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Photogrammetric analysis for inspection and damage detection: preliminary assessment and future extension to large-volume structures

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Abstract. This work aims to provide a preliminary understanding of the advantages of using visual techniques for the inspection and damage detection of large-volume structures. Some preliminary results provide a precise indication of tolerance of photogrammetric reconstructions and some indications to avoid the effect of reflectance of materials. Moreover, the overlap between reference CAD and the reconstructed model provides a picture of the most critical areas to cover with the camera. Finally, some colorband plots exploit the distribution of distances between reference and reconstructed models.

Introduction

Nowadays, the widely spread of composite materials into the aeronautical sector has improved the mechanical performances of components, with a significant reduction of weight [1]. Still, their multi-scale nature requires the development of numerical models for analyzing their mechanical behavior, achieving an accuracy comparable to isotropic materials. Unfortunately, simulating the behavior of composites involves time and effort. One of the most critical aspects of numerical simulation of composites concerns the study of the propagation of the crack within the material, which can have a hard-to-understand progression. Moreover, the constituents have different behavior, creating a gap in the literature regarding the prediction of fatigue life of composites. Some empirical models have been developed [2,3], but designing components in composites using a damage tolerant approach is still complicated. Consequently, the impact of maintenance and health monitoring of composite structures is therefore crucial within the whole aeronautical sector. In order to maintain a high level of flight safety, planes are periodically inspected [4] by human operators. However, the inspection of structures is conducted manually and is time-consuming. Consequently, the recent development of vision-based equipment and evolute image processing technologies has provided a new era of structural monitoring [5].

Among the well-established visual techniques, photogrammetry has a significant role [6]. The main attractive point of using photogrammetry is the capability of reconstructing 3D shape of large-volume structures, e.g., airplanes and large ships and identifying surface defects [7]. In [8], the authors mapped cracked areas by determining the strain field on the surface. Various Image Processing algorithms are applied to these areas: High-Pass Filter, to improve the quality of the image; Otsu's Thresholding, to transform the image into binary code; morphological operators, for noise reduction.

This work presents some preliminary results of using photogrammetry for geometry reconstruction of a 3D printed component with a parabolic shape. This preliminary part consists of the first stages in developing a geometry reconstruction and damage detection system using photogrammetry for operating large-volume structure. At this stage, a relevant aspect is given to the classification of damage issues. As a matter of fact, a structure can contain a non-conformity, defined as a variation from a design specification or a defect, considered as a lack of fulfillment of an operative requirement. Within this context, damage detection stems from localizing and classifying both non-conformities and defects, thus enriching data collection of the structure and achieving better health status and operating life prediction. In order to inspect structures in areas that are difficult to access, the use of a drone assumes an essential function, leading to more precise health monitoring, thus scheduling maintenance activities more accurately. Meanwhile, digital twin (DT) models will be developed to receive real-time data from drone inspection activities and physical sensors, also incorporating high-order structural theories based on Carrera Unified Formulation (CUF) [9] and progressive failure models [10]. Progressive damage models consist of numerical approaches for predicting the initiation and evolution of defects, e.g., cracks and interface debonding within the component. As described in [11], a digital twin is a digital representation of an engineering system that can simulate, monitor, diagnose, predict and optimize the behaviors of its corresponding engineering system in real-time. The simulated data will be coupled with photogrammetric results to perform real-time monitoring and life prediction of structures.

Description of instrumentation

This section describes the tools useful for photogrammetric analysis. First of all, a camera with an appropriate resolution is required: Basler Lens C125-0818-5M-P f8mm - Lens (see Fig. 1). Moreover, using a rotary shelf, shown in Fig. 2a, avoids the excessive movement of the camera, thus maintaining the exact resolution. Above the platform, 6 markers are set and their relative distance permits getting the true coordinates of the cloud points. The position of markers can be detected in Fig. 2b, whereas their coordinates from the origin of the reference system, located in the center of the platform, are given in Table 1. Table 2 contains the name of the employed programs and a brief description of their function.

Figure 1 Camera Basler Lens C125-0818-5M-P f8mm - Lens used for images collection.

(a) **(b)**

Figure 2 Rotating shelf (a) with markes (b) above the surface.

Table 1 Reference frame of the markers.

Marker	X coord [mm]	Y coord [mm]	Z coord [mm]
Target 4	-0.925	114.288	-0.303
Target 7	84.197	41.484	-0.049
Target 15	86.652	-43.806	0.036
Target 14	6.067	-108.842	0.317
Target 6	-89.377	-47.805	0.112
Target 11	-86.613	44.681	-0.114

Table 2 Software toolkit involved in the photogrammetric process.

Tool	Function
Pylon Viewer	Images takeover and storage
Agisoft Metashape	Images processing and points cloud/mesh generation
MeshLab	Points cloud/mesh view
CloudCompare	Overlapping CAD/reconstructed model and data processing

Preliminary results

The preliminary test case involves the 3D reconstruction of an Onyx-made dish component, designed using Inspire and manufactured via fused deposition modeling (FDM). In order to reduce the reflectance of the dish component, a thin film of anti-reflex spray MR 2000 is applied. This spray is suited for optical 3D-metrology and guarantees an extensive and durable white coating, as shown in Fig. 3. For the sake of clarity, no repetitive or well-establish manual techniques are adopted during the spray application, since the operator generates a random blast over the surface of the component.

(a) **(b)**

Figure 3 Representation of the component without surface treatment (a) and covered with a solvent-based anti-reflex spray (b).

The first assessment consists of the geometry reconstruction performed using a deployment of 106 photos taken from 5 different stalls. This procedure aims to verify the capability of the spray to prevent the effect of light. Consequently, any study of convergence on the overlap of images is taken into account. Figure 4 illustrates an example of pictures collected for each camera position.

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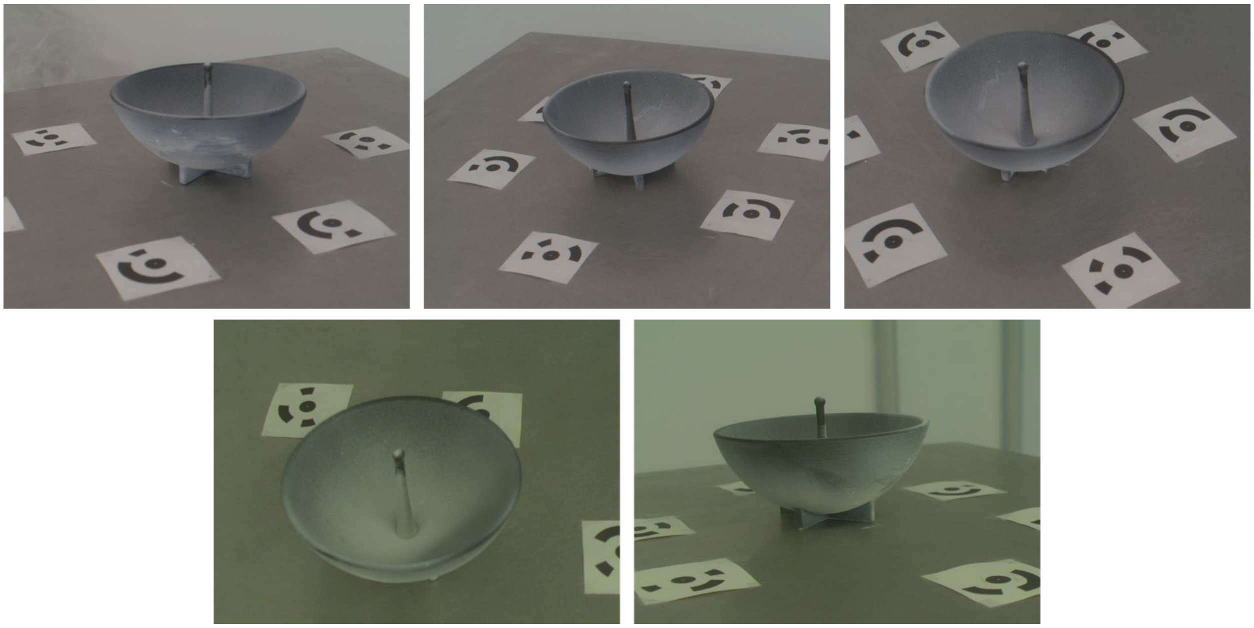


Figure 4 Five different stalls for images capture.

The images are directly imported into Agisoft Metashape Professional. The elaborating process for points cloud and mesh generation required more than 40 minutes. Table 3 collects the parameters associated with the processing. Considering the model generation, the memory usage can be split as illustrated in Table 4, whereas Table 5 contains the numerical outcomes associated with both points cloud and the mesh.

Table 3 Parameters associated with the generation of points cloud and mesh.

Object	Time [s]	Quality	Memory usage [MB]	File size [MB]
Points cloud	2,598	Medium	1291.48	12.42
Model	2,593	Medium	3481.71	21.49

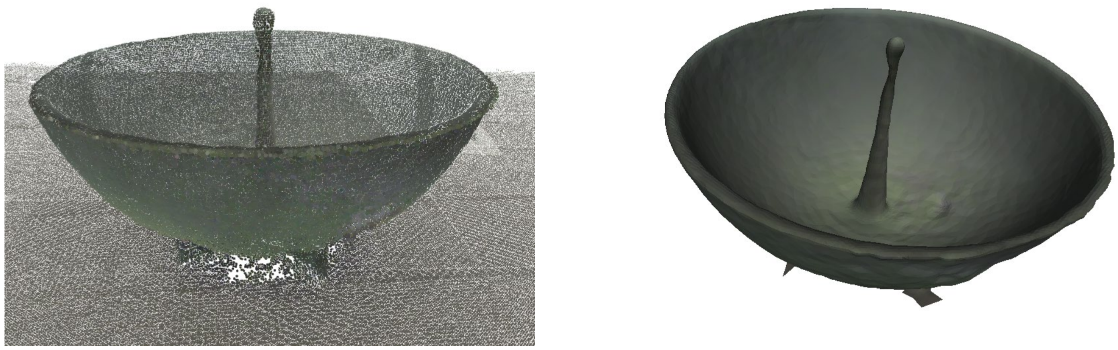
Table 4 Partition of memory usage during the generation of the mesh.

Step	% of memory usage
Points cloud	4.93%
Model	19.79%
Texturing	75.28%

Table 5 Number of points, faces and vertices in the reconstructed models.

Step	Points cloud	Model
Number of points	923,553	-
Number of faces	-	66,672
Number of vertices	-	33,438

The final shape of the points cloud and the model is shown in Fig. 5, inside MeshLab environment. Subsequently, the model and the related file *.stl* are imported within CloudCompare environment.



(a) **(b)**

Figure 5 Final points cloud (a) and reconstructed mesh (b).

The overlapping between the reference and reconstructed model is performed by selecting 8 reference points, corresponding to the vertices at the edges of the base (see Fig. 6). Figure 7 illustrates the final superposition from four different views, including the colorband containing the distances between the models. Furthermore, histogram in Fig. 8 plots the number of counts with the relative distance, whereas the range of distances between the models is observed in the following relation:

$$-1.607 \text{ mm} \leq \text{distance} \leq 2.140 \text{ mm} \quad (1)$$

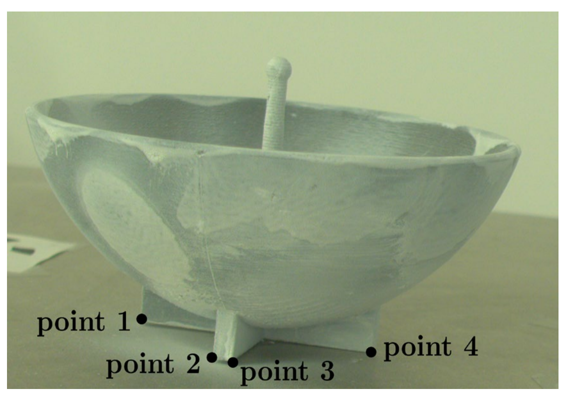


Figure 6 Localization of some reference points in the component.

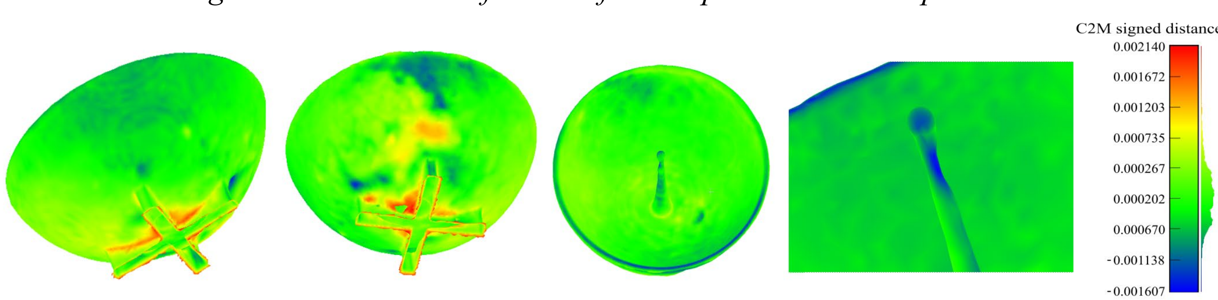


Figure 7 Colorbands concerning the distances between the reconstructed points cloud and the reference geometry. The distances are in given in [m].

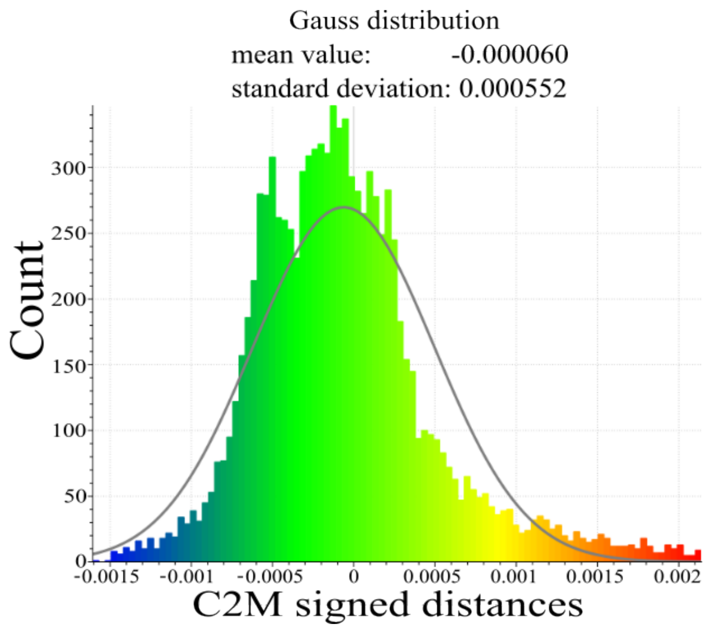


Figure 8 Histogram with counts plot over the signed distances in [m].

The results suggest that:

1. The anti-reflex treatment successfully avoids the effect of reflectance. The number of acquisitions is high (106), but a good distribution of points is detected.
2. The overlapping between reconstructed and CAD models demonstrates a reasonable accuracy. The internal part of the dish correctly represents the reference, whereas the most relevant differences are in the lower part of the component. Furthermore, the middle upright section results less precise than expected.
3. Most distances between the models are held in the range [-0.5 mm;0.3 mm]. In addition, the larger errors in the geometry reconstruction correspond to values around -1.6 cm in case of underestimating and 2.1 cm if the reference CAD is overestimated.

Conclusions and future perspectives

This work initially investigated the employment of photogrammetry for reconstructing component geometry. At first, a description of the equipment used for the experimental campaign is given and some outcomes are shown.

Then, the following considerations are made:

1. The best outcomes demonstrate that the measurement errors are around 0.5 mm. Consequently, there are better solutions than photogrammetry for visualizing small structures with small dimensions and deformations.
2. The initial test cases highlight a set of photogrammetry-related problems. For instance, the reflectance of materials can generate very poor results in model reconstruction.

Future investigations will focus on extending photogrammetry as the primary visual technique to extract relevant features of operative large-volume structures. Also, cameras will become the payload of a drone for monitoring specific areas of structures and localizing the defects and geometric deviations. Moreover, the DT model will be used as a virtualized representation with real-time updating combining photogrammetric results, physical sensors and numerical assessments.

Some thematic areas of research can be identified:

1. The extension of photogrammetry to large-volume structures (planes, ship hulls, spacecraft).

2. Using the camera as the payload of a drone and performing damage detection of harsh-to-observe areas, aiming to monitor and classify non-conformities and defects.
3. Coupling photogrammetry and high-order finite elements based on CUF to develop and improve digital twin models for life prediction of components.

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