An Augmented Reality Framework for Remote Factory Acceptance Test: An Industrial Case Study

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Abstract. Factory acceptance test is the inspection of equipment and components at the supplier's premises before delivery or final inspection. However, this control can represent a considerable cost for the customer, especially when the manufacturer's company is geographically far from the customer one and inspections must be frequent. In this paper, the authors present a framework to support the factory acceptance test based on augmented reality (AR) techniques and model-based definition aimed at dimensional checks that does not require the physical presence of the customer at the supplier's premises. The supplier must be previously equipped with an automatic measuring machine. Once the component under inspection is placed inside the machine, this reads the type and the position of the features to be measured along with the related specification limits directly from the annotated 3D model of the component. The results are automatically transmitted to the customer's site. Through a tablet, the supplier, guided by the customer, reads the results of the measures directly on the measured object through augmented or mixed reality techniques. Any out-of-specification dimension can be remeasured in real time with the customer's remote assistance using traditional measurement techniques. The proposed architecture, at an advanced stage of experimentation, is discussed with reference to an industrial case study proposed and using an entry level commercial 3D scanner.

Keywords: Factory acceptance test · Augmented reality · Metrology · Dimensional inspection

1 Introduction

Nowadays 3D computer-aided design (CAD) is widely adopted for industrial product design and development. However, production and inspection documentation is still mostly based on traditional 2D drawings prepared according to ISO or ASME standards. Geometric Dimensioning and Tolerance (GD&T) is currently the reference for drawings in the automotive, aerospace and precision equipment sectors and is becoming

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increasingly popular in many other sectors. Although generated from 3D models, 2D documentation often has its own lifecycle and remain the reference documentation for production and control purposes.

Model-Based Definition (MBD) is a more advanced approach that extends the use of 3D models also to the fabrication and control phase. The MBD methodology uses annotated 3D models rather than traditional 2D drawings. The reference standards for MBD are ISO 16792 and the American version, ASME Y14.41. With MBD, associative annotations such as tolerance prescriptions are applied directly to the digital 3D model rather than "attached" separately through 2D drawings. The annotated model constitutes a single "source of truth" that can be used in all company domains, from design, to production and control, but also for tolerance and assembly analysis, finite element analysis, and design review with virtual or augmented reality tools. A single source ensures that all stakeholders deal with the same data, rather than subsequent interpretations where inconsistencies and discrepancies are likely to exist. It is clear that it is always possible to generate traditional 2D drawings based on annotated 3D models. However, although the first standard dates back to 2003, MBD is still rarely adopted in industry.

Factory acceptance test (FAT) is the inspection of equipment and components at the supplier's premises before delivery or final inspection. However, in practice, traditional measuring instruments such as manual gauges and calipers are not fully suitable to verify all the tolerances prescribed with the GD&T method. Generally speaking, once the production process has been qualified, for the purposes of FAT, only a limited subset of measurements is actually verified by a technician at the supplier's premises. This control can be still a considerable cost, especially when the manufacturers are geographically far from the customer one and inspections must be frequent. Furthermore, limitation in travelling and specific restriction can forbid this control, having impact on the supply chain flow.

Therefore, for the purposes of the FAT, the authors propose a novel product inspection framework based on the implementation of MBD and a compact 3D scanning system at supplier's premises, capable of measuring the entire piece automatically and of transmitting the results to the remote client for the final geometrical and dimensional verification.

From this point of view, the Coordinate Measuring Machines (CMMs) would certainly provide the highest dimensional and geometric measurement accuracies (in the order of few μm for portal systems), but the need of skilled personnel, the low acquisition speed (in the order of tens of points per minute), cost and size of the equipment make their implementation prohibitive at the premises of one or more suppliers.

Laser technology certainly is the most widespread 3D scanner technology [1] and there are a wide range of solutions, including portable ones, for large, medium and small size acquisitions. Those devices are often combined with automated systems (robotic arms) that ensure greater scanning speed and repeatability of the measurement even on large volumes. Even laser systems, albeit faster, for the purposes of FAT suffer from cost and complexity issues.

Although less precise than laser systems, structured light systems are cheaper and faster than laser systems because they are full-field (i.e. they acquire a large area in a single shot), but they are more sensitive to ambient light and to the surface texture of the object. In other words, translucent, transparent, or reflective surfaces must be opacified with appropriate spray paints to be acquired. This makes these systems not suitable when the finished surfaces of the part are reflective and cannot be altered.

From this point of view, the photogrammetric technique is emerging as an economical and competitive technology capable of providing 3D scans comparable to those obtained with active instrumentation. The latest developments have concerned the automation of the image orientation phase, with structure from motion technique [2, 3] and dense image matching, such as semi-global matching (SGM) [4] comparable to active sensors. The high degree of automation of the photogrammetric process has led to the creation of black box solutions, including open-source ones [5], which make it possible to obtain 3D models very simply, making 3D modelling from images easy, even for non-experts. However, the reliability aspects of these methods should not be neglected, especially if you intend to adopt such solutions in the metrological field. In this regard, it should be remembered that photogrammetric returns are always based on redundant measurements (2 or more homologous rays) and the 3D coordinate estimates are always associated with quality indicators derived with statistical procedures.

Eventually, the so-called mixed reality systems (through tablet computers or wearable viewers) are also equipped with depth cameras capable of measuring the distance to objects in real time. However, the most advanced products currently available on the market do not provide enough accuracy in measurement for metrology applications in the automotive or aeronautical sectors [6, 7].

Augmented or mixed reality, however, can still find another interesting application in metrology field. For example, for the purposes of geometric and dimensional testing, the dimensions to be checked could be displayed directly on the piece to be measured as a 3D annotation. The indications in augmented reality would improve the readability of the information and speed up the control process. Moreover, by coupling an automated measurement system with an AR system, it would also be possible to highlight the deviation of the detected model from the nominal one.

Based on those considerations, the authors explored this possibility with reference to an industrial case study.

2 Remote Factory Acceptance Test Architecture

As mentioned, the authors propose a framework to support the factory acceptance test based on augmented reality (AR) techniques and model-based definition aimed at dimensional checks that does not require the physical presence of the customer at the supplier's premises. The supplier must be previously equipped with an automatic measuring machine. Once the component under inspection is placed inside the measurement machine, a software application reads the type and the position of the features to be measured along with the related specification limits directly from the annotated 3D model of the component. The results are automatically transmitted to the customer's site. Through a tablet computer, the supplier reads the results of the measurement directly on the part under inspection through augmented or mixed reality techniques. Any out-of-specification dimension can be remeasured in real time with the customer's remote assistance using approved measurement techniques (Fig. 1). Thus, our system does not need the presence of the client at supplier's premises. Moreover, the tolerance specifications are superimposed on the real part by means of AR technology in order to speed up the manual measurement process.

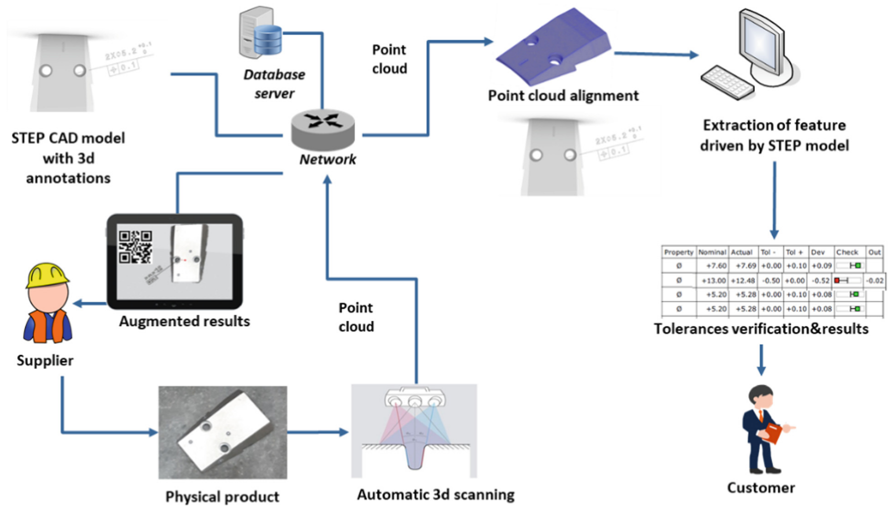

Fig. 1. Architecture proposed for remote factory acceptance test.

The application of the methodology requires that the proprietary CAD models are exported according to STEP AP 242 format defined by ISO 10303, which provides a way to exchange annotated 3D models between different software platforms. Moreover, STEP files are vendor-independent and can be easy parsed with free software [8].

Given the annotated STEP file and the corresponding point cloud properly aligned, the measurement software can automatically detect the type of the feature, its location inside the point cloud and its specification limits saved in the STEP file. Eventually, the point cloud can be trimmed and the corresponding feature can be easily extracted. Once extracted, the feature (e.g. a cylinder) is measured and compared with the specification limits. This process can be automated to provide repeatable and meaningful inspection data.

More precisely, a remote acceptance system is here proposed with the following functions:

- Automatic 3D scanning
- Display of augmented nominal dimensions via tablet computer
- Automatic measurement of selected features on the basis of the annotated STEP model
- Possibility of superimposing, through AR technologies, the map of the deviations detected with respect to the nominal model for a qualitative evaluation

At the supplier's premises, the piece to be measured is positioned in the correct configuration thanks to a precision jig. The point cloud is transferred to the company to recreate the 3D model. The operator at the supplier's premises, by framing the piece made with the tablet camera, placed near the optical marker, can see the map of the deviations directly on the piece together with the 3D annotations saved in the nominal model for a first qualitative evaluation of the 3D scan. This system, fully automatable, allows the operator a quick qualitative evaluation of the piece in terms of compliance with tolerances and the indication of any out-of-specification measurements. The dimensions of an annotated 3D model should be able to be selectively shown or hidden. Furthermore, being arranged on different annotation planes, each characterized by a normal vector unit, it is possible via software to make their visualization consistent with the user's current point of view on the digital model (see ISO 16792: 2015).

3 Case Study

The proposed architecture was tested against a case study provided by MBDA Italia, relating to the measurement of an aeronautical deflector (Fig. 2).

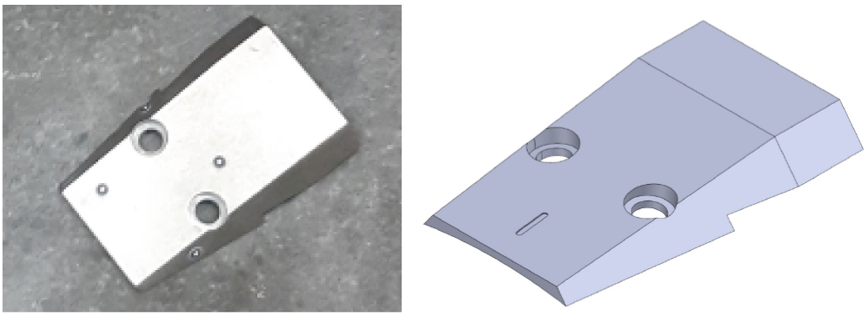

Fig. 2. Case study and its corresponding 3D CAD model.

Born in December 2001, MBDA is jointly owned by Airbus (37.5%), BAE Systems (37.5%), and Leonardo (25%). – Fig. 2 (Fig. 3)

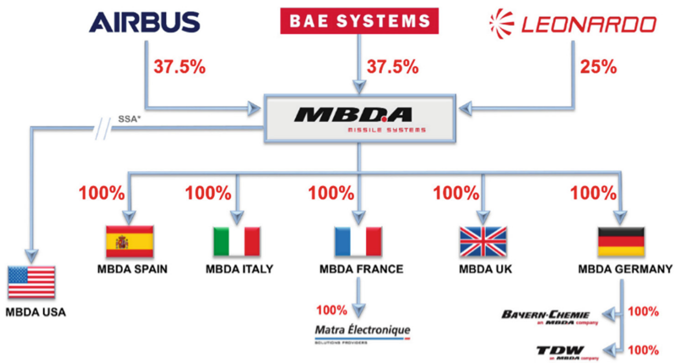

Fig. 3. MBDA worldwide. Source: www.mbda-systems.com.

MBDA is the only European defense group capable of designing and producing missiles and missile systems that correspond to the full range of current and future operational needs of the three armed forces (land, sea and air). With a significant presence in five European countries and within the USA, in 2020 MBDA achieved revenue of 3.6 billion euros with an order book of 16.6 billion euros. In total, the group offers a range of 45 missile systems and countermeasures products already in operational service and more than 15 others currently in development. MBDA carries out national and international projects among its national companies (NATCOs), promoting and implementing cooperation programs among the various European company sites. MBDA promotes the development of cutting-edge defence technologies in order to maintain a leading position in the market. Among the R&D projects currently underway, in this paper, we discuss one of the major projects developed at the production site of MBDA Italia located in Fusaro (Naples, Italy).

For the purposes of the FAT, sixteen dimensions of the defector are actually measured at supplier's premises using manual methods.

In particular, the authors focused on the measures of the diameters of some holes and on the measurement of the distance between selected planes. The dimensions with too narrow tolerances with respect to the characteristics of the measuring device and those that refer to derived references (e.g., axes) have been excluded. The 3D CAD model was then enriched with 3D annotations of the dimensions under study and exported as a STEP file. The objective of the study was to make experiments and find the optimal set-up for implementing the remote measuring procedure described above.

4 Experimental Set-Up

As mentioned, the experimental setup comprehends a 3d scanning system, a measuring software and a mobile computer device for augmented reality.

4.1 3D Scanning System

EinScan SP - 3D scanning system by SHINING 3D [10] was selected for the case study (Fig. 4). EinScan SP is a low-cost (<3 K €) solution characterized by a rotating table and an accuracy of ±0.05 mm.

Fig. 4. EinScan SP structured light system 3D scanning system.

Other functionalities include automatic alignment and automatic mesh generation.

To automate the measurement process, it is essential to make the positioning of the component within the acquisition system repeatable. For this purpose, some positioning jigs have been designed to fix the component in different configurations depending on the dimensions of interest. The jigs are black in order not to be detected from the scanning system and can be fixed at the center of the scanning system, by replacing the removable central cover of the turntable. Different solutions were explored for the jigs by means of additive manufacturing techniques. The final design provided a square reference on the jigs for the QR-code that is used for augmented reality applications (Fig. 5).

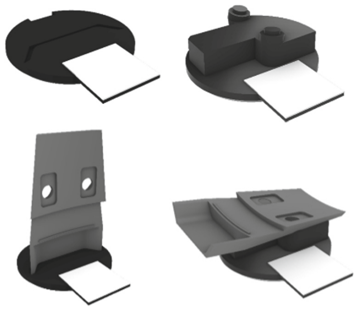

Fig. 5. Jigs for fixing the component under study in vertical and horizontal position.

In order to obtain the best possible acquisitions, it was decided to use the vertical jig for the detection of the hole dimensions, and the horizontal jig for the detection of the distance dimensions between planes.

4.2 Measuring Software

Several research activities were conducted about reverse engineering (RE) techniques aimed at reconstructing CAD models from measured data. A quiet comprehensive survey can be found in [11]. However, the objective of this study is not the RE, since the reference nominal CAD model is already available, but instead the automatic extraction and measurement of already-known features (i.e. holes and planes) from given space locations. Thus, a software was developed to extract features from point cloud locations and to measure them. The software was entirely developed in the MatLab environment. The input data is an STL file, but the tessellation is ignored and just the point cloud is considered. In particular three main function were developed that are discussed in the following subsections.

Point Cloud Alignment. A preliminary procedure aligns the point cloud to the reference system of the reference CAD model. This procedure is mandatory to proceed with the subsequent extraction of the geometric features and their measurement. The alignment algorithm first finds the geometric center of the point cloud and align it with the geometric center of the reference CAD model (imported as STL file). Afterwards, it uses an iterative procedure based on the iterative closest point algorithm (ICP) to find the transformation matrix that best overlaps the two clouds. It is possible to set a certain number of iterations. The ICP returns the quality of the alignment in terms of root mean square error (RMSE). We have extensive tested the alignment procedure on several point-cloud acquired in different reference systems. We found that the error was always below 0.3 mm, which is more than enough to correctly crop the point cloud.

Measurement of Diameters. An algorithm was developed for the calculation of the diameter of the holes. A preliminary crop procedure isolates a "region of interest" comprehending the points around the holes highlighted in the annotated STEP CAD model. Afterwards, a cylinder is extracted with a best fitting procedure. The workflow for hole feature extraction is summarized in Fig. 6.

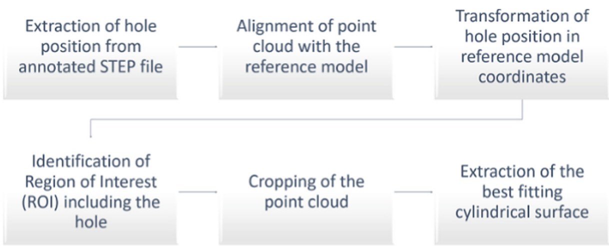

Fig. 6. Algorithm for measurement of diameters.

Measurement of Linear Dimensions. The procedure for measuring linear dimensions is summarized in Fig. 7. As in the case of diameters a ROI has to be preliminarily identified in order to crop the point cloud. For measuring linear dimensions, the algorithm extracts two reference planes that best approximate the ROIs of the point cloud. The procedure is based on the M-estimator SAmple Consensus (MSAC) algorithm to find the plane that best approximates a three-dimensional point cloud [9].

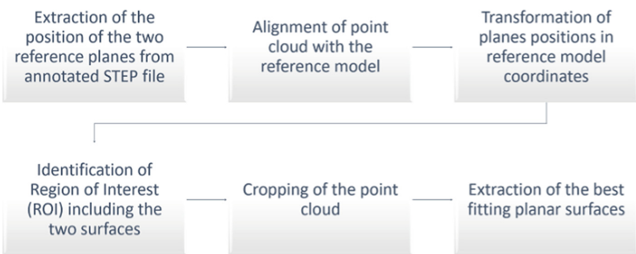

Fig. 7. Algorithm for measurement of linear dimensions.

4.3 Device for Augmented Reality

Toshiba dynaEdge AR100 Viewer and Microsoft Surface Pro tablet (Fig. 8) were selected as the most suitable mobile systems for the case study.

Fig. 8. Toshiba dynaEdge AR100 viewer and Microsoft surface pro tablet.

Toshiba dynaEdge AR100 is an augmented reality head-mounted display made by Toshiba. It requires a connection to Toshiba's dynaEdge DE-100 battery-powered Windows 10 mini-PC. Microsoft Surface is a series of touchscreen-based tablet designed and developed by Microsoft, running the Microsoft Windows operating system. The choice of these devices was dictated by their compatibility with the corporate cyber security policies, which are very stringent as MBDA is a defence sector company, and with the compatibility policies of the corporate ICT domain. In fact, the SW architecture, which was designed and implemented by MBDA with the support of NAIS, is quite articulated and includes two client applications (one for the supplier and one for the MBDA operator running the FAT) connected to a back-end, which resides on premise in corporate data centre. On the server side, the platform implements a microservices architecture, using Docker, and running on the Windows Server 2019 operating system. All data and algorithms exclusively reside in the back-end, while no data (numerical and/or images) or algorithms are stored in the clients (Fig. 9). The connection between the two clients and the back-end takes place on a corporate VPN (Virtual Private Network) authorized with domain credentials.

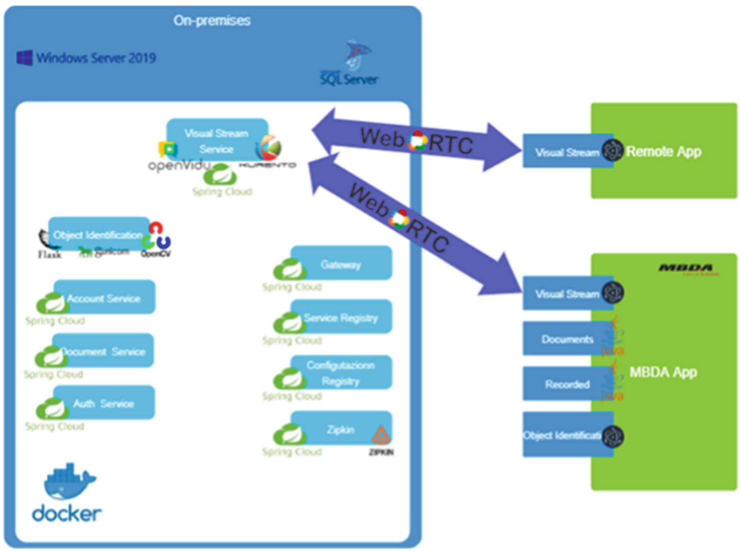

Fig. 9. Remote acceptance platform SW architecture

5 Experiments and Results

Several experiments were conducted to find the most suitable configuration for the automatic measurement system. The deflector was preliminarily sprayed with an anti-glare paint. The following factors were chosen as control parameters for the experimentations.

- **distance & orientation**: The object has to be positioned within the acquisition range of EinScan SP system (290mm and 480mm). However, the distance from the scanning camera and the angle of incidence of the structured light beam on the surfaces to be acquired has an impact on the quality and completeness of the point cloud.
- **number of turntable steps**: A discrete number of shots are acquired when the turntable rotates around its vertical axis. For each step, the instrument scans and acquires a partial view of the object being scanned; at the end of the complete rotation, the system generates the overall point cloud. Therefore, the higher the number of steps chosen, the more points acquired, but the longer the scanning time.

Furthermore, the scanner has always to be higher than the turntable on which the object being scanned is placed to capture all the markers present on the surface of the turntable, which allow the alignment of the partial scans obtained in each step.

The environmental light was considered as a noise factor.

The best configuration resulted the one characterized by the distance between the scanned object and the structured light scanner of 310mm, the angle of incidence of light respect to the deflector of 14° and the number of the steps of the turntable of 24 (Fig. 10).

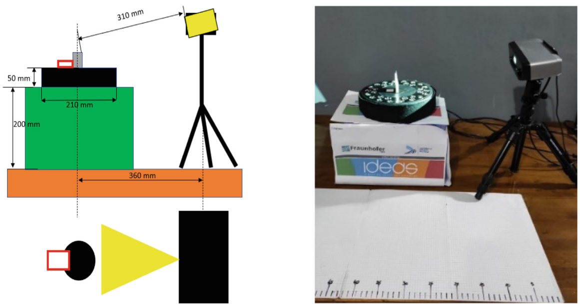

Fig. 10. Configuration of experimental setup for positioning of the deflector in the vertical jig.

More than one hundred acquisitions of the piece were done in that configuration. The results from a previous approved measurement procedure done by the client were taken as a reference. Our results show that our automated measuring system gives outcomes that are compliant with the reference measurements in most cases (Table 1).

Table 1. Measurement results

Distance	Angle	Turntable steps	Feature	% Compliance
310 mm	14°	24	Diameter 1	99%
310 mm	14°	24	Diameter 2	78%
310 mm	14°	24	Distance 1	99%
310 mm	14°	24	Distance 2	99%

However, it is worth emphasizing that the deflector received an anti-glare treatment.

The use of AR proved to be very useful in showing the measurements done directly on the deflector. By selecting a feature, the relative static view of the object is shown with the measures highlighted. Figure 11 shows a dynamic view of the values measured by the algorithms with the aid of Augmented Reality techniques, with an immediate visual indication (green or red) to differentiate the measures with a positive outcome from those with a negative outcome.

Measures are superimposed to the camera live video stream by projecting geometric features (lines and text) into the live scene. The 3D camera pose, essential to project the synthetic geometric features, is reconstructed by the identification and matching of key-points extracted in real-time from the video-frames thanks to the use of Computer Vision techniques.

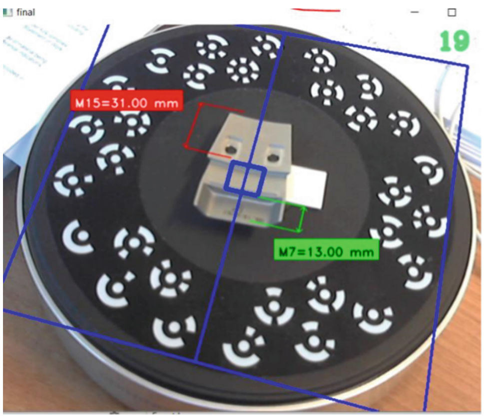

Fig. 11. Augmented reality view of the deflector.

6 Conclusions and Future Works

In this paper, the authors proposed a framework to support the factory acceptance test based on augmented reality (AR) techniques and model-based definition aimed at dimensional checks that does not require the physical presence of the customer at the supplier's premises. The industrial interest is very high in this activity, because FAT has still a considerable cost especially when the manufacturers are geographically far from the customer and inspections must be frequent. Therefore, remote FAT can be a solid opportunity for cost reduction and a useful risk mitigation strategy in case of limitations in travelling or specific restriction (e.g. Covid-19 pandemic) that can have a strong impact on the supply chain.

The remote measuring framework proposed was tested against an industrial case study provided by MBDA Italia. Results, although obtained with an entry level commercial 3D scanner, are promising. After several experiments the most robust experimental set-up was found. Results showed that the main issues concerned 3D scanner limitations in accuracy. Moreover, the component under study required an anti-glare treatment to be acquired. This could be overcome with non-optical 3D scanning systems. Future work will focus on the measurement of different features with more accurate scanning systems.

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