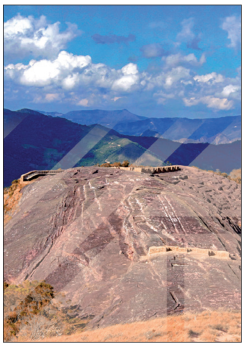

Architectus

2020
2(62)

DOI: 10.37190/arc200205

Jacek Kościuk*, Bartłomiej Ćmielewski, Małgorzata Telesińska***, Anna Kubicka******

3D terrestrial laser scanning of El Fuerte de Samaipata

Naziemne laserowe skanowanie 3D El Fuerte de Samaipata

Purpose of research

El Fuerte de Samaipata is a pre-Hispanic archaeological site on the eastern slopes of the Andes at an altitude of ca. 1890–1925 m. Due to its historical and cultural value, the site was placed on the UNESCO World Heritage List in 1998. The entire archaeological site covers about 40 hectares and consists of two main parts: an administrative and ceremonial complex in the southern part of the site, and a natural rock (ca. 80 × 250 m) in the northern part of the site. The rock was the main subject of the project "Architectural examination and complex documentation of Samaipata (Fuerte de Samaipata/Bolivia) site from the World Heritage List"[1]. The research presented here is part of this larger project.

Due to the rapid erosion of the rock, one of its main objectives of the project was to produce comprehensive documentation of the entire sacred rock with the highest possible degree of accuracy and detail.

The proper selection of technology, equipment, software, and workflow was fundamental to the success of the entire project. Due to the scale of the entire site (the Samaipata rock itself measures 80 × 240 m, while the entire site is ca. 400 × 500 m; Fig. 1) and the required data density (not worse than 3 × 3 mm on average), 3D TLS was the first choice of technology for the project, especially since by that time (2016), the 3D Scanning and Modeling Laboratory (LabScan3D), which was involved in the project, had already been familiar with this technology for over ten years [1]. In the last decade, TLS has become a widely used method in the documentation of architectural and archaeological monuments [2]–[4], generally favoured over traditional and other documentation methods [5], [6]. It has also been successfully used in projects similar to ours [7].

Method, equipment, software, and general workflow

TLS has been used extensively for heritage documentation in the last several years. This technique creates precise 2D documentation as well as a high-resolution and high-quality 3D models. The point clouds obtained are important data sources. Within a specific distance, TLS measures the 3D spatial information of the surroundings using a laser distance meter and a high resolution protractor for horizontal and vertical angles [8], [9]. This method can quickly acquire the geometry of a large area with an accuracy of millimetres since the quality and rate of data acquisition for TLS is very high. A similar use of TLS on large-scale stone engraved monument, was conducted in 2008 by a Chinese team [10] on the World Heritage Yungang Grottoes, which were seriously destroyed by wind erosion. Another example of a place where TLS was used is Çatalhöyük, a nine-thousand-year-old Neolithic city [11] where

* ORCID: 0000-0003-0623-8071. Faculty of Architecture, Wrocław University of Science and Technology, e-mail: jacek.kosciuk@pwr.edu.pl

** ORCID: 0000-0002-1035-3905. Faculty of Architecture, Wrocław University of Science and Technology.

*** ORCID: 0000-0002-1100-642X. Faculty of Architecture, Wrocław University of Science and Technology.

**** ORCID: 0000-0001-5442-3947. Faculty of Architecture, Wrocław University of Science and Technology.

[1] Cf. J. Kościuk, M. Ziółkowski, B. Ćmielewski, D. Ulloa Vidaurre, *Samaipata project – aim of the research, methodology, and methods of documentation*, in the same issue of "Architectus".

the state of its preservation was monitored during several surveying epochs. 3D scanning and modeling has also been used for the documentation, preservation, and restoration of other cultural heritage objects and historical sites [12]–[14]. TLS is even mentioned by UNESCO in their guidelines for World Heritage Sites management [15].

Fig. 1. The El Fuerte de Samaipata site on GoogleEarth ©. Satellite image taken on 05.03.2018 [accessed: 12.07.2019]

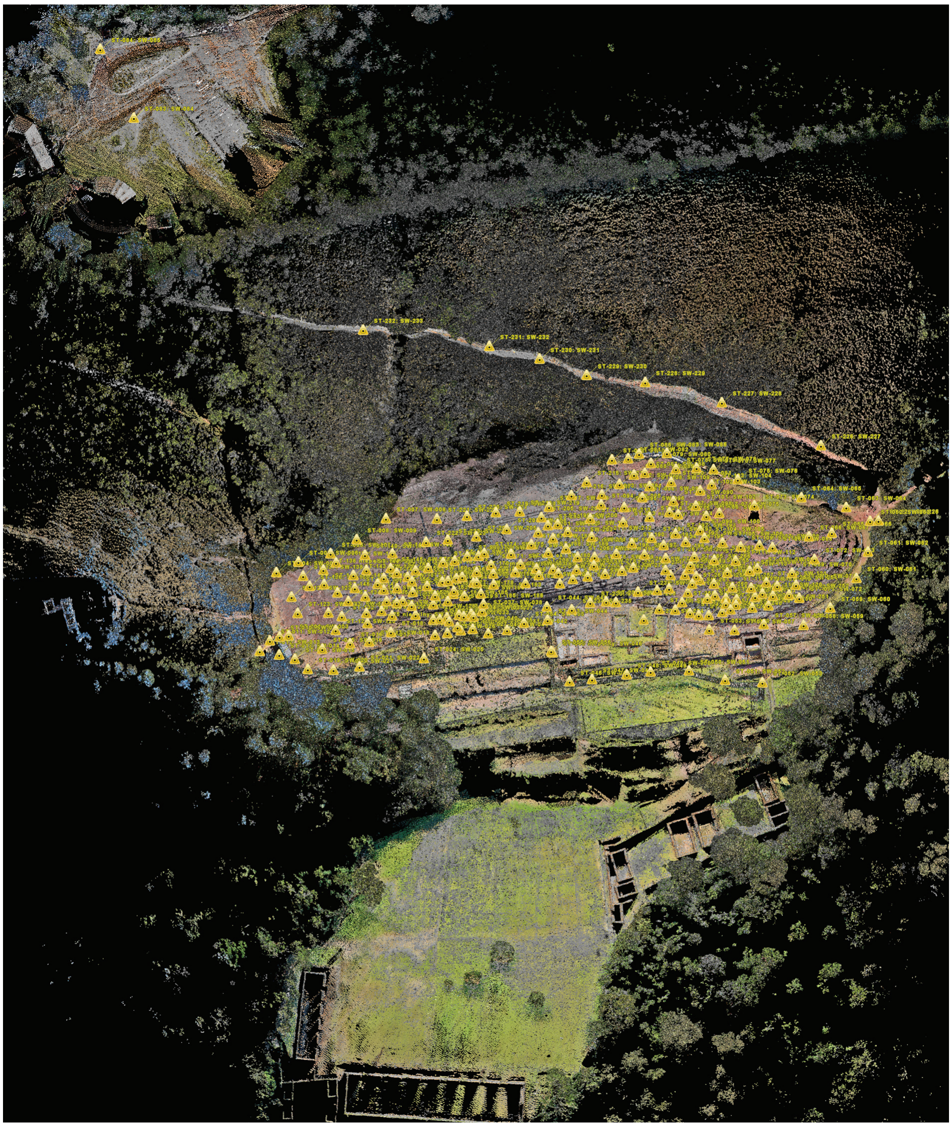

Fig. 2. Distribution of scanner stations for the TLS of El Fuerte de Samaipata (elaborated by J. Kościuk)

Fig. 3. Printed B & W target (photo by J. Kościuk)

Fig. 4. Leica HDS target on a tripod (photo by J. Kościuk)

A Leica ScanStation P40 scanner was used for this project. Its technical specification guaranteed one of the highest accuracies available in 2016 – a range accuracy of ±1.2 mm + 10 ppm over full 270 m range; 3D position accuracy of 3 mm at 50 m and 6 mm at 100 m; range noise of 0.4 mm RMS at 10 m and 0.5 mm RMS at 50 m, both at 78% albedo; and 2 mm standard deviation at 50 m. In total, 278 scanner stations were placed over the entire hill (Fig. 2). Each station covered a horizontal range of 360° with a resolution of 3 mm at 20 m. This assured proper overlapping of scans and appropriate density of recorded data.

Despite the technical characteristics, scanning the Samaipata rock was challenging as we could not fix any points directly onto the rock. This forced us to establish a network of fixed reference points in adjacent areas. Most of the points were attached to the platforms for visitors surrounding the rock. For this purpose, we used black and white (B & W) targets printed on a plastic, weather resistant material (Fig. 3).

Platforms for visitors, however, did not surround Samaipata rock from all sides, and in addition, the distance from the top of the hill to the nearest printed B & W target often exceeded 50 m, making their precise locations on the 3D scan unreliable. Six small tripods ordered from a local blacksmith solved the problem (Fig. 4). Leica HDS targets were placed on the tripods and moved alongside subsequent scanner stations.

The targets were used to tie individual scanner positions together in a local coordinate system. As far as possible, the principle was that from each scanner position, a minimum of two Leica HDS targets and two printed B & W targets should be visible. Considering that thanks to the dual-axis compensator the scanner was always aligned vertically, this guaranteed sufficient data redundancy for each scanner station and allowed errors in referencing each of the targets to be calculated. In total, over 14.5 thousand constraints were used for the final registration of all scanner stations in local coordinates. The error distribution for all constraints is shown in Figure 5.

The mean absolute error for constraints was 3 mm. The biggest errors were on the printed B & W targets attached to the platforms surrounding the rock, due to heavy vibrations caused by people walking. Very strong winds also partially affected the small tripods for the Leica HDS targets. Weighting was used for registration errors not exceeding 10 mm, and for larger errors, the constraint was removed from calculations.

The referencing of all printed B & W targets to the common survey network was done with a Leica TCRP1203 Total Station. Its angular accuracy was of 3″ and the distance error was ±2 mm + 2 ppm. The device parameters together with the measured angles and distances between all pairs of mutually visible positions of the instrument

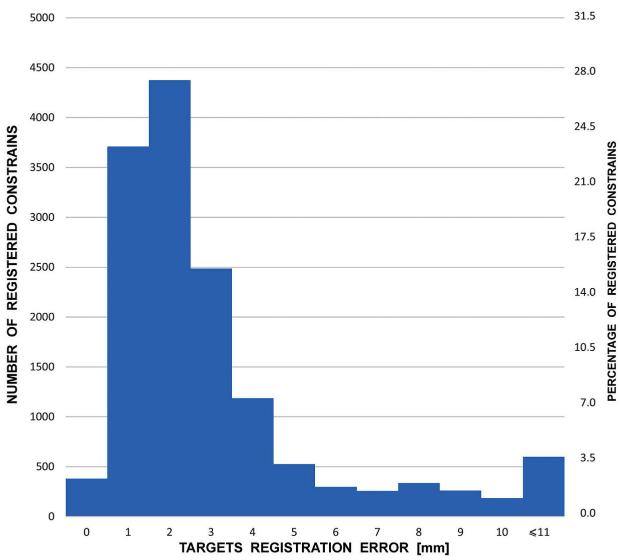

Fig. 5. Distribution of errors in target registration (elaborated by J. Kościuk)

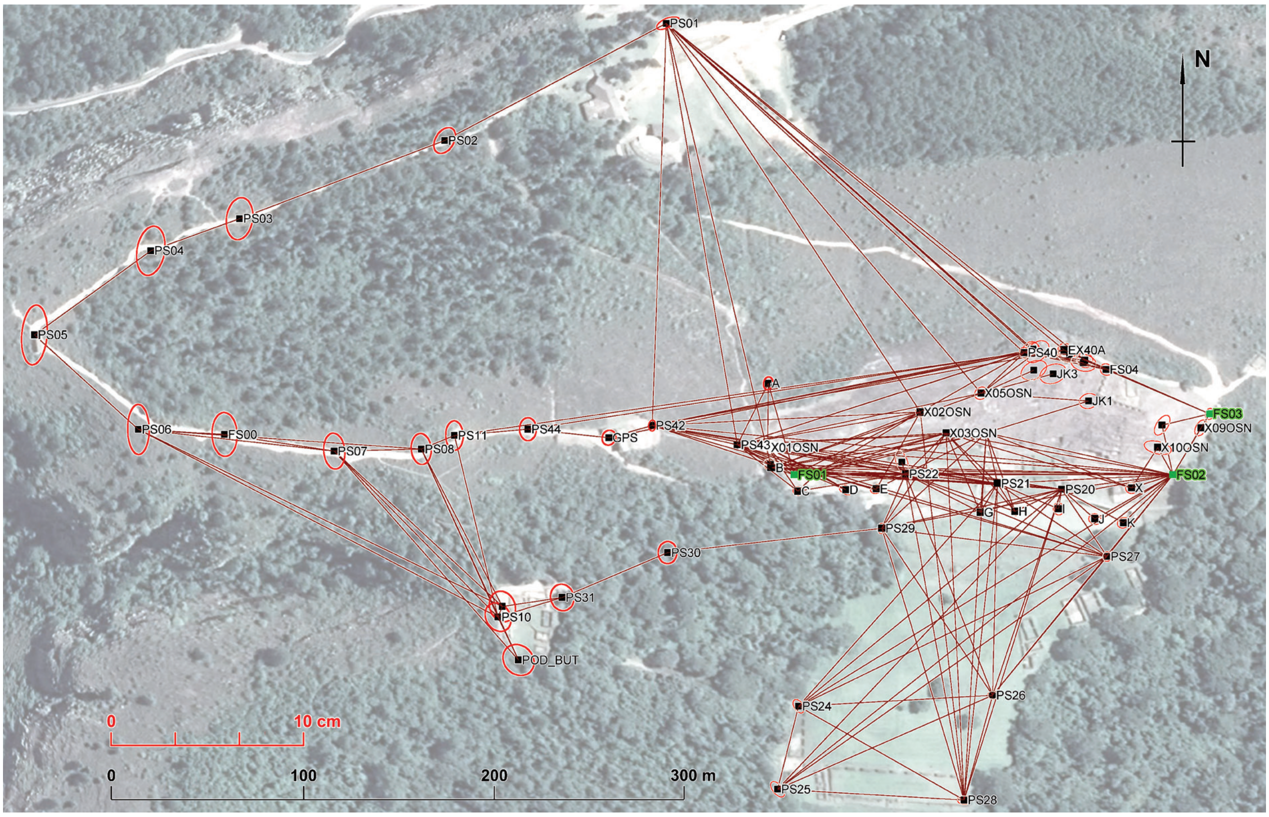

Fig. 6. Survey network after adjustment. Error ellipses (in red) exaggerated (elaborated by B. Ćmielewski)

Constraint ID	ScanWorld	ScanWorld	Type	Status	Weight	Error	Error Vector
D	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	1.0000	0.002 m	(-0.001, -0.001, -0.002) m
B	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	1.0000	0.003 m	(-0.003, 0.000, -0.001) m
E	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	1.0000	0.003 m	(-0.003, -0.001, -0.001) m
I	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	1.0000	0.003 m	(0.003, 0.000, 0.001) m
G	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	1.0000	0.003 m	(-0.003, 0.001, 0.000) m
C	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	1.0000	0.003 m	(-0.001, 0.000, -0.003) m
H	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	1.0000	0.004 m	(0.004, -0.001, 0.000) m
J	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	1.0000	0.004 m	(0.003, -0.002, 0.002) m
K	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	0.5000	0.006 m	(0.004, -0.004, 0.001) m
F	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	0.5000	0.006 m	(-0.005, 0.003, 0.001) m
L	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	0.5000	0.007 m	(-0.003, 0.005, 0.003) m
FS04	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	0.5000	0.007 m	(0.004, 0.003, 0.006) m
30	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	0.2500	0.008 m	(0.002, 0.005, 0.005) m
PS23	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	0.2500	0.008 m	(-0.005, 0.007, -0.002) m
A	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	0.1000	0.009 m	(-0.001, 0.006, -0.006) m
PS40	ScanWorld Registartion (Leveled)	Geodetic Control Network (Leveled)	Coincident: Vertex - Vertex	On	0.1000	0.010 m	(0.007, 0.006, 0.004) m

Fig. 7. Transformation errors for registering into UTM coordinate system. Screenshot from the Leica Cyclone (elaborated by B. Ćmielewski)

allowed the survey network to be aligned with an average *x*, *y* point position square error equal to 6.8 mm and average height square error equal to 2.9 mm (Fig. 6).

The next step was to transform the local coordinates to the global reference system using isometric transformation. The network coordinates were transformed to the WGS 84/UTM zone 20S, EPSG:32720 coordinate system by referencing four governmental surveying benchmarks (points FS01, FS02, FS03, and FS04) found on the site. Their coordinates were kindly supplied by officials from the Archaeological Research Centre in Samaipata.

In the last step, the whole scanning project, which up to this moment was in local coordinates, was registered into the WGS 84 global positioning system (GPS). The global coordinates of 12 printed B & W targets, three governmental surveying benchmarks, and one additional point from the surveying network were used for the registration (Fig. 7). Weighting was used again, in this case for errors greater than 4 mm.

Obtaining colour information for each of the millions of 3D points was a separate problem. Gaining the most accurate colour reproduction was, however, not our top priority. This was instead solved by the photogrammetry sub-project running in parallel with this one[2]. The main problem in our project was time we need to spend on the field.

[2] Cf. B. Ćmielewski, I. Wilczyńska, C. Patrzałek, J. Kościuk, *Digital close-range photogrammetry of El Fuerte de Samaipata*, in the same issue of "Architectus".

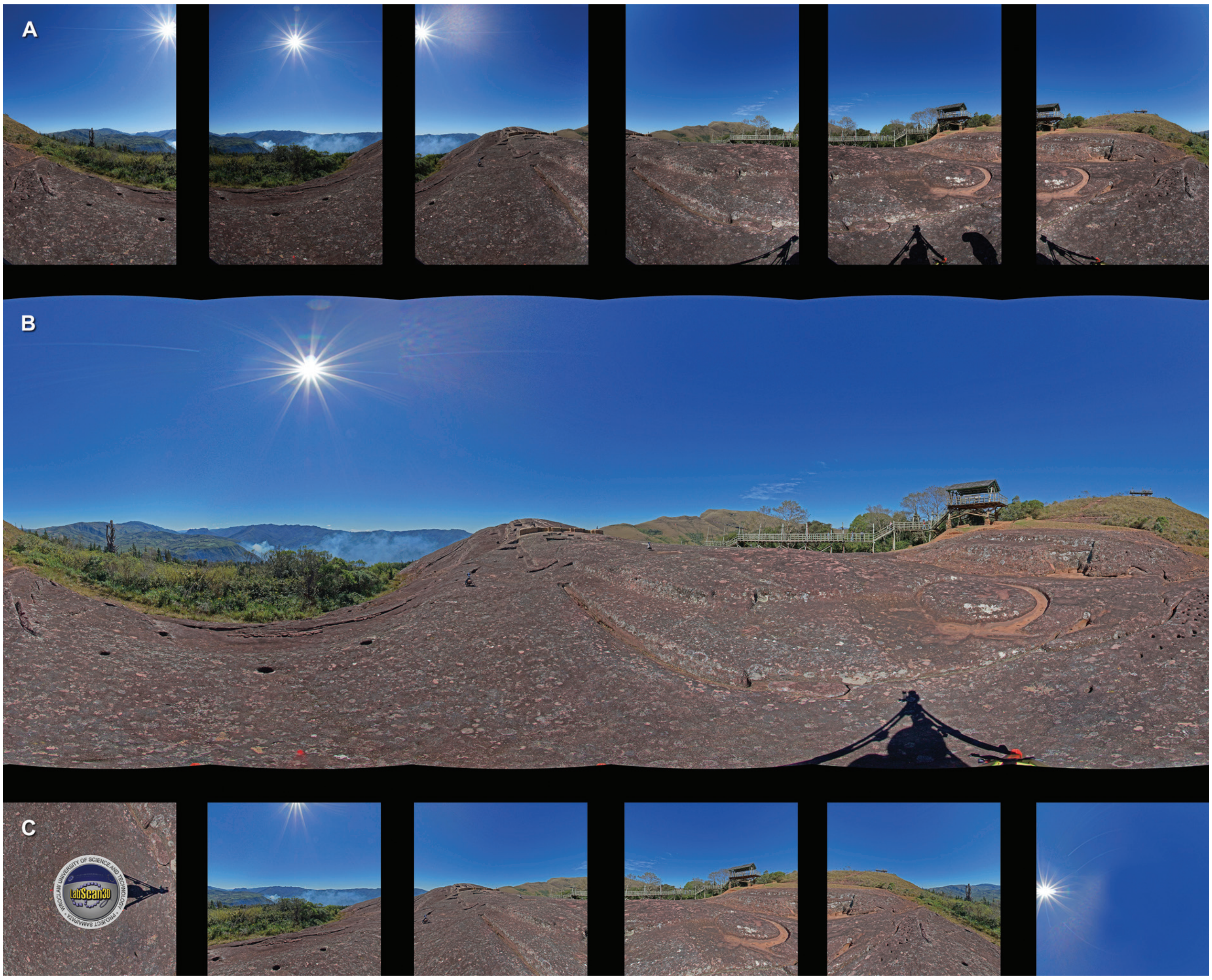

Fig. 8. Acquisition of RGB values: A – HDR images; B – equirectangular panorama; C – image cubes ready to port to the Leica Cyclone (elaborated by M. Telesińska)

The Leica ScanStation P40 is equipped with an internal HDR RGB camera that takes photos at a resolution of 4 megapixels for each 17° × 17° colour image. All 270 images are automatically converted into a panoramic image with a resolution of up to 700 megapixels and mapped as RGB values on a 3D point cloud. The time required for this – over 7 min to shoot 270 images in our lighting conditions and with medium resolution – was difficult to accept. Due to the very capricious weather that we found in Samaipata, the time needed in the field was of fundamental importance to us, even at the price of extended data post-processing time in the back office.

For this reason, the internal RGB camera on the Leica ScanStation P40 was replaced with a Sony Alpha STL-A65 camera with an APS-C sensor matrix of 24 megapixels. The Sigma EX 10 mm fisheye HSM lens f/2.8 was attached to the camera box, and everything was mounted on the Nodal Ninja 3 MKII panoramic head adjusted for 60° intervals. The camera was used in automatic HDR mode, resulting in well balanced lights and shadows on all the pictures (Fig. 8A). Compared to the use of an internal camera, we saved about 5 min at each scanner station.

The further workflow required PTGui Pro (version 10.0.16) for stitching single images into an equirectangular panorama (typically with a resolution of 107 megapixels), and in the next step, image cubes (16 megapixels each) were produced, to be ported into Leica Cyclone to map RGB values on the 3D point cloud. The last step required a time-consuming and tedious selection of analogous points on the 3D cloud and each of the cubes. Fortunately for us, the new version of Leica Cyclone Register launched just after our return from the field, and this greatly simplified the process. Now it is enough to import the equirectangular panorama to the Leica Cyclone Register module and the whole process of mapping the RGB values on the 3D point cloud is automatic. Colouring scans, registering and cleaning unwanted objects (moving people, tripods with Leica HDS targets, dust particles in the air, etc.) ended in Autumn 2017.

Results and discussion

The resulting 3D point cloud well documents even the most difficult parts of the rock – the flat terrain on its ridge, where it was hard to obtain an appropriate angle (>30°) of incidence of the laser beam (Fig. 9).

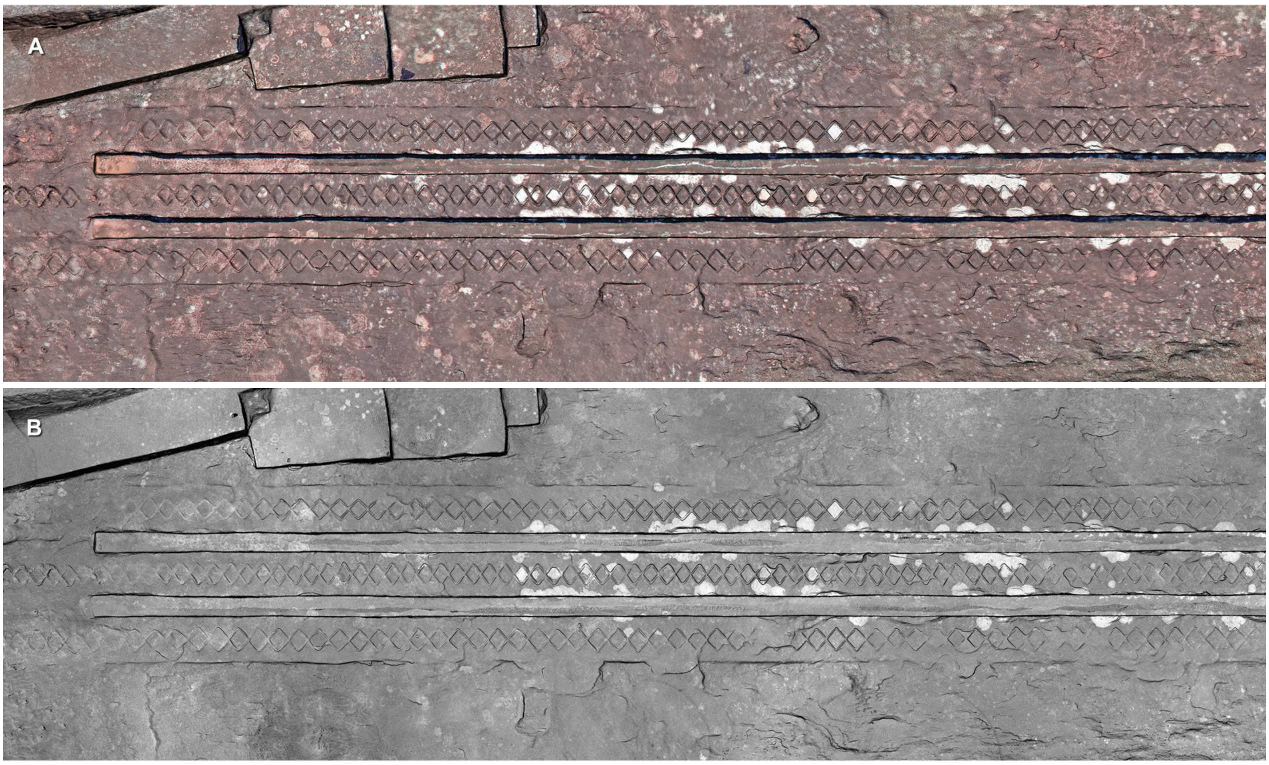

Fig. 9. Fragment of 3D point cloud. The so-called "Great Snake" petroglyph on the top of the Samaipata rock:
A – RGB textured 3D point cloud; B – 3D point cloud represented in intensity reflection values (grey scale) (elaborated by J. Kościuk)

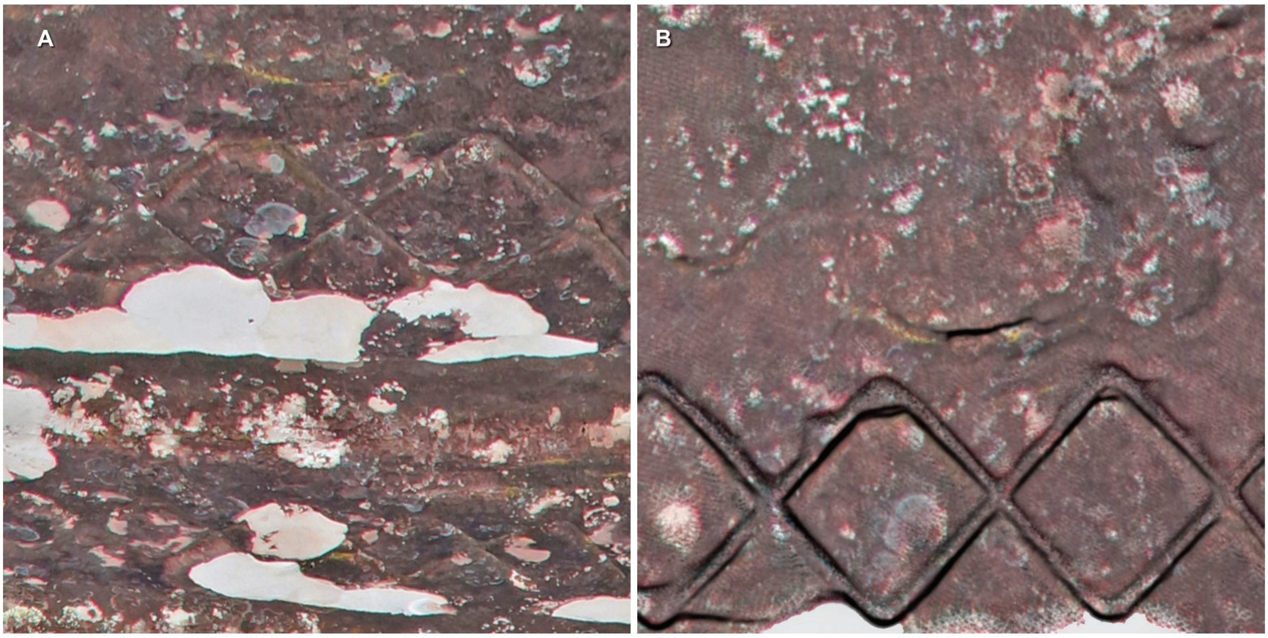

Fig. 10. Detail of the so-called "Great Snake" petroglyph on the top of the Samaipata rock:
A – fragment of the petroglyph as photographed on the field (photo by J. Kościuk);
B – the same fragment as RGB textured 3D point cloud with hill-shading algorithm (elaborated by J. Kościuk)

For almost horizontal surfaces, the density of coverage with measuring points was not worse than 3 × 3 mm. For slopes, where the angle of incidence of the laser beam was more favourable, the density of the 3D point cloud was usually better than 2 × 2 mm.

It was also possible to capture small differences, hardly exceeding 1 cm in depth, of the rock relief. Thanks to this, blurred portions of petroglyphs, unclear on the field in natural lighting (Fig. 10A), became clearly visible in the shaded 3D cloud image (Fig. 10B). The latter is an ortho-image derived from 3D scans from 68 scanning stations – some distant by more than 50 m. The points overloaded with reflection intensity were filtered and the "Cloud Shaded" algorithm available in Leica Cyclone was used.

The whole picture was refined by applying a negative version of the black and white image obtained from the "Cloud Silhouette" algorithm.

It is noteworthy that the colour reproduction on the 3D point cloud turned out to be close to the colours obtained on uncalibrated digital photos from the field (compare Figs. 10A, B).

Conclusions and project limitations

The chosen method of documentation turned out to be adequate for its purpose of providing the most accurate reproduction of the surface of the Samaipata rock including its smallest details. However, the resulting database is so large (265 GB) that it requires computers with high computing power, high-speed graphics cards, and a large amount of RAM to operate it. We had an acceptable level of work comfort when using a computer with two Xeon processors (Intel®Xeon®CPU E5-2630 v2), 128 GB RAM, and two NVIDIA GTX 1070 graphics cards.

The practical use of such a large and detailed scan database brings problems. Assuming that the scanned area measures only 80 × 240 m with an average scanning density of 3 × 3 mm, and assuming that the intention is to get a full graphical representation of the entire area, we will end up with a file size of 24 000 by 72 000 pixels (1728 megapixels). Using files of this size on a daily basis is not convenient. However, this was not the purpose of scanning with such a high density. The main value of this scan database is that of a document that is a detailed (as far as today's technical possibilities permit) representation of the state of the monument at a specific moment (July 2016).

In the next ten years it would be advisable to repeat, if not a scan of the whole rock, then at least a scan of its most important fragments. Comparison of data from the two different periods would determine the speed of erosion and indicate the places most exposed to it. The use of TLS data for monitoring the state of heritage monuments is becoming increasingly common [16]–[19] and is particularly worth recommending in the case of el Fuerte de Samaipata.

References / Bibliografia

[1] Kościuk J., *Modern 3D scanning in modelling, documentation and conservation of architectural heritage*, [in:] J. Jasieńko (ed.), *Structural analysis of historical constructions: proceedings of the International Conference on Structural Analysis of Historical Constructions 2012, 15–17 October 2012*, Vol. 1, Dolnośląskie Wydawnictwo Edukacyjne, Wrocław 2012, 64–76.

[2] Barber D.M., Dallas R.W., Mills J.P., *Laser scanning for architectural conservation*, "Journal of Architectural Conservation" 2006, Vol. 12, Iss. 1, 35–52, doi: 10.1080/13556207.2006.10784959.

[3] Van Genechten B., *Theory and Practice on Terrestrial Laser Scanning: Training Material Based on Practical Applications*, Universidad Politecnica de Valencia Editorial, Valencia 2008.

[4] Remondino F., Campana S., *3D Recording and modelling in archaeology and cultural heritage theory and best practices*, BAR international series, 2598, Archaeopress, Oxford 2014.

[5] Fiorillo F., Remondino F., Barba S. *et al.*, *3D digitization and mapping of heritage monuments and comparison with historical drawings*, "The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences" 2013, Vol. II-5 W, 1, 133–138, doi: 10.5194/isprsannals-II-5-W1-133-2013.

[6] Grussenmeyer P., Landes T., Voegtle T. *et al.*, *Comparison methods of terrestrial laser scanning, photogrammetry and tacheometry data for recording of cultural heritage buildings*, "The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences" 2008, Vol. 36, 213–218.

[7] Kottke J., *An Investigation of Quantifying and Monitoring Stone Surface Deterioration Using Three Dimensional Laser Scanning*, Master's Thesis, University of Pennsylvania, Philadelphia, PA, 2009, https://repository.upenn.edu/cgi/viewcontent.cgi?article= 1126 &context=hp_theses [accessed: 21.05.2019].

[8] Rüther H., Chazan M., Schroeder R. *et al.*, *Laser scanning for conservation and research of African cultural heritage sites: The case study of Wonderwerk Cave, South Africa*, "Journal of Archaeological Science" 2009, Vol. 36, Iss. 1, 1847–1856, doi: 10.1016/j.jas.2009.04.012.

[9] Fabbri S., Sauro F., Santagata T. *et al.*, *High-resolution 3-D mapping using terrestrial laser scanning as a tool for geomorphological and speleogenetical studies in caves: An example from the Lessini mountains (North Italy)*, "Geomorphology" 2017, Vol. 280, 16–29, doi: 10.1016/j.geomorph.2016.12.001.

[10] Zhou K., Zhao X., Zhou J. *et al.*, *Application of terrestrial laser scanning for heritage conservation in Yungang Grotto*, "The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences" 2008, Vol. 37, Part B5, 337–340.

[11] Lercari N., *Monitoring Earthen Archaeological Heritage using MultiTemporal Terrestrial Laser Scanning and Surface Change Detection*, "Journal of Cultural Heritage" 2019, Vol. 39, 152–165, doi: 10.1016/j.culher.2019.04.005.

[12] Remondino F., *3D recording for cultural heritage*, [in:] D. Cowley (ed.), *Remote Sensing for Archaeological Heritage Management. Proceedings of the 11th EAC Heritage Management Symposium, 25–27 March 2010, Reykjavík*, Occasional Publication of the Aerial Archaeology Research Group No. 3, Europae Archaeologia Consilium (EAC), Brussels 2011, 107–116, doi: 10.1179/146195712X13 382850644938.

[13] Guarnieri A., Fissore F., Masiero A. *et al.*, *From Tls Survey To 3D Solid Modeling for Documentation of Built Heritage: the Case Study of Porta Savonarola in Padua*, "The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences" 2017, Vol. XLII-2/W5, 303–308, doi: 10.5194/isprs-archives-XLII-2-W5-303-2017.

[14] Murtiyoso A., Grussenmeyer P., *Documentation of heritage buildings using close-range UAV images: dense matching issues, comparison and case studies*, "The Photogrammetric Record" 2017, Vol. 32, Iss. 159, 206–229, doi: 10.1111/phor.12197.

[15] *Periodic Reporting: A Handbook for Site Managers, The World Heritage Convention Third Cycle of Periodic Reporting 2018–2024*, 2018, https://whc.unesco.org/en/periodicreporting/ [accessed: 22.08.2018].

[16] Guarnieri A., Milan N., Vettore A., *Monitoring of Complex Structure for Structural Control Using Terrestrial Laser Scanning (Tls) and Photogrammetry*, "International Journal of Architectural Heritage" 2013, Vol. 7, Iss. 1, 54–67, doi: 10.1080/15583058.2011.606595.

[17] Selbesoglu M.O., Bakirman T., Gokbayrak O., *Deformation measurement using terrestrial laser scanner for cultural heritage*, "The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences" 2016, Vol. XLII-2/W1, 89–93, doi: 10.5194/isprs-archives-XLII-2-W1-89-2016.

[18] Park H.S., Lee H.M., Adeli H. *et al.*, *A New Approach for Health Monitoring of Structures: Terrestrial Laser Scanning*, "Computer-Aided Civil and Infrastructure Engineering" 2007, Vol. 22, Iss. 1, 19–30, doi: 10.1111/j.1467-8667.2006.00466.x.

[19] Tapete D., Casagli N., Luzi G. *et al.*, *Integrating radar and laser-based remote sensing techniques for monitoring structural deformation of archaeological monuments*, "Journal of Archaeological Science" 2013, Vol. 40, Iss. 1, 176–189, doi: 10.1016/j.jas.2012.07.024.

Acknowledgements/Podziękowania

The presented work is a part of the research sponsored by the grant given to the Wrocław University of Science and Technology by the Polish National Science Centre (grant No. 2014/15/B/HS2/01108). Additionally, the municipality of Samaipata, represented by Mayor Falvio Lópes Escalera, contributed to this research by providing the accommodation during the fieldwork in June and July 2016, as well as in July 2017. The Ministry of Culture and Tourism of Bolivia kindly granted all necessary permits (UDAM No. 014/2016; UDAM No. 060/2017). The research was conducted in close cooperation with the Centre for Pre-Columbian Studies of the University of Warsaw in Cusco. Specialists from many other universities and research centres also joined the project.

Abstract

This paper concerns El Fuerte de Samaipata – one of Bolivia's most important monuments inscribed on the UNESCO World Heritage List. The study describes the hardware and software used in the project "Architectural examination and complex documentation of Samaipata (Fuerte de Samaipata/Bolivia) site from the World Heritage List", as well as the workflow adopted for the terrestrial laser scanning (TLS) of the site. It also explains the important role that TLS played in the entire project.

Key words: Bolivia, Samaipata, UNESCO World Heritage List, rock art, 3D scanning

Streszczenie

Artykuł dotyczy El Fuerte de Samaipata – jednego z najważniejszych zabytków Boliwii wpisanego na Listę Światowego Dziedzictwa UNESCO. Opisano aparaturę i oprogramowanie zastosowane w projekcie „Badania architektoniczne i kompleksowa dokumentacja stanowiska Samaipata (Fuerte de Samaipata/Boliwia) z Listy Światowego Dziedzictwa", a także metodologię przyjętą dla naziemnego skanowania laserowego (TLS). Wyjaśniono również ważną rolę, jaką w całym projekcie odgrywa TLS.

Słowa kluczowe: Boliwia, Samaipata, Lista Światowego Dziedzictwa UNESCO, sztuka naskalna, laserowe skanowanie 3D