Novel system for the automatization of photogrammetric data capture for metrological tasks: application to study of gears

M Rodríguez1* and P Rodríguez2

1 Dept. of Mechanical Engineering, University of Salamanca. Av. Requejo 33, 49029, Zamora, Spain
2 Dept. of Mining Technology, Topography and Structures, University of León, Av. Astorga, s/n, 24401 Ponferrada, Spain

*Corresponding author: ingmanuel@usal.es

Abstract: This paper presents a novel methodology for the macro-photogrammetric reconstruction of gears for metrological and maintenance purposes. The process presented includes the automation of close-range photogrammetric data acquisition using a referenced platform supported by measures gathered using an Articulated Coordinate Measure Machine and the subsequent Structure for Motion processing that allows the generation of dense 3D point cloud models with metrical scale and photorealistic colour texture of the gears. On these models, it is possible to directly take measurements, extract different profiles that can be exported in 2D formats and apply advanced processes that allow the computation of roughness and curvature parameters to evaluate the wear and possible defects or pathologies.

Keywords: Non-contact inspection, Measurement, Photogrammetry, Gears, 3D scanning.

1. Introduction

Gears are the most used mechanism for transmission in machines and machinery for many different fields. Gear dynamics has been deeply studied in an experimental way by many authors [1]. Specifically, the gear faces are easily exposed to wear from improper lubrication and continued operation. Furthermore, sliding friction provokes noise, vibrations and can cause faults in the gears [2]. Therefore, breakage from intense wear in gears is a typical fail. Severe pitting, spalling or abrasive wear can remove sufficient metal and, in this manner, reduce the strength of the tooth of the gears below the breaking points [3]. So, it is important to evaluate the gears in order to detect these pathologies before they occur. The inspection of gears is generally carried out using contact measuring machines [4]. Therefore, it is appropriate to establish other optics procedures to evaluate the deterioration of the gears in a non-contact way and measure the main quality parameters of the gears, which can be consulted in [4]. One example is interferometry which can be used to measure in a non-contact way the profile of the gears tooth [5]. Thus, it is important that techniques exist that allow us to study gear defects in-depth, to know their severity, and evaluate possible causes, and also verification methods to complement the devices used for the inspection [6].

For the three-dimensional reconstruction of small objects, different techniques can be employed, such as structured light, laser scanning, or photogrammetry. Laser scanning is an active technique that uses a controlled light source to make a sweep of the surface the object’s surface and analyze the reflected energy [7]. However, the price of a laser scanning device is between 80-100 times the cost of
basic photogrammetric equipment [8]. Structured light-based depth cameras work through the projection of specific light patterns which are recorded with cameras to obtain the geometric information of the scene, and they are based on the structured-light triangulation principle [9]. These systems are compact, versatile, and enable suitable 3D models, but sometimes and depending on the object to scan, the reflections and brightness areas in the object can generate zones without spatial information, provoking problems in the 3D documentation process [10]. Close Range Photogrammetry, in combination with Structure for Motion (SfM) techniques, is an attractive alternative to other scanning technologies as laser scanning systems [7, 11] and/or also for structured light systems due to its low cost and the achieved resolution and precision. The photogrammetric technique is traditionally most frequently applied in geomatics and cartographic tasks. However, 3D imaging systems have been also used in the industrial context for different tasks related to quality analysis [12]. The non-contact measurement devices directly affect the quality of the products, since poor, or non-traceable approaches, may lead to an increase of waste material, and therefore affect the business performance [13].

The input for the photogrammetric process is the set of photographic images that can be taken using a commercial camera. If the images are taken with macro lenses, the technique is called macro-photogrammetry. The camera with the lens can be integrated into different platforms (e.g.: robots) to acquire images in an automatic way. The final output of the process is a dense 3D point cloud with radiometric information and a real metrical scale. Furthermore, photogrammetry can consider as low-cost since the required hardware is a commercial photographic camera, lens, and commercial or free software. With this equipment, the 3D point clouds can be adequately generated. It provides radiometric information and has a high spatial density. The software for the application of the photogrammetric pipeline can be open/free (such as MICMAC [14], Regard3D [15], GRAPHOS [16], ColMAP [17]), or commercial like Metashape [18]. This last is one of the most used commercial photogrammetric and SfM packages since allows a wide configuration of the alignment, densification, and meshing parameters.

2. Methodology

The specimen chosen is a used steel gear of 77.3 mm of the outside diameter and of 30 mm of the face width. The specimen is taken from an industrial machine and has not been cleaned or maintained in order to test the method's ability to detect anomalies, dirt, and deterioration. Therefore, its surface contains traces of oil and contamination.

The procedure established for this research (figure 1) starts with the automatic acquisition of images that will then be processed using the SfM approach. Finally, the generated 3D point cloud will be analysed with the different processes as sectioning and geometrical features which will be explained below.

![Figure 1. Process to generate the three-dimensional models.](image)

2.1. Automatic data acquisition

For the development of this research there were employed an automatic camera positioning system, a DSLR camera Canon EOS 70d, and a referenced platform on which the gear will be placed. This platform has a pseudo-random pattern that facilitates the photographic reconstruction by having different textures on each of its faces allowing easy differentiation between each of them. The referenced
platform also has a series of reference holes that were measured using an Articulated Coordinate Measure Machine (ACMM), specifically the Hexagon Metrology Absolute Arm 7325SI. The ACMM was employed to probe these references as high accuracy Ground Control Points (GCP) on the platform in order to provide a real scale to the model. The platform is placed on a stand to adjust the working height. Different lenses can be used [19]. To obtain greater magnification and detail, a macro lens has been employed for this work (table 1).

**Table 1.** Features of the devices used for this research

| Camera                  | Canon EOS 77D |
|-------------------------|---------------|
| Sensor type             | CMOS          |
| Sensor size             | 22.3 x 14.9 mm (APS C) |
| Pixel size              | 0.0037 mm     |
| Image size              | 6000 x 4000 pixels |
| Effective pixels        | 24.2 Mp       |
| Lens                    | Canon EF-S 60 mm Macro |
| Principal distance      | 60 mm         |
| Diagonal field of view  | 25.2°         |
| Aperture                | f2.8 – f32    |
| Closer focused distance | 0.20 m        |
| ACMM                    | Hexagon Absolute Arm 7325SI |
| Measuring range         | 2.5 m         |
| Probing point repeatability | ±0.049 mm  |
| Scanning system accuracy| ±0.089 mm      |

First, the gear is placed on the platform, next camera parameters are established to guarantee an adequate exposition, focus, and a correct depth of field. In this way, shot speed, aperture, and sensibility (ISO) are established. ISO sensibility is fixed in ISO100 to minimize the noise in the images as it was applied in [20]. The focal length is established at 60 mm to adequately cover the shape of the gear. The experiment is performed inside a light box, with a diffused light bulb on top. The mobile platform is then programmed to rotate around it and perform several equiangular shots (kinematic configuration) (figure 2).

![Figure 2. Configuration of the experiment in which the mobile platform equipped with the camera rotates around the referenced platform.](image-url)
2.2. Photogrammetric processing

Once the dataset has been obtained, the images are introduced as input in the software Agisoft Metashape. In addition, the camera calibration parameters are entered into the software to enhance the quality of the reconstruction. These parameters were obtained previously using a calibration pattern specified designed to work with the chosen lens and according to the optical working conditions (focal length of 60 mm). The coordinates of 3 CGP measured through probing using ACMM are introduced in the software as markers, so in this way, the model will be properly scaled. Other two additional control points were included as check points.

The 3D point cloud generation is not carried out over the original images’ resolution, namely for each pixel, due to the excessive computational weight, but over downscaled images by a factor of 16 (factor 4 for each side). However, the photogrammetric reconstruction parameters can be adapted to each case study, if a higher spatial resolution is needed. During the reconstruction, there was employed a mild depth filtering mode to avoid the loss of small details in the gear. However, as a disadvantage of this filtering mode, the presence of outliers in the final point clouds is more probable. Finally, a 3D point cloud model with texture and real scale is generated.

2.3. Analysis of the model

Once the 3D model has been generated, it can be evaluated as a whole by visual inspection and with different approaches. Please note that the photogrammetric models have radiometric texture, so pitting and other defects can be detected directly by observing the colour. It is also possible to take measurements directly from the 3D model since it is scaled. Furthermore, the 3D point cloud can be meshed to generate a solid model. However, in the present approach, it is advisable to work with the raw 3D point cloud to avoid metric and interpretation errors produced by the meshing process. The gear is segmented from the 3D point cloud for detailed study without taking into account other elements that appear in the model, such as the referenced platform. As derived products of the 3D point cloud, the following elements can be extracted: cross-sections of the gear and geometrical features.

To perform an automatic sectioning process, a Principal Components Analysis (PCA) is firstly applied to properly orient the model. This analysis allows to extract the z-axis and from it to perform a custom cross-sectioning, with the number of sections and the gap desired. Once it has been sectioned, a spline can be set for each section, and it can be exported in .dxf and other 2D formats.

Additionally, to the cross-sectioning, it is possible to extract geometrical properties from the point cloud. There are several geometrical features as stated in [21], but due to the scope of the gear’s wear, two are selected. The first is the roughness, which can be defined as the distance of each point in relation to the best fitting plane for the surrounding neighbourhood. The plane is computed by means of a least-square fitting on its nearest neighbours; and as a result, the higher roughness values will denote areas with a change of geometry, as for example edges. The second geometrical feature is the radius of curvature of each 3D point computed in a spherical neighbourhood. This feature is computed fitting a local surface on the points, and the curvature is stated as the rate of change of the surface allowing to highlight irregularities in the gear.

3. Results

In this case, 44 images were taken in three different rings around the object (figure 3). As the movement and the shot were carried out automatically, human errors were avoided. The experiment was repeated using 87 images without finding significant apparent changes (table 2).

The error of the photogrammetric process for the control points (provided by the software Metashape) [18] is between 54 and 95 µm (table 2), compatible with the order of magnitude achieved in other works where close-range photogrammetry has been applied [7, 20]. Please note that this error is only caused by the photogrammetric reconstruction process, so to obtain the final error component it is necessary to take into account other possible sources of error. The error for the check points was greater than the control point error, depending on the combination of control and reference points established, but these remained in the order of magnitude of the tenth of millimetre for the two datasets.
This should be the subject of a more precise study in which the discrepancies of the model generated by photogrammetry will be extracted with more accurate ground truth.

![Figure 3. Cameras and 3D model in the alignment process for both datasets: 44 images (left) and 87 images (right).](image)

| Points | Tie points | Error<sup>a</sup> (mm) | Error<sup>b</sup> (px) |
|--------|------------|-------------------------|------------------------|
| 44 images | 5,319,957 | 3,273,923 | 0.054 | 0.268 |
| 87 images | 5,670,765 | 3,410,097 | 0.095 | 0.551 |

<sup>a</sup> After segmentation.<br>
<sup>b</sup> Computed for the control points.

As the reader can see in figure 4, the 3D point cloud model has high geometric fidelity and presents photorealistic texture that allows detecting oxidations, zones with pollution, etc. In addition, the 3D model is provided with a real scale, so different measurements can be made on it.

![Figure 4. Model of the gear: only geometry (left), geometry and texture (centre), geometry and roughness map (right).](image)

Furthermore, different geometrical features can be computed over the 3D model to better visualize areas with irregularities due to changes in roughness or curvature. This information could be used for a qualitative analysis of areas of wear, impact, or breakage. In figure 5, the roughness was computed in a specific area using a local neighbour radius between 1 and 2 mm which has been empirically established. Similarly, the rate of change of the fitted local surface for each point is generated (curvature feature). The reader can see the differences in the distribution of roughness on the faces of the gear tooth or the detection of the rest of soot and lubricant (figure 5(c)).
Figure 5. Features computed for the model (87 images). Roughness map (a), curvature (b) and curvature color palette adapted to detect rests of lubricants (c).

Once the model has been generated, a PCA is applied to extract the edges of the gear. Thus, a sectioning process is applied (figure 6). This process can be configured to choose the gap, the number of sections required, and spacing among sections. After the sections have been made, an adjustment is made to extract the profile as a two-dimensional polyline which can be exported to CAD software in order to implement the necessary measures for quality control.

Figure 6. Automatic sectioning of the 3D model.

4. Discussion

The main weakness of the close-range macro-photogrammetry applied to small objects is the dependence of a specialized camera operator to configure the camera parameters and to obtain a suitable set of images taking into account that some optical parameters, such as depth of field, can be difficult to control. Furthermore, if the images are not acquired taking into account the particularities and goals of the photogrammetric process, the quality of the reconstruction will be affected by the presence of noise and/or reconstruction errors. It can even happen that the software fails to perform a correct alignment and the model does not correspond to reality. Moreover, the arrangement and size of the control points and their correct marking on the images are critical steps to assure an accurate scaled reconstruction.

This last point is a clear disadvantage of photogrammetry because as it is a passive technique, it needs external references to be introduced in the process to scale the model. However, the proposed solution in this article allows to solve these problems and make the scanning process easier and more precise.

On the other hand, the accuracy of photogrammetry for the study of gears can be as high as a tenth of a millimeter according to the literature for similar studies, such as quality control in welding [7, 20]. Please note that possible inaccuracies in the referencing process, possible uncertainties and/or tolerances in the manufacturing process of the referenced platform can generate additional sources of uncertainty that
cause the final error budget to be greater than could be achieved under more controlled conditions. Therefore, a conservative statement about that in a production stage, according to errors of photogrammetric process, the ACMM precision (49 µm) and the rest of uncertainty sources, is that the accuracy of the method could not be higher than a tenth of millimeter. However, using an appropriate protocol and considering the completeness and capture precision which allow obtaining the proposed system and a high-end camera and lens, the accuracy of the method could be higher. Considering that the research raised in this paper is a proof of concept, these deeper studies will be addressed in future works.

5. Conclusions

A new based on photogrammetry and SfM method for the three-dimensional reconstruction of gears has been proposed. This method allows a systematic and automatic data acquisition that improves the results of macro-photogrammetric reconstruction and allows to obtain real color and metric models of gears for quality control and maintenance tasks.

The models generated are dense 3D point clouds, on which direct measurements can be taken. Likewise, advanced point cloud processing algorithms can be applied to compute geometrical features as roughness and curvature which allow detecting of wear and damage areas being these results compatible with other photogrammetric applications where these processes were applied for quality analysis [7, 20]. Finally, automatic sectioning protocols can be applied to extract the profile of the gears and be able to be exported to CAD software.

The research was implemented using two different sets of images (87 and 44 images). The error results due to the photogrammetric process are higher for the model with a higher number of images but the two control points errors and errors calculated from the check points are in the same magnitude order for the two sets of images, so the difference does not seem significant and may be due to the variability of the photogrammetric process. No apparently significant differences in the geometry were found between the two models generated with both sets of images; however, this should be the subject of a more thorough study.

Future work will address the optimization of the methods and more specific quality studies in model making, as well as a comparison of precision results with other more accurate techniques like laser scanning or structured light system using non-gaussian robust statistical techniques [22].

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