Proceedings of the Colour and Space in Cultural Heritage session at the Denkmäler 3D Conference, "From low-cost to high-tech. 3D-Doc. in Archaeology & Monument Preservation", The LWL Industrial Museum Zeche Zollern, Dortmund, 18 October 2013, *COSCH e-Bulletin*, No. 1 (2014), Edited by A. Bentkowska-Kafel and O. Murphy

Low-cost 3D Scanning Technology Based on Active Stereovision

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COSCH WORKING GROUP 2: SPATIAL OBJECT DOCUMENTATION

KEY WORDS: 3D, stereovision, digital fringe projection, RGB texture, low-cost, off-the-shelf components

ABSTRACT:

The Authors present a low-cost optical technology for measuring the 3D shape of objects together with the RGB colour texture. The measuring principle is based on stereovision combined with the projection of structured-light patterns. Four shifted sinusoidal fringe patterns are projected onto the object to get the corresponding phase map. Common phases are then identified in the pair of cameras. Finally 3D data are obtained by triangulation, based on the epipolar geometry and the system's calibration parameters previously computed. The RGB colour information is retrieved from the captured images when the object is illuminated with a uniform field from the projector. A 3D scanner prototype based on this technology has been developed for digitising objects of around 0.5 x 0.5 m^2 over 180 degrees. Two lateral low-cost sensing units, each with a pair of CMOS colour cameras and a DLP-based projector scan the left and right sides of the object. Both 3D views are then precisely stitched with the aid of the system's calibration parameters. A graphical user interface has also been implemented to operate with the prototype. Preliminary experimental results showing the performance of the prototype to digitise different body parts of a female mannequin are presented.

1. INTRODUCTION

Technologies for contactless 3D digitisation of cultural heritage objects have gained popularity in recent years (Blais, 2007; Sitnik, 2010; Bunsch, 2012). A number of optical techniques, depending on the characteristics of the test object, can be selected for 3D scanning of artworks. Laser scanning (Barber, 2011), structured light projection (Tang 1990) and photogrammetry (Debevec, 1996) being the most common ones. All these technologies have advantages and disadvantages, making it difficult to establish categorically which one is more adequate for a particular application.

Photogrammetry enables the reconstruction of the 3D shape from a minimum of two single images (stereophotogrammetry) taken from different views. The main benefits of this technique are its simplicity and the relatively low cost of the setup. However, it requires higher computational effort and the results are not always very accurate. As opposed to this passive technique, both laser profilometry and structured-light projection are active techniques. They use a light source and share the same measurement principle, based on 3D triangulation from the deformation of the projected light over the surface to be measured. The most significant difference between the two techniques is the way in which light is projected for scanning the object, being a single point or laser line. The method of laser scanning involves moving the laser line mechanically along the object A structured-light pattern, comprising a full-field, is projected over the object surface, yielding a significant reduction of acquisition time.

The paper describes the design and development of a 3D scanner prototype, based on a combination of two aforementioned technologies, namely stereophotogrammetry (also called stereovision) and structured-light projection. Similar systems combining structured-light and stereo into a common framework can also be found in literature (Zhang 2003; Davis, 2005; Bräuer-Burchardt, 2008). Our system is built with commercially available, low-cost components. In case of system failure, the faulty components can be replaced with those readily available in the technical component market. A graphical user interface (GUI) has been developed alongside hardware to fully control the prototype in a user-friendly way.

The paper is divided into three sections. The first describes the 3D scanner prototype, while in the second, some preliminary 3D measurements, together with the RGB colour texture obtained with the scanner are presented. Finally, the last section offers some conclusions and outlines future work.

2. DEVELOPMENT OF THE 3D SCANNER PROTOTYPE

The contactless 3D scanner prototype was developed based on well-known techniques of stereovision combined with the projection of fringe patterns. The device is conceived for scanning medium-sized objects at a relatively fast acquisition time. The main instrument parameters are as follows:

- Field of view (FOV) ≈ 0.5 x 0.5 mm^2
- Spatial resolution < 1 mm
- Accuracy (Z dimension) < 0.5 mm RMS
- Acquisition time < 5 s per whole FOV
- Scanning limited to 180 degrees
- Output 3D cloud of points plus RGB texture
- Low-cost scanner prototype

Based on the aforementioned specifications, the scanner is designed with computer-aided design (CAD) software and includes readily available components. The CAD design of the prototype is shown in Figure 1, while the built prototype is depicted in Figure 2.

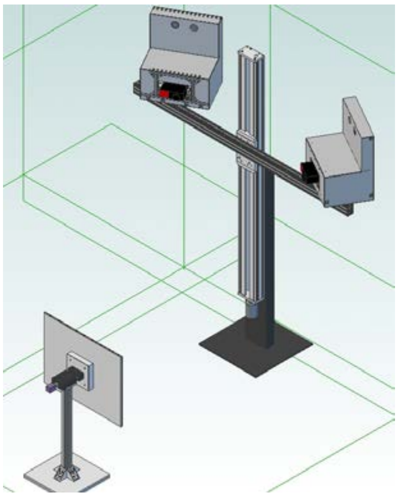


Figure 1. Computer aided design (CAD) of the 3D scanner prototype.

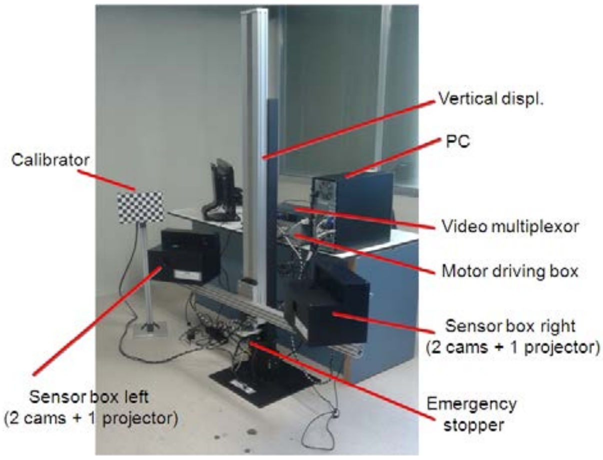


Figure 2. 3D scanner prototype developed to measure medium-sized objects over 180 degrees positioned at a meter distance.

The system consists of: two lateral sensing units (placed right and left), each with a digital light projector (DLP), based on the digital micromirror device (DMD) technology developed by Texas Instruments; a pair of megapixel colour cameras in a standard stereo geometry; a motorised vertical guide to adjust the position of the sensing units relative to the height of the object; a board to accurately multiplex the projected patterns between the sensing units, and a standard personal computer (PC) to control the scanner. For each sensing unit the commercial DLP sequentially projects four sinusoidal patterns shifted π/2 over the object, which are then captured by the stereo cameras. Through applying a conventional, four step phase-shifting processing algorithm, the phase maps of both cameras are retrieved (Malacara, 2007). Afterwards, phase maps are unwrapped, based on the well-known Goldstein algorithm, which shows a good balance between a fast processing time and good quality of performance (Ghiglia, 1998). Finally, corresponding phases between both cameras are identified and 3D data are obtained by triangulation based on the epipolar geometry and the system's calibration parameters previously computed. The RGB colour information is retrieved from the images captured when the object is illuminated with a uniform field from the projector. Figure 3 shows schematically this measurement procedure.

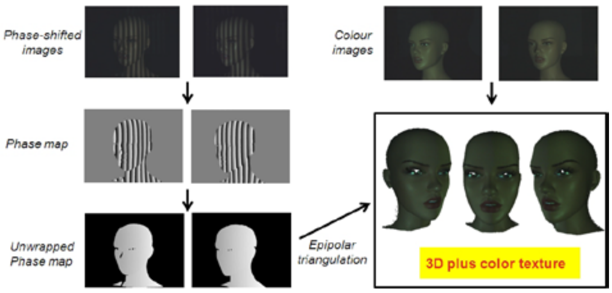


Figure 3. Measurement procedure performed to obtain the 3D data with RGB colour superimposed for each sensing unit. Images of the face of a female mannequin are presented as an example.

The individual 3D data sets measured from the left and right views are then automatically stitched together to get the complete 3D topography, with the aid of the system's calibration parameters previously computed for both units. The calibration is performed using the technique proposed by Tsai (Tsai, 1987) with a calibration rigid board wearing a black and white checkerboard pattern, which can be seen within the system's components in Figure 2. In our case, the calibration board is attached to a motor that places it in five different Z positions (i.e. normal direction relative to the plane of the calibrator) with a precision of 5 μm. The centroids (i, j) of the intersection of checkerboard squares are computed for the cameras at the different images. As far as real 3D world coordinates (X, Y, Z) of the checkerboard points are known, the calibration parameters are thus obtained by solving the equations that account for the correspondences between the points in the scene and the points in the images, according to Tsai's method.

In addition to the hardware, a GUI was developed to control the scanner prototype (Figure 4). The GUI allows the user to visualise in live mode the images shown by the cameras and adjust their vertical position relative to the object with the aim of facilitating its positioning. This device also allows controlling the light intensity in order to avoid saturation of the images depending on the reflectance characteristics of the object. Both the automatic calibration and the 3D measurement process are executed through this user interface. The GUI also provides a basic form to input some information about the object (name, date of acquisition, etc.) which is also stored in the computer together with the 3D cloud of points file.

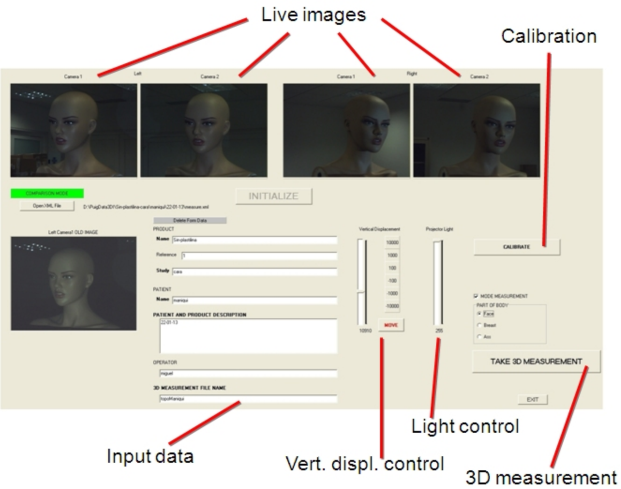
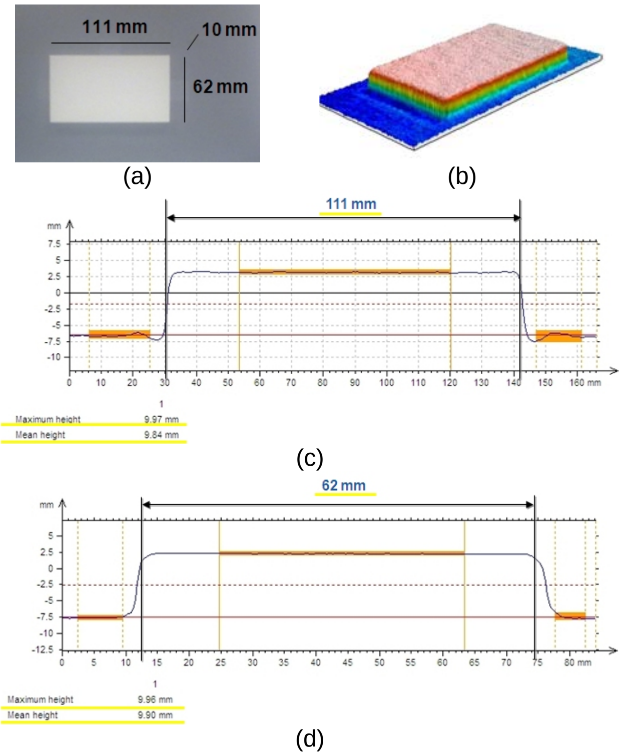


Figure 4. Image of the GUI developed to control the scanner prototype in a friendly way, particularly designed for operators with no specialist engineering knowledge.

3. PRELIMINARY RESULTS

3.1 Accuracy of measurements

A reference rectangular object with well-known dimensions and almost perfect flat surface was employed to validate the accuracy of the 3D measurements (Figure 5a).



(a) (b)

(c)

(d)

Figure 5. (a) Reference object with a white flat surface used to validate the measurement accuracy of the scanner, (b) 3D reconstruction of the measured object, and extraction of the mean (c) horizontal and (d) vertical profiles with dimensions highlighted.

Ten measurements of the reference object were carried out. An example is shown in Figure 5b. From these 3D measurements, the RMS difference between the ideal uniform Z values expected and the real Z values obtained was computed. The results showed a Z accuracy of 0.279 ± 0.007 mm, which is within the expected specification. The small deviation (± 7 µm) between measurements highlights the good repeatability performance of the scanner. The dimensions were analysed with a surface imaging and metrology software called MountainsMap Universal 6.2 (Digital Surf SARL, 2013). Figures 5c and 5d represent the results of the mean profiles along X and Y dimensions, matching the reference horizontal and vertical dimensions, and also providing a good approximation of the nominal Z dimension (10 mm) with average height values of 9.84 mm and 9.90 mm, respectively.

3.2 3D measurements of a mannequin

Preliminary measurements have been carried out for testing the performance of the 3D scanning prototype when measuring diffusive objects. Measurements of different body parts of a female mannequin placed at a one meter distance from the scanner are shown to demonstrate the scanning capabilities of the system in an object that resembles a human sculpture. Scans of the face, torso and legs are shown in Figures 6a, 6b and 6c, respectively. The system takes 4 s to acquire each 3D scan with a spatial resolution of 0.3 mm, computed as the average distance between neighbouring points of the 3D cloud.

(a)

(b)

(c)

Figure 6. 3D cloud of points with RGB colour superimposed. (a) the face (b) the torso and (c) the upper part of the legs of a female mannequin.

4. CONCLUSIONS AND FUTURE WORK

A 3D scanner prototype based on the stereo fringe projection technique was designed and constructed. The system provides full-field scanning of diffusive objects giving the 3D cloud of points and the colour information (X, Y, Z, R, G, B). The prototype has been developed using low-cost, readily available components, making it a cost-effective device with the possibility of quick replacement of parts in the eventual case of failure during normal use. A GUI has also been implemented to operate the scanner in a user friendly way.

The scanner provides contactless measurements of medium-sized objects (around 0.5 x 0.5 m^2) with a spatial resolution of 0.3 mm and accuracy below 0.3 mm RMS. It should be stressed that the technology is easily scalable for digitising, both smaller or larger objects, by simply changing the optics. The current system has been designed for scanning objects over 180 degrees. This means that for example in the particular case of a face scanning, a 3D reconstruction of the face from the right ear to the left ear is obtained.

Preliminary measurements of different zones of a female mannequin have demonstrated the capabilities of the prototype.

Two main directions are envisaged for future research into adapting the system for cultural heritage digitisation. These are: (1) the optimisation of the algorithms to enable the scanning of artworks over 360 degrees and (2) the redesign of the mechanical part for building a handheld device that can be relatively easier to handle and transport.

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Acknowledgements

The Authors gratefully acknowledge the support of the European Cooperation in Science and Technology, the COST Action TD1201 "Colour and Space in Cultural Heritage" (www.cosch.info). The authors also would like to thank the Organisation and Program Committee of the Denkmäler3.de 2013 conference for giving us the opportunity to present our work at this event. The authors are truly grateful to ACC1Ó for supporting the work through a public funding of the research project “3DI: Noves Aplicacions de la Imatge 3D”. Finally, the Authors also acknowledge the MINECO DPI2011-25525 project which has partially funded this research.