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Influence of high dynamic range images on the accuracy of the photogrammetric 3D digitization: A case study

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ABSTRACT

Small and start-up companies that need product quality control can usually only afford low-cost systems. The main goal of this investigation was to estimate the influence of high dynamic range images as input for the low-cost photogrammetric structure from motion 3D digitization. Various industrial products made of metal or polymer suffer from poor visual texture. To overcome the lack of visual texture and ensure appropriate 3D reconstruction, stochastic image in the form of the light pattern was projected on the product surface. During stochastic pattern projection, a set of low dynamic range and sets of high dynamic range images were captured and processed. In this investigation digital single lens reflex camera that supports five different tone-mapping operators to create high dynamic range images were used. Also, high precision measurements on a coordinate measuring machine are performed in order to verify real product geometry. The obtained results showed that reconstructed polygonal 3D models generated from high dynamic range images in this case study don't have a dominant influence on the accuracy when compared to the polygonal 3D model generated from low dynamic range images. In order to estimate 3D models dimensional accuracy, they were compared using computer-aided inspection analysis. The best achieved standard deviation distance was +0.025 mm for 3D model generated based on high dynamic range images compared to the nominal CAD model.

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1. Introduction

The need for improving methods for 3D (three dimensional) digitization has long been in the focus of research circles [1-4]. That trend includes the image-based methods, such as SfM (structure from motion) and DMVS (dense multi view stereo) photogrammetry [5-8]. Because of an initial small investment in hardware and software, SfM photogrammetry is very suitable for small and start-up companies that need product quality control. Low-cost, contactless 3D digitization method such as SfM photogrammetry can be competitive with the expensive and demanding contact 3D digitization systems, such as various CMMs (coordinate measuring machines). SfM uses 2D (two dimensional) images captured by a digital camera, extracting 3D data from them. Only minimum information about the about digital camera, such as sensor size, image resolution and focal length, are needed for solving bundle adjustment within the self-calibration process [9, 10]. Different types of metals and polymers are dominant materials used in the modern product design [11]. Bearing in mind the crucial importance of their optical properties for SfM photogrammetry (especially visual texture of the surface), this cheap and widely available 3D digitization method is used for products that demand less dimensional accuracy [12]. SfM 3D digitization requires images with rich visual textures (irregular lines, shapes, points, blobs, etc.), while poorly textured surfaces may lead to unsuccessful 3D digitization. Furthermore, the dimensional accuracy may vary and is connected with product size and complexity, as well as the overlap of images during the acquisition process used as input for 3D reconstruction [13-15]. Quality of visual texture can be improved by projecting light pattern.

During pattern projection, captured images of products with monotone visual texture often exhibited under or overexposed areas. Feature detectors, such as SIFT (Scale Invariant Feature Transform) and SURF (Speeded up Robust Feature), can detect key points in slightly different light conditions [16], but they are not so efficient with projected patterns which renders reconstruction impossible. The number of collected points depend on the capability of SfM software algorithms to detect, match, and estimate the position of the 3D point from the physical surface [17]. Lu *et al*. [18] presented a technique for reconstructing a high-quality HDR (high dynamic range) image from a set of differently exposed and possibly blurred images taken with a handheld camera. The main advantage of HDR is in the elimination of shadowy or washed out areas from the image. It combines detail from the brightest and darkest parts of a scene, without having to sacrifice one for the other. Gomez-Gutierrez *et al*. [19] estimated geomorphic changes using comparison of the geometrical accuracy of rock glacier 3D models obtained using LDR (low dynamic range) and HDR images in a three-year period. They concluded that there is no significant improvement in observation using HDR pre-processing. Suma *et al*. [20] investigated the influence of four different HDR tone-mapping operators used in CH (Cultural Heritage) applications. The evaluation criteria they used were the number of key-points, the number of valid matches achieved, and the repeatability rate.

In contrast to previous investigations, this study focuses on the influence of HDR tone-mapping operators on the geometrical accuracy of generated 3D models by SfM photogrammetry. For that purposes five different HDR tone-mapping operators was chosen. The geometrical accuracy of generated 3D models is investigated on real industrial parts, using DSLR camera, Canon 5D Mark III series. The results are compared with those obtained with LDR images. As a reference values, measurement results obtained on high accuracy CMM Carl Zeiss Contura G2 are used.

2. Materials and methods

Image-based 3D digitization represents an approach for collecting information about the physical shape in the form of Cartesian coordinates (x, y, z) from 2D digital images. It can also be contemplated as an inevitable part of RE (reverse engineering) as well [21]. The proposed methodology for estimating the influence of different input images for SfM photogrammetric 3D reconstruction is shown in Fig. 1. Methodology consists of three general parts:

- the laboratory work,
- data processing, and
- CAI (computer-aided inspection).

The 3D CAD (computer-aided design) model is the initial feature for the fabrication of the physical product. When fabrication is finished, under laboratory work, there are two directions. One direction is image acquisition and second is the measurement on CMM. Regarding image acquisition, the most important design decision is the selection of the camera and its optics. Independently of the optics quality, the main characteristic of an optic is the focal length that, in combination with distance to the target, determines the caption area of the image [22]. In this methodology, besides HDR images, one set of LDR images, also known as normally exposed images, will be captured as well. Every set of captured images will have the same number of captured photos, taken from the same view position and the same resolution. Since HDR image presents a fusion of multiple images of the same scene that is captured under different exposure (which in return allows obtaining greater dynamic range than a camera could achieve in a single shot), the difference in exposure is set to maximum dynamic range for the used camera. Each of the proposed HDR tone-mapping operators provides a different output image [23]:

- natural – produces a flat effect, but with greater detail,
- art standard – slightly more stylised than natural, with more aggressive toning to tease out detail in the highlights and shadows,
- art vivid – the contrast and detail are similar to art standard,
- art bold – applies greater contrast and pushes the detail further than art vivid or art standard, but can lead to unattractive haloes along edges, particularly in busy scenes like this,
- art embossed- reduces colour saturation so that midtones appear greyed out, while edge details are enhanced.

Measurements on high accuracy CMM in this methodology provide credibility apropos provide reference to perceive the ability of one low-cost system such as SfM photogrammetry.

Data processing, as a second phase, is referred to an image processing which includes in rough steps building of sparse point cloud, building dense point cloud and building polygonal mesh model [24-26], while obtained measurement results from CMM (point cloud) go directly to building the polygonal mesh model [27, 28].

Afterward, to estimate the influence of high dynamic range images on the results of 3D digitization, CAI is used as a final part of the methodology. CAI is a fast and easy technique for estimation of the geometrical accuracy of generated polygonal 3D models. Here all obtained polygonal 3D models are compared with 3D CAD model of the product. Overlapping 3D CAD model and polygonal 3D model was performed using "best-fit" registration method where, as a result, quantitative values such as maximum, minimum, mean, and standard deviation distances are obtained.

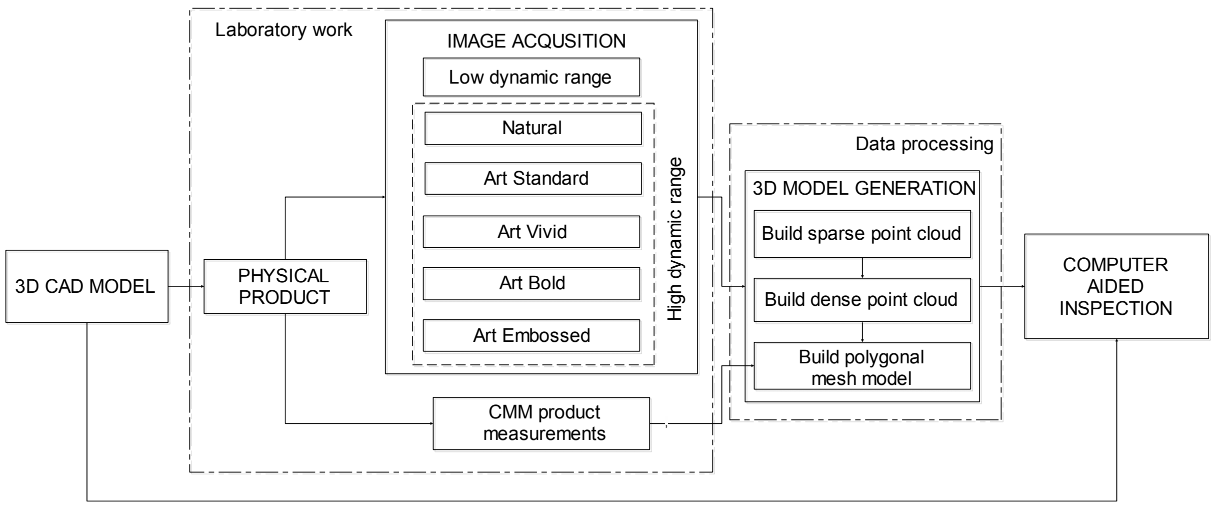
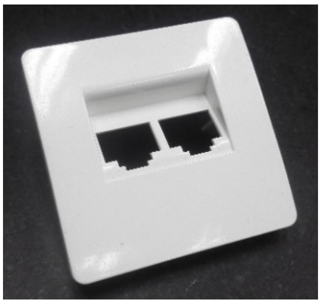


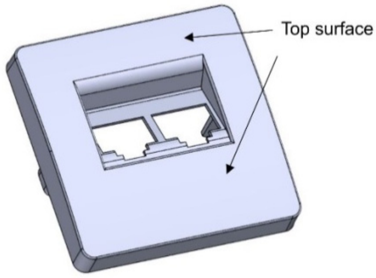
Fig. 1 Workflow of the proposed methodology

3. Experimental work and obtained results

Cover plate internet socket (Fig. 2a) was selected as a physical product to estimate the influence of HDR images in the process of 3D model digitization. Dimensions of cover plate internet socket are 52x52x19mm and it was made from a polymer based on its 3D CAD model (Fig. 2b). Because of poor visual texture, this product is unsuitable for the application of SfM photogrammetry, and it must undergo enhancement in order to provide a visual texture that will enhance the detection of points on the product surfaces. The surface of interest (top surface) for this investigation is marked on the CAD model (Fig. 2b). It was selected because of its size and easy accessibility. To ensure appropriate visual texture, Epson video projector was mounted on a tripod and it was used from minimal distance that provides sharp and clear texture on the product surface. In this way image with stochastic texture was projected. Nearly orthogonally texture projection was



(a)



(b)

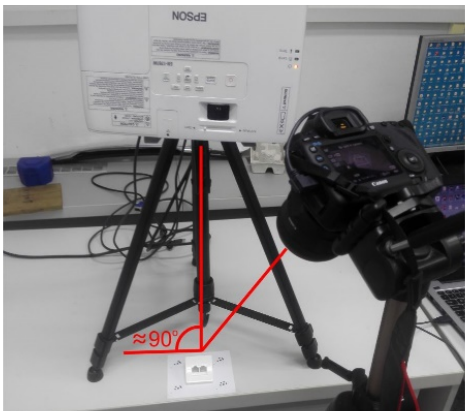
Fig. 2 Cover plate internet socket: (a) physical product, (b) CAD model

achieved with this setup. In laboratory condition (Fig. 3a) photo acquisition setup was set. For image acquisition was used Canon 5D Mark III DSLR camera with full frame CMOS (complementary metal–oxide–semiconductor) sensor and Canon EF 50mm f/1.2L USM lens, which was also mounted on a tripod and connected to a laptop.

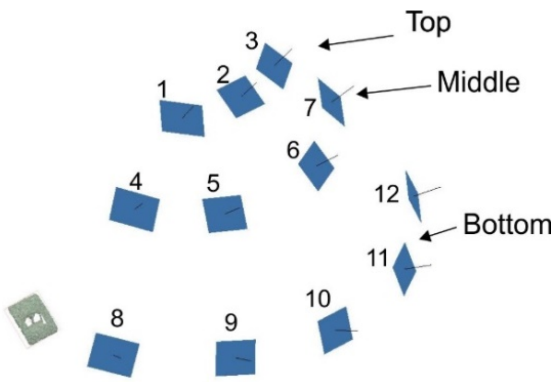
Total of twelve images were captured for each set. Images were distributed in the top, middle and bottom positions with three (1-3), four (4-7), and five (8-12) images, respectively (Fig. 3b). In the top position, the camera optical axis, relative to the optical axis of the video projector, has the smallest angle (approximately 20°), while in the bottom level that angle was around 70°. During image acquisition, product, video projector, and the camera were fixed until LDR and all HDR images were captured. After that the camera was moved in a new position and process was repeated. All photogrammetric measurements are dimensionless. To determine the proper scale, a coded target generated by Agisoft Methashape software [29] was used. Four coded targets were previously printed on the white paper with a known distance between them and captured together with the physical product. Fig. 4 shows examples of a single image from each set of images.

When image acquisition is finished, the product was prepared for measurement on CMM (Fig. 5). It was mounted on an assembled modular fixture which was specially designed and adapted for this product. The measurements were performed using CMM Contura G2 by CARL ZEISS (maximum permissible error $MPE_E=(1.8 + L/300)$ µm, where L is the measured length expressed in mm).

Measurement of the top surface of cover plate internet socket was realized in a total of 8432 measured points. The number of measured points is defined within measuring strategy, and it is calculated on the basis of point step and length of the touch probe styli trajectory. Touch probe styli with 1mm sphere diameter was selected for this measuring task, and as a result, the point cloud was obtained.



(a)



(b)

Fig. 3 Laboratory work: (a) photo acquisition setup, (b) image acquisition positions

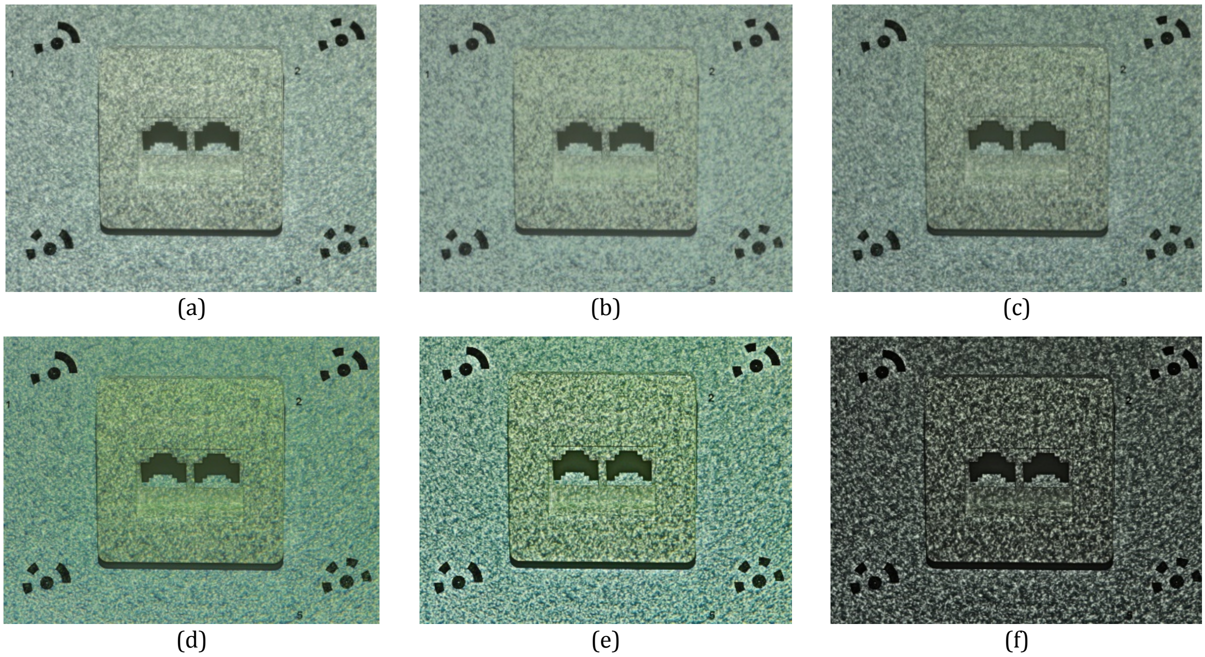


Fig. 4 Image examples: (a) LDR normal, (b) Natural, (c) Art standard, (d) Art vivid, (e) Art bold, (f) Art embossed

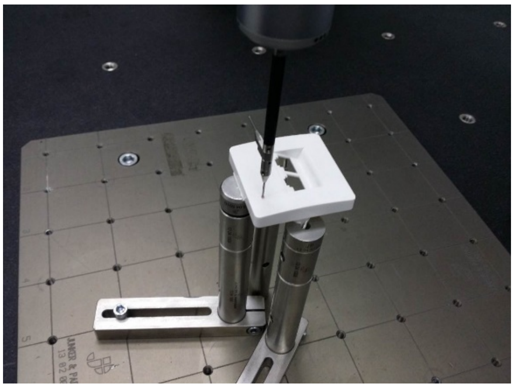


Fig. 5 Laboratory work – Measurements on CMM

Within data processing, polygonal 3D models were generated. The complete photogrammetric 3D reconstruction, from sparse point cloud to polygonal 3D model, was performed using Agisoft Methashape software, while GOM Inspect software [30] was used to generate a polygonal 3D model from point cloud obtained from CMM. In Table 1 are shown the results of the first photogrammetric phase "Build sparse point cloud". The results present numbers of tie points and RMSE (root mean square error). According to [31] RMSE reprojection error is defined as the distance between the point on the image at which a reconstructed 3D point can be projected and the original projection of that 3D point detected on the image.

Next two phases in data processing present building dense point cloud and the polygonal 3D model. AgiSoft Metashape software offers five different levels of quality for building dense point cloud (lowest, low, medium, high and highest). For this study high quality level was selected, based on previous research [32, 33].

Table 1 Results of obtained sparse point cloud

Image type	Tie points	RMSE
LDR normal	**16170**	**0.141**
Natural	14441	0.154
Art standard	15734	0.151
Art vivid	15541	0.155
Art bold	15115	0.153
Art embossed	14438	0.153

In order to quantify the geometric deviation of the real geometry, in relation to its ideal geometry, CAI analysis was carried out. CAI was performed using GOM Inspect software [30] and results are shown on Fig. 6 and Table 2. Within CAI, maximum, minimum, mean and standard deviation distances were calculated for each obtained polygonal 3D model.

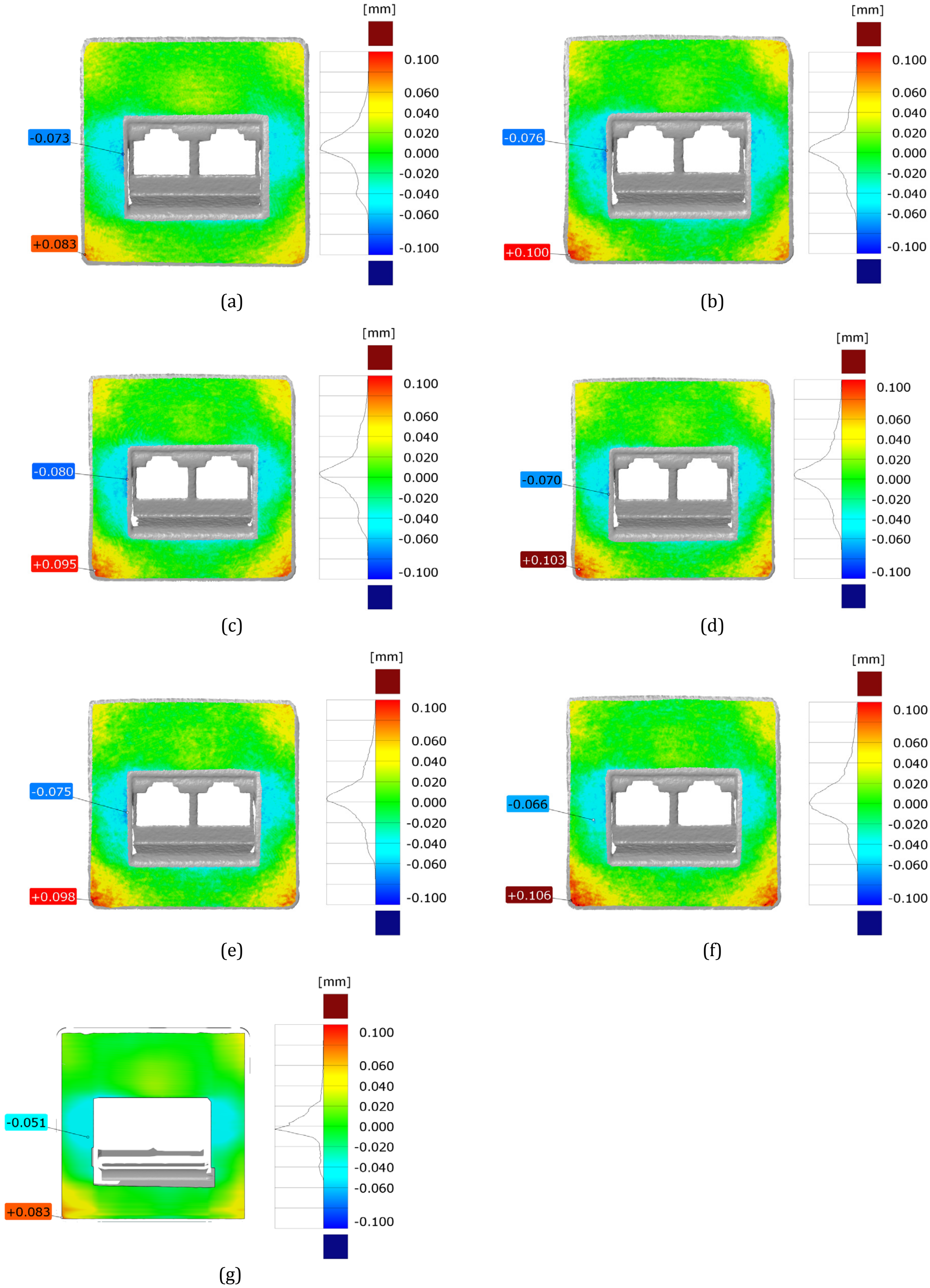


Fig. 6 Results of comparison between 3D CAD model and generated polygonal 3D models by CAI: (a) LDR normal, (b) Natural, (c) Art standard, (d) Art vivid, (e) Art bold, (f) Art embossed, (g) CMM

Table 2 CAI accuracy estimation of photogrammetric and CMM polygonal 3D models

Polygonal 3D model	Mean distance	Min. distance	Max. distance	Std. deviation
LDR normal	**+0.002**	**-0.073**	**+0.083**	**+0.023**
Natural	+0.002	-0.076	+0.100	+0.025
Art Standard	+0.003	-0.080	+0.095	+0.026
Art Vivid	+0.004	-0.070	+0.103	+0.025
Art Bold	+0.003	-0.075	+0.098	+0.025
Art Embossed	+0.006	-0.066	+0.106	+0.025
CMM	**+0.001**	**-0.051**	**+0.083**	**+0.017**

4. Discussion

The main objective of this investigation is to estimate the influence of HDR images as input for the SFM photogrammetric 3D digitization. According to the sparse point cloud results that are shown in Table 1, LDR images give the lowest RMSE value of 0.141, calculated on 16170 extracted points, while for the best HDR tone-mapped images Art Standard gave RMSE of 0.151 based on 15734 extracted points. These results indicate slightly better results in 3D digitization with the LDR images. The reason for obtaining these results can be explained by data loses that can occur during HDR image processing.

Based on Fig. 6 and Table 2, it can be noticed that the highest accuracy of the photogrammetric polygonal 3D models has LDR normal polygonal 3D model with mean and std. deviation distances of +0.002 and +0.023 mm, respectively. In the other hand, when observing all polygonal 3D models (including polygonal 3D model obtained by CMM), as expected CMM polygonal 3D model has better accuracy than all photogrammetric 3D models with a mean distance of +0.001 mm and std. deviation distance of +0.017 mm.

Distribution of deviations in all generated polygonal 3D models is similar and indicates that during the production of physical product some errors have appeared. The largest positive deviations are in outer corners on the top surface, while the highest deviation is located in the bottom left outer corner. The largest negative deviations are also manifested in all 3D models on the same place and that was the inner left side of the top surface. This distribution of deviations is a consequence of the technology of product manufacturing. After molding the product, the ejectors placed in the outer corners acted on the underside by pushing the product out of the mold. Due to the ejector force action, some deformations of the product have occurred.

5. Conclusion

In this paper, the influence of HDR images on photogrammetric 3D digitization results was presented. The presented results in this case study showed that there was no improvement in accuracy when HDR images were used as input images for 3D digitization. On the contrary, the accuracy is slightly decreased. Moreover, some significant data are lost during the creation of HDR image using Canon tone-mapping operators. However, generalization of this assertion is partially possible, because different products have different visual textures.

Since the selected product has unsuitable visual texture (monotone visual texture), the achieved accuracy of the LDR polygonal 3D model is very significant. Low-cost contact-less 3D digitization methods such as photogrammetry can be concurrent to expensive and demanding contact 3D digitization systems (CMMs).

The directions of further researches will be oriented towards investigations of the influence of different input images on the results of 3D digitization using SFM photogrammetric method.

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References

[1] Vujica Herzog, N., Buchmeister, B., Beharic, A., Gajsek, B. (2018). Visual and optometric issues with smart glasses in Industry 4.0 working environment, *Advances in Production Engineering & Management*, Vol. 13, No. 4, 417-428, doi: 10.14743/apem2018.4.300.

[2] Danzl, R., Helmli, F., Scherer, S. (2011). Focus variation – A robust technology for high resolution optical 3D surface metrology, *Strojniški Vestnik – Journal of Mechanical Engineering*, Vol. 57, No. 3, 245-256, doi: 10.5545/sv-jme.2010.175.

[3] Cviljušac, V., Divjak, A., Modrić, D. (2018). Computer generated holograms of 3D points cloud, *Tehnički Vjesnik – Technical Gazette*, Vol. 25, No. 4, 1020-1027, doi: 10.17559/TV-20160726200355.

[4] Burghardt, A., Kurc, K., Szybicki, D., Muszyńska, M., Szczęch, T. (2017). Robot-operated inspection of aircraft engine turbine rotor guide vane segment geometry, *Tehnički Vjesnik – Technical Gazette*, Vol. 24, Supplement 2, 345-348, doi: 10.17559/TV-20160820141242.

[5] Gajic, D.B., Mihic, S., Dragan, D., Petrovic, V., Anisic, Z. (2019). Simulation of photogrammetry-based 3D data acquisition, *International Journal of Simulation Modelling*, Vol. 18, No. 1, 59-71, doi: 10.2507/ijsimm18(1)460.

[6] Verma, A.K., Bourke, M.C., (2019). A method based on structure-from-motion photogrammetry to generate sub-millimetre-resolution digital elevation models for investigating rock breakdown features, *Earth Surface Dynamics,* Vol. 7, No. 1, 45-66, doi: 10.5194/esurf-2018-53.

[7] Cao, M., Cao, L., Jia, W., Li, Y., Lv, Z., Zheng, L., Liu, X. (2018). Evaluation of local features for structure from motion, *Multimedia Tools and Applications*, Vol. 77, No. 9, 10979-10993, doi: 10.1007/s11042-018-5864-1.

[8] Vučina, D., Bajić, D., Jozić, S., Pehnec, I. (2013). Evaluation of 3D tool wear in machining by successive stereo-photogrammetry and point cloud processing, *Tehnički Vjesnik – Technical Gazette*, Vol. 20, No. 3, 449-458.

[9] Fraser, C.S., (2013). Automatic camera calibration in close range photogrammetry, *Photogrammetric Engineering & Remote Sensing*, Vol. 79, No. 4, 381-388, doi: 10.14358/PERS.79.4.381.

[10] Hartley, R., Zisserman, A. (2004). *Multiple view geometry in computer vision, Second edition*, Cambridge University Press, Cambridge, United Kingdom, doi: 10.1017/CBO9780511811685.

[11] Surmen, H.K., Akalan, N.E., Fetvaci, M.C., Arslan, Y.Z. (2018). A novel dorsal trimline approach for passive-dynamic ankle-foot orthoses, *Strojniški Vestnik – Journal of Mechanical Engineering,* Vol. 64, No. 3, 185-194, doi: 10.5545/sv-jme.2017.4987.

[12] Mandić, M., Galeta, T., Raos, P., Jugović, V. (2016). Dimensional accuracy of camera casing models 3D printed on Mcor IRIS: A case study, *Advances in Production Engineering & Management*, Vol. 11, No. 4, 324-332, doi: 10.14743/apem2016.4.230.

[13] El-Din Fawzy, H. (2019). Study the accuracy of digital close range photogrammetry technique software as a measuring tool, *Alexandria Engineering Journal*, Vol. 58, No. 1, 171-179, doi: 10.1016/j.aej.2018.04.004.

[14] Percoco, G., Sánchez Salmerón, A.J. (2015). Photogrammetric measurement of 3D freeform millimetre-sized objects with micro features: An experimental validation of the close-range camera calibration model for narrow angles of view, *Measurement Science and Technology*, Vol. 26, No. 9, 1-9, doi: 10.1088/0957-0233/26/9/095203.

[15] Hosseininaveh Ahmadabadian, A., Karami, A., Yazdan, R. (2019). An automatic 3D reconstruction system for texture-less objects, *Robotics and Autonomous Systems*, Vol. 117, 29-39, doi: 10.1016/j.robot.2019.04.001.

[16] Mistry, D., Banerjee, A. (2017). Comparison of feature detection and matching approaches: SIFT and SURF, *GRD Journals – Global Research and Development Journal for Engineering*, Vol. 2, No. 4, 7-13.

[17] Santoši, Ž., Budak, I., Šokac, M., Puškar, T., Vukelić, Đ., Trifković, B. (2018). 3D digitization of featureless dental models using close range photogrammetry aided by noise based patterns, *Facta Universitatis, Series: Mechanical Engineering*, Vol. 16, No. 3, 297-305, doi: 10.22190/FUME170620029S.

[18] Lu, P.-Y., Huang, T.-H., Wu, M.-S., Cheng, Y.-T., Chuang, Y.-Y. (2009). High dynamic range image reconstruction from hand-held cameras, In: *Proceedings of 2009 IEEE Conference on Computer Vision and Pattern Recognition,* Miami, USA, 509-516, doi: 10.1109/CVPRW.2009.5206768.

[19] Gómez-Gutiérrez, Á., De Sanjosé-Blasco, J.J., Lozano-Parra, J., Berenguer-Sempere, F., De Matías-Bejarano, J. (2015). Does HDR pre-processing improve the accuracy of 3D models obtained by means of two conventional SfM-MVS software packages? The case of the corral del veleta rock glacier, *Remote Sensing*, Vol. 7, No. 8, 10269-10294, doi: 10.3390/rs70810269.

[20] Suma, R., Stavropoulou, G., Stathopoulou, E.K., Van Gool, L., Georgopoulos, A., Chalmers, A. (2016). Evaluation of the effectiveness of HDR tone-mapping operators for photogrammetric applications, *Virtual Archaeology Review*, Vol. 7, No. 15, 54-66, doi: 10.4995/var.2016.6319.

[21] Tang, C.H.H., Tang, H.E., Tay, P.K.J. (2016). Low cost digital close range photogrammetric measurement of an as-built anchor handling tug hull, *Ocean Engineering*, Vol. 119, 67-74, doi: 10.1016/j.oceaneng.2016.04.016.

[22] Cajal, C., Santolaria, J., Samper, D., Garrido, A. (2015). Simulation of laser triangulation sensors scanning for design and evaluation purposes, *International Journal of Simulation Modelling*, Vol. 14, No. 2, 250-264, doi: 10.2507/IJSIMM14(2)6.296.

[23] Pierce, M., George, C., Dive, R., Ferguson, N. (2015). *The ultimate Canon SLR handbook, Volume 4*, Future Publishing Limited, United Kingdom.

[24] Eltner, A., Kaiser, A., Castillo, C., Rock, G., Neugirg, F., Abellán, A. (2016). Image-based surface reconstruction in geomorphometry – merits, limits and developments, *Earth Surface Dynamics*, Vol. 4, No. 2, 359-389, doi: 10.5194/esurf-4-359-2016.

[25] Bianco, S., Ciocca, G., Marelli, D. (2018). Evaluating the performance of structure from motion pipelines, *Journal of Imaging*, Vol. 4, No. 8, Article number: 98, doi: 10.3390/jimaging4080098.

[26] Santoši, Ž., Šokac, M., Korolija-Crkvenjakov, D., Kosec, B., Soković, M., Budak, I., (2015). Reconstruction of 3D models of cast sculptures using close-range photogrammetry, *Metalurgija*, Vol. 54. No. 4, 695-698.
[27] Galantucci, L.M., Percoco, G., Ferrandes, R. (2006). Accuracy issues of digital photogrammetry for 3D digitization of industrial products, *Revue Internationale d'Ingénierie Numérique,* Vol. 2, No. 1-2, 29-40.
[28] Page, D., Koschan, A., Voisin, S., Ali, N., Abidi, M. (2005). 3D CAD model generation of mechanical parts using coded-pattern projection and laser triangulation systems, *Assembly Automation*, Vol. 25, No. 3, 230-238, doi: 10.1108/01445150510610953.
[29] Agisoft LLC. Metashape – photogrammetric processing of digital images and 3D spatial data generation, from *https://www.agisoft.com*, accessed February 19, 2019.
[30] GOM Inspect. Software for 3D measurement data, from *https://www.gom.com/3d-software/gom-inspect.html*, accessed September 6, 2018.
[31] Agisoft LLC. (2018). *Agisoft metashape user manual, Professional edition, Version 1.5,* Agisoft LLC, St. Petersburg, Russia, from *https://www.agisoft.com/pdf/metashape-pro_1_5_en.pdf*, accessed June 2, 2019.
[32] Koutsoudis, A., Vidmar, B., Ioannakis, G., Arnaoutoglou, F., Pavlidis, G., Chamzas, C. (2014). Multi-image 3D reconstruction data evaluation, *Journal of Cultural Heritage*, Vol. 15, No. 1, 73-79, doi: 10.1016/j.culher.2012.12.003.
[33] Baier, W., Rando, C. (2016). Developing the use of Structure-from-Motion in mass grave documentation, *Forensic Science International*, Vol. 261, 19-25, doi: 10.1016/j.forsciint.2015.12.008.