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DIGITISING 3D SURFACES OF MUSEUM OBJECTS USING PHOTOMETRIC STEREO-DEVICE

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COSCH WORKING GROUP 2: Spatial Object Documentation

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ABSTRACT:

The paper describes technical and procedural implementation of an optical method for digitisation of 3D surfaces for documentation, monitoring and virtual replication of cultural heritage objects. The technique is based on the so-called photometric stereo method utilising the relationship between apparent brightness of a point on the object's surface and its orientation towards direction of illuminating light. The method yields the field of surface slopes first, which can be further transformed into surface topography. Although used less frequently than methods based on stereoscopic principles, this technique can be advantageous for digital recordings of the objects for several reasons. For example, it is easy to acquire surface texture and the surface topography in order to preserve the complete information about the object. Another advantage, implied by underlying physical principle, concerns the precision of the method being independent on the distance to the studied object. Furthermore, the measurement resolution of the method can be easily tuned to roughness and variation of the object's surface. The authors explain the potential of the method further by demonstrating an innovative technique of image processing that may benefit from a set of redundant data acquired from the surface. The processing 'recognises' 'bad' areas in images and ignores them while mining out all useful data in remaining part of the image. Improvement of objects' surface depiction, using a multiple-image method over a minimal set of images required by the principles of the method is demonstrated in results section.

1. INTRODUCTION

Creating 3D digital models of objects has become ever more popular since 2000s; the reasons being the maturisation of 3D technologies for digitisation, the affordability of 3D tools and the existence of a global network as medium for storage and presentation of virtual objects. The rationale behind these activities include: making collections in museums available to anyone; to replicate; to use more precise models of objects in physical simulations; to enable comparison of objects and to detect counterfeit objects. There are many well-known techniques for successful 3D digitisation of objects. Let us mention a few of them: stereoscopic imaging based on use of two cameras; photogrammetry; fringe projection and moiré techniques; laser scanning and 3D scanning based on time of flight calculation. However, these techniques are hindered by some drawbacks such as limited height resolution for flat or distant objects, loss of information on surface texture and color, limited density of yielded data in some cases (fringe, moiré). These limitations may therefore make a technique hardly usable in the case of fine shaped surfaces. The method presented in this paper, namely photometric stereo, has been developed by several laboratories since the 1980s. In comparison to other stereoscopic techniques, the method saw rather little implementation, yet it has a host of interesting properties. The properties worth noting are: the method's adjustability to various degrees of flatness of the object under examination; the ability to capture the textures and topography of the surface at the same time; the precision's independence on distance between the camera and the object. The early applications of photometric stereo were in the field of astronomy and then the method was applied to digitisation of surfaces of 3D objects. Photometric stereo is related to the shape from shading method (SFS), (studied by Horn, 1975). The SFS uses a single image to infer surface topography, which is only possible under specific assumptions and constrains overcoming ill-posed problem: because the single image can help in determination of one parameter, but there are in fact three independent variables - two components of the surface normal vector and albedo. Photometric stereo differs: several images acquired under controlled light conditions are processed simultaneously, forming set of equations enabling to calculate all variables

2. PRINCIPLE OF THE PHOTOMETRIC METHOD

The principles of photometric stereo were described in detail in now a standard work (Woodham, 1980) and were further developed by other authors (Solomon, 1996, Drew, 2000, Barsky 2003). As only a summary is presented here, an overview of the method can be found for example in Argyriou 2009. The photometric stereo method is based on the fundamental relation between apparent radiance of a given point on the surface under examination, and its orientation towards a source of light. This means that under controlled illumination, apparent radiance of pixel of object's surface can be used to first determine surface slopes and then the topography of the surface. The quantitative dependence between the orientation of the surface towards the light source and the surface radiance, depends on properties of the surface and can vary dramatically. The method works best on the so-called Lambertian surface that scatters incident light equally into all directions, but also can be used on specular surfaces that obey law of reflection, i.e. where light is concentrated predominantly in the direction of reflection. The general reflective properties of the surface

can be characterised by the Bidirectional Reflectance Distribution Function (BRDF) (Hertzmann 2005).
The Lambertian law can be mathematically expressed by the equation

$$I = \rho\, \vec{S}.\vec{n},$$

where *I* is the apparent radiance, *ρ* is the albedo, ***n*** is the surface normal and ***S*** is the direction of illumination.

The albedo and two components of surface normal of any point on the surface under examination represent a set of three unknowns that have to be found. Therefore at least a set of three equations has to be formed. This condition can be satisfied by creating at least three independent surface illuminations to capture the scenes. As mentioned above, there is no correspondence problem in photometric stereo. It means that because of fixed camera-object position, given image pixel corresponds to a specific point on object's surface on the whole set of acquired images. Solving the system of equations for every image pixel, brightness and direction of normal is determined for surface points. The plot of surface normals is frequently called 'a needle map' because of its resemblance to a cushion with sawing needles. Normals define slopes at surface point, indicating change of height of the terrain in a given direction, thus integrating the slopes (gradients) yields surface topography. The direct method based on straightforward integration

$$Z(x,y) = Z_0 + \int_{\Gamma} p(x,y)dx + q(x,y)dy,$$

where *Z* is the surface function and *p* and *q* are slopes of the surface provided by the photometric stereo method, leads to error accumulation in the integration paths *Γ*. In order to minimize error accumulation, it is preferable to adopt global approach. The global methods are mostly based on minimisation techniques applied to the whole surface at once. The approaches proposed by Frankot-Chellapa and Kovesi respectively (Frankot, Chellappa, 1988; Kovesi 2005) should be mentioned as these are implemented in the computer code used in present work. The Frankot-Chellappa algorithm is a global technique that is based on minimizing the cost function

$$W = \iint \left[(Z_x - p)^2 + \left(Z_y - q\right)^2\right] dxdy,$$

where Z_x and Z_y are partial derivatives of the surface function *Z(x,y)* to be determined. The algorithm was futher developed by Wei and Klette, 2001, by adding in the cost function two more terms describing small deflection approximation of the surface area and surface curvature.

3. IMPACT OF MULTIPLE IMAGES ON THE RELIABILITY OF THE METHOD

As already mentioned, the optical properties of the surface, expressed by BRDF, and the quality of illumination determine the results. When the surface is complex, it is frequently a case of one area casting a shadow over another area, or a directed reflection from the surface facet makes it difficult to determine the brightness at a given point. Therefore the system of equations cannot be solved properly for some points. If the number of these exceptional points is limited and they are scattered all over the surface, their height can be guessed from the neighbouring points, but generally a more robust technique is needed that can rely on increasing the number of images acquired. In order to achieve this quality enhancement, a new level of illumination and automation of the image acquisition process had to be introduced. Improved codes for image processing had to be written to select for every point the best subset of data. The automation has been made possible through the introduction of a new device (shown on Figure 1 – schematic drawing and Figure 2 – photograph) thus enabling the computer-controlled movement of specimen, lights and camera.

4. DEVICE DESCRIPTION

The device consists of several parts: an enclosing case ensures the rigidity of attached components and blocks the external light as can be seen in Figure 1 (letter A). The portable illumination system has been integrated into the device (letter B in Figure 1). It is mounted on a turn-table with a vertical axis and is based on monochromatic (red, green and blue) lights, as described in Valach, Bryscejn 2011 and Vavřík *et al.* 2005.

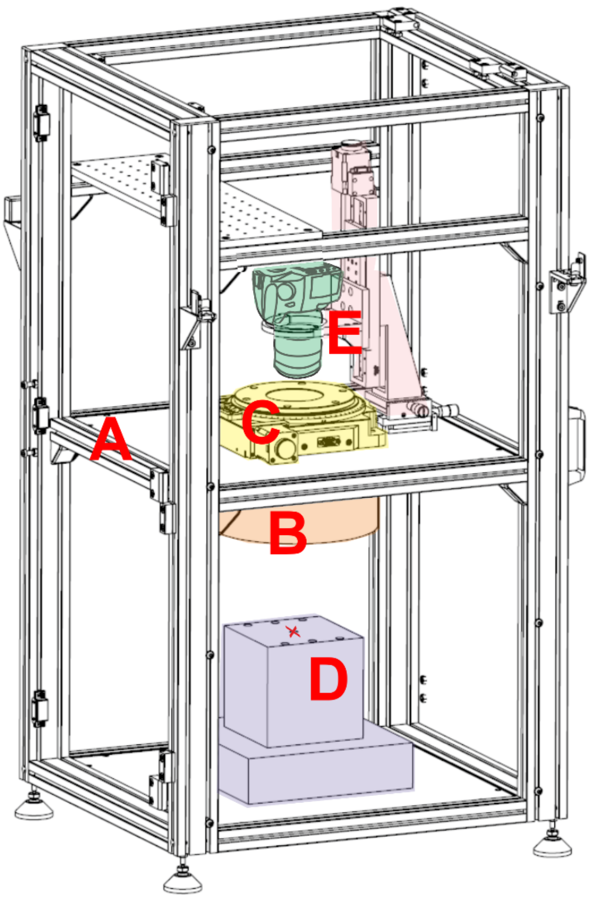

Figure 1. Schematic drawing of device for 3D digitisation. The illumination part is shown in the inset. A – modular frame, B – illumination, C – rotating stage, D – positioning table, E – DSLR camera.

The device makes it possible to capture the image by rotating lights by an arbitrary angle (letter C). Bellow the lights there is a table for placing the object to be digitalised. The table enables the object to be moved in two independent horizontal directions and vertically (letter D). A motorised vertical movement of the camera (letter

E), placed above the illumination system, is also possible. It enables bypassing the sharpening logic of the DSLR camera and allows the operator to decide upon the optimal image.

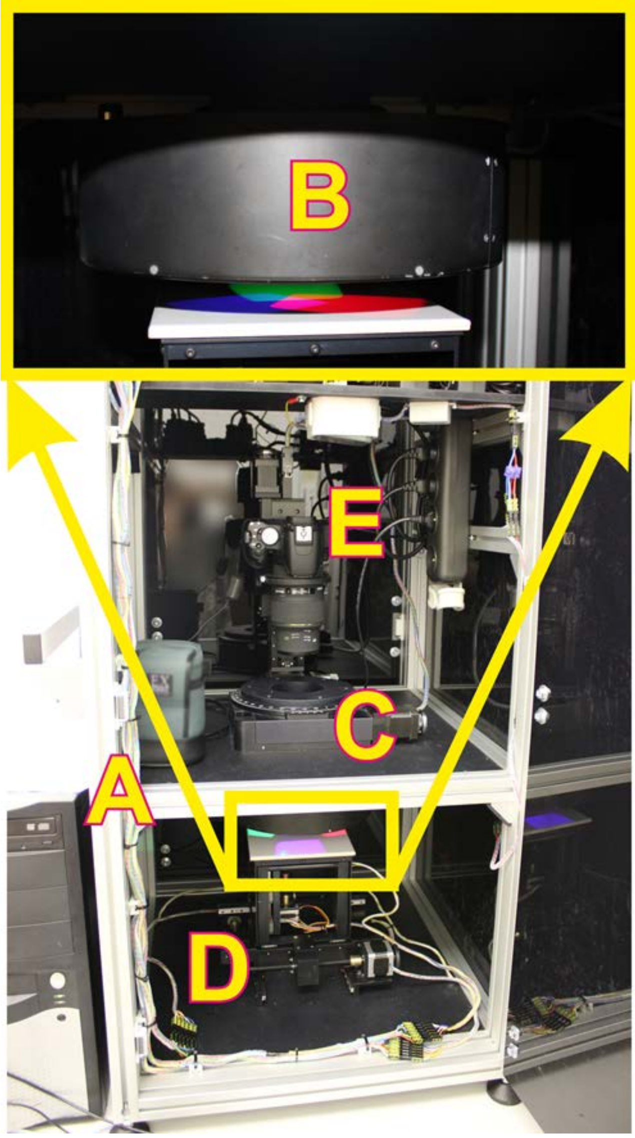

Figure 2. Device for 3D digitisation. The illumination part is shown in the inset. A – modular frame, B – RGB illumination, C – rotating stage, D – positioning table, E – DSLR camera.

The control elements built into the device enable a further image enhancement. This is possible owing to the incorporation of techniques for the extension of depth of focus, based on the combined hardware capability and the focus stacking technique.
The device can be operated manually using a game console. It can also be programmed for the automatic operation. It takes minutes to complete the task, including the rotation of lights covering the full angle in steps of few degrees, and capturing the images. The final processing of acquired images is a computer-intensive task. It involves handling significant volume of data in the form of many, high-resolution images recorded on each run of the device and stored in raw format. The computer code for processing the image stack (that represents the object in different illumination conditions) selects a suitable subset for every pixel of the surface. Based on the subset, a normal orientation and brightness is subsequently determined of a given pixel in such a way that it also enhances the consistency of the results by means of the Frankot-Chellapa procedure. It has to be said that the topography can be determined up to the scaling factor. Therefore, in order to arrive at true height values, a calibration object has to be included in the scene.

5. PRESENTATION OF RESULTS

Among many suitable applications in the area of cultural heritage objects documentation, the capability of the device is demonstrated on trilobite fossil from the collection of Natural History of National Museum in Prague. Fossils' collection is especially suitable for the photometric stereo method because of the size and optical properties of the objects. Photometric stereo 3D recording of the trilobite is found comparable to the result obtained by an alternative technique – laser profilometry. The profilometric technique scans a surface in steps of 0.02mm length, creating a fine record of the surface points measured with 20 micrometer resolution. Finer resolution cannot be achieved by this technique, therefore some details on the fossil tail are missing, while the photometric stereo depicts them as shown on Figure 3A and 3B. On the other hand, the necessity to scale the recorded surface in photometric stereo implies exaggeration of some surface features as seen on comparison of height profiles over selected line on the surface – Figure 4.

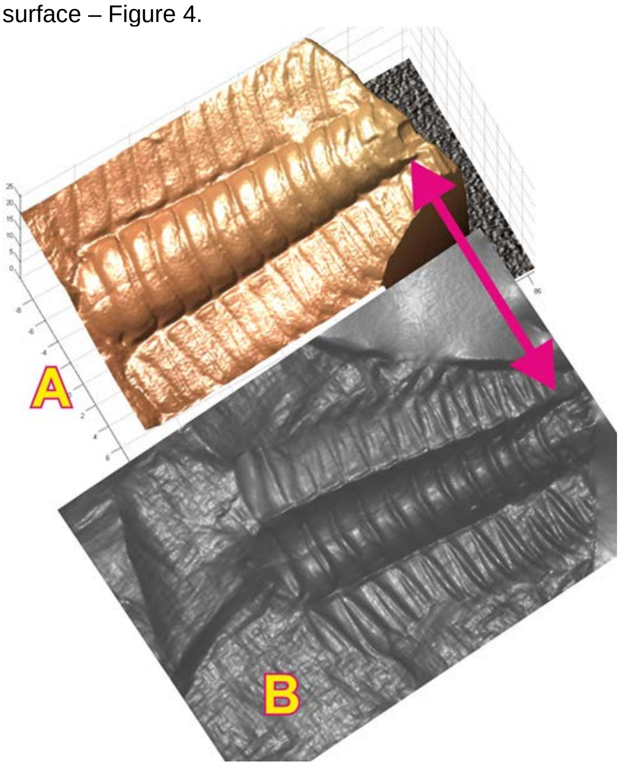

Figure 3. Comparison of the 3D model of trilobite as rendered through (A) laser profilometry and stereo (B) photometric. Arrow points to difference in details.

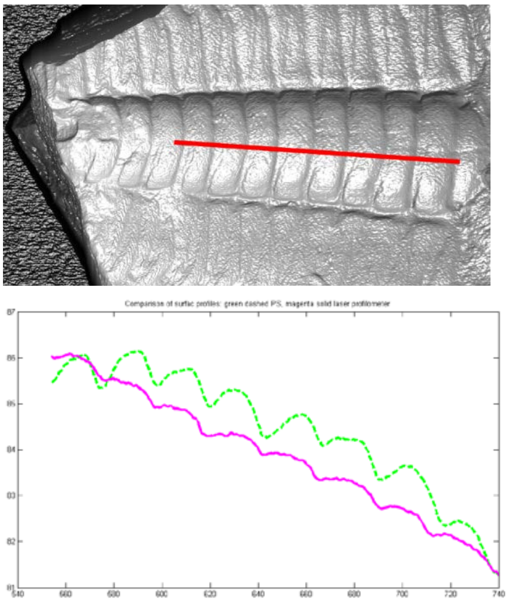

Figure 4. Comparison of the results from laser profilometry (magenta line) and photometric stereo (green dashed line) for selected line on the object (red line in the upper part of the figure).

6. CONCLUSION AND FUTURE WORK

The device utilising principles of photometric stereo 3D digitisation method was demonstrated and physical background of the method outlined. Although less popular than other 3D recording methods, it is capable of comparable results to those obtained by established methods. The device can be used for scanning and subsequent replication of small object as shown in Figure 5 depicting original fossil and its enlarged 3D printed replica. A class of relatively flat objects with one significant side containing relief like coins, medals, engravings, seals, fossils is especially suitable for the photometric stereo method.

Future development will focus on increasing the size of objects that can be measured by combining digital models of adjoining parts of the object.

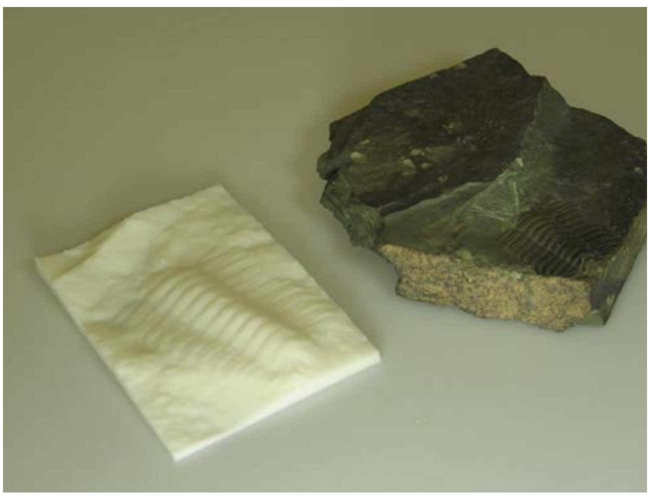

Figure 5. Original fossil and its enlarged replica created using 3D printer

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8. ACKNOWLEDGEMENTS

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