3D Digitization of Selected Collection Items Using Photometric Stereo

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Abstract. Digitization of exhibits and the creation of virtual exhibitions is undergoing a period of stormy development and is a dynamic area of care for museum collections. The availability of digital models has a major share in the growing trend of on-line access to collections. At the same time, digitization can improve the protection of items and increase their availability for the public as well as for professionals. It can be performed using procedures based on different physical principles and their technical implementation, with different requirements for the captured objects and different quality levels of the achieved outputs. This paper introduces a technique of 3D digitization based on the principle of photometric stereo. First, it describes typical objects, followed by the physical fundamentals of the method and the selected technical solution. A section on the examples of results introduces the application of this method for creating digital models of various objects and, finally, the conclusion contains contemplations on further development of this method in the future.

Keywords: Digitization · Museum collections · 3D models
Photometric stereo

1 Introduction

Ideal digitization of collections involves a degree of precision that allows future researchers to find answers in the created digital model that were not known and asked at the time of digitization, so that any new research would not have to go "back to the object". Unfortunately, this requirement is in conflict with the capabilities of the current technology as well as ordinary work budgets, and it is therefore necessary to maximize the current options based on an understanding of the goals of documentation and the studied phenomena.

However, the goal is not just to select the right method for the object in question; it has been shown that the problems of commercial digitization solutions used for the purposes of technical documentation of objects consists in unknown parameters determining the capture conditions, which are not controlled by the user and which may vary from case to case according to the undocumented decision-making logic of the application. Compliance with the requirement for full control over the conditions of digitization is another reason why it is worth it to continue developing customized methods.

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The ITAM develops the optical photometric stereo method (hereinafter PS). PS currently lies outside the main stream of 3D scanning, which brings some limitations, but at the same time some benefits and new horizons [1, 3]. Just like other technologies, PS can also provide useful services only if used in compliance with its principles and for the study of suitable object types. Such objects can be characterized as relief-based, i.e. with one embossed side of an exclusive significance and special importance for documenting its shape and condition.

Examples of objects and applications suitable for PS include the digitization of seals, coins, plaques and medals, punches, petroglyphs, but also the shallow reliefs of carved stones, engraved wood or linoleum, and jewels such as cameos and ivory carvings, documentation of carpentry and stone marks, trasology of tool marks. Artefacts from bone products to a detailed study of brush strokes in paintings can also be included. An important area of application of PS is the documentation of degradation of objects and their surfaces, whether they are processes accompanied by material loss or, conversely, by the emergence of an extraneous layer. The possibility to increase the method's sensitivity by changing the conditions of illumination of the studied surface can be employed in this case; such surfaces may include paper fibres or other similarly smooth textured surfaces, which may be indicative for example of the presence of degradation processes, such as corrosion of metals or decay of polymer materials due to solar radiation. These studied signs of damage can cover a large range of dimensions - from single centimetres to meters, for example to detect subsurface defects of plaster, wall paintings and frescoes of historical buildings. The common thing about the aforementioned examples is that they are mostly 2.5D and conventional photographic documentation is unsuitable for them because their appearance may vary significantly depending on the lighting used. Sometimes even the changing appearance resulting from changes in shadows as the object is rotated in light is key for the user to understand the stored information. This claim applies for example to cuneiform tablets, but also to the trasology of marks left by tools used by medieval craftsmen working on beams. Another interesting result of the robustness of the method is the possibility to use even images not created by standard optical systems - but for example by outputs from thermal imaging cameras or a scanning electron microscope - as the input images to be processed by the procedure. Other notable application of digital three-dimensional models of object consists in reverse engineering, which can involve, in case of heritage preservation, speculative filling-in of missing parts of statues (usually noses and limbs) to precisely match the fracture surfaces of the original digitized by photometric stereo.

2 Description of the Method and Technical Resources

PS historically originated in astronomy, where it was used to study the shapes of crater walls on the surfaces of planets. Stereoscopic methods for digitizing remote surfaces would not yield the desired results since the height of the relief is negligible compared with the distance between the Earth and the investigated body. For photometric stereo, the distance (or, more precisely, the ratio of distance and height of surface features) is not a problem: the structure and contrast of the surface in incident light is decisive [2, 4]. PS is able to detect any microscopic surface irregularities, which remain hidden in the margins of error of measurement using other optical methods. The flexibility of the method consists in the fact that the results are independent of the distance from the studied surface and in the scalability of sensitivity by choosing lamp elevation.

The reflected light carries information on the colour of the object's surface (determined by different albedo for different colours), but also on the roughness and granularity of the surface. The human eye has been shaped by evolution to look for shapes and rhythmic regularities in images, based on relative differences in space or in time, but it does not excel in performing measurements through vision. That is any area where digital equipment is used as it has the ability to determine the required quantity accurately.

The technical execution of surface illumination is the core of the PS technical design (Fig. 1). The camera and the studied subject are held in a fixed relative position and the only thing that changes is the illumination of the object; one image is attributable to each change of illumination. The set of surface images constitutes input data that are further processed. To determine the shade and surface inclinations at every point, at least three images of the object are necessary in different lighting conditions, but in an automatic digitization system acquires typically set of fifteen images at minimum. At some

Fig. 1. View of two generations of PS equipment developed in ITAM. The height of the bigger one is approximately 170 cm. The object is placed on a table, where it is illuminated from different directions and inclinations by means of telecentric lamps (i.e. lamps whose beams do not broaden with distance, do not create a cone) and individual scenes are captured by a digital SLR camera.

workplaces, the requirement for varying object illumination is met by switching between many fixed lamps; our solution is based on mechanical movements of lamps with respect to the fixed camera-object pair. The next step in the processing of input data ensures additional calculation of the surface topography using the inclinations of such surfaces.

PS equipment is able to carry out 3D digitization of object surfaces in a fully automated mode, where the position of lamps with respect to the object is changed by means of computer-controlled motorized drives and the camera is operated. Currently, development work focuses on fine-tuning the third-generation system, especially by implementing additional features and improving technical parameters.

The output format is a matrix of heights, wrapped with a texture image. This format is suitable for further calculations and handling operations performed in the Matlab environment. However, to create digital replicas it is useful to be able to convert the data to the STL (stereolitography) format, which is a common input dataset for 3D printers that can change a digital replica into a physical replica. The importance of this step is evident for example in experimental archaeology, where it is important to determine, through physical handling of the object, what it was used for or how it was created, but it cannot be touched because of the uniqueness of the original, while there are no such restrictions for a replica. Another option of using 3D replicas consists in ensuring access to collection items to visually impaired people who can use the sense of touch to get to know the objects. Unlike casts which reproduce the object on the same scale, digital replicas can be scaled – enlarge a small animal to fit in the hand or change an ancient amphitheatre to fit in a shoe box...

3 Reconstruction

It is not possible to present all the results of PS implementation for documenting object surfaces, and attention will be therefore paid to examples depicted in Figs. 2, 3 and 4, which demonstrate some interesting or typical applications. Comments are given

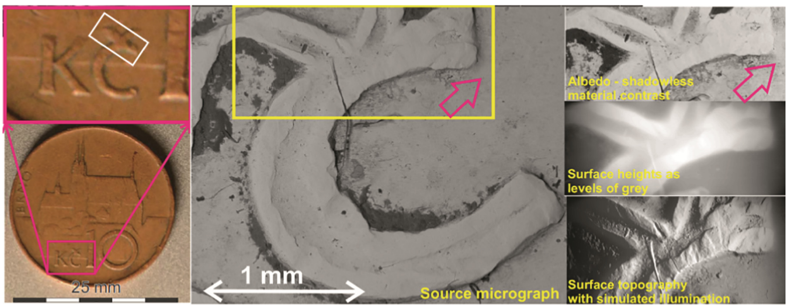

Fig. 2. Example of reconstruction of the surface of a contemporary coin using photometric stereo, carried out based on images from a scanning electron microscope (SEM), demonstrating various scales with which the method can work as well as the initial set of images not formed optically. The selected detail, highlighted with a yellow box, shows the original image as well as a height map and a view of the 3D reconstruction with simulated lighting. (Color figure online)

directly in the captions. The selected examples demonstrate the range of situations in which the PS method can be applied and bring results not achievable by simple photographic documentation and even some 3D digitization methods. Although the class of objects suitable for this technique is limited, it is still a major subset of objects typical to museum collections.

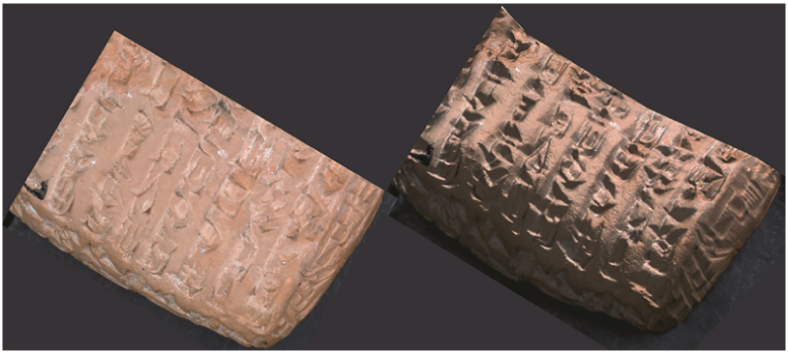

Fig. 3. For experts studying cuneiform tablets, it is essential to be able to rotate the tablets and have the symbols visible in side lighting to deepen the shadows within them. In case of conventional photography or when using a scanner, the legibility remains limited, unlike 3D reconstruction based on PS and enhanced with simulated shadows. (The longer edge is approx. 5 cm long)

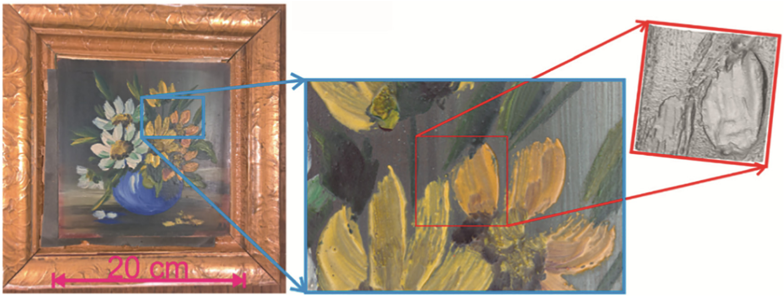

Fig. 4. The 3D details of brush strokes revealing the painter's working method can be separated from their colours to highlight the expressive execution of the work. The 3D dimension can be "amplified" as needed. (Color figure online)

4 Conclusion

This paper describes the photometric stereo method and its technical implementation, including some of its results. The technique offers the possibility to obtain visually compelling digital models of three-dimensional surfaces across a wide range of scales and sources of input images. Taking into account its physical conditions, this method is particularly suitable for "relief" surfaces; its application for objects with complex 3D shapes, for example objects with multiple topologies (such as a cup with a handle), is problematic. Further development will aim to create an easily transportable version of the device because it is easier in terms of organization for institutions, such as museums, to permit the digitization of collection items directly in their premises rather than to negotiate their loan outside the institution, which also requires extra costs of insurance.

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