Perspectives for the application of Reflectance Transformation Imaging in cultural institutions

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The Reflectance Transformation Imaging (RTI) technique[1] has been known and used as a method for digitising artefacts for more than two decades. It is also used relatively frequently (as evidenced by numerous publications[2]) as an auxiliary technique in scientific research in archaeology and art conservation; however, until recently, its use was rare in cultural institutions. This most likely stems from a broader issue concerning the lack of universally recognised standards for creating digital documentation of cultural heritage artefacts. Cultural institutions – museums, libraries and archives – embark on digitisation procedures due to a variety of needs; not only as a way to create conservation documentation or to document their collections, but also to promote particular artefacts or to make digital copies of the objects in their collections available to the general public. The quality level of two-dimensional digital reproductions and the techniques for sharing them online – either using various types of repositories or sharing standards, such as the International Image Interoperability Framework (IIIF),[3] enable achieving the desired outcomes. The objective of this paper is to outline the issues relevant to the goal of standardising and developing the Reflectance Transformation Imaging technique in cultural institutions carrying out the digitisation process on a statutory basis.

In the context of the RTI technique in the analysed field, a question may be posed whether it is possible to use it more broadly in these institutions, not only in connection with the specific research projects, but also as part of the standard digitisation process, taking into account the same objectives as the creation of studio-based, documentary digital photography.

1 The technique was developed 24 years ago (in a 2000 study by Tom Malzbender from Hewlett-Packard Laboratories on polynomial texture mapping); a Polish term for it does not exist yet, so it is commonly referred to by its abbreviated English term both in professional practice and in Polish-language trade publications. Digital outputs are typically saved in .ptm format, which stores both the image and lighting information.

2 When queried about 'reflectance transformation imaging rti', the Google Scholar search engine finds more than 900 papers concerning various disciplines that have been published in the last five years (between 2018 and 2023), e.g. H. Mytum, J. R. Peterson, 'The application of reflectance transformation imaging (RTI) in historical archaeology', *Historical Archaeology*, vol. 52, 2018, pp. 489–503; H. E. Coules, P. J. Orrock, C. Er Seow, 'Reflectance Transformation Imaging as a tool for engineering failure analysis', *Engineering Failure Analysis*, vol. 105, 2019, pp. 1006–1017. For other studies, see scholar.google.com/scholar?q=%22reflectance+transformation+imaging+rti%22&hl=pl&as_sdt=0%2C5&as_ylo=2018&as_yhi=2023 (accessed 18 April 2024).

3 IIIF (International Interoperability Framework) is a set of open standards for sharing high quality digital objects along with descriptive metadata. It is also the name of an international association developing and promoting software solutions enabling the process; cf. IIIF API, iiif.io (accessed 30 Nov. 2023).

Incidentally, a similar question can also be posed in relation to multispectral photography. In thinking about the standardisation of these techniques in libraries, museums and archives, the various aspects concerning the purpose of such digitisation must be acknowledged. A scholar using the RTI technique is likely to focus on imaging areas of particular interest, adjusting the technical parameters and number of shots to suit the needs of their research.[4] Imaging the same object without a clear research perspective will probably result in its more general presentation, perhaps even in slightly lower quality or with a limited number of shots. The main benefit of the RTI technique is the ability to showcase the texture of the object in a dynamic manner, giving the user the tools to freely manipulate the lighting. This manner of presenting at the very least a part of the collection makes the conventional static presentation more attractive and potentially brings additional benefits, aiding research in the field of the digital humanities in its broadest sense of the word.

The arguments in favour of the broader use of RTI technique include the relative ease of generating a digital file due to the simple photographic process, especially if small objects are digitised using equipment that automates the process and software available under open licences.[5] Another advantage is the ability to capture multiple images with different lighting angles, which can also be used as stand-alone 2D digital images. Exported versions of the object can also be used for 2D presentation after the application of selected filters available in the .ptm file visualisation software. Thanks to its characteristics, the RTI technique is particularly useful in situations where the surface texture of the documented object is to be showcased. The presentation of knights' seals held in the collection of the State Archive in Wrocław is an example of this method of rendering an artefact.[6] Each object has its own RTI reproduction, which is available with a web browser, allowing the user to manipulate the lighting; the .ptm file and 2D reproduction are also available for downloading. This enables viewing the object in a variety of ways, as photographs taken in directional and diffused light, along with shots generated with RTIViewer[7] with enhanced texture, with enhanced

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4 This assumption does not apply to small objects, such as coins or medals, in the case of which comprehensive documentation of the entire surface of each side can easily be created within a single measurement sequence.

5 E.g. a free software package for creating and viewing RTI documentation is available at the Cultural Heritage Imaging non-profit organisation website: culturalheritageimaging.org/What_We_Offer/Downloads/ (accessed 30 Nov. 2023).

6 The exhibition 'Pieczęcie rycerstwa obcego na Śląsku do 1335 r. w zbiorach Archiwum Państwowego we Wrocławiu', www.wroclaw.ap.gov.pl/wystawy/pieczecie-rycerstwa-obcego-na-slasku-do-1335-r-w-zbiorach-archiwum-panstwowego-we-wroclawiu (accessed 30 Nov. 2023).

7 The Cultural Heritage Imaging website offers free access to a .ptm file viewer: culturalheritageimaging.org/What_We_Offer/Downloads/View/index.html (accessed 30 Nov. 2023).

Fig. 1

An example of an online presentation of seals held in the collection of the State Archive in Wrocław: a 2D version (top) and a RTI version (bottom)

greyscale texture, as well as with the application of other visualisation methods such as ‘normal mapping’.[8]

The standardisation of this technique, like any other in the given context, requires an approach that takes into account determining several key factors:

a) requirements and quality parameters for reproductions;
b) standardisation of the long-time storage of produced data;
c) tools for making digital objects available to end users.

8 ‘In 3D computer graphics, normal mapping, or Dot3 bump mapping, is a texture mapping technique used for faking the lighting of bumps and dents – an implementation of bump mapping’; cf. en.wikipedia.org/wiki/Normal_mapping (accessed 15 Sept. 2024).

Developing RTI documentation

The rules for developing RTI digital production processes in cultural institutions should be based on the following guidelines:

1. Recommendations specific to the RTI technique itself, taking into account the constraints of the source data collection (images) using a manual or automated process.
2. General recommendations concerning the rules of digitising cultural heritage objects, which form the basis for digitisation activities in the given cultural institutions.
3. Recommendations concerning any special techniques that can be used to enhance RTI documentation, such as multispectral measurement performed in narrow wavelength ranges (e.g. infrared or ultraviolet).

The actual taking of a series of shots can be done in two ways (based on the number of light sources used):

a) a single light source method – one source is moved (manually or mechanically) according to a preset sequence. This method is particularly suitable for large objects and objects in locations that do not allow the use of a dedicated device;
b) with the use of various types of equipment with multiple light sources, such as domes and moving arms. There are many such solutions available publicly, with examples of completed projects.[9] The vast majority are dome-shaped devices of various sizes; these range from prototypes built by institutions and individuals to mass-produced commercial solutions.

A detailed description of the technique is available at the Cultural Heritage Imaging[10] and the American Institute for Conservation (AIC) Collaborative Knowledge Base[11] websites; it comprises both the manual variant and a variant using dedicated equipment.[12] The essential software required for making the .rti or .ptm file and the viewers supporting these formats is available on the Cultural Heritage Imaging website. When developing RTI documentation, it is crucial to have the necessary tools. In addition to a suitable camera for capturing baseline images with a lighting set-up, a grey or colour test target and a ball marking the position of the light source (for manual measurement) should be used. Since the main objective is to analyse the texture of the object, it may

9 Digitisation of drawings by Leonardo da Vinci held at the Windsor Castle (Great Britain), www.timzaman.nl/rti-dome (accessed 30 Nov. 2023).

10 Cultural Heritage Imaging homepage: culturalheritageimaging.org/Technologies/RTI/ (accessed 30 Nov. 2023).

11 Information on RTI gathered by the American Institute for Conservation: www.conservation-wiki.com/wiki/Reflectance_Transformation_Imaging_(RTI) (accessed 30 Nov. 2023).

12 Description of an inexpensive dome design: artid.readthedocs.io/en/latest/index.html (accessed 30 Nov. 2023).

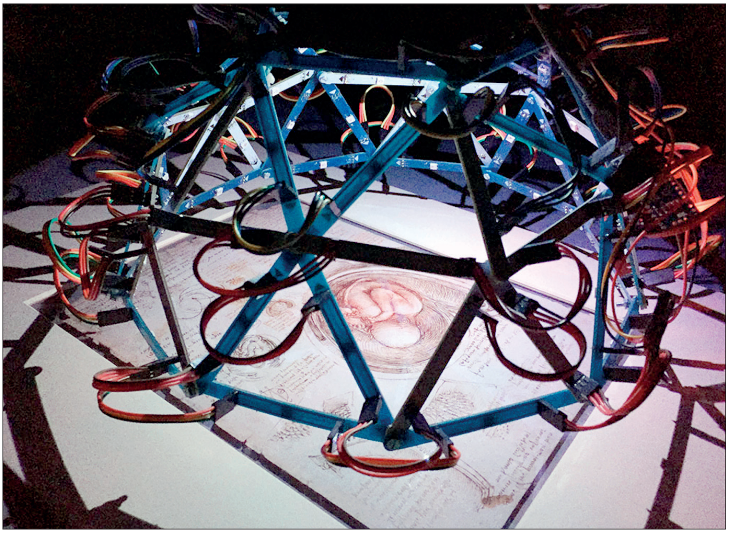

Fig. 2

An example of the RTI dome: digitisation of drawings by Leonardo da Vinci held at the Windsor Castle (Great Britain)

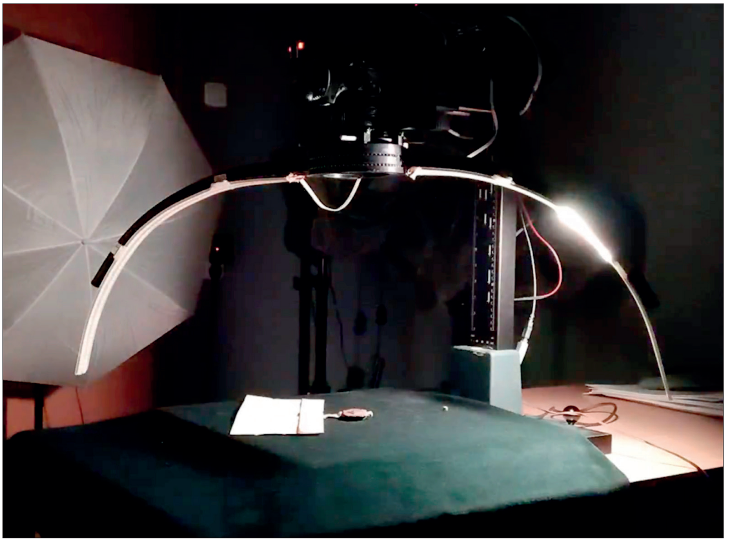

Fig. 3

Rotary arm for RTI digitisation designed and built by Marcin Szala, Michał Żurawski and Paweł Kmiecik

also be a good practice to use a resolution test target, at least in the test shot. In the case of an automated process with fixed and repeatable positions of the light source, a whole series of shots can be taken with the sphere and the aforementioned test targets as reference material for all measurements performed. This data can then be collected once for a larger group of similar objects documented during the same session. Due to the lack of uniform lighting in individual shots, obtaining an averaged colour profile for the entire presentation is a rather complicated task, thus problematic in everyday use. Thus, in the case of the RTI technique, colour correction can be effectively implemented down to the level of establishing the correct white balance and placing a colour target in the test shot (not included among the processed files).

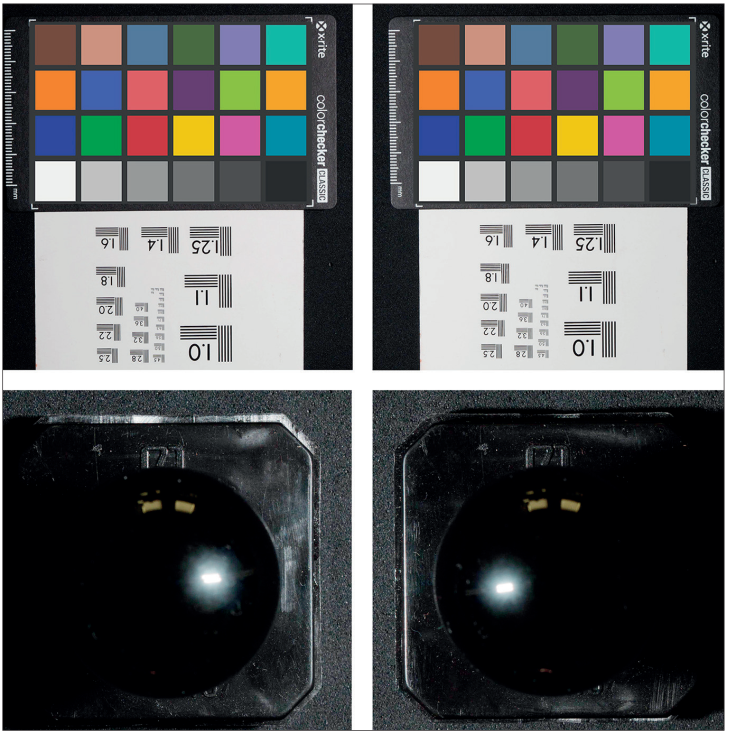

Fig. 4

A summary of sample reference shots: a colour chart (ColorChecker Classic by XRite) and a Modulation Transfer Function (MTF) chart, with a black sphere visible at the bottom of the image along with a flare showing the position of the light source at the time of taking the shot

The .rti or .ptm files, used as the main file format, contain a set of individual shots saved in the JPG format.[13] To ensure quality, RAW files should be used for initial processing before exporting to JPG.[14] The aim of this approach is to minimise the amount of lossy compression in the production of the final presentation file.

In reference to the document *Catalogue of good practices for the digitisation of museum objects* issued by the National Institute for Museums,[15] a few key points are worthy of particular attention. The first of them concerns the composition of the baseline images. In the shot, the object should be put in front of a uniform and neutral background, the colour of which can be adjusted according to the colour of the object. The visible background is an important element that also demonstrates the reliability of the documentary photographs; thus, if the emphasis is on the documentary aspect, the extent of interference with the source material should be kept to a minimum. This includes removing parts of

13 A .jpg file can also be saved as a .jpeg file, as in Joint Photographic Experts Group (editor's note).

14 The RAW format is the equivalent of a digital negative. Depending on the device and software used, it may be saved with various extensions, e.g. .crw for the Canon system, .nef for Nikon, and .dng for the Adobe software.

15 Narodowy Instytut Muzeów (NIM) *Katalog Dobrych Praktyk Digitalizacji Obiektów Muzealnych*, nim.gov.pl/aktualnosci/katalog-dobrych-praktyk-digitalizacji-obiektow-muzealnych.html (accessed 30 Nov. 2023).

the background in a shot and replacing them with an artificially generated background fill in the image.[16] Another important rule is to frame the shot in a way that ensures that the object fills the frame. This is important because the positioning of the elements in the photographed scene must not change throughout the process and the scale of the object's reproduction must be identical in all shots. Choosing the right optical system components, such as the lens or sensor, should ensure the best possible quality; this will be irrelevant if the object fills only 10% of the shot.

Due to the variety of the equipment that can be used in the development of an RTI data recording station, the entire system should be documented. This is also relevant in the case of commercially manufactured devices, as some systems enable customisation, including replacing the lens on the camera. There are no clear recommendations describing what such documentation should look like. The Digital Lab Notebook application available on the Cultural Heritage Imaging website[17] may be worth considering. It is a database application that enables creating an inventory of the hardware, software, digitisation processes, documentation of the hardware set-up and the organisation and workflow of a given digitisation project.

Archiving of RTI documentation

The data produced in the process of digitisation needs to be archived for the long term; thus, making use of established standards (at least as far as the key data package to be archived is concerned) is a crucial matter. The key data package should encompass the folder structure created during the compilation of the final file. The content, shown in the following images, includes an extensive dataset created at each stage of the process.

The .raw files, which are used for generating the .jpg files, are not included in the structure in Fig. 5a–e. They can, however, be included as another component of the source data. The retention of .raw files is advisable due to the ability to use them to perform lossless conversions again; however, it must be kept in mind that this form of storage requires significant amount of disk space. The necessity of long-term storage of .raw files is up for debate; the decisions could depend on the type and nature of the project in question.

16 In this case, the documentary value is irrelevant, since it is impossible to determine whether a section of the documented object has been cut off in the process.

17 Free software which can be used to annotate the technical metadata of the system used in the digitalisation process (not just to develop RTI documentation) can be found at culturalheritageimaging.org/What_We_Offer/Downloads/DLN/index.html (accessed 30 Nov. 2023).

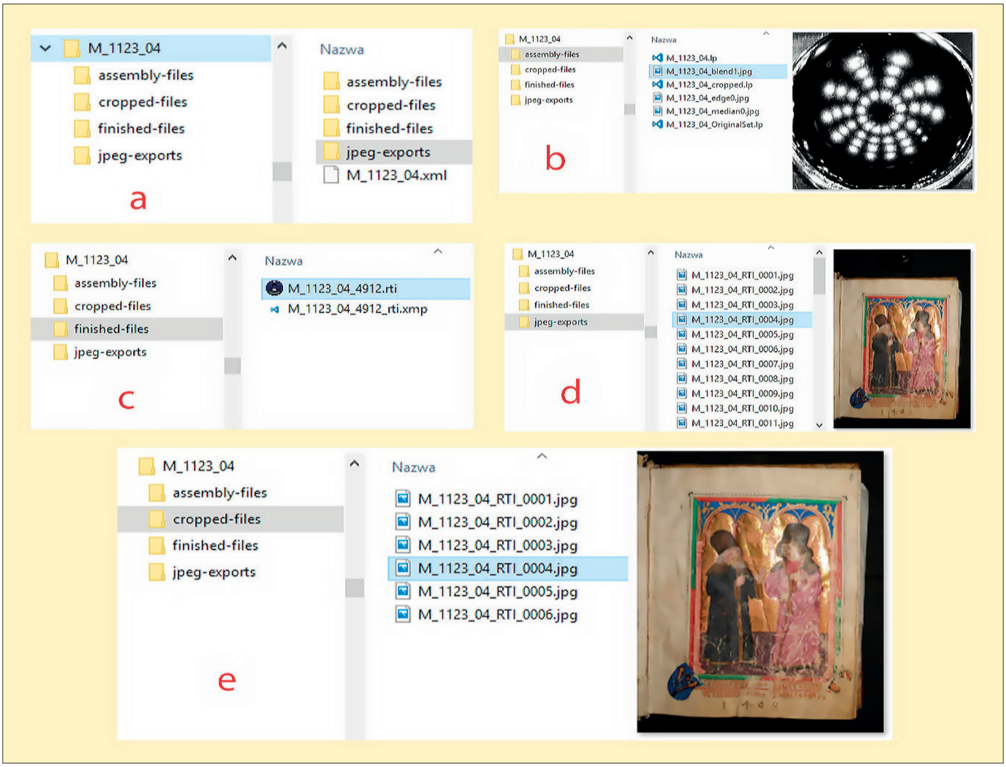

Fig. 5a–e

The RTI data structure: a) parent folder structure with subfolders, b) assembly-files – technical data containing the sphere lighting positions, c) finished-files – file in the .ptm or .rti format, d) jpeg-exports – .jpg files used as a source for the end result file, e) cropped-files – .jpg files including shot changes and the final presentation shot

As far as the features of the Digital Lab Notebook software is concerned, the archiving features are particularly noteworthy. It relies on the functionality of generating a so-called data packet, also known as a SIP (*Submission Information Packet*), which is the input data packet for an archiving system based on the OAIS (*Open Archival Information System*) model[18] used in many libraries, archives and museums worldwide. Independently of the SIP package, the software allows a report to be generated in the form of an HTML file containing technical information concerning the digitisation process. This information includes, among others, a description of the project indicating the techniques chosen, the documents and recommendations underpinning the process, the list of the hardware and software used in the process, a description of the workstation configuration, and the output data resulting from the process. This data is a valuable addition confirming the quality and reliability of digital representations, both in terms of systematically building the experience of the institution's regular digitisation staff, as well as in the cases where the process is carried out by third parties. Such reports can then help establish the quality assurance process. The example of the tool presented above should not be seen

18 Reference model Open Archival Information System (OAIS): public.ccsds.org/pubs/650x0m2.pdf (accessed 30 Nov. 2023).

as a recommendation; however, it can be used for standardisation and archiving data in RTI and other techniques.

Presenting the RTI data

The method and quality of RTI presentation can have a significant impact on the popularity of this technique. As of today, this area requires further work, as well as the development of existing tools for producing presentation images and making objects available online so that they are easily accessible to creators and organisers of digital collections. The most popular online presentation tool is the WebRTIViewer, which can be seen in Fig. 2.[19] It is a powerful tool that works well in all popular web browsers and on all devices. As far as the features are concerned, it allows the user to set the lighting angle; however, access to any additional features available in the local RTIViewer[20] application, such as other rendering modes, is not available. Seamless operation is ensured by the use of image streaming solutions, using a collection of many small images, the so-called static tiles, containing pieces of a bigger whole, which are then composited in the browser dynamically and on demand. The number of these files is influenced mainly by the size of the original file on which the online presentation is based. The presentation data structure based on static tiles can make it difficult to create repositories containing a large number of publications. This may be due to the difficulty of their handling by operating systems, as well as issues during the migration of this data. It is thus not the most optimal solution for mass deployment. Another key need concerns ensuring the interoperability of RTI data to enable web-based research, similar to the International Image Interoperability Framework (IIIF) standard.[21] Such a view and the concept of sharing RTI data (like in the case of the IIIF standard) are presented, for example, in the article 'Standardized Reflection Transformation Imaging (RTI) for Documentation and Research' by Peter Fornaro and Andrea Bianco.[22]

Other notable projects include the pixel+ viewer, created by a team of researchers and scientists within the framework of a project resulting from a cooperation between the Art & History Museum (eCollections), the KU Leuven Electrical Engineering (ESAT)/Processing Speech and Images (PSI), the KU Leuven Illuminare Centre for Medieval and

19 vcg.isti.cnr.it/rti/webviewer.php (accessed 30 Nov. 2023).

20 culturalheritageimaging.org/What_We_Offer/Downloads/View/index.html (accessed 30 Nov. 2023).

21 iiif.io (accessed 30 Nov. 2023).

22 P. Fornaro, A. Bianco, 'Standardized Reflection Transformation Imaging (RTI) for Documentation and Research', *Proc. IS&T Archiving*, vol. 16, 2019, pp 57–60, library.imaging.org/archiving/articles/16/1/art00013 (accessed 30 Nov. 2023).

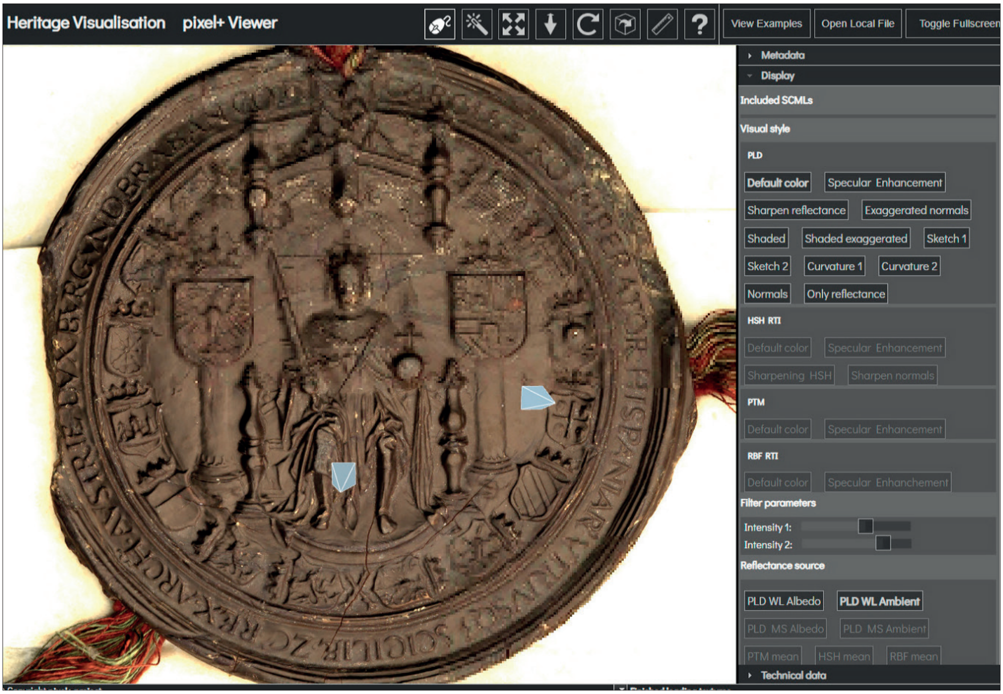

Fig. 6

The pixel+ viewer

Renaissance Art, and the KU Leuven ULS Digitisation and Document Delivery.[23]

The PIXEL+ viewer provides support for multiple file formats and multiple lights from a single camera, including CUN, CNS, PTM, RTI and glTF. The tool enables displaying a .ptm or .rti file uploaded from a local computer and offers a number of online tools that are usually only available in the browser version running locally (on the end-user's computer) for sharpening, shading, normal maps and more. In addition, it allows the use of two light sources.

Another interesting example of the integration of RTI presentation with a system providing access to virtual collections of museum collections is the *W Muzeach* website,[24] which was developed as the result of a project by several institutions carried out by a number of institutions, including the Museum of King Jan III's Palace at Wilanów, POLIN Museum of the History of Polish Jews, the National Museum in Lublin, the National Museum

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23 C. Vastenhoud, M. Proesmans, H. Hameeuw P. Konijn, B. Vandermeulen, F. Lemmers, A. Van der Perre, L. Watteeuw, L. Van Gool, V. Vanweddingen, *PIXEL+ Universal Web Interface for Interactive Pixel-Based file formats. Final Report*, Belgian Science Policy Office, BRAIN-be (Belgian Research Action through Interdisciplinary Networks), 2021. The pixel+ viewer is available at www.heritage-visualisation.org. (accessed 30 Nov. 2023).

24 wmuzeach.pl (accessed 30 Nov. 2023). For a file with RTI documentation for the artefact 'Gunpowder container with the coat of arms of the Lubomirski Szreniawa family', see wmuzeach.pl/all-objects/2VCqjlowUNWGgMBtY58l_gunpowder-container-with-the-coat-of-arms-of-the-lubomirski-szreniawa-family-

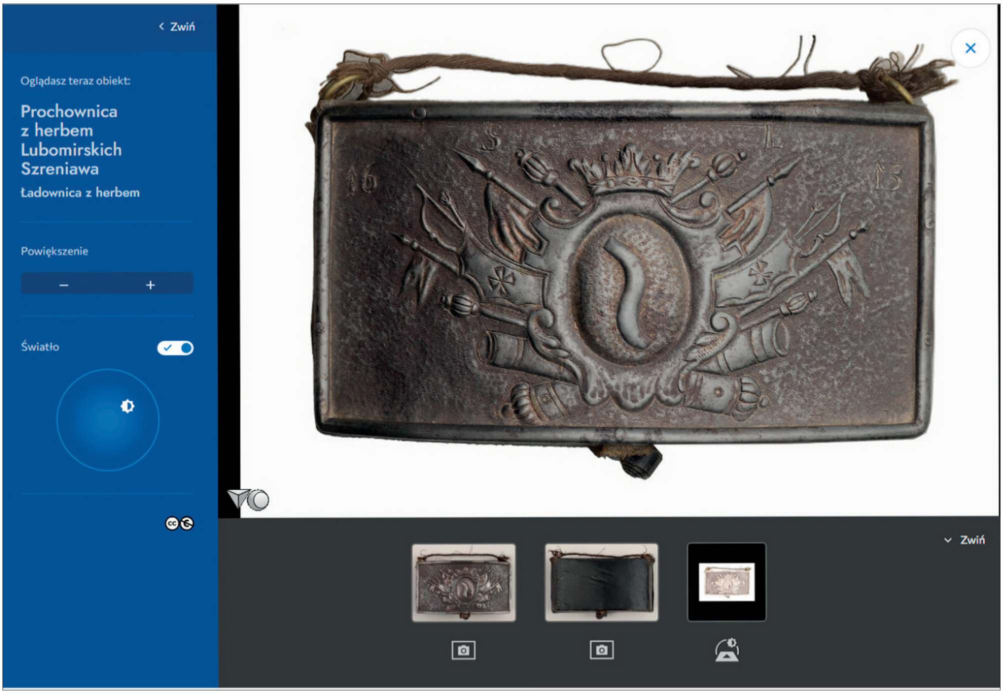

Fig. 7

RTI viewer on the *W Muzeach* website

in Szczecin and the Museum – Castle in Łańcut. The viewer running on the project's website offers the same features and accessibility characteristics as the popular WebRTIViewer; however, the functional and aesthetic integration of the presentation into the interface of the website are notable.

New RTI variants

Using the RTI technique as a tool for digitisation opens up many new possibilities. This is not caused by the technique itself; it is due to the need to equip the laboratory with the right equipment for data collection (e.g. automatic dome). With the right planning of its design, the same device can be used to obtain a wide range of results, including 3D data. The following review of techniques is not intended to be an assessment of the quality of specific solutions, but only as a demonstration of the potential use of existing hardware systems. The age of rapid development of techniques at the intersection of Computer Vision and Artificial Intelligence offer an ever-growing selection of methods that can be applied in digitisation of museum collections. The authors of the text believe that the ongoing revolution in software development has the potential to solve the most serious problems facing contemporary digitisation practices, namely the high costs arising from the labour-intensive nature of the process and the need to employ technicians with specific skill sets. The popularisation of digitisation and its deployment on a massive scale is closer than ever before; however, it requires a systemic, top-down initiative to implement quality standards, recommendations, as well as access to software available on open licences.

In addition to the well-known methods of 3D digitisation, such as photogrammetric triangulation[25] or the increasingly better AI models used to generate 3D objects,[26] there are techniques that enable using parameters concerning the illumination of an object in a 2D image (distribution of lights and shadows) to estimate its geometry. The shape-from-shading technique,[27] described in the 1970s, makes it possible to derive an approximate model of the geometry of the object. Although it has not become the primary technique for three-dimensional digitisation, it enables obtaining a 'depth map',[28] which is a map containing information about the relative distance of a given part of the photographed object from the camera. The technique is still popular and used in applications where more complex 3D data is not needed, as evidenced by the large number of implementations available on the GitHub platform (82 results). The shape-from-shading technique was brought up because the data collection process is very similar to that required for the RTI technique. Thus, in situations where it is not necessary to develop a very accurate 3D model, the shape-from-shading technique, which can be used with data collected in the context of RTI, can enrich the digitised rendition with a 3D estimation at low cost and low effort. Another solution is to obtain the 3D object directly from processing the values of the so-called normal map. Many current projects with 'shape-from-shading' in their titles most probably involve this very method. It is possible to estimate a 3D solid using the normal map obtained in the Photometric Stereo process.[29] In this case, the approximate geometry model is obtained from the product of the earlier digitisation process (used to obtain the .ptm file), so that the whole process can be automated and obtaining additional information will require even less work. It is worth pointing out, however, that 3D objects created with this method should be used mainly for illustrative purposes and the correctness of the measurements should not be assumed. By making use of the aforementioned solutions that enable taking advantage of the RTI or Photometric Stereo digitisation process in order to develop simple 3D visualisations, they are accessible both financially and organisationally to

25 Cf. e.g. AliceVision Photogrammetric Computer Vision Framework, alicevision.org/# (accessed 30 Nov. 2023).

26 Isha Salian, 'NVIDIA Research Turns 2D Photos Into 3D Scenes in the Blink of an AI', *NVIDIA*, 25 March 2022, blogs.nvidia.com/blog/2022/03/25/instant-nerf-research-3d-ai/ (accessed 30 Nov. 2023).

27 R. Zhang, T. Ping-Sing, J. E. Cryer et al., 'Shape-from-shading: a survey', *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 21, August 1999, no. 8, pp. 690–706, ieeexplore.ieee.org/abstract/document/784284 (accessed 30 Nov. 2023).

28 'In 3D computer graphics and computer vision, a depth map is an image or image channel that contains information relating to the distance of the surfaces of scene objects from a viewpoint'; en.wikipedia.org/wiki/Depth_map (accessed 15 Sept. 2024).

29 Cf. Chaman Singh Verma, Mon-Ju Wu, *Photometric Stereo*, online: pages.cs.wisc.edu/~csverma/CS766_09/Stereo/stereo.html (accessed 30 Nov. 2023).

the vast majority of cultural institutions in Poland. The result of such an exercise could be thousands of illustrative 3D models produced each year with very limited resources.

In a situation where a facility already has the infrastructure to automatically develop RTI documentation, integrating the Photometric Stereo process into the digitisation workflow may take an experienced Computer Vision programmer a couple of days. The use of such a solution thus does not depend on technical or financial barrier. The main factor hindering its use is a lack of motivation to implement such a process underpinned by doubts as to whether the digital products created as a result of such a process (3D models based on 'depth maps' or Photometric Stereo data) have any value. Such a decision cannot be made by a rank-and-file museum or library employee responsible for the collection. It is necessary to carry out a process to test the method in terms of possible uses and to give an opinion and recommendations on its use. Having the opinion of an expert group on a particular technique makes the decision to implement it much easier, especially if a tool tailored to the needs of the process is developed as well, enabling its use on a mass scale. Developing open software aimed at museums and libraries would not be a major effort, especially in the case of a centrally-planned national initiative. Of course, this would not be the case if the solution is developed by enthusiasts as a hobby. Should such a methodology be developed, very basic 3D digitisation could become so accessible and widespread that any museum, even the smallest museum in Poland[30] could decide to use photometric methods[31] for digitisation without incurring additional costs.[32]

The solution described above can be considered a low-cost addition to existing ones. They do not replace a full-fledged three-dimensional documentation, developed using photogrammetry or structured light, in all fields of application. The authors of this paper are not aware of any sources that speak to the accuracy or metrological calibration capabilities of shape-from-shading methods for 3D geometry mapping. Existing sources[33] do not exhaust the topic to the extent that they can answer the question of the potential scope of application of the technique. The need for expert opinions on a matter thus becomes all the more apparent. This

30 Which already has the infrastructure for automatic RTI documentation development, which means an expense of approximately 20,000 PLN, including the purchase of an automated dome, digital camera and a computer.

31 The Reflectance Transformation Imaging and Photometric Stereo techniques.

32 For objects that can be placed on such an automated measuring station.

33 Cf. e.g. Yvain Quéau, Jean Mélou, Fabien Castan, Jean-Denis Durou, Daniel Cremers, 'A Variational Approach to Shape-from-shading Under Natural Illumination', 11th International Workshop on Energy Minimization Methods in Computer Vision and Pattern Recognition (EMMCVPR 2017), Oct. 2017, pp. 342–357, normandie-univ.hal.science/hal-02118556/document (accessed 30 Nov. 2023).

justifies the need for laboratory and comparative studies on the basis of which such an analysis could be developed.

Shape-from-shading is not the only method that can be used to derive spatial data from processing an RTI or Photometric Stereo dataset. Another one, which offers higher potential for obtaining correct geometry representation, is the Multiview Photometric Stereo. The technique is still being actively developed,[34] but has not gained enough interest from large commercial companies to become widespread. This is most likely due to the fact that commercial products used in the development of 3D representations of cultural heritage objects are originally developed mainly for surveyors or VFX studios. The use of data acquisition devices for RTI-related methods in industries other than the broader cultural heritage documentation remains rare. The Multiview Photometric Stereo technique enables developing 3D models in a similar way to the Multi-View Stereo mechanism, which is part of the standard photogrammetry process. At the same time, it enables boosting the model accuracy if Multiview Photometric Stereo processing is combined with classic photogrammetric processing. In this case, the information contained in the normal map is not stored in bitmaps (as is the case, for example, with the RTI technique), but is converted to three-dimensional geometry.

The Multiview Photometric Stereo technique was mentioned due to the fact that the data acquisition process is very similar to the process that allows Photometric Stereo data to be combined with photogrammetry. The same data can be used to make a model using both methods, resulting in different end products. Multiview Photometric Stereo is a very promising technique. With today's developments in artificial intelligence, Multiview Photometric Stereo may soon prove to be the method offering the most accurate representation of detail. In addition, the same data can be used to analyse the reflectivity of an object's surface, thus resulting in a comprehensive 3D model. Despite the difficulties that Multiview Photometric Stereo has had in breaking into commercial markets, it offers the potential to create a correct 3D representation based solely on data collected using the same hardware as in the RTI method. The data collected for Multiview Photometric Stereo can also be used to develop a BRDF (Bidirectional Reflectance Distribution Function) model of a surface.[35] As of today, these techniques are characterised by a high

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34 Cf. Carlos Hernández, George Vogiatzis, Roberto Cipolla, 'Multiview photometric stereo', *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 30, 2008, no. 3, pp. 548–554, publications.aston.ac.uk/id/eprint/38514/ (accessed 30 Nov. 2023).

35 Wojciech Matusik, Hanspeter Pfister, Matthew Brand, Leonard McMillan, 'Efficient isotropic BRDF measurement', *Eurographics Symposium on Rendering 2003, Proceedings of the 14th Eurographics Workshop on Rendering: June 25–27, 2003, Leuven, Belgium*, eds S. Spencer, P. Christensen et al., ACM International Conference Proceeding Series, vol. 44, 2003, pp. 241–247, citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=989bdf72f21e01da3b8d0d8798fa98e4d62841bc (accessed 30 Nov. 2023).

barrier to entry as far as the knowledge of digital image processing techniques is concerned, to the extent that they remain inaccessible to most museum institutions; however, this situation may change in the coming years due to revolutionary advances in data processing methods using smart algorithms and machine learning.

Developing BRDF models can be seen as another way of using the RTI hardware for other purposes. Once again, the data collected for Photometric Stereo can be used to obtain additional information about the surface of the scanned object. Having accurate information about how an object's surface reflects light is important from the standpoint of documentation, while enabling the development of attractive 3D visualisations in which the surface of the 3D model will respond realistically to changing lighting conditions. Recently, there have been a number of scientific papers on the SVBRDF (Spatially Varying Bidirectional Reflectance Distribution Function) method,[36] which employs artificial intelligence algorithms to significantly speed up the computational process in order to enable its application to create material layers on three-dimensional models. This is referred to as the PBR (Physically Base Rendering) layers. This technique, which is garnering increasing interest among video game developers and the special effects industry, also has great potential for creating 3D models of cultural heritage objects.

Artificial intelligence algorithms, on the other hand, can also aid the development of the surface geometry of three-dimensional models, when they cannot be measured, for example due to technological constraints. Two decades ago, the Institute for Creative Technologies, University of Southern California (Playa Vista, CA, USA) carried out a project aiming to build a 3D model of the ruins of the Parthenon in Athens using BRDF techniques.[37] Today, this experiment would be much easier thanks to artificial intelligence. In addition to the lower cost, it would probably be possible to achieve higher accuracy due to the much greater analytical capabilities of today's artificial intelligence algorithms, compared to the method used by the authors of that project. It is worth noting that HDRI (High Dynamic Range Image) light mapping techniques used in the project[38] are also widely used in the film industry.

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36 Valentin Deschaintre, Miika Aittala, Fredo Durand, George Drettakis, Adrien Bousseau, 'Flexible SVBRDF Capture with a Multi-Image Deep Network', *Eurographics Symposium on Rendering 2019*, eds T. Boubekeur, P. Sen, Computer Graphics Forum (EGSR Conference Proceedings), vol. 38, 2019, no. 4, www-sop.inria.fr/reves/Basilic/2019/DADDB19/Flexible_multi_inputs_svbrdf.pdf (accessed 30 Nov. 2023).

37 ICT Vision and Graphics Lab, *Capturing the Geometry and Reflectance of the Parthenon*, youtube.com/watch?v=DmRu0Ze8gwY (accessed 30 Nov. 2023).

38 Digital image capturing devices (sensors in cameras and camcorders) have a limited dynamic range, which means that they are only able to capture image detail in appropriately illuminated parts of the frame. As a result, they fail to register detail in areas

The intersection of techniques used in the film and games industries into the cultural heritage documentation field is hardly a new phenomenon. Due to its negligible economic potential, the field of the history of material culture can rarely count on the development of dedicated advanced technologies and is thus forced to adapt other solutions to its needs, often borrowing them from larger industries (in this case, the so-called creative industries). According to the authors, the siloisation of the cultural heritage digitisation process as a part of the world of technology unrelated to other fields would be a mistake and would lead to isolation and backwardness. Users of photometric techniques who are focused on developing objects to be used in video games and special effects are developing a range of simple and efficient methods at a much higher rate than in the cultural heritage industry. Even if the potential of a technology (such as BRDF) is recognised by the cultural heritage documentation community, such technologies tend to garner much greater interest in the aforementioned creative industries. This results in the rapid development of these methods, which not only reduces production costs but also increases the level of detail in the 3D models developed. To date, materials (models and textures) used in 3D modelling are developed in a way that, due to a completely different methodological approach, is far removed from the criteria for producing archival documentation. The materials intended to represent the surface of 3D models are usually developed by graphic artists at their discretion, mainly based on an analysis of the RGB image components. This approach results in low accuracy of the representation of the real object and high costs due to due to its labour-intensive nature. AI-driven SVBRDF methods can be used as an alternative. They lower the cost and optimise the quality of the visualisation, as well as improve the accuracy of the mapping of the actual object. One of the prerequisites enabling broader use of these methods in the process of modelling heritage objects is their comprehensive documentation, including clear information about the expected quality of the resulting files.

The RTI technique is not particularly popular beyond museums and libraries, mainly due to the usage of the special .ptm file format, an image file with nine channels (as opposed to three in .jpg files or four in .png files) that is not supported by popular software. For this reason, Photometric Stereo based on the more widespread three-channel file formats is gaining popularity and growing rapidly, as evidenced by 231 results on GitHub. This development opens up new opportunities for cultural heritage digitisation. Using Photometric Stereo, the author prepared

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that are too bright and too dark. In 1986, Gregory Ward invented HDRI files, which solve the problem of limited dynamic range by combining the tonal variants recorded in multiple images taken at different exposure parameters (shutter speed) into a single file.

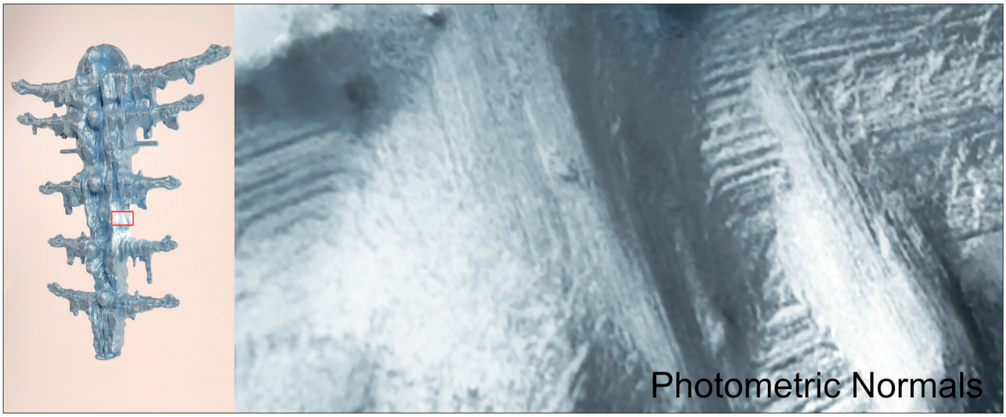

Fig. 8

Three-dimensional model of the metal sculpture *Auschwitz Cross 1977* by Gustaw Zemła from the collection of the Museum of the Archdiocese of Warsaw, developed using SVBRDF (Spatially Varying Bidirectional Reflectance Distribution Function) method

a 3D model of a sculpture in the form of a metal cross (Fig. 8).[39] Owing to the reflective nature of the sculpture's surface, the details would have been impossible to document even with high-quality laser scanners or structured light scanners. The only viable technique would be macro scanning, which requires incomparably more time and expensive equipment. Despite the fact that the Photometric Stereo method described above is becoming more and more common in the film industry, it is still met with scepticism among experts working for cultural institutions.

Employing techniques that are prevalent in other fields not only makes digitisation faster and cheaper, but also the results are compatible with the vast majority of 3D model rendering engines on the market and the use of .ptm files is not required. It may therefore be concluded that the RTI technique and the resulting .ptm files are obsolete and should be abandoned as soon as possible. The authors do not share this view, however, as RTI has found its niche for a reason. It responds to the demands of contemporary digitisation processes in a specific way that makes it indispensable as a tool for developing documentation. However, the authors believe that since it is possible to develop a rough 3D model by using the same data, this opportunity should be used on a large scale. By performing additional calculations that do not increase the cost of the process, the institution can obtain objects that work with popular rendering engines, which enables their easier presentation. Regrettably, the Photometric Stereo technique remains virtually unknown in the world of digital heritage documentation due to the fact that it is primarily used by the film industry.[40]

The greatest advantage of implementing photometric techniques in museum or library digitisation is the fact that the initial cost is very low compared to techniques such as structured illumination scanning or laser scanning.

39 Michał Żurawski, *Artwork*, photogrammetry + photometry + polarisation project, artstation.com/artwork/498DmY (accessed 30 Nov. 2023).

40 The abbreviation VFX (from *visual effects*) denotes digitally created visual effects (editor's note).

The equipment required is easily accessible and can be easily built, without having to purchase off-the-shelf solutions. The resulting data are valuable and can be used for both 2D and 3D representations. The use of photometry in digitisation processes does not even remotely reflect the existing possibilities. This calls for an initiative aimed at documenting and promoting these methods for widespread use. The average museum employee should not be expected to know all the latest computer vision news. One great example of a top-down initiative changing the 3D scanning market is Slovakia's Reality Capture programme. The software stems from a project, whose aim was to digitise a large number of 3D objects in Slovak museums. In just a few years, the photogrammetry suite developed by a Slovakian studio has become one of the leading solutions in the global market, and compute times went down significantly thanks to the pressure that Reality Capture has put on its competitors. Photometry may have a similar future, if proper action is taken, based on expert opinion and jointly developed standards. Widespread, low-cost and easy digitisation is achievable these days. It should be pursued now.

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LIST OF ILLUSTRATIONS

cese of Warsaw, developed using SVBRDF (Spatially Varying Bidirectional Reflectance Distribution Function) method; 3-D model by Michał Żurawski; fig. by Michał Żurawski

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Involved in the digitisation of collections (manuscripts, incunabula, old prints, lithographs, photographs, maps, contemporary prints) at the University Library in Wrocław since 2004. At this institution, he developed and implemented a process for documenting bindings and watermarks. He designed and built (together with M. Żurawski and P. Kmiecik) a digitisation device employing the Reflectance Transformation Imaging method. He is active in the field of developing digitisation processes for processing and archiving digital collections and making them available to the public. He is a co-developer of the functional concept for the collection presentation system and the processing of digital cultural heritage objects at the University of Wrocław based on the International Image Interoperability Framework. He is a former member of expert groups on digitisation at the National Institute of Museums and Collections Protection (NIM). He authored several publications on the digitisation of collections.

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An expert in developing 3D documentation of material culture objects and an author of training courses on photogrammetry and data processing. He has completed various projects in partnership with many Polish institutions, such as the University of Warsaw (first 3D printed map for the blind) and the University of Wrocław (automated RTI station design, together with M. Szala and P. Kmiecik). His interests focus on the application of novel digital techniques in the optimisation and automation of digitisation processes.

The study was conducted as part of the author's individual research.

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