …; BASTONERO, Paola et al. Fusion of 3D models derived from TLS and image-based techniques for CH enhanced documentation. In: *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2(5), 2014, pp. 73–80; MEDIUM, How 3D Scanning helps to preserve historical buildings; HERMAN, Grigore Vasile et al. 3D modeling of the cultural heritage: Between opportunity and necessity. In: *Journal of Applied Engineering Sciences*, 10(23), 2020, pp. 27–30; MIŁOSZ, Marek et al. 3D scanning and visualization of large monuments of Timurid architecture in Central Asia — A methodical approach. In: *Journal on*

small museum objects[28] including sculptures and statues.[29] Digital 3D copies are often made available to the public via virtual museums,[30] Internet portals[31] or even via 3D copies created using 3D printers.[32]

---

*Computing and Cultural Heritage*, 14(1), 2021, pp. 1–31; OOSTWEGEL, L.J.N. et al. Digitalization of culturally significant buildings: Ensuring high-quality data exchanges in the heritage domain using OpenBIM. In: *Heritage Science*, 10(10), 2022, pp. 1–14. TYSIAC, Pawel et al. Combination of terrestrial laser scanning and UAV photogrammetry for 3D modelling and degradation assessment of heritage building based on a lighting analysis: Case study—St. Adalbert Church in Gdansk, Poland. In: *Heritage Science*, 11(53), 2023, pp. 1–14; MAŁYSZEK, Hubert Aleksander et al. The case study of using photogrammetric systems and laser scanning for three-dimensional modeling of cultural heritage sites. In: *Advances in Science and Technology Research Journal*, 17(6), 2023, pp. 345–357; CACIORA, Tudor et al. Digitization of the built cultural heritage: An integrated methodology for preservation and accessibilization of an art nouveau museum. In: *Remote Sensing*, 15, 2023, pp. 1–25; KĘSIK, Jacek et al. A methodical approach to 3D scanning of heritage objects being under continuous display. In: *Applied Sciences*, 13(1), 2023, pp. 1–20.

[28] KIM, S. H. et al. A study on convergence modeling of cultural artifact using x-ray computed tomography and three-dimensional scanning technologies. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 48(2), 2023, pp. 851–856; MERELLA, Marco et al. Structured-light 3D scanning as a tool for creating a digital collection of modern and fossil cetacean skeletons (Natural History Museum, University of Pisa). In: *Heritage*, 6, 2023, pp. 6762–6776. MOUSSA, Wassim. *Integration of digital photogrammetry and terrestrial laser scanning for cultural heritage data recording*. Doctoral dissertation, University of Stuttgart, Stuttgart, Germany, 2014.

[29] RUIZ, Rafael Melendreras et al. Comparative analysis between the main 3D scanning techniques: photogrammetry, terrestrial laser scanner, and structured light scanner in religious imagery: The case of The Holy Christ of the Blood. In: *ACM Journal on Computing and Cultural Heritage*, 15(1), 2021, pp. 1–23; CALVO-SERRANO, María Araceli et al. Historical-graphical analysis and digital preservation of cultural heritage: Case study of the baptismal font of the church of Santiago Apóstol in Montilla (Córdoba, Spain). In: *Heritage Science*, 10(149), 2022, pp. 1–14; GHERARDINI, Francesco and SIROCCHI, Simone. Systematic integration of 2D and 3D sources for the virtual reconstruction of lost heritage artefacts: The equestrian monument of Francesco III d'Este (1774–1796, Modena, Italy). In: *Heritage Science*, 10(96), 2022, pp. 1–19; NEAMTU, Calin et al. Component materials, 3D digital restoration, and documentation of the imperial gates from the wooden church of Voivodeni, Sălaj County, Romania. In: *Applied Sciences*, 11(8), 2021, pp. 1–18.

[30] BARSZCZ, Marcin et al. 3D scanning digital models for virtual museums. In: *Computer Animation and Virtual Worlds*, 34, 2023, pp. 1–12; ŻYŁA, Kamil et al. VR technologies as an extension to the museum exhibition: A case study of the Silk Road museums in Samarkand. In: *Muzeologia a Kulturne Dedicstvo*, 8(4), 2020, pp. 73–93; LEE, Woo-Hee et al. Students' reactions to virtual geological field trip to Baengnyeong Island, South Korea. In: ISPRS International Journal of Geo-Information, 10, 2021, pp. 1–13; SURYANI, Mira et al. Development of historical learning media based on virtual reality of The National Awakening Museum. In: *Jurnal Ilmiah Bidang Teknologi Informasi dan Komunikasi*, 7(2), 2022, pp. 125–131.

[31] Wooden monuments of the Carpathians in 3D, https://carpatia3d.com; 3D Digital Silk Road portal, https://silkroad3d.com; BARBIERI, Loris et al. Virtual museum system evaluation through user studies. *Journal of Cultural Heritage*, 26, 2017, pp. 101–108; CACIORA, Tudor et al. The use of virtual reality to promote sustainable tourism: A case study of wooden churches historical monuments from Romania. In: *Remote Sensing*, 13(9), 2021, pp. 1–22; POUX, Florent et al. Initial user-centered design of a virtual reality heritage system: Applications for digital tourism. In: *Remote Sensing*, 12(16), 2020, pp. 1–32.

[32] HEVKO, Ihor et al. Methods building and printing 3D models historical architectural objects. In: SHS Web of Conferences, 75, 2020, pp. 1–6; PARSINEJAD, Hossein et al. Production of Iranian architectural assets for representation in museums: Theme of museum-based digital twin. In: Body Space & Technology, 20(1), 2021, pp. 61–74; MONTUSIEWICZ, Jerzy and MIŁOSZ, Marek. Architectural Jewels of Lublin: A modern computerized board game in cultural heritage education. In: Journal on Computing and Cultural Heritage, 14(3), 2021, pp. 1–21; DONG, Qianli et al. 3D scanning, modeling, and printing of Chinese classical garden rockeries: Zhanyuan's south rockery. In: Heritage Science, 8(1), 2020, pp. 1–15; VERNIZZI, C. and GHIRETTI, A. Methodologies capture three-dimensional high-definition of sixteenth wooden frames. The case of works by Correggio. In: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences – ISPRS Archives, 38, 2009, pp. 1–8.

In recent years, thanks to the enormous progress in digital photography and software, several studies have been published on practical methods for integrating the TLS and TSRP.[33] Some interesting activities related to Romania were described by Caciora et al.,[34] who created a digital 3D model of the Darvas-La Roche House (Oradea) by integrating TLS, TSRP and SRAP (short range airborne photogrammetry) technologies using an unmanned aerial vehicle (UAV).

A literature review revealed that 3D scanning of wooden architectural objects is very rare.[35] In the case of the churches studied for this article, this is in part due to the fact that they occur in the difficult mountainous terrain in the Carpathian Region and are not on the radar of scientists from Western countries

## 3. Materials and methods

### 3.1. Historic wooden churches of Romania

The works presented in the article concern four wooden churches in Romania's Carpathian Region (Figure 2 and 3):

- The Orthodox Church of Saint Archangels Michael and Gabriel in Păniceni.
- The Orthodox Church of Saint Nicholas in Creaca.
- The Orthodox Church of Saint Archangels Michael and Gabriel in the village of Târgușor.
- The Orthodox Church of Holy Hierarch Nicholas in the village of Păusa.

### Orthodox church of Saint Archangels Michael and Gabriel in Păniceni

The wooden church in the village of Păniceni (Cluj province) was built in 1730 and is located on a hill in the village (monument under the LMI code: CJ-II-m-B-07734; LMI – Lista Monumentelor Istorice, ang. list of historical monuments)[36] in an east–west orientation (Figure 2A). The church was built of oak beams connected in dovetail fashion, on a rectangular plan with the following dimensions: pronaos 2.90 m x 5 m; main nave 5.50 m x 5 m; and presbytery on the eastern side with cut corners 3.10 m x 3.70 m. The building is covered with a ridged roof and on the south side there is a porch added during renovations in the nineteenth century. A tower resting on a pillar structure sits above the pronaos. It has a distinct room (overhanging storey) and a hipped roof with a square base decorated with four turrets (one at each corner) which tapers into a slender cone as it ascends. The interior of the church is decorated with paintings made by Dimitrie Ispas from Gilău in 1809.[37]

### Orthodox Church of Saint Nicholas in Creaca

The wooden Orthodox church from Creaca is located in the centre of the town of the same name (Sălaj district), in an east–west orientation (Figure 2B). It was probably built in the eighteenth century but there are no written materials on this subject (monument code LMI: SJ-

[33] BASTONERO et al., Fusion of …, 2014, pp. 73–80; WU, Bo and TANG, Shengjun. Review of geometric fusion of remote sensing imagery and laser scanning data. In: *International Journal of Image and Data Fusion*, 6(2), 2015, pp. 97–114.

[34] CACIORA et al., Digitization …, 2023, pp. 1–25.

[35] Komańcza – Cerkiew Opieki Matki Boskiej …; WIERZEJSKA and MARKOWSKI, Laser scanning …, 2020, pp. 141–159; BASTONERO, et al., Fusion of …, 2014, p. 73–80; HERMAN et al., 3D modeling …, 2020, pp. 27–30.

[36] Ministerul Culturii, Lista monumentelor istorice, http://www.cultura.ro/lista-monumentelor-istorice

[37] CÎMPIAN, Felicia Elena. *Bisericile de lemn din zonele Călatei, Gilăului, Hășdatelor* și *Clujului. Aspecte istorico-etnografice* și *arhitectură tradițională.* Cluj Napoca, 2002.


**Fig. 2:** *Appearance of the Marmures-type wooden churches analysed: (A) Saint Archangels Michael and Gabriel in the village of Păniceni, (B) Saint Nicholas in Creaca, (C) Saints Archangels Michael and Gabriel in the village of Târguşor, (D) Saint Nicholas in the village of Păusa.*

II-m-A-05044).[38] According to locals, the church was moved twice. The interior wall painting is attributed to the painter Ioan Pop from Românaşi. The church only has a window on the south side, where there is an almost completely erased external wall painting. The eaves are located

[38] Ministerul Culturii, Lista monumentelor …

on the north side and strongly connected to the top of the structure. A tower with a pillar structure is located above the pronaos with a slightly marked room and a slender hipped roof. The church underwent restoration in 1972 and 1998.[39]

### Orthodox Church of Saint Archangels Michael and Gabriel in the village of Târguşor

The wooden church in Târguşor (Sânmartin commune, Cluj province) dates back to the seventeenth century and is one of the oldest buildings of this type in Romania. Located on the slope of a small hill, it is surrounded by a cemetery (monument code LMI CJ-II-m-B-07779).[40] The structure does not stand out for its beauty, especially since the wooden oak logs of its walls were plastered and painted salmon-colour, causing the building to lose its historic character (Figure 2C). The damaged shingles of the ridged roof were replaced with new ones several years ago. It has a relatively low tower without a room, covered with a hipped roof. Currently, no liturgy is held in the facility. The interior contains historic carved decorations and the barrel vault is decorated with a keystone formed from a carved beam. A few traces of paintings have survived on the vault of the main nave and in the altar. In the early twentieth century, a layer of canvas was glued to an old painting on which scenes inspired by the Bible were reproduced.[41]

### Orthodox Church of the Holy Hierarch Nicholas in the village of Păusa

The wooden church in Păuşa (Sălaj district) dates back to 1730 (monument under the LMI code: SJ-II-m-A-05092).[42] The church was built on a rectangular plan, with a recessed, five-sided apse, covered with a ridge roof (Figure 2D). Above the women's gallery there is an impressive tower with a column structure and a slightly marked room covered with a hipped roof which tapers into an extremely slender cone. The external walls are decorated with a rope motif carved into the beams. The entrance door frames are richly decorated with rosettes, rope motifs (so-called ropes), and geometric motifs. The door frames leading from the women's gallery to the main nave are decorated with rope borders, geometric patterns and spiral rosettes. External paintings have been preserved on fragments of the walls showing scenes from the New Testament, such as the Assumption of the Virgin Mary or Mary surrounded by the Apostles. The church was restored in 1966–1968.[43]

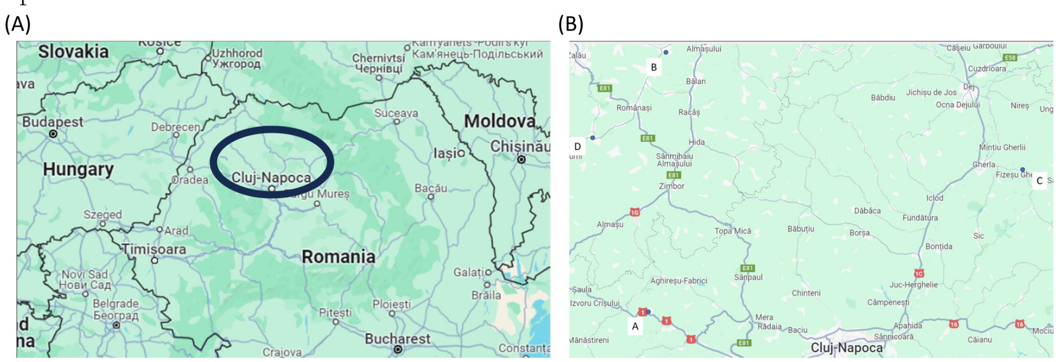


**Fig. 3:** *Location of the wooden churches analysed: A – area of the location of wooden churches, B – location of the scanned churches* – markings as in Fig. 2.

[39] GODEA, Ioan. *Biserici de lemn din România (nord-vestul Transilvaniei).* Bucureşti: Editura Meridiane, 1996.

[40] Ministerul Culturii, Lista monumentelor …

[41] CÎMPIAN, *Bisericile de lemn* ….

[42] Ministerul Culturii, Lista monumentelor ….

[43] CRISTACHE-PANAIT, Ioana. Bisericile de lemn din Sălaj. In: *Buletinul Monumentelor Istorice*, 1, 1971, pp. 31–40.

## 3.2. Problems and possible solutions

When carrying out 3D scanning of wooden religious buildings in Carpathian Region, the generally proven TLS technology was selected as the basis due to its high accuracy. This technology, like any other, has limitations that become important in the context of the specific appearance and location of the objects being scanned.

The purpose of 3D scanning in this case was to obtain the most complete representation of the external shape of the object. The typical shape of a church building, presented schematically in Figure 4, consists of cuboid shapes (the widest one forming the nave, the narrower one forming the gallery and the presbytery, with sharp corners or a rounded apse in the case of the presbytery) covered with a ridged roof (with a steep angle of inclination), usually covered with wooden shingles (or, less often, sheet metal). Above the section known as the women's gallery, there is usually a slender, medium-height tower, usually covered with four or eight sloping roof faces. The overall height of the object is usually under 20 m, although in northern Romania (Maramureș) it often exceeds 30 m.

The manner in which points in space are registered by the TLS scanner is based on analysis of the laser beam sent from the device and reflected from the surface of the object. In order for a given point on the object's surface to be correctly measured by the scanner, the following conditions must be met:

1. There must be a straight path between the scanner and the measured point that is clear of any obstacles obstructing the laser beam.
2. The point to be measured must be no further from the scanner than its maximum measurement range.
3. The power of the laser light reflected towards the scanner must be not less than the minimum recorded by the scanner's receiver. The rebound power depends on two factors:
   - o The reflective (albedo) properties of the object's surfaces at that point (lower albedo means a smaller percentage of incident light is reflected).
   - o The angle at which the laser beam hits the surface of the object at this point (according to Lambert's cosine law,[44] the maximum reflection is recorded by the scanner when the laser hits the surface perpendicularly and decreases with the cosine of the angle of deviation from this direction).

The second aspect of the TLS scanner's operation is that the measurement of the distance to the reflection of the laser beam is not performed continuously while the scanner (and the mirror) rotates. A sampled measurement is performed with a shift by a constant angle, because the number of measurements during one revolution is finite and constant. Therefore, the density of samples read on a given surface of the object depends on the scanner's distance from this place and decreases with its square. Therefore, during scanning, it is necessary to select the distance and operating parameters of the scanner in such a way that the sampling density of a given surface of the object is sufficient to reproduce it in a satisfactory manner.

Another not insignificant factor is the vegetation: trees and bushes growing around the structure. Vegetation is a significant impediment to TLS scanning. In certain cases, it also prevents photographing the object. It is usually not possible to remove shrubs or trees before scanning the target.

The above discussion shows that optimal scanning of the external body of an object requires the possibility of establishing a set of TLS scanner positions such that for each external surface

[44] What is Lambert's Cosine Law? https://www.gophotonics.com/community/what-is-lambert-s-cosine-law

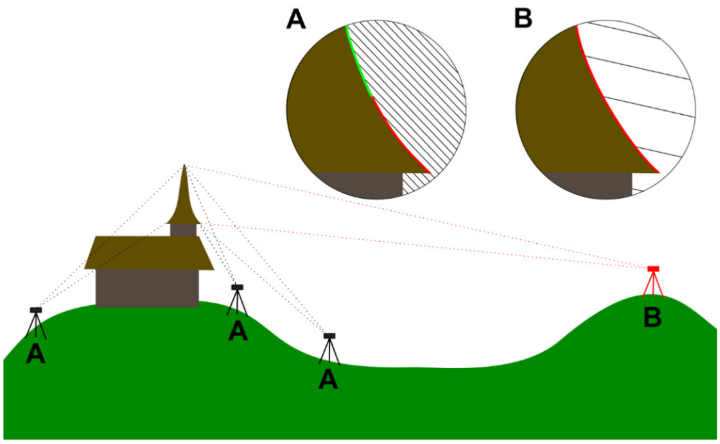


**Fig. 4:** *Illustration of the problems of scanning historic wooden churches in mountainous areas. A – scanner positions that are useful but do not provide visibility of the surface of higher parts of the object (marked in red) due to too sharp an angle of incidence of the laser beam. B – scanner positions unusable due to too great a distance or too low a density of scanning points.*

of the object there is a scanner position that ensures the appropriate distance and angle of incidence (preferably perpendicular to the scanned surface) of the laser beam.

In the case of the objects discussed, the possible area in which the scanner can be placed is often additionally limited due to the mountainous terrain. Using scaffolding or elevators to place the scanner close and high enough to obtain accurate scans of missing surfaces is a time-consuming, expensive and often impossible operation due to conditions specific to this type of building (lack of access, steep terrain, bodies of water, no permission to bring heavy equipment into the church cemetery, etc.).

The structure of the church itself does not allow the building itself to be used to place the scanner on a higher level. For example, attempts to use the tower would be very limited due to its small interior and the view being significantly obscured by structural elements. Nor would using this space make it possible to scan the roof, the area which commonly presents the most serious and numerous problems and deficiencies.

Possible countermeasures have been suggested:

1. Using unmanned laser scanning (ULS).
2. Using terrestrial short-range photogrammetry (TSRP).

The first method involves mounting a laser scanner on a drone that can move through the air around the scanned object. This would allow the scanner to be placed optimally in relation to the object. Despite the slightly lower accuracy compared to terrestrial options, it would still be sufficient to obtain a satisfactorily accurate representation of the shape of the surface of the scanned object.[45]

This proposal, however, has two significant drawbacks. The first is a significant increase in the cost of the scanning equipment. The second, much more important one is the existence of

[45] RIEGL Laser Measurement Systems GmbH. Unmanned Laser Scanning, http://www.riegl.com/products/unmanned-scanning/; Leica Geosystems. Leica BLK2FLY Autonomous Flying Laser Scanner, https://leica-geosystems.com/en-gb/products/laser-scanners/autonomous-reality-capture/blk2fly

regulations prohibiting the use of UAVs without time-consuming procurement of appropriate permits.

The second method is based on filling in the gaps left using the TSRP method, which reproduces the shape of a 3D surface based on a series of 2D photos. The accuracy of this method depends on the cameras used and the method and number of source photos. However, it does obtain a satisfactory level of detail of the surface's appearance. The main disadvantage of photogrammetry – a lack of knowledge of the scale (i.e., the size) of the obtained model – is in this case eliminated by matching it to the scale of the model created from TLS scans.

UAVs are also used in photogrammetry, but their use was rejected due to legal restrictions. In this case, however, it is possible to use other solutions that do not require the use of heavy equipment or scaffolding.

Carrying out a TLS measurement requires maintaining a stable position throughout a measurement period ranging from a few to several dozen minutes. If it is necessary to lift the scanner one must build a stable base (Figure 5A). Taking a photo takes a fraction of a second and the camera weighs no more than 1 kg. It is therefore possible to use simple hand-held booms (monopods) to place the camera in a position that ensures proper coverage of a surface not visible from the ground (Figure 5B).

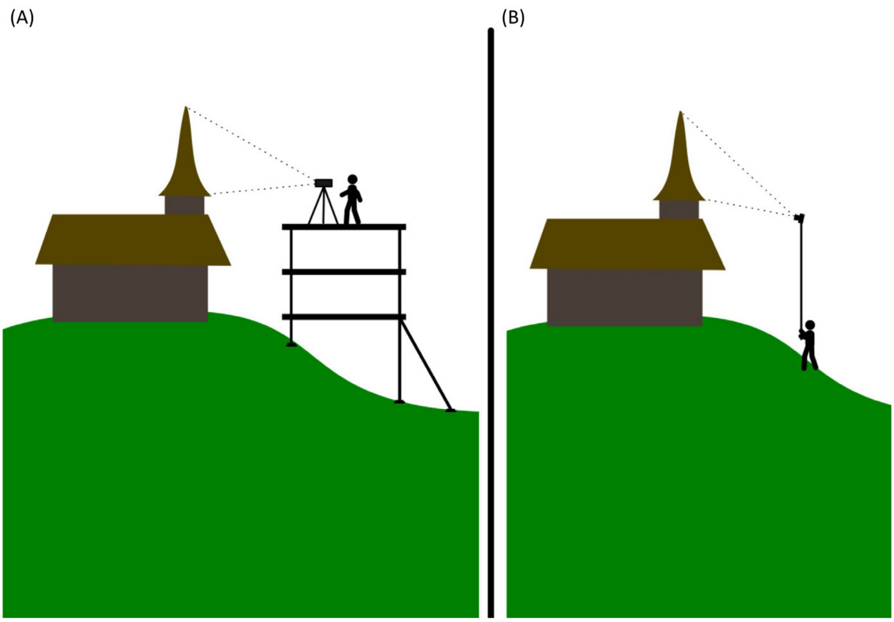


**Fig. 5:** *Illustration of how to place the recording device at the required height. A – in the case of a TLS scanner; B – in the case of taking photos for photogrammetry.*

Additionally, classic photos used in photogrammetry technology are based on ambient light reaching the lens. Depending on the settings, it is possible to record surfaces that cannot be recorded by a TLS scanner placed in the same position due to the inclination of the slope and/or low albedo. As a result, even photos taken from ground level should make it possible to at least partially fill in the gaps.

In summary, the use of TLS scanning using only basic tripods and photogrammetry based on photos taken using simple methods (manual, tripod, monopod, zoom from a hill) should be sufficient to obtain a representation of the external shape of the object with a satisfactory level of detail.

### 3.3. Methods

In order to meet the requirements of scanning in difficult terrain, presented in the previous chapters, it was decided to develop an original methodology of organisation, scanning and post-processing as well as dissemination of results. The methodology defines, among other things, a workflow for 3D scanning of historical wooden churches (Figure 6). It draws upon experiences the author team gained during previous digitisation works in Asia and Europe.[46] Due to the challenges of conducting fieldwork in the chosen terrain, emphasis was placed on the simplicity and self-sufficiency of digitisation tools. This led to the development of a methodology with a wide range of applications and a low cost that nevertheless obtained results of the requisite quality.

Due to the complexity of the problem, the methodology (Figure 6) was implemented in three parts: preliminary planning activities (at home), acquisition and initial validation of 3D data (in situ) and post-processing of the collected data (at home).

The first part of the methodology involves preliminary planning activities ("Initial planning" activity) related to the selection of objects for 3D scanning and the dates on which the scanning process can take place. It also takes into account the specific features of the area, the local climatic conditions, time of year (e.g., lack of leaves on trees and bushes), and organisational and legal issues related to access to the facility, as well as the selection of appropriate equipment. Documentation relating to the facility is collected, including historical documentation. The result is a plan for a scientific expedition.

The next part of the methodology is carried out in the field in the vicinity of the scanned object. During the "In situ planning" activity, the fieldwork plan is adapted to the conditions on the ground. It is determined which elements (areas, parts) of the object will be scanned using which specific techniques. The initial positions of the equipment, its settings, the number of repetitions, and areas of the facility requiring special attention are determined. Problematic scanning steps, as well as likely countermeasures, are identified. Again, the result is a modified in-situ activity plan.

After completing the "In situ planning" activity, digitisation activities begin. They are implemented in parallel and carried out such that they do not interfere with each other. They are also repeated many times until the assumed requirements are met, that is, when it can be concluded that sufficient data has been collected to satisfactorily reproduce the object in 3D space.

The "TLS scanning" activity involves using a scanner based on laser light to obtain a coloured cloud of points in 3D space. This map is usually saved in the proprietary format of the company that made the 3D scanner. This means that the initial verification of the quality and completeness of the scan ("Initial verification") is performed using proprietary software dedicated to the scanner used.

At the same time, photos of the object are taken for 3D scanning ("Taking photos" activity). Areas designated during the "In situ planning" activity are photographed, with emphasis on

[46] MIŁOSZ et al., 3D scanning …; KĘSIK et al., A methodical approach ….

areas of the object that were problematic for the 3D scanner. Thanks to this, areas of the 3D model of the object that were not possible to be acquire correctly with a 3D scanner can be supplemented by elements of the 3D model obtained using photogrammetry. The photos are saved in RAW or JPG format.

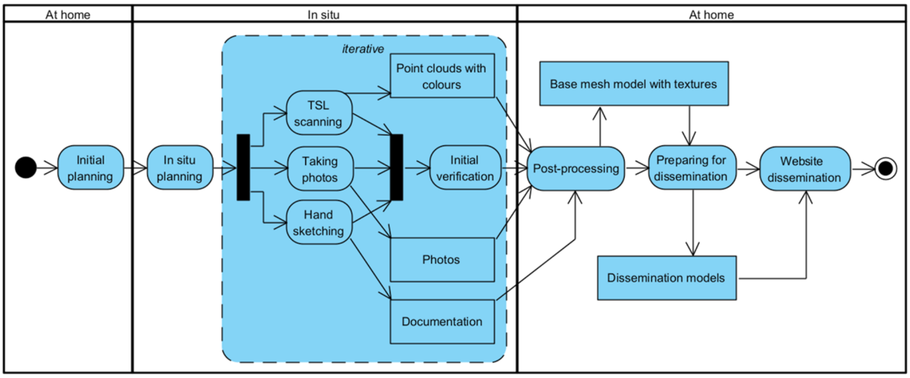


**Fig. 6:** *Workflow for 3D scanning of historical wooden churches.*

As part of the “Hand sketching” activity, documentation is created including a diagram of the entire object, as well as individual diagrams of important selected areas. The diagrams include information about the actual positions of the equipment and its specific settings. This documentation can be additionally supplemented by in situ historical and architectural data about the facility.

The aim of the “Initial verification” activity is to verify the currently held data in terms of quality and completeness. As a result, it may lead to a decision to rescan or photograph certain areas of the object that were not scanned well enough.

Data collected during fieldwork are then post-processed (“Post-processing” activity). This is a time-consuming activity and requires efficient computer equipment, so it is not carried out in the field. Post-processing begins with cleaning and aligning the cloud points acquired through TLS scanning. This phase is performed using the scanner’s dedicated software, which may have certain limitations. Therefore, it is recommended to use the program Reality Capture, to which point clouds can be imported, for example, in PTX format. The photos are then imported and matched to the imported point clouds. The next step is to select photos that can be used to recreate the areas of the scan that are missing or of poor quality. Then a base mesh model is generated. It is covered with textures based on selected photos and colour information about individual points recorded by the 3D scanner. As a result of post-processing, a base mesh model with textures is created that is characterised by high accuracy of object mapping, but also has a large file size. Such models can be saved in OBJ or GLB format.

In order to disseminate the obtained base mesh model, it must be adapted to the specificity of the end devices that will be used to present it. Typically, these devices (e.g. VR headsets) are unable to efficiently process such a model. Therefore, the “Preparing for dissemination” activity involves producing simplified 3D models (dissemination models) and tailoring them to the capacity of end devices. These models require re-texturing, after which they can be saved in OBJ or GLB format.

The “Website dissemination” activity involves placing a dissemination model on a website. As a result, users can interact with the model (cultural heritage) without needing to install specialised software. Another advantage is that this enables use of highly effective content dissemination techniques typical of the Internet, such as social media.[47]

### 3.4. Hardware and software

A FARO Focus S 350 scanner and a NIKON D5300 digital SLR camera were used for data acquisition (Table 1). All computations were performed on the laptop computer equipped with an Intel i9 processor (8 cores), 64 GB RAM, nVidia RTX 2080m graphics, and SSD M2 disk drive, Windows 11 operating system. 3D data were processed in SCENE and Reality Capture software (Table 2).

**Tab. 1:** *Data acquisition equipment used in the digitisation process*

| **Hardware** | TLS 3D scanner | Digital SLR camera |
|---|---|---|
| **Model** | Faro Focus S 350 | Nikon D5300 |
| **Main parameters** | • Range 0.6 – 330.0 m<br>• Distance measurement error ±1 mm<br>• 70 Mpix colour photo module with automatic brightness adjustment<br>• 305° vertical and 360° horizontal field of view<br>• Class I laser with a wavelength of 1.550 nm | • Nikkor lens with a focal length of 18–140 mm<br>• Nikkor lens with a focus length of 70–300 mm<br>• Matrix CMOS 24 Mpix APS-C<br>• Max resolution 6,000 x 4,000 |
| **Main settings** | • Point resolution 10240 pts/360°<br>• Noise reduction 4x<br>• Colour: even weighted HDR | • exposure time: 1/320–1/4000 s<br>• focal length: 18–155 mm<br>• maximum relative aperture: 7.1–9.0 |
| **Procedure notes** | • Scans taken from a tripod from various distances and angles<br>• Coverage of adjacent scans at least 40% | • Photos taken without a tripod from various distances and angles<br>• Both lenses have the option to turn on vibration compensation<br>• Coverage of adjacent photos at least 60% |

**Tab. 2:** *Software used in the digitisation process*

| **Program name** | Faro SCENE v. 2019 | Reality Capture 1.3 |
|---|---|---|
| **Purpose of the program** | Point cloud alignment and export | Overlaying photos on aligned point clouds<br>Generating a base mesh model<br>Generating dissemination models<br>Texturing 3D models |
| **Data formats used** | PTX – for storing the point cloud | OBJ, GLB – for storing the 3D model |

[47] PEI, Jin and YI, Liu. Fluid space: Digitisation of cultural heritage and its media dissemination. In: *Telematics and Informatics Reports*, 8, 2022, pp. 1–10.

# 4. Results

## 4.1. Obtained models

Figure 7 shows models of four wooden churches obtained in the post-processing process in accordance with the methodology set out in the previous section (Figure 6.).

Most of the models in Figure 7 are available in the form of dissemination models on the website http://carpatia3d.com.


**Fig. 7:** *Appearance of the obtained base mesh models with the texture of the studied churches: (A) Saint Archangels Michael and Gabriel in the village of Păniceni, (B) Saint Nicholas in Creaca, (C) Saint Archangels Michael and Gabriel in the village of Târgușor, (D) Saint Nicholas in the village of Păusa.*

## 4.2. Analysis of the scanning results of the historical wooden church in Creaca

A wooden historic church from Creaca is presented as an example of scanning, post-processing and its results. The parameters of the data obtained during in situ scanning are presented in Table 3.

**Tab. 3:** *Parameters of the obtained and processed church data in Creaca.*

| | Unit | Quantity |
|---|---|---|
| Number of TLS scans | – | 13 |
| TLS scan resolution | pts/360° | 10,240 |
| Raw data size (scans) | GB | 3.95 |
| Number of photos taken: | – | 147 |
| Photo format | – | JPG |
| Photo resolution | px | 6000 x 4000 |
| Size of raw data (images) | GB | 0.98 |
| Number of photos used | – | 141 |
| Resulting point cloud (TLS) | Million pts | 155.7 |
| Base mesh model (TLS + Photogrammetry) | Million triangles | 39.9 |

The location of the scanner placement points in the field during the digitisation of the church in Creaca is shown in Figure 8A. The church was scanned from 13 possible positions. The scanning was complemented by 141 photos of the object taken both from close up and from accessible hills (Figure 8B).

(A) (B)

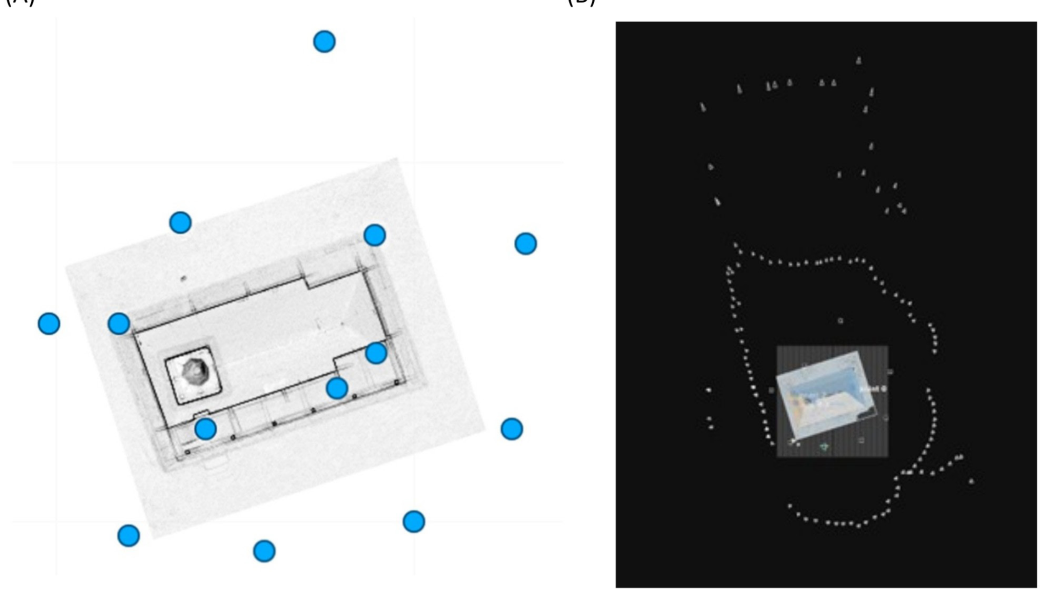

**Fig. 8:** *TLS scanning points of the church in Creaca (A) and places where photos of the object were taken (B).*

In the process of registering and combining the TLS scans, an integrated point cloud of the scanned object was obtained. It shows deficiencies in the roof covering resulting from the limitations of TLS scanning mentioned in section 3.2. Figure 9 shows areas of the cloud containing discontinuities (A) and the resulting distortions of the triangle mesh generated (in Reality Capture 1.3 software) (B).

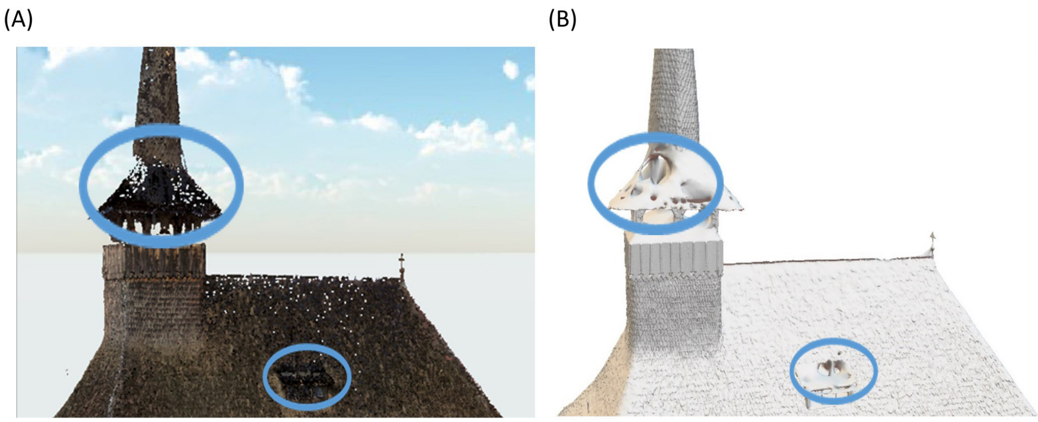


**Fig. 9:** *Cloud of coloured points (A) and mesh model (B) of the church in Creaca developed using TLS data.*

Using photos to build a mesh model makes it more accurate. Due to the fact that, as seen in Figure 10A, the point cloud obtained using TLS had quite large areas without points (so-called "holes", marked with ovals), the generated mesh model in this area was highly inaccurate – resulting in the very large triangles visible in Figure 10B. After incorporating the photos and combining them with the TLS data, these areas were generated much more accurately, as seen in Figure 10C.

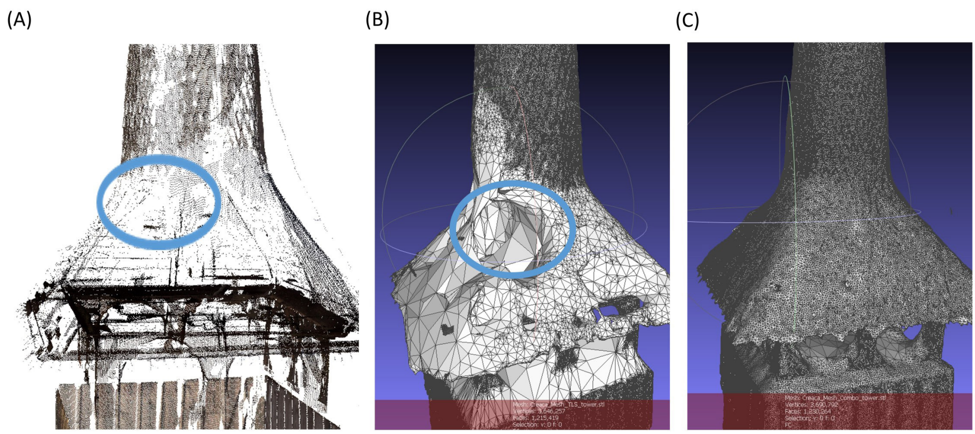


**Fig. 10:** *Results of completing the mesh model using photogrammetry. A – approximation of the turret: cloud of coloured points obtained from TSL, B – mesh model from TSL data, C – mesh model obtained by the described method with TLS and photogrammetry data. Areas with large missing points and model inaccuracies are indicated with ellipses.*

## 5. Discussion

3D digitisation of wooden religious monuments is rarely undertaken by scientific communities due to the fact that they tend to occur across a limited geographical region (for example, in the Carpathian Region) and the practical difficulties of accessing them. Therefore, developing a methodology that is effective in typical mountainous field situations is very important. Previous publications have not dealt with this issue.

Generating 3D mesh models of scanned Orthodox churches using only TLS data obtained from the ground level does not guarantee a sufficiently good quality model due to limited access to the object and its specific geometry. The digital model presented by Wierzejska and Markowski (2020)[48] was a cloud model which to some extent masks the deficiencies in the information obtained about the scanned surfaces.

Supplementing the TLS data with a set of photos of the scanned object and introducing a hybrid approach to generating a 3D mesh model of the church‘s body which enhanced data from the 3D scans with data from the photographs allowed us to create a 3D model with the characteristics of a realistic model. Therefore, we can state that the effectiveness of this approach, which has already been confirmed for stone architectural objects,[49] is also satisfactory in the case of wooden objects discussed in this article.

## 6. Conclusion

This article presents a methodology for data acquisition activities to generate digital 3D models of wooden architectural heritage using a TLS scanner and TSRP with a SLR camera equipped with two lenses with variable focal lengths. The results allow us to formulate several conclusions.

(i) Data acquisition using the TLS method, using appropriate process parameters, can be used for effective 3D scanning of a wooden structure, such as an Orthodox church, capturing complex architectural structures such as steep roofs of various heights, soaring, slender towers with chambers, and arcades with supports in the form of columns.

(ii) Due to the difficulty involved in accessing objects located in hard-to-reach mountainous regions, it is important to select 3D digitisation parameters in such a way that the required number of scans (usually 2–3 dozen) can be performed within a few hours and in situations where natural lighting is appropriate.

(iii) Photographic documentation using two lenses with different focal ranges enables capture of many additional photos from different perspectives and distances from the object, which can be used to complement the scan data and map textures onto the model. This choice of equipment partly contradicts the commonly held views that a lens with a fixed focal length should be used for photogrammetry, and that photos should be taken at one focal length when using lenses with a zoom function.

(iv) Reality Capture software (version 1.3) is a highly effective tool for building models that combine data from TSL and photographic images. Modern software facilitates the synthesis of data from TSL and photogrammetry.

(v) The 3D mesh models generated by our methodology provide a basis for preparing dissemination versions of the models that can be printed on 3D replicators. This means they

[48] WIERZEJSKA, Anna and MARKOWSKI, Wojciech. Laser scanning …, 2020, pp. 141–159.

[49] TYSIAC, Paweł et al. Combination of terrestrial laser scanning …, 2023, pp. 1–14; MAŁYSZEK, Hubert Aleksander et al. The case study of using photogrammetric ..., 2023, pp. 345–357.

can be made available in the form of scaled copies, which could be of benefit to people with visual impairments, among others.

## References


ARMSTRONG, Brian J., BLACKWOOD, Alex F., PENZO-KAJEWSKI, Paul, MENTER, Colin G., HERRIES, Andy I. R. (2018). Terrestrial laser scanning and photogrammetry techniques for documenting fossil-bearing palaeokarst with an example from the Drimolen Palaeocave System, South Africa. In: *Archaeological Prospection*, 25(1), pp. 45–58. ISSN 1075-2196. DOI 10.1002/arp.1580

BARBIERI, Loris, BRUNO, Fabio, MUZZUPAPPA, Maurizio (2017). Virtual museum system evaluation through user studies. In: *Journal of Cultural Heritage*, 26, pp. 101–108. ISSN 1296-2074. DOI 10.1016/j.culher.2017.02.005

BARSZCZ, Marcin, DZIEDZIC, Krzysztof, SKUBLEWSKA-PASZKOWSKA, Maria, POWROŹNIK, Paweł (2023). 3D scanning digital models for virtual museums. In: *Computer Animation and Virtual Worlds*, 34, pp. 1–12. ISSN 1546-4261. DOI 10.22541/au.168279666.61146873/v1

BASTONERO, P., DONADIO, E., CHIABRANDO, F., SPANÒ, A. (2014). Fusion of 3D models derived from TLS and image-based techniques for CH enhanced documentation. In: *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2(5), pp. 73–80. DOI 10.5194/isprsannals-II-5-73-2014

BEDNARZ, Łukasz, OPALKA, Piotr, GÓRSKI, Artur, WOJCIECHOWSKA, Gabriela (2019). Analysis of the condition of damaged vaults after a construction disaster in a historic church. In: *Key Engineering Materials*, 817, pp. 613–620. ISSN 1662-9795. DOI 10.4028/www.scientific.net/KEM.817.613

BRUNO, Fabio, BRUNO, Stefano, DE SENSI, Giovanna, LUCHI, Maria-Laura, MANCUSO, Stefania, MUZZUPAPPA, Maurizio (2010). From 3D reconstruction to virtual reality: A complete methodology for digital archaeological exhibition. In: *Journal of Cultural Heritage*, 11, pp. 42–49. ISSN 1296-2074. DOI 10.1016/j.culher.2009.02.006

BRYKOWSKI, Ryszard (1995). *Drewniana architektura cerkiewna na koronnych ziemiach Rzeczypospolitej*. Towarzystwo Opieki nad Zabytkami. ISBN 8390279371.

BRYKOWSKI, Ryszard (1986). *Łemkowska drewniana architektura cerkiewna w Polsce na Słowacji i Rusi Zakarpackiej*. Wrocław: Ossolineum. ISBN 8304019892.

BUXTON, David (2008). *Wooden churches of Eastern Europe. An introductory survey.* Cambridge University Press. ISBN 0521090547.

CACIORA, Tudor, HERMAN, Grigore Vasile, ILIEȘ, Alexandru, BAIAS, Ștefan, ILIEȘ, Dorina Camelia, JOSAN, Ioana, HODOR, Nicolaie (2021). The use of virtual reality to promote sustainable tourism: A case study of wooden churches historical monuments from Romania. In: *Remote Sensing*, 13(9), pp. 1–22. ISSN 2072-4292. DOI 10.3390/rs13091758

CACIORA, Tudor, JUBRAN, Ahmad, ILIES, Dorina Camelia, HODOR, Nicolaie, BLAGA, Lucian, ILIES, Alexandru, GRAMA, Vasile, SEBESAN, Bogdan, SAFAROV, Bahodirhon, ILIES, Gabriela, HASSAN, Thowayeb H., HERMAN, Grigore Vasile (2023). Digitization of the built cultural heritage: An integrated methodology for preservation and accessibilization of an art nouveau museum. In: *Remote Sensing*, 15, pp. 1–25. ISSN 1947-9832. DOI 10.3390/rs15245763

CALVO-SERRANO, María Araceli, ORTIZ-CORDERO, Rafael, HIDALGO-FERNANDEZ, Rafael E., MESAS-CARRASCOSA, Francisco Javier, DE PAULA MONTES-TUBÍO, Francisco, TRIVIÑO-TARRADAS, Paula (2022). Historical-graphical analysis and digital preservation of cultural heritage: Case study of the baptismal font of the church of Santiago Apóstol in Montilla (Córdoba, Spain). In: *Heritage Science*, 10(149), pp. 1–14. ISSN 2050-7445. DOI 10.1186/s40494-022-00782-7

CÎMPIAN, Felicia Elena (2002). *Bisericile de lemn din zonele Călatei, Gilăului, Hășdatelor* și *Clujului. Aspecte istorico-etnografice* și *arhitectură tradițională.* Cluj Napoca: Risoprint. ISBN 973-656-219-0.

CRISTACHE-PANAIT, Ioana (1971). Bisericile de lemn din Sălaj. In: *Buletinul Monumentelor Istorice*, 1, pp. 31–40.

DONG, Qianli, ZHANG, Qingping, ZHU, Lingxi (2020). 3D scanning, modeling, and printing of Chinese classical garden rockeries: Zhanyuan's south rockery. In: *Heritage Science*, 8(1), pp. 1–15. ISSN 2050-7445. DOI 10.1186/s40494-020-00405-z

EL-GAMAL, Rehab, NIKOLAIVITS, Efstratios, ZERVAKIS, Georgios I., ABDEL-MAKSOUD, Gomaa, TOPAKAS, Evangelos, CHRISTAKOPOULOS, Paul (2016). The use of chitosan in protecting wooden artifacts from damage by mold fungi. In: *Electronic Journal of Biotechnology*, 24, pp. 70–78. ISSN 0717-3458. DOI 10.1016/j.ejbt.2016.10.006

FRANKL, Jiri (2015). Wood-damaging fungi in truss structures of baroque churches. In: *Journal of Performance of Constructed Facilities*, 29(5), pp. 1–5. ISSN 0887-3828. DOI 10.1061/(ASCE)CF.1943-5509.0000632

GHERARDINI, Francesco, SIROCCHI, Simone (2022). Systematic integration of 2D and 3D sources for the virtual reconstruction of lost heritage artefacts: The equestrian monument of Francesco III d'Este (1774–1796, Modena, Italy). In: *Heritage Science*, 10(96), pp. 1–19. ISSN 2050-7445. DOI 10.1186/s40494-022-00711-8

GODEA, Ioan (1996). *Biserici de lemn din România (nord-vestul Transilvaniei)*. București: Editura Meridiane. ISBN 9733303151.

HERMAN, Grigore Vasile, CACIORA, Tudor, ILIES, Dorina Camelia, ILIES, A., DEAC, Anca, STURZA, Amalia, SONKO, S.M., SUBA, N.S., NISTOR, S. (2020). 3D modeling of the cultural heritage: Between opportunity and necessity. In: *Journal of Applied Engineering Sciences*, 10(23), pp. 27–30. ISSN 2247-3769. DOI 10.2478/jaes-2020-0005

HEVKO, Ihor, POTAPCHUK, Olha, LUTSYK, Iryna, YAVORSKA, Viktorya, TKACHUK, Viktoriia (2020). Methods building and printing 3D models historical architectural objects. In: *SHS Web of Conferences*, 75, p. 1–6. ISSN 2261-2424. DOI 10.1051/shsconf/20207504016

HORST, Michael, CLEMONS, Benjamin (2015). Evaluation and repair of tornado damage to a historic church. In: *Forensic Engineering: Performance of the Built Environment – Proceedings of the 7th Congress on Forensic Engineering*, pp. 387–397. ISBN 978-1-5108-2390-7.

KĘSIK, Jacek, ŻYŁA, Kamil, MONTUSIEWICZ, Jerzy, MIŁOSZ, Marek, NEAMTU, Calin, JUSZCZYK, Marta (2023). A methodical approach to 3D scanning of heritage objects being under continuous display. In: *Applied Sciences*, 13(1), pp. 1–20. ISSN 2076-3417. DOI 10.3390/app13010441

KIM, S. H., JO, Y. H., SONG, J., KIM, D. S., KIM, H. S. (2023). A study on convergence modeling of cultural artifact using x-ray computed tomography and three-dimensional scanning technologies. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 48(2), pp. 851–856. DOI 10.5194/isprs-archives-XLVIII-M-2-2023-851-2023

KLOIBER, Michal, REINPRECHT, Ladislav, HRIVNÁK, Jaroslav, TIPPNER, Jan (2016). Comparative evaluation of acoustic techniques for detection of damages in historical wood. In: *Journal of Cultural Heritage*, 20, pp. 622–631. ISSN 1296-2074. DOI 10.1016/j.culher.2016.02.009

KOVAČOVIČOVÁ-PUŠKAROVÁ, Blanka, PUŠKAR, Imrich (1971). *Derev'jani cerkvi*. Bratislava: Muzeum ukrajinskiej kultury vo Svidniku, Slovenske Pedagogicke Nakladatelstvo.

LAMBERS, Karsten, EISENBEISS, Henri, SAUERBIER, Martin, KUPFERSCHMIDT, Denise, GAISECKER, Thomas, SOTOODEH, Soheil, HANUSCH, Thomas (2007). Combining photogrammetry and laser scanning for the recording and modelling of the late intermediate period site of Pinchango Alto, Palpa, Peru. In: *Journal of Archaeological Science*, 34(10), pp. 1702–1712. ISSN 0305-4403. DOI 10.1016/j.jas.2006.12.008

LAMBERT, Simon, ROCKWELL, Cynthia (eds.) (2012). *Protecting cultural heritage in times of conflict: Contributions from the participants of the International Course on First Aid to Cultural Heritage in Times of Conflict*. Italy, Roma: ICCROM (International Centre for the Study of the Preservation and Restoration of Cultural Property). ISBN 978-92-9077-233-0.

LEE, Woo-Hee, KIM, Cheolhong, KIM, Heejung, KIM, Hee-Soo, LIM, Chungwan (2021). Students' reactions to virtual geological field trip to Baengnyeong Island, South Korea. In: *ISPRS International Journal of Geo-Information*, 10, pp. 1–13. ISSN 2220-9964. DOI 10.3390/ijgi10120799

LIÑÁN, Carmen Rodríguez, MORALES CONDE, María Jesús, DE HITA, Paloma Rubio, GÁLVEZ, Filomena Pérez (2014). Application of non-destructive techniques in the inspection of wooden structures of protected buildings: The case of Nuestra Señora de los Dolores Church (Isla Cristina, Huelva). In: *International Journal of Architectural Heritage*, 9(3), pp. 324–340. ISSN 1558-3058. DOI 10.1080/15583058.2013.771292

LIPECKI, Tomasz (2022). Non-contact diagnostics of the geometry of a historic wooden building as an element of periodic safety assessment. In: *Sensors*, 22(4), pp. 1–23. ISSN 1424-8220. DOI 10.3390/s22041301

MAŁYSZEK, Hubert Aleksander, STACHULA, Seweryn, KĘPOWICZ, Barbara (2023). The case study of using photogrammetric systems and laser scanning for three-dimensional modeling of cultural heritage sites. In: *Advances in Science and Technology Research Journal*, 17(6), pp. 345–357. ISSN 2299-8624. DOI 10.12913/22998624/174063

MATTES, Julia (2011). *Die nordischen Stabkirchen*. AV Akademikerverlag. ISBN 9783639384826.

MERELLA, Marco, FARINA, Simone, SCAGLIA, Patrizia, CANEVE, Gaia, BERNARDINI, Giada, PIERI, Alice, COLLARETA, Alberto, BIANUCCI, Giovanni (2023). Structured-light 3D scanning as a tool for creating a digital collection of modern and fossil cetacean skeletons (Natural History Museum, University of Pisa). In: *Heritage*, 6, pp. 6762–6776. ISSN 2571-9408. DOI 10.3390/heritage6100353

MIŁOSZ, Marek, KĘSIK, Jacek, MONTUSIEWICZ, Jerzy (2021). 3D scanning and visualization of large monuments of Timurid architecture in Central Asia - A methodical approach. In: *Journal on Computing and Cultural Heritage*, 14(1), pp. 1–31. ISSN 1556-4673. DOI 10.1145/3425796

MONTUSIEWICZ, Jerzy, MIŁOSZ, Marek (2021). Architectural Jewels of Lublin: A modern computerized board game in cultural heritage education. In: *Journal on Computing and Cultural Heritage*, 14(3), pp. 1–21. ISSN 1556-4673. DOI 10.1145/3446978

MOSOARCA, Marius, GIONCU, Victor (2013). Historical wooden churches from Banat Region, Romania. Damages: Modern consolidation solutions. In*: Journal of Cultural Heritage*, 14, pp. 45–59. ISSN 1296-2074. DOI 10.1016/j.culher.2012.11.020

MOUADDIB, El Mustapha, PAMART, Anthony, PIERROT-DESEILLIGNY, Marc, GIRARDEAU-MONTAUT, Daniel (2024). 2D/3D data fusion for the comparative analysis of the vaults of Notre-Dame de Paris before and after the fire. In: *Journal of Cultural Heritage*, 65, pp. 221–231. ISSN 1296-2074. DOI 10.1016/j.culher.2023.06.012

MOUSSA, Wassim (2014). *Integration of digital photogrammetry and terrestrial laser scanning for cultural heritage data recording*. Doctoral dissertation, University of Stuttgart, Stuttgart, Germany. http://dx.doi.org/10.18419/opus-3943

NEAMTU, Calin, BRATU, Ioan, MĂRUȚOIU, Constantin, MĂRUȚOIU, Victor Constantin, NEMEȘ, Olivia Florena, COMES, Radu, BODI, Ștefan, BUNA, Zsolt, POPESCU, Daniela (2021). Component materials, 3D digital restoration, and documentation of the imperial gates from the wooden church of Voivodeni, Sălaj County, Romania. In: *Applied Sciences*, 11(8), pp. 1–18. ISSN 2076-3417. DOI 10.3390/app11083422

NEAMTU, Calin, COMES, Radu, POPESCU, Daniela (2016). Methodology to create digital and virtual 3D artefacts in archaeology. In: *Journal of Ancient History and Archaeology*, 3, pp. 65–74. ISSN 2360-266X. DOI 10.14795/j.v3i4.206

OOSTWEGEL, Laurens Jozef Nicolaas, JAUD, Štefan, MUHIČ, Sergej, REBEC, Katja Malovrh (2022). Digitalization of culturally significant buildings: Ensuring high-quality data exchanges in the heritage domain using OpenBIM. In: *Heritage Science*, 10(10), pp. 1–14. ISSN 2050-7445. DOI 10.1186/s40494-021-00640-y

ORTIZ, P., SÁNCHEZ, H., PIRES, H., PÉREZ, J. A. (2006). Experiences about fusioning 3D digitalization techniques for cultural heritage documentation. In: *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences – ISPRS Archives*, 36, pp. 224–229.

PARSINEJAD, Hossein, CHOI, Insook, YARI, Mohammad (2021). Production of Iranian architectural assets for representation in museums: Theme of museum-based digital twin. In: *Body Space & Technology*, 20(1), pp. 61–74. ISSN 1470-9120. DOI 10.16995/bst.364

PASCU, Ştefan (1982). *Monumente Istorice* şi *de Arta Religioasa din Arhiepiscopia Vadului Feleacului* şi *Clujului*. Editata de Arhipiscopia Ortodoxă Română a Vadului, Feleacului şi Clujului, Cluj-Napoca.

PEI, Jin, YI, Liu (2022). Fluid space: Digitisation of cultural heritage and its media dissemination. In: *Telematics and Informatics Reports*, 8, pp. 1–10. ISSN 2772-5030. DOI 10.1016/j.teler.2022.100022

PEPE, Massimiliano, COSTANTINO, Domenica, ALFIO, Vincenzo Saverio, RESTUCCIA, Alfredo Garofalo, PAPALINO, Nicola Massimiliano (2021). Scan to BIM for the digital management and representation in 3D GIS environment of cultural heritage site. In: *Journal of Cultural Heritage*, 50, pp. 115–125. ISSN 1296-2074. DOI 10.1016/j.culher.2021.05.006

POUX, Florent, VALEMBOIS, Quentin, MATTES, Christian, KOBBELT, Leif, BILLEN, Roland (2020). Initial user-centered design of a virtual reality heritage system: Applications for digital tourism. In: *Remote Sensing*, 12(16), pp. 1–32. ISSN 2072-4292. DOI 10.3390/rs12162583

RUIZ, Rafael Melendreras, TORRES, Ma Teresa Marín, ALLEGUE, Paloma Sánchez (2021). Comparative analysis between the main 3D scanning techniques: photogrammetry, terrestrial laser scanner, and structured light scanner in religious imagery: The case of The Holy Christ of the Blood. In: *ACM Journal on Computing and Cultural Heritage*, 15(1), pp. 1–23. ISSN 1556-4673. DOI 10.1145/3469126

SILVA, Pinto da Fábio (2011). *Usinagem de espumas de poliuretano e digitalização tridimensional para fabricação de assentos personalizados para pessoas com deficiência.* Porto Alegre: Tese Doutorado – Curso de Engenharia, Minas, Metalúrgica e Materiais, Universidade Federal do Rio Grande do Sul, Porto Alegre.

SURYANI, Mira, RUSIDIAWAN, Rispansah Sakti, ROSADI, Rudi (2022). Development of historical learning media based on virtual reality of The National Awakening Museum. In: *Jurnal Ilmiah Bidang Teknologi Informasi dan Komunikasi*, 7(2), pp. 125–131. ISSN 2502-3470. DOI 10.25139/inform.v7i2.4709

TYSIAC, Paweł, SIEŃSKA, Anna, TARNOWSKA, Marta, KEDZIORSKI, Piotr, JAGODA, Marcin (2023). Combination of terrestrial laser scanning and UAV photogrammetry for 3D modelling and degradation assessment of heritage building based on a lighting analysis: Case study—St. Adalbert Church in Gdansk, Poland. In: *Heritage Science*, 11(53), pp. 1–14. ISSN 2050-7445. DOI 10.1186/s40494-023-00897-5

VERNIZZI, C., GHIRETTI, A. (2009). Methodologies capture three-dimensional high-definition of sixteenth wooden frames. The case of works by Correggio. In: *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences – ISPRS Archives*, 38, pp. 1–8.

VLAHOULIS, Themistoklis, OIKONOMOPOULOU, Apostolia, SALEMI, Niki, GIARLELI, Mariliza (2019). Post-seismic restoration project of basilica churches in Kefallonia Island. In: *Transdisciplinary Multispectral Modeling and Cooperation for the Preservation of Cultural Heritage,* pp. 131–142. ISBN 978-3-030-12959-0. DOI 10.1007/978-3-030-12960-6_9

WIERZEJSKA, Anna, MARKOWSKI, Wojciech (2020). Laser scanning of the wooden church of the Assumption of the Blessed Virgin Mary and St Michael the Archangel in Haczów, Poland. In: *Protection of Culture Heritage*, 9, pp. 141–159. ISSN 2543-6422. DOI 10.35784/odk.1441

WU, Bo, TANG, Shengjun (2015). Review of geometric fusion of remote sensing imagery and laser scanning data. In: *International Journal of Image and Data Fusion*, 6(2), pp. 97–114. ISSN 1947-9832. DOI 10.1080/19479832.2015.1024175

ŻYŁA, Kamil, MONTUSIEWICZ, Jerzy, SKULIMOWSKI, Stanisław, KAYUMOV, Rahim (2020). VR technologies as an extension to the museum exhibition: A case study of the Silk Road museums in Samarkand. In: *Muzeologia a Kulturne Dedicstvo*, 8(4), pp. 73–93. ISSN 1339-2204. DOI 10.46284/mkd.2020.8.4.6

## Internet sources

3D Digital Silk Road portal, accessed 5 February 2024, https://silkroad3d.com

Komańcza – Cerkiew Opieki Matki Boskiej – Świątynia 3D, accessed 5 February 2024, https://swiatynia3d.pl/project/komancza-cerkiew/

Leica Geosystems. Leica BLK2FLY Autonomous Flying Laser Scanner, accessed 5 February 2024, https://leica-geosystems.com/en-gb/products/laser-scanners/autonomous-reality-capture/blk2fly

Medieval Heritage, Libusza – Church of the Nativity of the Blessed Virgin Mary, accessed 5 February 2024, https://medievalheritage.eu/en/main-page/heritage/poland/libusza-church-of-the-nativity/

MEDIUM, How 3D Scanning helps to preserve historical buildings, accessed 5 February 2024, https://medium.com/imerso/how-3d-scanning-can-help-to-preserve-historical-buildings-7c8515904b4a

Ministerul Culturii, Lista monumentelor istorice, accessed 5 February 2024, http://www.cultura.ro/lista-monumentelor-istorice

RIEGL Laser Measurement Systems GmbH. Unmanned Laser Scanning, accessed 5 February 2024, http://www.riegl.com/products/unmanned-scanning/

TRUDYMASON, The largest wooden church in Europe and Książ Castle, Poland, accessed 5 February 2024, https://trudymason.com/2019/09/07/the-largest-wooden-church-in-europe-and-ksiaz-castle-poland/

UNESCO, Wooden Churches of the Slovak part of the Carpathian Mountain Area, accessed 5 February 2024, https://whc.unesco.org/ru/list/1273

What is Lambert's Cosine Law?, accessed 5 February 2024, https://www.gophotonics.com/community/what-is-lambert-s-cosine-law

Wooden monuments of the Carpathians in 3D, accessed 5 February 2024, https://carpatia3d.com/en/