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Procedia Manufacturing 11 (2017) 1207 – 1214

Procedia MANUFACTURING

27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017, 27-30 June 2017, Modena, Italy

Cost Effective Quality Assessment in Industrial Parts Manufacturing via Optical Acquisition

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Abstract

We tackle the problem of dimensional verification via optical acquisition systems in the context of industrial manufacturing processes. Optical methods for quality inspection play a crucial part in the transition process to industry 4.0 and, despite the lack of international standardization, several solutions are available to industries that need to provide dimensional verification to their customers. Unfortunately most of these solutions are still economically unavailable to the majority of small or medium companies. In this paper we present an optical system based on low-cost components and we demonstrate that it provides useful and reliable information in quality inspection procedures.

Peer-review under responsibility of the scientific committee of the 27th International Conference on Flexible Automation and Intelligent Manufacturing

Keywords: Dimensional verification; Quality inspection; Optical acquisition; 3D reconstruction; 3D model acquistition; Smart manufacturing; Industry 4.0;

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Peer-review under responsibility of the scientific committee of the 27th International Conference on Flexible Automation and Intelligent Manufacturing
doi:10.1016/j.promfg.2017.07.246

1. Introduction

Dimensional control of mechanical pieces is a key component in today's Industry 4.0. The capability to verify that the designed geometry meets the project requirements in terms of expected dimensional constraints imposed by the specific part functional role is an ongoing challenge during the manufacturing process.

In an effort to verify product form, fit and function, the majority of companies are adopting traditional contact measurement techniques, e.g. using coordinate-measuring machines (CMM). These techniques are highly accurate but provide punctual information, hence they are effective on parts that feature simplistic shapes with easy to measure spots (e.g. circular holes, edges with regular thickness and, in general, regular geometries). Unfortunately product verification becomes a very costly and time consuming process when the parts present complicated characteristics, such as contoured surfaces, heavily featured geometry and product assemblies that render contact techniques impractical. Optical 3D scanning techniques are less accurate than traditional methods [4, 5, 6], but they have proven to be both an accurate and a cost-effective alternative solution to the problem of dimensional information estimation, allowing to create measuring reports that are more meaningful, complete and informative and that can be delivered in a visual fashion (e.g. full color rainbow plots, sectional comparisons), or as traditional CMM-style reports that are compiled automatically. Moreover optical acquisition methods are useful in other time consuming tasks such as reverse engineering of manufactured parts.

Today, many of the industrial sectors have implemented optical 3D scanning technologies to address their inspection and quality assurance requirements, but in many cases highly accurate systems are not affordable for small or medium enterprises (SME). This makes them less competitive in the 4.0 industry evolution. There is a wide gap, in both cost and measuring performance, between high-end systems and affordable solutions available for SME.

Currently there are different optical technologies available for non-contact dimensional verification. Although a complete presentation of the commercially available systems is outside the scope of this work, we can define the following categories, where most systems fall in: photogrammetry, structured light projection, laser scanners, and time of flight (ToF) sensors.

Photogrammetry is only based on the information that can be extracted from images: corresponding points across image pairs are triangulated in order to build a point cloud that is then processed into a mesh. It has the advantage of being a passive technique, i.e. besides capturing images, it does not require any interaction with the scene or object. On the other hand it is much less accurate than active methods such as structured light projection and laser scanners. In structured light systems (see [7] for an excellent in depth survey on this category), known patterns are projected onto the object whereas laser scanning systems project a laser blade. Both type of approaches share the idea of projecting light onto the target of the acquisition. Structured light can also be shed in the form of non-visible light (e.g. infrared). The projection provides aid to the triangulation step which is consequentially much more precise, yielding finer results. At last, ToF sensors measure the time of flight of an emitted light signal between themselves and the target of the acquisition, but they are much less accurate and more suited for the reconstruction of large scenes [8] where less precision is required.

High-end active systems provide high level technical specifications that partially motivate high costs. Therefore, the design and development of a cost-effective and reliable 3D scanning and measurement system suitable for SME is a priority for allowing them to tackle the problem of dimensional control at the same level as bigger stakeholders. Thanks to the technological progress boosted by the mobile phone market, the cost of vision systems has been significantly reduced while precision is constantly improving. It will soon be possible to build a cost effective optical measuring system targeting SME requirements in terms of technical specification and budget. In this work we pursue this idea.

The fundamental part of the system that most influences the performance is the 3D scanning system. In this work we adopt a low-cost optical acquisition system based on two cameras and a projector mounted on a tripod; the same setup is used in several commercial high-end measuring systems. We compare the proposed system with other optical 3D scanning systems with increasing cost and accuracy: a RGB-D time of flight sensor, a state-of-the-art photogrammetry reconstruction software, and a professional 3D scanner.

In order to validate our system we provide quantitative results obtained on a synthetic part manufactured by our industry partner (Modelleria Pozzan Srl, Schio (VI), Italy) with *ad hoc* challenging characteristics, such as holes, protuberances, indentations, curved surfaces and low-visible areas. The original CAD model is used as reference for performance comparison against other systems in terms of standard point cloud and mesh distances. Moreover we provide qualitative results on a real mechanical part, using the same systems. The comparison results indicate that our system is a reliable source of dimensional information that would be useful to all those industries that cannot afford expensive high-end systems.

The paper is organized as follows: in Section 2 we describe our system's components and the method, and we provide some background notion and references as well. In Section 3, we show the experimental validation with both quantitative and qualitative comparison compared to other strategies. Finally, conclusions and future work directions are drawn in Section 4.

2. System setup and method

In this section we describe the hardware set up and the methods that are implemented in the software modules of our measuring system.

2.1. Hardware setup

The hardware module is based on the standard setup for stereo structured light scanning. In particular, we adopted the setup proposed in the *Scan in a Box* system (Open Technologies Srl, Brescia, Italy), made by two USB cameras IDS UI-154xLE models (IDS Imaging Development Systems GmbH, Obersulm, Germany), 1280x1024 resolution with 1/2" CMOS sensor and one Asus S1 projector (AsusTek Computer Inc., Taipei, Taiwan), with R/G/B LED light Source and 854x480 native resolution. The three components are rigidly connected by a linear metal bar which is then mounted on a tripod. The baseline between the two cameras is 260 millimeters and the projector is positioned in the midpoint between the two cameras

2.2. .Software and method description

The software module defines a processing pipeline covering all the steps from data acquisition to metrological comparison with reference model. The different steps composing the software module are: range image acquisitions, alignment of different acquisitions, refinement of the scanned model and comparison with reference geometry. The pipeline is depicted in Fig. 1.

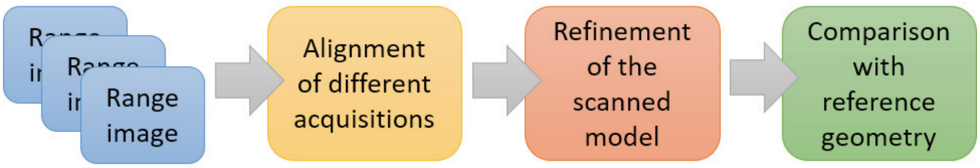

Fig. 1. The optical acquisition pipeline.

The first block consists of a set of individual acquisitions (obtained with the hardware scanner described in Section 2.2) each one generating a range image, i.e. a point cloud. For each point cloud, the 3D position of points is obtained by estimating the distance of each point from the focal plane of the first camera of the stereo pair: this quantity is usually known as *depth*. Depth estimation is a two-step process: identification of corresponding points across the two cameras (stereo-matching) and triangulation of each corresponding pair to determine the 3D position. The projection of structured known patterns of light onto the object, plays a key role in the accuracy of the stereo matching: each point of the object is enlightened by a temporal sequence of black or white light. Such sequence is then encoded into a binary word that allows to univocally determine a correspondence across the two images. All the described steps are implemented in the IDEA software (Open Technologies Srl, Brescia, Italy). The total number of acquisitions needed depends on the dimension of the object under reconstruction.

Single acquisitions are then aligned through the following procedure: the first step is the identification of the transformation between a set of point pairs that are manually (i.e. via mouse clicks) picked. This transformation is used to perform a rough alignment. The second step is the fine alignment of the two clouds using the Iterative Closest Point (ICP) algorithm [1] and [2]. In order for the alignment to be successful there must be a substantial overlap between the two point clouds. This alignment procedure is very common and is adopted in most of the optical acquisition systems. We used the implementation featured on the open source software Cloud Compare [3], which is based on the originals algorithms [1] and [2]. The main variation among different methods is the initialization step: some systems adopt an initialization using visual marker recognition instead of point pairs picking.

Once completed, the acquired model is compared with the original CAD model. This procedure consists of two main steps: first, the acquired model is aligned to the same reference frame of the original model, performing the same procedure used for the partial alignments but using two complete models instead of two partially overlapping reconstructions. Second, the distance between the two meshes is computed: i.e. a vector that contains the point-to-plane distance of each vertex of the acquired mesh from the CAD mesh. These two steps are implemented using the Cloud Compare software [3].

3. Experiments

In this section we provide the experimental validation of our system. All the experiments were performed in the same room at 20 Celsius degrees temperature (with minus/plus three degrees of tolerance). The room was lit with standard office diffused lighting (500 lux and 5000 K light color). The experiments are presented in two subsections: self-validation in Section 3.1 and comparison with other commercially available systems in Section 3.2. Please note that the experiments were performed on a synthetic object and on a mechanical piece: the original CAD model was available only for the former, hence we provide both quantitative and qualitative results in this case, whereas for the latter we only provide qualitative comparison against other methods.

3.1. Self –validation of the system

At first we study the performance repeatability of our system. The purpose of this experiments is to establish the reliability of our system and to determine the optimal conditions to achieve the best performance possible. The experiments are performed on a synthetic object that was manufactured by our industrial partner and that can be seen in Fig. 2. The the CAD model, the *.stl* files and any other data regarding the manufactured object are available upon request via e-mail to the authors.

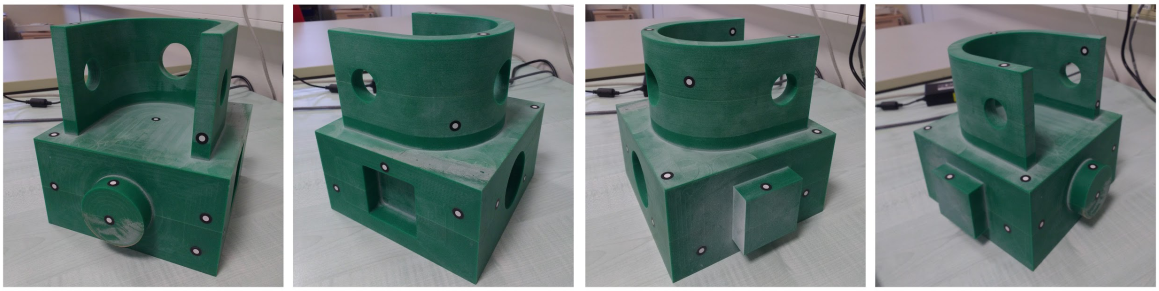

Fig. 2. Photos acquired from different angles of the synthetic object manufactured by our industrial partner.

The part was manufactured by using a five axis computerized numerical control machine with a tolerance of 10 μm. The base is a square with a side of 180 mm and the total height of the solid is 190 mm. For abbreviation purposes, further in the document we refer to this object as *the cube*.

First we measures the variability of the measurements obtained by our scanner when neither the scanner or the cube were moving, the same lighting conditions were kept constant and all the acquisitions were performed within a five minutes period. Each reconstruction is obtained with a single acquisition so that there is no potential error introduced by the process of aligning the partial reconstructions. An example is shown in Fig. 3.

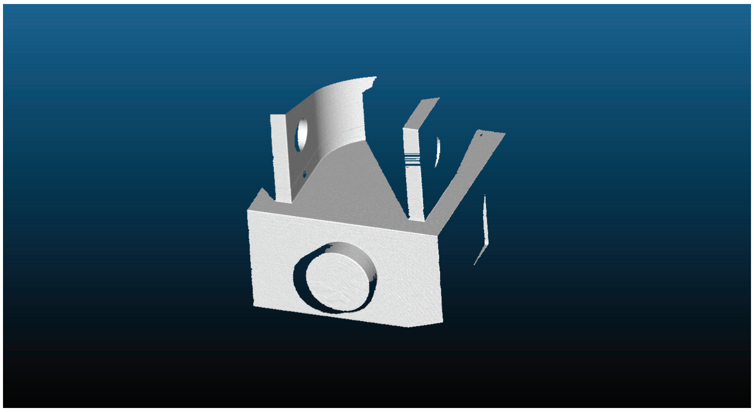

Fig. 3. Example of a single acquisition of the cube.

The subsequent test is similar to the first one but in this case, before each acquisition, we introduce a manual slight repositioning by a few centimeters of either the scanner or the cube. This test aims at simulating several acquisitions of the same part at different moments/point of view.

The two graphs in Fig. 4 report the results obtained from two experiments. Each graph shows the root mean square error (RMSE), the average error (AVG) and the maximum error (MAX), all expressed in millimetres, of the acquired point cloud. The left graph shows the behaviour of 43 acquisitions with unchanged conditions: in this situation the system is almost completely stable, as expected. On the right graph we report the results obtained for 26 different positions of the pair scanner-cube, the system shows a stable behaviour in terms of RMSE and AVG scores, although the maximum error presents a slightly higher variance.

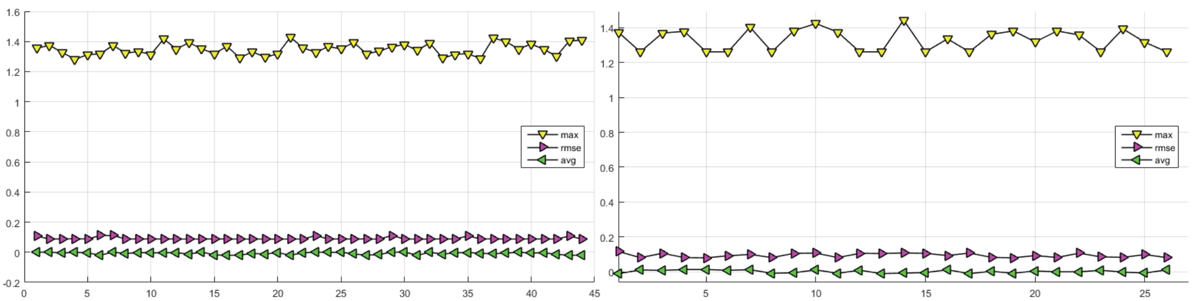

Fig. 4. Repeatability performances of our method. Each graph shows the variation of the root mean square error (RMSE), the average error (AVG) and the maximum error (MAX), all expressed in millimeters (on the vertical axis), of a number of acquisitions (on the horizontal axis).

3.2. Comparison against other methods

We now compare our system with commercial devices of higher cost and performance. The systems that are used for comparison are a commercial RGB-D camera based on a time of flight sensor Kinect 2 (Microsoft Corporation, Redmond, WA, USA), a state-of-the-art photogrammetry reconstruction software 3DF Zephyr 3.0 (3Dflow Srl, Udine, Italy), and a professional 3D scanner ATOS 5M (GOM GmbH, Braunschweig, Germany).

All tests are performed on the same synthetic object used for the experiments of self-validation of the system described in the previous section, plus on a real mechanical piece, a metal spoon-shaped bucket of a Pelton wheel shown in Fig. 5.

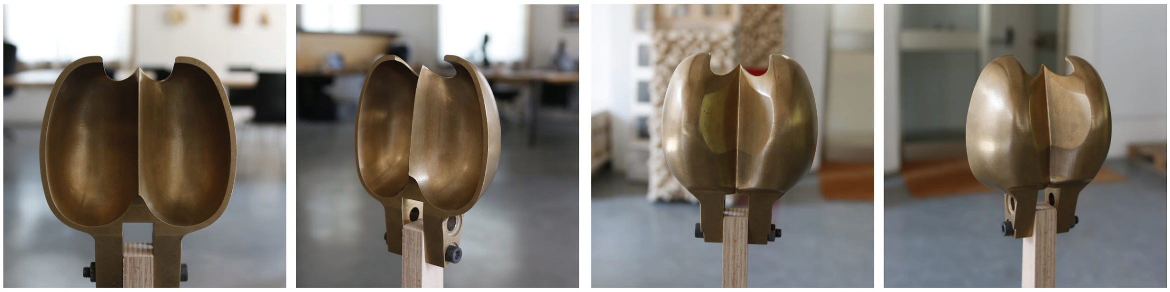

Fig. 5. The spoon-shaped bucket of a Pelton wheel.

In the following figures (6 to 9) we report 3D models reconstructed with the different acquisition methods described to ease the qualitative comparison among them. In Fig. 6 and Fig. 7 we report the whole view for the reconstructions obtained with each method, while in Fig 8 and 9 we provide zoomed views of the reconstructed model to better appreciate the differences. For both objects (apart from the results obtained with the RGB-D sensor on the cube), all methods provide qualitatively accurate results, although the photogrammetry approach shows its limitations. The reconstruction obtained by our method is quite impressive considering the difference in cost with respect to the high-end system. The reconstruction obtained with the RGB-D sensor, as expected, is of very poor quality not suitable for dimensional verification in industrial applications.

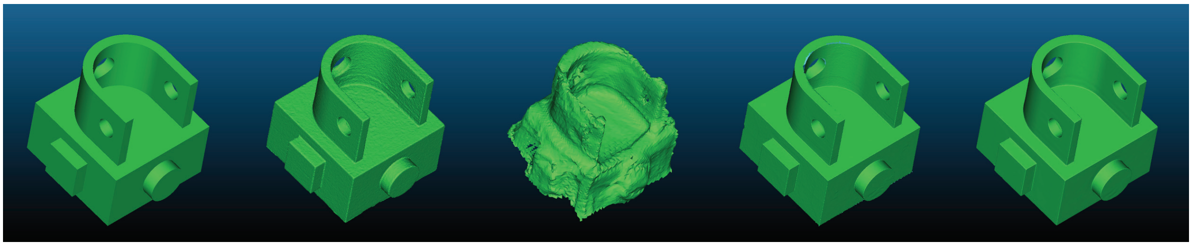

Fig. 6. From left to right: the original CAD model of the cube and then the reconstructions obtained with different methods: photogrammetry (76 pictures with a Canon EOS1100D camera), RGB-D sensor, our method and the high-end scanner.

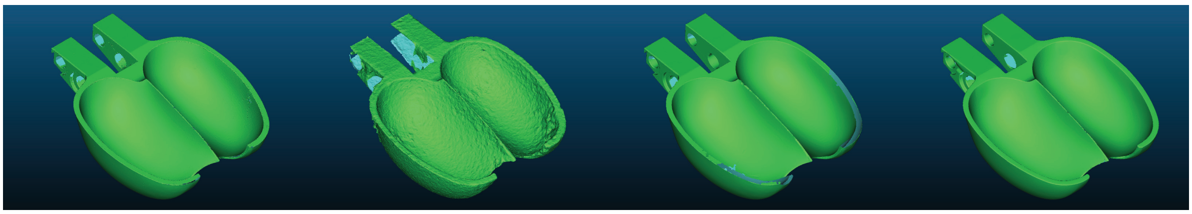

Fig. 7. Reconstructions of the Pelton bucket. From left to right: a model obtained by a reverse engineering procedure followed by the photogrammetry (98 pictures with a Canon EOS1100D camera) reconstruction then the ones obtained by our method and the high-end scanner at last.

In Fig. 8 and Fig. 9 we provide some detailed views of the two objects: the same conclusions can be drawn from these images but it can be better appreciated the qualitatively satisfactory results obtained by our method.

Fig. 8. Detailed views of the reconstruction of the cube. From left to right: photogrammetry, our method and high-end scanner.

Fig. 9. Detailed views of the reconstruction of the Pelton bucket. From left to right: photogrammetry, our method and high-end scanner.

Finally, we provide a quantitative performance evaluation of our system compared to the other methods. The results in Table 1 confirm the observations from the qualitative results: our system is outperformed by the high-end scanner but the gap is not dramatic and, taking in consideration its much lower cost, it proves to be a valuable tool for SME that cannot afford the investment of a high performance system.

Table 1. Quantitative performance comparison of different methods

	RGB-D	Photogrammetry	Ours	High-end scanner
Max error	39.081642	7.926321	4.331455	3.899861
Average error	3.954064	0.376608	0.295317	0.305954
RMS error	5.326945	0.530645	0.350741	0.343784

The quantitative data can then be used to produce color rainbow plots, which are very useful for quality assessment. In Fig. 10 we report three examples of color plots of reconstructions obtained with the photogrammetric method, our system and the high-end scanner. Each figure, associated with its color bar, enables a quality inspector to catch manufacture problems at a glance.

4. Conclusions and future work

In this work we have presented a cost-effective hardware and software system for 3D high resolution dimensional verification, specifically designed considering the SME cost-constraint in the context of smart manufacturing and Industry 4.0 evolution. From the hardware side, the proposed system is based on a cost effective structured light scanning method, the same technology employed in high level optical measuring device. Frome the software side, we defined a processing pipeline covering all the steps from optical scanning to metrological comparison with reference design/geometry. All pipeline steps are implemented using freely available software solutions, thus reducing the overall cost of the final system. From the economical point of view the final hypothetical price of the proposed system is 3 to 10 times cheaper than the available solutions with comparable measuring accuracy. The experimental evaluation was based on a self-validation (for repeatability) and on a comparison with other scanning technologies. Accuracy and repeatability are sufficient for most of the applications within the SME market. The obtained results corroborate the idea that our system would prove to be a precious tool for many small enterprises that otherwise could be left behind in the Industry 4.0 revolution.

Future works will focus on improving the evaluation of the system extending the case studies and on implementing an integrated software solution including all the processing steps in a single application.

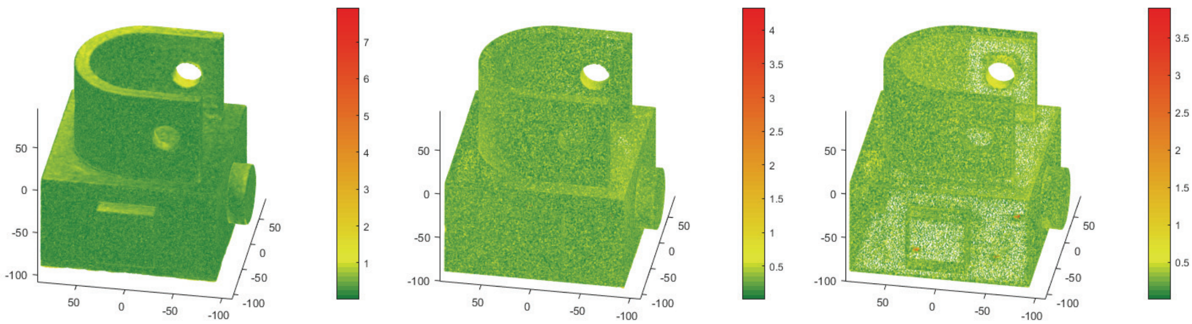

Fig. 10. Examples of color rainbow plots of reconstructions obtained with the photogrammetric method (left), our system (center) and the high-end scanner (right).

Acknowledgements

This work is supported by the European Social Fund (FSE) and is part of the "Development of a cost-effective hardware and software system for tridimensional high-resolution dimensional verification for smart manufacturing mechanical applications" project CUP B36J16001020002 (project's unique code). The authors wish to thank Nicola Carollo and Massimo Reghellin of Modelleria Pozzan for the design and manufacture of the cube.

References

[1] Chen, Y. and G. Medioni. "Object Modelling by Registration of Multiple Range Images." Image Vision Computing. Butterworth-Heinemann Vol. 10, Issue 3, April 1992, pp. 145-155.

[2] Besl, Paul J., N. D. McKay. "A Method for Registration of 3-D Shapes." IEEE Transactions on Pattern Analysis and Machine Intelligence. Los Alamitos, CA: IEEE Computer Society. Vol. 14, Issue 2, 1992, pp. 239-256.

[3] CloudCompare (version 2.8) [GPL software]. (2016). Retrieved from http://www.cloudcompare.org/

[4] Barbero, Basilio Ramos, and Elena Santos Ureta. "Comparative study of different digitization techniques and their accuracy." Computer-Aided Design 43.2 (2011): 188-206.

[5] Mahmud, M., Joannic, D., Roy, M., Isheil, A., & Fontaine, J. F. "3D part inspection path planning of a laser scanner with control on the uncertainty." Computer-Aided Design 43.4 (2011): 345-355.

[6] Bernal, C., De Agustina, B., Marín, M. M., & Camacho, A. M. (2013). Performance evaluation of optical scanner based on blue LED structured light. Procedia Engineering, 63, 591-598.

[7] Salvi, J., Fernandez, S., Pribanic, T., & Llado, X. (2010). A state of the art in structured light patterns for surface profilometry. Pattern recognition, 43(8), 2666-2680.

[8] Lindner, M., Schiller, I., Kolb, A., & Koch, R. (2010). Time-of-flight sensor calibration for accurate range sensing. Computer Vision and Image Understanding, 114(12), 1318-1328.