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Preliminary Study on the 3D Digitization of Millimeter Scale Products by Means of Photogrammetry

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Abstract

Photogrammetry is a passive 3D digitization technique, mainly oriented to large sized objects, since its origins are in architectural and civil engineering. With the continuos development of digital imaging hardware and software, photogrammetric applications are involving smaller and smaller fields of view, with some critical aspects such as the depth of field getting narrower. In this conditions the lack of focus becomes important and affects heavily the possibility of accurately calibrate cameras. Bi-dimensional calibration patterns are affected by this problem when the camera principal axis has an angle with the pattern plane higher than a critical value. Moreover, the accuracy of the pattern, in terms of both shape and 3D positions of the targets, becomes critical decreasing the size of the pattern. In this paper the authors address these problems through a comparison of several calibration patterns included into the open source computer vision software library called OpenCV. 3D digitization of a small object is presented to test the best resulting calibration, using a consumer reflex camera equipped with macro lens and extension tube.

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1. Introduction

Photogrammetry can be defined as the technique to determine the geometric properties of objects from photographic images. It can be considered a quite old measurement technique and can be dated to the mid-nineteenth century. Its main applications have been related for more than one century essentially to very large scale measurements in fields such as topographic mapping, architecture, geology.
The development of digital photography and the continuous evolution in sensors resolutions and the increasing power of image matching software, have pushed the applications smaller scale in several fields such as manufacturing engineering, with the name of Digital Close Range Photogrammetry (DCRP).
DCRP can be used as an integration of 3D laser scanner or alternatively to it. The tools needed are digital cameras, a dedicated software and a computer. The object to be detected are provided eventually with markers or control points, and subsequently photographed from different angles.
The images obtained are then loaded into a software which finds relationships between areas in adjacent images, associating each marker in each image to a 3D point processable by Computer Aided Design (CAD) software.
Hundreds of 3D points can be measured in very short time. Using professional digital cameras, at the end of 90s, the first commercial software allowed (at high cost -> $ 100,000) excellent accuracies, for example in aeronautics for the measurement of 15 m helicopters (3000 points, accuracies of 0.1 mm [1]). Special cameras with intelligent integrated computers were used for the immediate processing of images, getting on a 1.2 m parabolic antenna diameter (Accuracy of 1/10000 [2]). Other research has developed user-friendly software to use non-professional digital cameras for metrological purposes [3].
Estler [4] proposed in 2002 a review of methods for the metrology of large objects: photogrammetry resulted significant for structural monitoring of components of a very large electric motor (diameter 23 m, with uncertainty of 0.5 mm or 1/50000), where it was impossible to use other techniques such as laser tracking, due to instability and vibrations. At CERN a photogrammetric system was used for positioning, quality control and dimensional deformations of large objects [5], from 15 to 20 m, measured at distances of few meters (accuracy of 1/110000) [6].

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Actually photogrammetry is also used for the reconstruction of entire complex surfaces [7] with matching algorithms based on feature areas generating dense point clouds of complex objects. As regards the generation of virtual models of cultural heritage parts, digital photogrammetry has slightly higher costs of terrestrial laser scanning, however, justified by the much higher degree of detail achieved (5mm/10 m) [8]. The accuracy of photogrammetry increases with the number of images, the measured points per image and the resolution (number of pixels) [9]. One of the most recent developments is the production of digital Dense Surfaces Models (DSM) with aerial photography [10]. It can generate the DSM of archaeological objects nature quickly and with high precision [11]. The combined use of commercial software and digital cameras allows accurate measurement and modeling at affordable prices (accuracy 1/10.000), verified by comparison with a Leica TC2002 total station [12]. The major software vendors are realizing photogrammetry algorithms to automatically extract surface models (DSM) from images, for example to process thousands of images and create 3D models of cities. Thanks to the superior data collection capability of digital cameras, the DSM generation now leads to higher density of points at a lower cost than Lidar scanning [13]. Specific techniques and algorithms for automatic extraction of features and area matching have been developed for the generation of the DSM model [14] also in images that do not meet the conditions of normal acquisition of photogrammetry, in extreme geometric conditions. The investigation was carried out in [15][16] reporting the development of an automatic procedure for the generation of point clouds from a network of high precision multi-images.

Small objects need to be 3D Digitized with high magnification ratios, for example using macrophotography, where macro reproduction ratio of the subject is greater than or equal to 1. This condition can be reached essentially using properly designed lenses, called macro lenses that can be powered by extension tubes to increase magnification. A macro lens is designed to obtain focused images at low distance from the object, allowing to put in evidence details. To do this, manufacturers exploits the following basic photographic optics equation:

$$h = \frac{d}{2} \pm \sqrt{\frac{d^2}{4} - fd} \qquad (1)$$

which describes the image distance h (between lens and image plane) as a function of the selected focusing distance d (between object and image plane) and focal length f. If f is lower than $d/4$ a focused image cannot be obtained. As a consequence there is a maximum value for d but there is not a minimum value. Moving the lens very near to the object and increasing the distance d will increase the magnification ratio and does not contrast the (1). This task can be performed easily and cheapily with extension tubes. The advantages are that the solution is much less expensive than purchasing a dedicated lens, it provides a flexible and upgradable increase in magnification with virtually any camera lens, no additional glass elements are positioned between subject and camera minimizing any potential loss in image quality. The disadvantages are that extension tubes reduce depth of field, cause the lens to focus more closely than it was designed for and high magnification images usually have lower quality than with a dedicated lens.

As regards the use of photogrammetry for small objects, in [18] one of the first attempts is described. In that paper three systems are compared, namely a macro-lens stereomicroscope, a partial metric camera, equipped with zoom lenses with focal lengths in the range 40 to 120 mm and a solid state video-camera with zoom lenses, where the best performance is obtained with the use of macro lenses.

Digital imaging is also used in [19] where the photogrammetric 3D Digitization of small features is addressed with the expression Digital Very Close Range Photogrammetry. Also in this paper, a comparative evaluation of the zoom lens and the macro lens has been discussed, after mounting a macro lens and a zoom lens on a digital single lens reflex camera: the result is a better performance of macro lens for small objects.

For any object size the photogrammetric approach is composed of the following phases [20]:

- Camera Calibration to obtain intrinsic parameters;
- Images acquisition, minimum two pictures;
- Pre-processing with digital filters;
- Correspondence search;
- 3D Computation for matching and triangulation;
- Mesh and texture generation;
- 3D Model analysis and visualization.

Among these tasks, the calibration is crucial for an accurate 3D digitization.

2. Related Research

Actually the most diffused methods are based on Brown's model [21], founded on the first order pinhole camera model. Alternative models exist but the distortion coefficients introduced by Brown have shown to be adequate even for accurate metrology applications. Most calibration methods exploit the correspondences between 3D points of known geometry and 2D points on the image plane, seek for a set of model parameters (intrinsic calibration) and camera orientation with respect to the world coordinate system (extrinsic calibration). The distance between the measured 2D points and their respective projections obtained by applying the calibrated camera model to the 3D points is minimized and is defined as Reprojection error. It is possible to solve the calibration problem by using simple linear techniques, such as those suggested by Faugeras [22] and Hall [23]. Alternatively, it is necessary to introduce more complex approaches that usually alternate a linear technique to optimize a subset of the parameters and an iterative refinement step.

One of the first calibration methods accounting for one radial distortion coefficient was proposed by Tsai [24], while subsequent approaches by Zhang [25] and Heikkilä [26] have been able to deal respectively with two and three radial distortion coefficients and the latter estimates two tangential distortion coefficients too. For an exhaustive comparative evaluation of calibration models please refer to [27].

The choice of the calibration object must take into account the calibration accuracy required and the manufacturing accuracy of the targets. In general, 3D calibration objects should lead to a better calibration since intrinsic and extrinsic parameters are decoupled. Moreover, the presence of distinct depth information reduces the correlation between focal length and the lens distortion. Unfortunately, the fabrication of an accurate 3D target can be a very complex task.

However, planar calibration patterns are the most used and in literature some studies are also dedicated to the interesting task of calibrating with inaccurate planar patterns [28][29]. In this paper, the comparison between three kinds of calibration patterns when applied to 3D Digitization of small objects is presented.

3. Proposed Approach

The hardware used in this paper is constituted by a Canon 400D with an extension tube equal to 32 millimeters and a Canon EF-S 60mm Macro USM lens, aperture: f/2.8-f/32, focal length: 60 mm, minimum focus range: 20 cm.

As regards the computation of the size of the calibration pattern and assuming that the best possible configuration is achieved covering the field of view as large as possible, the size of the pattern has been adapted. On the other hand it is well known that the quality of calibration, as regards perspective information, increases with the angle between the pattern plane and the sensor plane. As a consequence it is very important to take images of the pattern with angles as high as possible. But being the depth of field narrow, high angles lead to blurring for the more extreme dots. Consequently, a geometrical study founded on photographic optics is necessary.

In order to know the dimension of the calibration pattern it is not possible to consider the well known equation (2):

$$\frac{1}{f} = \frac{1}{g} + \frac{1}{h} \qquad (2)$$

where f is the focal length of the lens, g is the distance between object and lens, and h is the distance between lens and sensor. Indicating with d the focusing distance: $d=g+h$ and substituting it into the lens equation we obtain the equation (1). It is possible to obtain a solution only if d is greater than $4f$, but according to manufacturer specification we had d= 200 mm and f= 60 mm, and the above condition was not satisfied.

In order to know the dimension of the pattern calibration, a practical engineering approach has been used, extrapolating the parameters by manufacturers declaration that is: for a 12mm Extension Tube a magnification equal to 0.2x at infinite focus, and 25mm Extension Tube a magnification equal to 0.44x. Extrapolating these data it is possible to obtain for a 32 Extension Tube a magnification equal to: (0.44-0.2)/(25-12)(32-25)+0.44=0.57. Consequently it is possible to compute the scene size, just applying the magnification ratio and knowing the sensor size, that was in our case: 22.2 mm x 14.8 mm, leading to a maximum dimension of the scene equal to: 22.2/0.57=39 mm and 14.8/0.57=26 mm.

As regards the patterns used, the authors' choice was to configure the three calibration patterns of the open source camera calibration library OpenCV [31], namely the Checkerboard, the Symmetric Dots Pattern and the Asymmetric Dots Pattern, to obtain the same number of points for each pattern and approximately the same size of the pattern to cover an as large as possible area. This choice was due to the need for unique comparisons between the behavior of the kind of pattern to calibration quality, which excluded other effects, since it is well known that the number of points considerably affects calibration quality.

The experimental campaign was carried out by means of a full factorial plan. The variables chosen as input for the plan were pattern geometry and the number of photos. Both these two parameters were chosen considering that the capability of the pattern can change in relation to the position and number of images.

In common practice photogrammetry it is well known that the greater the number of images, the more affordable the calibration. As stated in [30], the images must include perspective information obtained by means of images with high angles of view (the angle between the principal axis of the camera and the pattern) but this is in contrast with a narrow depth of field.

As a consequence the authors have defined a protocol to capture the images, correlating the number of images to the perspective information included in the images. Only rotations of the pattern have been considered. The rotation angles have been chosen imposing that the 4 image set is made up only of fully focused images as were the 7 images too but three images are borderline as regards focus, while the 10 image set also includes blurred images.

4. Results

4.1. Calibration

The behavior of the calibration patterns has been analyzed in this paper, using a full factorial plan with 2 factors and 3 levels. The two factors are the pattern type and the number of images. The output variable is the re-projection error defined as the average of the image distances, in pixels, between the measured points belonging to the pattern and the same points on the corrected image after calibration.

As stated before, the patterns used are OpenCv calibration patterns [31] and the authors' choice has been to configure the three possible patterns to have the same number of points for each and approximately the same size of the pattern to cover an area of the field of view as large as possible. This choice was due to the need to compare uniquely the behavior of the pattern affecting the calibration quality, excluding other effects, since it is well known that the number of points and the dimension of the pattern affects heavily the Reprojection error. Considering the geometry of the patterns and of the camera sensor this choice resulted in quasi-square patterns. In all cases, the computed intrinsic parameters have been both tangential and radial distortions.

In Figure 1 the mean of the means of all the response variables is shown where the lowest values of Reprojection errors are for the asymmetric dot patterns, moreover considering the patterns in a global view the re-projection error tends to increase more slowly increasing the number of photos.

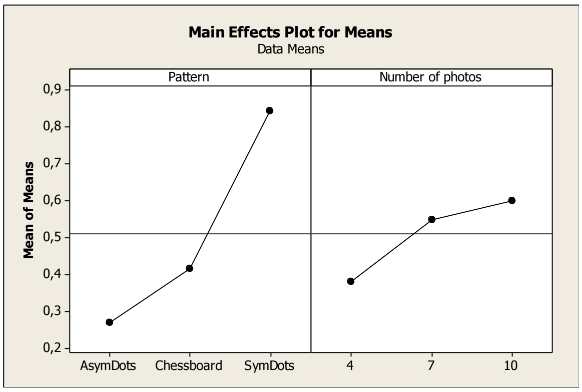

Figure 1: Main effect plot of the average values of Reprojection error

Analyzing more deeply the results, through the interaction plots showed in Figure 2 and Figure 3, in both cases patterns with dots behave better than the checkerboard with the increase of the number of images. The difference between these figures is that in Figure 2 the Reprojection error is computed forcing tangential distortion parameters to zero while in Figure 3 the tangential distortions are computed.

They put in evidence a lower growth of the Reprojection error for Asymmetric Dots with respect to the checkerboard, while Symmetric Dots, characterized by higher errors in general, show an interesting result of reduction or near stabilization of the error with 10 images. This behavior can be justified very well by a better behavior of both symmetric and asymmetric dots with respect to checkerboard in blurring conditions. In particular, the Reprojection error decreases for Symmetric dots when tangential distortions are not computed for 10 images. This can be due to the reduction of unknowns in the model coupled with a high average error for seven images and asymmetric dots. However these results put in clear evidence that asymmetric pattern gives in blurring conditions a better performance than other patterns.

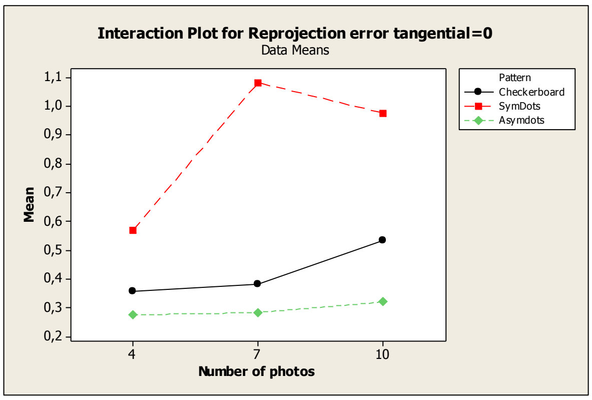

Figure 2: Interaction plot for Reprojection error with no computation of tangential distortions

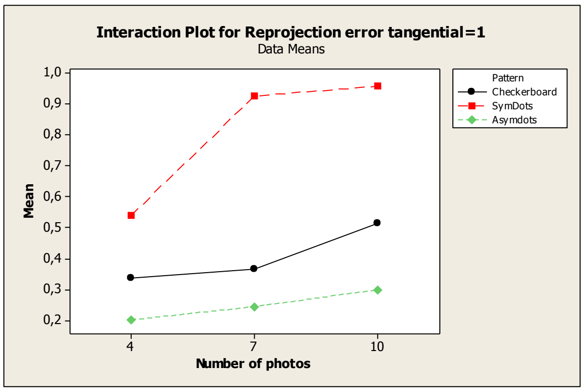

Figure 3: Interaction plot for Reprojection error with computation of tangential distortions

4.2. 3D reconstruction

In order to evaluate the capability of the calibration method with the asymmetric pattern, the authors modified the pattern in order to get an area, as large as possible, covered by the dots. The pattern used is shown in Figure 4, it is compatible with Opencv routines and its ratio is 1.69, as near as possible to the camera format 3:2, while the largest size was as high as possible since the maximum size of the scene was 39x26 mm, as stated before.

The pattern was used to capture the 16 images shown in Figure 5, that shows the reduction of focused dots when increasing the angle.

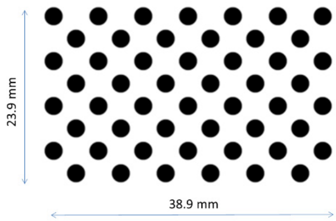

Figure 4: Calibration pattern

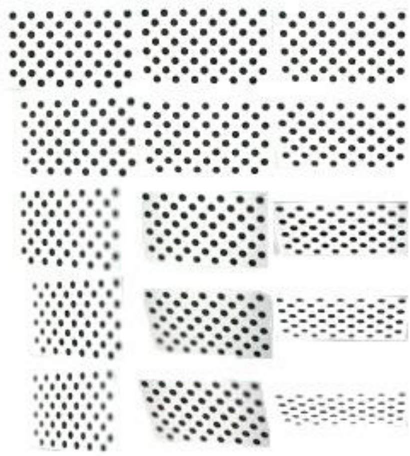

Figure 5: Collection of the Calibration images

In Table 1, the Reprojection error in pixels is shown for several subsets of the entire set of images used for this calibration.

Pattern	Number of photos	Reprojection error with tangential computation
AsymDots	4	0,310
AsymDots	7	0,397
AsymDots	10	0,485
AsymDots	13	0,514
AsymDots	16	0,546

Table 1: Added rotation angles of the pattern in degrees

Reprojection error is a geometric quantity that compares the measured positions of image points (2D) to the Reprojection of the 3D points, via the estimated camera parameters. The Reprojection error tends to increase with the number of images especially if higher angles are used to take photos. In fact, the approximation error in detecting the center of the dots increases since the each dot tends to reduce its circularity in the images.

The test has been carried out using the commercial software Agisoft Photoscan version 0.9.1, changing the calibration intrinsic parameters as resulting from Opencv calibration for the aperture f/32 and infinite focus, to approximate at best the pin-hole model since diffraction effects were not evident during calibration.

As regards non–contact measuring devices, metrological standards have already been developed deriving by contact-based techniques, but suffer of checking parameters, which are very similar to those attainable from Coordinate Measuring Machines [32]. In this paper, a preliminary evaluation of dimensional accuracy has been made by comparing point clouds with commercial Computer Aided Design (CAD) software after scaling the photogrammetric point cloud and a best-fit alignment.

The evaluation was carried out measuring the coin both with the photogrammetric calibrated camera and with the 3D digitizing system Optimet Conoscan 4000 as gold standard. This combines a non-contact, single-point laser measuring sensor (Conoprobe Mark 3.0 equipped with a 50 mm lens HD, a declared accuracy of 2.5 microns on the z axis) with an accurate 3 axis motion system.

As a case study, a 20-eurocent coin was digitized with the calibrated camera and with the Conoscan. Details of the textured point cloud are shown in Figure 6. The point cloud of the coin has been scaled with a CAD procedure, measuring the real diameter with a digital caliper and scaling the measured point cloud consequently. Dimensional analysis has been carried out by comparing the scaled point cloud to the point cloud digitized with the Conoscan 4000 (Figure 7).

The average distance resulted to be -4 microns, the average of positive distances was 24 microns, the average of negative distances was -36 microns; standard deviation was 89 microns. These results put in evidence the validity of the 3D alignment and an interval of 60 microns between the averages of positive and negative values. The areas with the highest differences are non-green areas that are concentrated near the protrusion of the coin. This effect can be explained by a loss of resolution of the laser sensor since protrusions generate areas hidden to the laser. This effect does not regard the photogrammetric relief since the camera can be oriented in any direction and digitize also these areas accurately.

Figure 6: Detail of the textured point cloud

Figure 7: Coloured comparison map of the point clouds

5. Conclusions

In this paper a preliminary study of the OpenCv calibration algorithm based on the pin-hole model, when applied to the 3D photogrammetric digitization of small features, has been presented. The photogrammetric approach showed in this case a low accuracy comparable to more expensive micro-scanning systems but with the intrinsic and very powerful advantage of a 3D digitizing system with a practically infinite depth of view, this feature being dependent on the number of images, while commercially available systems have limited depths of view. Further research will be aimed to improve the digitization results verifying the accuracy of the calibration pattern and applying compensations to measured inaccuracies of the calibration patterns.

References

[1] C. S. Fraser: "Some Thoughts On The Emergence Of Digital Close Range Photogrammetry", Photogrammetric Record, 16(91): 37–50 (April 1998)

[2] G Ganci..: "Developments in Non-Contact Measurement Using Videogrammetry", Boeing Large Scale Optical Metrology Seminar. Long …, 2000

[3] C.S. Fraser, K.L. Edmundson, "Design and implementation of a computational processing system for off-line digital close-range photogrammetry", ISPRS Journal of Photogrammetry & Remote Sensing 55, 2000. 94–104

[4] W. T. Estler, K. L. Edmundson, G. N. Peggs, D. H. Parker: "Large-Scale Metrology – An Update"; CIRP Annals- 51-2, 2002 – Elsevier, pp 587

[5] Mayoud M.: "Large Scale Metrology for Research and Industry – Application to Particle Accelerators and Recent Developments", TS23 – Engineering Surveys for Industry and Construction Works, TS23.5 FIG Working Week 2004, Athens, Greece, May 22-27, 2004, 1-15 Behrens A., Lasseur C., Mergelkuhl D.: "New Developments In Close Range Photogrammetry Applied To Large Physics Detectors", IWAA2004, CERN, Geneva, 4-7 October 2004

[6] . G. W. Johnson, S.E. Laskey, S. Robson, M. R. Shortis: "Dimensional & Accuracy Control Automation In Shipbuilding Fabrication: An Integration Of Advanced Image Interpretation, Analysis, And Visualization Techniques", ISPRS 2004 Congress XX; Istanbul, Turkey

[7] T. P. Kersten: "Combination and Comparison of Digital Photogrammetry and Terrestrial Laser Scanning for the Generation of Virtual Models in Cultural Heritage Applications", The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage, VAST (2006), pp. 207–214, M. Ioannides, D. Arnold, F. Niccolucci, K. Mania (Editors)

[8] F. Remondino, S. El-Hakim "Image-Based 3d Modelling: A Review", The Photogrammetric Record 21(115): 269–291 (September 2006)

[9] R. B. Haarbrink, H. Eisenbeiss, "Accurate DSM Production From Unmanned Helicopter Systems", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Vol. XXXVII. Part B1. Beijing 2008

[10] J. Zheng, W. Yuan, S. QingHong: "Automatic Reconstruction For Small Archeology Based On Close-Range Photogrammetry", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Vol. XXXVII. Part B5. Beijing 2008 24. J. Muelaner, P.G. Maropoulos: "Large Scale Metrology In Aerospace Assembly", Proceedings of DET2008 5th International Conference on Digital Enterprise Technology, Nantes, France 22-24 October 2008 (Paper no. 52)

[11] J. Muelaner, P.G. Maropoulos: "Large Scale Metrology In Aerospace Assembly", Proceedings of DET2008 5th International Conference on Digital Enterprise Technology, Nantes, France 22-24 October 2008 (Paper no. 52)

[12] A. Wiechert, M. Gruber; "Photogrammetry versus Lidar: Clearing the Air", aerial perspective", Professional Surveyor Magazine, August 2009

[13] M. Farenzena, A. Fusiello, R. Gherardi: "Structure-and-Motion Pipeline on a Hierarchical Cluster Tree", 2009 30.

[14] Jazayeri, C.S. Fraser & S. Cronk: "Automated 3d Object Reconstruction Via Multi-Image Close-Range Photogrammetry", Commission V Symposium, Newcastle upon Tyne, UK. 2010 – 305

[15] W.Cuypers, N.VanGestel, A.Voet, J.-P.Kruth, J.Mingneau, P.Bleys : "Optical measurement techniques for mobile and large-scale dimensional metrology", Optics and Lasers in Engineering, 47 (2009) 292–300.

[16] J. Muelaner, P.G. Maropoulos: "Large Scale Metrology In Aerospace Assembly", Proceedings of DET2008 5th International Conference on Digital Enterprise Technology, Nantes, France 22-24 October 2008 (Paper no. 52)

[17] Luhmann T. Close range photogrammetry for industrial applications - ISPRS Journal of Photogrammetry and Remote Sensing, 17 giugno 2010.

[18] Jacobsen, K., 1992, Surface determination with an accuracy of few microns, International Archives of Photogrammetry and Remote Sensing, 29 (B5), pp. 628-632.

[19] H. Yanagi, H. Chikatsu 3D Modeling Of Small Objects Using Macrolens In Digital Very Close Range Photogrammetry, 2010, ISPRS Archives – Volume XXXVIII - Part 5, 2010, Proceedings of the ISPRS Commission V Mid-Term Symposium 'Close Range Image Measurement Techniques', 21-24 June 2010, Newcastle upon Tyne, United Kingdom.

[20] J. Xu, Z. P. Fang, A. Malcolm, H. Wang - "A robust close-range photogrammetric system for industrial metrology" - Machine Vision and Sensors Group, Gintic Institute of Manufacturing Technology, Singapore, 2003.

[21] Brown, D.C. 1971, Close-range camera calibration, Photogrammetric Engineering, 37/8, pp. 855-866.

[22] O. D. Faugeras and G. Toscani. The calibration problem for stereo. In Proceedings, CVPR '86 (IEEE Computer Society Conference on Computer Vision and Pattern Recognition, Miami Beach, FL, June 22–26, 1986), pages 15–20. IEEE, 1986.

[23] E. L. Hall, J. B. K. Tio, C. A. McPherson, and F. A. Sadjadi. Measuring curved surfaces for robot vision. Computer, 15(12):42–54, 1982.

[24] R.Y. Tsai - "A versatile camera calibration techniques for high-accuracy 3D vision metrology using off-the-shelf TV cameras and lenses" - IEEE International Journal Robotics and Automation, Vol. 3(4), pp. 323-344, 1987.

[25] Z. Zhang - "A flexible new technique for camera calibration" IEEE Trans. on PAMI, Vol. 22(11), pp. 1330-1334, 2000.

[26] J. Heikkila, O. Silven - "A four-step camera calibration procedure with implicit image correction" - CVPR97, 1997.

[27] Ricolfe-Viala C, Sanchez-Salmeron AJ. Lens distortion models evaluation, 2010, Applied Optics; 49 (30): 5914-5928.

[28] A. Albarelli, E. Rodolà, and A. Torsello, "Robust Camera Calibration using Inaccurate Targets." In 21st British Machine Vision Conference (BMVC2010), ISBN 1901725383, doi:10.5244/C.24.16, 2010.

[29] Lei Huang, Qican Zhang, and Anand Asundi, "Flexible camera calibration using not-measured imperfect target," Appl. Opt. 52, 6278-6286 (2013) http://www.opticsinfobase.org/ao/abstract.cfm?URI=ao-52-25-6278.

[30] Ricolfe-Viala, Carlos; Sanchez-Salmeron, Antonio-Jose; ,Camera calibration under optimal conditions,Optics Express,19,11,10769-10775,2011,Optical Society of America.

[31] http://docs.opencv.org/trunk/doc/tutorials/calib3d/camera_calibration/camera_calibration.html

[32] Guidi, G. Metrological characterization of 3D imaging devices Proceedings of SPIE - The International Society for Optical Engineering, 2013; 8791: art. no. 87910M.