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# Enhancing Aircraft Engine Part Inspection Using a Handheld 3D Scanner

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## Abstract

Accurate defect quantification is crucial for ensuring the serviceability of aircraft engine parts. Traditional inspection methods, such as profile projectors and replicating compounds, suffer from inconsistencies, operator dependency, and ergonomic challenges. To address these limitations, the 4D InSpec® handheld 3D scanner was introduced as an advanced solution for defect measurement and analysis.

This article evaluates the effectiveness of the 4D InSpec scanner through multiple statistical methods, including Gage Repeatability and Reproducibility (Gage R&R), Isoplot®, Youden plots, and Bland–Altman plots. A new concept of Probability of accurate Measurement (PoaM)© was introduced to capture the accuracy of the defect quantification based on their size. The results demonstrate a significant reduction in measurement variability, with Gage R&R improving from 39.9% (profile projector) to 8.5% (3D scanner), thus meeting the AS13100 Aerospace Quality Standard. Additionally, the 4D InSpec scanner improved detection accuracy, provided automated defect quantification, and eliminated the need for time-consuming replication processes.

Beyond performance improvements, the adoption of the 4D InSpec scanner led to a 75% reduction in direct labor time, significant cost savings, and the elimination of ergonomic risks and human error associated with traditional inspection methods, and enhanced defect reporting and data collection. The article closes with implementation requirements and areas for future improvement.

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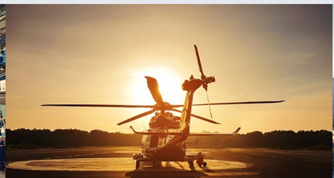


# 1. Introduction

Accurate defect quantification is crucial for ensuring the serviceability of aircraft engine parts [1]. Traditional inspection methods, relying on replicating compounds and profile projectors, are prone to inconsistent measurements, operator variation, human error, and ergonomic challenges [2]. Furthermore, they are inefficient and time-consuming due to the manual input required to apply, cure, and cut the replica, manual alignment by hand, visual judgement on the profile projector, and recording the dimensions. In a world of big data and digitalization, these methods fall behind. The only way to save measurement results electronically is by taking photos of the profile projector monitor with a camera.

To address these issues, the adoption of a handheld 3D scanner offers great potential and shows a promising advancement in defect measurement and analysis through improved accuracy, repeatability, and efficiency. This study aims to compare the two measurement systems using statistical methodologies for performance evaluation, complemented by a qualitative assessment of other benefits.

# 2. Materials and Methods

The objective of this study was to assess and compare two different methods for quantifying inspection findings. To represent a real-world environment, a mix of five aircraft maintenance technicians of different ages and levels of experience was tasked to measure 15 defects ranging from 0.0001″ to 0.003″ in randomized order using both measurement systems. The test was repeated three times with a gap of several weeks to avoid any memory effects. Defects that could not be measured with both systems had to be excluded from the statistical comparison.

The first measurement system was a Mitutoyo PH-3515F Profile Projector (Figure 1), also known as shadowgraph machine or optical comparator [2, 3]. One limitation of the shadowgraph is that the direct measurement of parts is only possible for edge defects. All other defects require replication using a silicone compound [4]. For the defects analyzed in this study, a high-resolution replicating compound was applied to the part, cured, and prepared for measurement by cutting a thin slice [5].

The performance of the profile projector was then compared to the 4D InSpec® Surface Gage, a handheld 3D scanner using blue-light technology [6]. This device allows direct measurement of the defects and comes with a mirror set for improved accessibility.

A defect template was specifically designed and manufactured for the gage comparison (Figure 1). It incorporates different severities of damage and defect types commonly detected during aircraft engine maintenance, including dents, pits, nicks, scratches, scores, and burrs [7].

After the data collection was completed, *Gage Repeatability and Reproducibility* (*Gage R&R*), *Isoplot®*, *Youden Plot*, *Bland–Altman Plot*, and *Probability of Accurate Measurement* (*PoaM*)© studies were performed in Minitab [8], Shainin Red X Tracker [9], and MedCalc software [10] to assess and compare the measurement systems.

# 3. Statistical Analysis

## 3.1. Gage Repeatability and Reproducibility Analysis

The *Gage R&R* analysis assesses the measurement system's variability by partitioning it into repeatability and reproducibility [13]. Repeatability measures the variation observed when the same operator measures the same part multiple times, while reproducibility is the variation observed when different operators measure the same part. The results show that the 4D InSpec scanner has a significantly lower measurement variation of 8.5% compared to the profile projector (39.9%), thus meeting AS13100 Aerospace Standard requirements [14]. The repeatability improved by 75.2%, and the reproducibility by 78.9%. While this observation was consistent for all operators, the novice inspector had the biggest improvement when using the 4D InSpec.

## 3.2. Probability of Accurate Measurement

Achieving an accurate (acceptable) measurement of a defect using a profile projector depends on both the quality of the replicating process and the accuracy and precision of the measuring device itself. The replicating process has several human inputs that can directly affect the result, including correct preparation and application of the compound, sufficient curing time, precise slicing of the replica, careful positioning, as well as accurate reading and correct interpretation of the results. The performance of the measuring device can be assessed using *Isoplot* (see below) or other statistical methods, such as root mean square error. However, there was no performance metric available for evaluating a good versus a bad replica measuring process.

In *non-destructive testing* (*NDT*), the *probability of detection* (*PoD*) is a widely recognized metric for binary data used to evaluate whether a flaw—such as a crack in aircraft components—is successfully detected or missed during inspection [15, 16]. The outcome is typically represented by a PoD curve, which plots the likelihood of detection as a function of defect size, providing critical insight into detection reliability [17]. However, in the present study, defects were already known since they were presented to inspectors using a standardized defect template (Figure 1). The key objective was to assess the performance of the

**FIGURE 1** Overview of test equipment: Mitutoyo Profile Projector (top left); 4D InSpec Surface Gage (top right); Defect Inspection Template© (bottom).




defect quantification process from start to finish, i.e., how good is the achieved measurement based on the defect size.

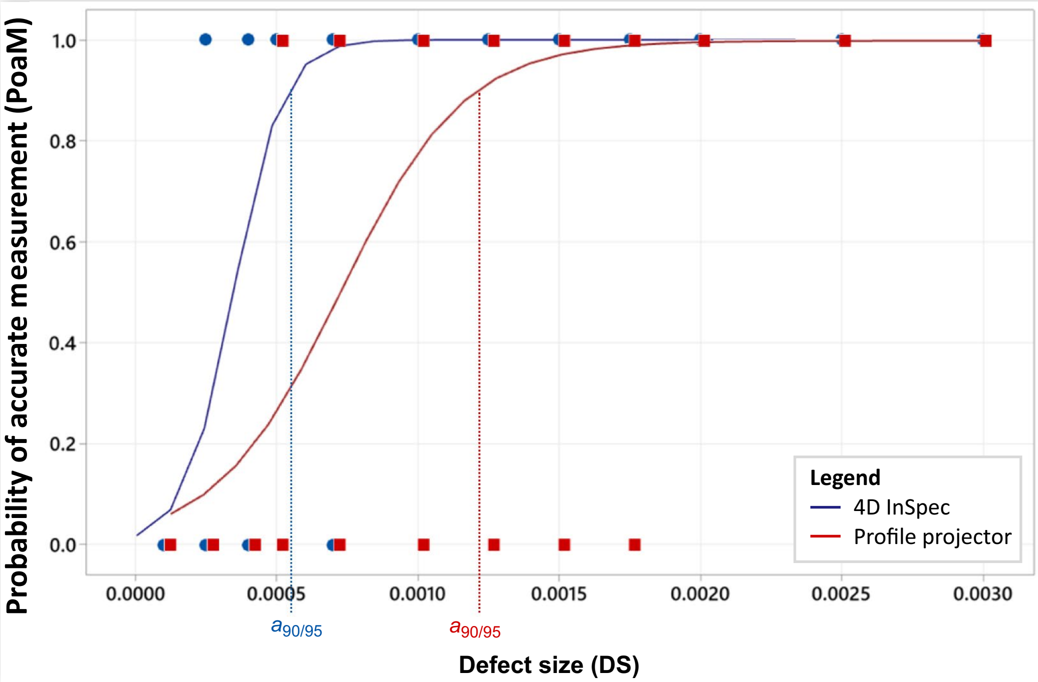
To capture this, a new concept of *PoaM* was introduced. While conceptually similar in format to PoD—producing a curve that correlates accurate (acceptable) measurement to defect size—the PoaM emphasizes the successful quantification rather than the detection of a defect. This distinction marks a shift in focus: from mere identification of non-conformance to the accurate characterization of its size, which is essential for critical applications where measurement fidelity directly impacts decision-making. The PoaM curve can be expressed as:

$$\text{PoaM}(x) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x)}} \quad (1)$$

where $x$ is the defect size and $\beta_0$ and $\beta_1$ are the model coefficients fitted to the data.

The results, shown in Figure 2, illustrate that for small defects measuring 0.0005″, the probability of accurate quantification using a 3D scanner is approximately three times higher than replicating and measuring a defect with a profile projector. The profile projector only reaches an acceptable 90% PoaM threshold for defects larger than 0.0012″, highlighting the benefit of advanced scanning technologies for small defect sizes.

**FIGURE 2** Probability of accurate Measurement for 4D InSpec and Profile Projector.






## 3.3. Isoplot Analysis

*Isoplot analysis* is a graphical technique for separating product variation ($\Delta P$) and measurement error ($\Delta M$) to evaluate a measurement system's ability to discriminate [18, 19]. The product variation is the range of defect size, i.e., the difference between the largest and smallest defect. A successful separation of $\Delta P$ and $\Delta M$ is evident when the so-called *discrimination ratio* is equal or greater than six (Equation 2) [20].

$$\text{Discrimination ratio} = \frac{\text{Product variation}}{\text{Measurement error}} = \frac{\Delta P}{\Delta M} \geq 6 \tag{2}$$

Two measurements were taken for each defect and plotted on an X-Y graph (Figure 3). The discrimination ratios were calculated and the results show a ratio of 3.6 for the profile projector, which is smaller than six, and therefore the system cannot discriminate $\Delta P$ and $\Delta M$. In other words, this means that the measurement system (profile projector) is not sensitive enough to detect meaningful differences between defects. The measurement variation (error) is too large compared to the actual differences between defect sizes. In contrast, the discrimination ratio for the 4D InSpec is 41.2 and significantly greater than six. Therefore, it is a suitable measurement system with sufficient resolution and sensitivity for the presented defect sizes.

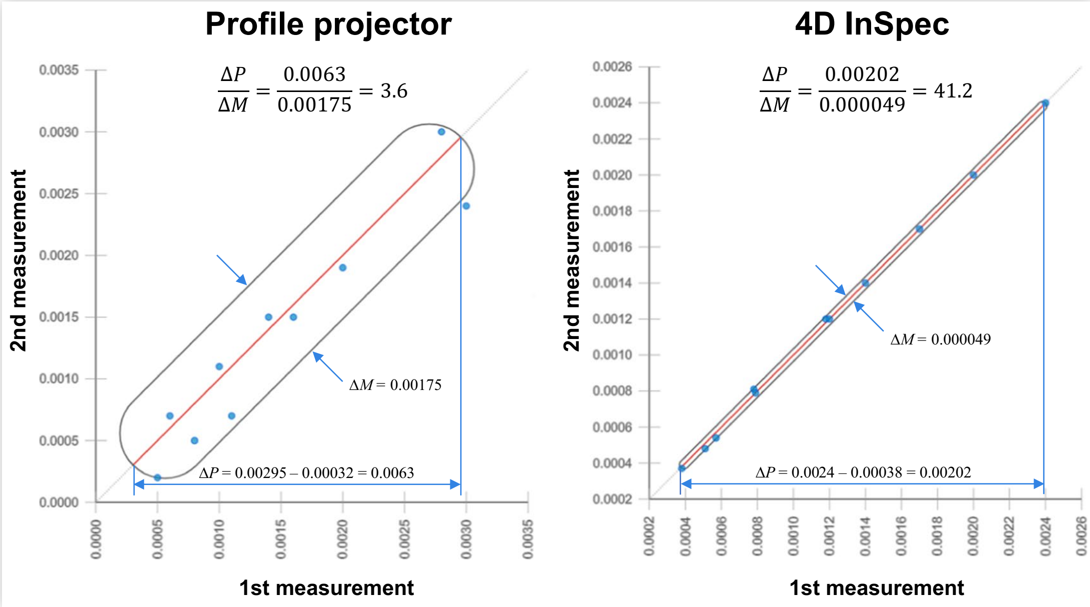
## 3.4. Youden Plot

A *Youden Plot* is a graphical tool designed to identify outliers, biases, and variability in both measurement instruments, and to separate systematic and random errors [21]. Also known as *two-sample collaborative testing plot* or *two-sample diagram*, it provides an excellent visual assessment of the variation within the data based on categorical information such as different defect types, operators, or engine shops [22]. If measurements are accurate and consistent, the points will lie near the 45-degree reference line, indicating minimal bias and variability. Deviations from this line, as shown in Figure 4, can highlight systematic errors (bias) or random errors (imprecision) within and between profile projector and 4D InSpec. Defects #5 and #8 show the greatest variation when measured on the profile projector, while the measurements with the 4D InSpec are highly consistent and repeatable. This information is not accessible when solely using *Gage R&R* or *Isoplot*. The observed variation of the profile projector can negatively impact the inspector's decision-making and serviceability decision when inspecting aircraft parts.

## 3.5. Bland–Altman Plot

The *Bland–Altman plot*, also known as *difference plot* or *Tukey mean difference plot*, assesses agreement between two measurement techniques by plotting the differences against the averages of the two methods. Like the *Youden plot*, the *Bland–Altman plot* presents the gage comparison for different categories, e.g., for each defect type, and helps identifying systematic differences between the measurements, such as fixed biases, and outliers. These analyses (Figure 4) revealed that there was a much larger variation when measuring defects with the profile projector

**FIGURE 3** Isoplot for profile projector (left) and 4D InSpec (right)





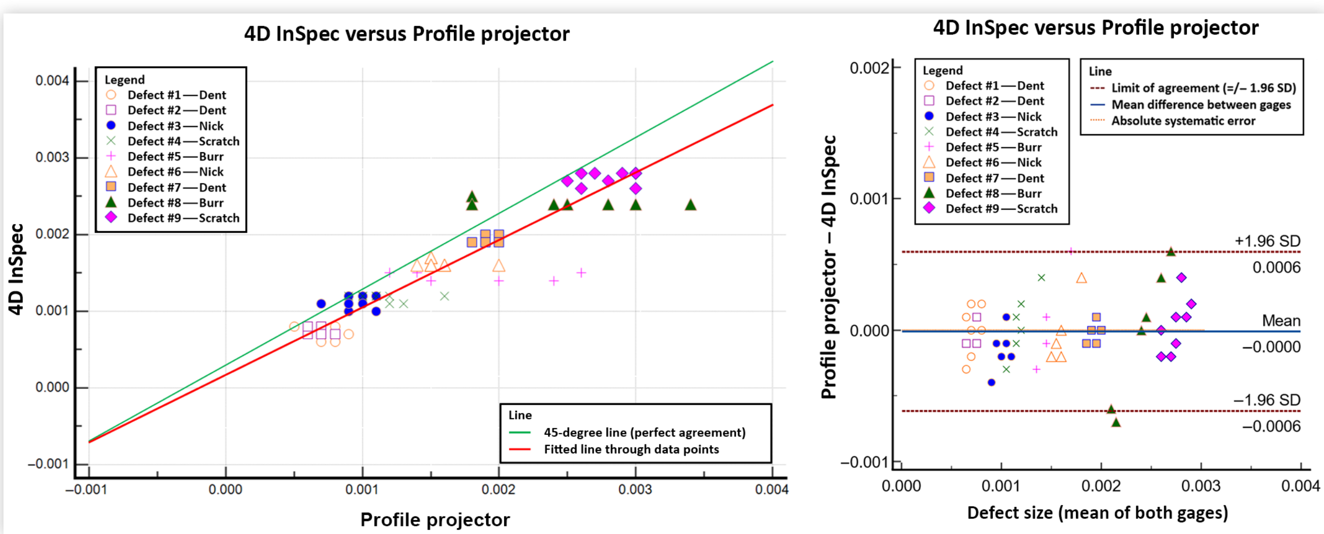

compared to the 4D InSpec scanner. The results varied particularly for burrs and scratches, while the measurements for nicks and dents appear to be quite consistent.

# 4. Results and Discussion

The results of the *Gage R&R*, *Isoplot*, *Youden plot*, *Bland–Altman plot*, and *PoaM* study showed that the 4D InSpec significantly improved the accuracy, repeatability, and reproducibility when quantifying defects as small as 0.0004″, compared to the profile projector. The Isoplot suggests that this is likely due to the higher sensitivity and resolution of the 3D scanner.

The Youden plot and Bland–Altman plot provided important information on the performance and revealed that the measurement error was not equally consistent for all defects. Scratches and burrs seem to be particularly difficult to measure on the profile projector. This may not be surprising, as the operator must assess the replica and, with a steady hand, cut it in the right location to be able to measure the maximum depth of the defect. For burrs, any raised material must be excluded from the measurement, which can be difficult, particularly when the surface is curved or the overall contour has worn

**FIGURE 4** Youden plot (left) and Bland–Altman plot (right) for 4D InSpec versus Profile Projector



during service. Nicks and dents, in contrast, showed relatively good and repeatable results. It seems to be easier to cut the replica—resembling the shape of a "mountain"—at the right location, i.e., slicing through the "peak".

Throughout the study, the time taken to measure each defect was recorded and indicate that using the 3D scanner is 80% faster than the shadowgraph machine, mainly due to the application, 20-minute cure time [23], preparation and positioning of the replica. This time saving, as well as the redundancy of the replicating consumables (compound and single-use nozzles), directly correlate to the annual cost savings of US$ 32K. With the elimination of the replicating process, the 3D scanner also eliminates measurement inaccuracies associated with cross-sectioning errors and ergonomic risks including cutting injuries.

Furthermore, the integration of the 4D InSpec scanner can improve the consistency across operators with different experience and skill levels. The automated defect recognition and quantification feature inside the 4D InSpec software enhances measurement reliability and minimizes human error. The 3D scan data can be visualized in the form of 2D heatmaps and 3D contour maps, which provide a better understanding of the true defect shape and characteristics. Those results can then be exported into an inspection report and saved electronically.

To ensure successful adoption, personnel training on metrology and 3D scanning principles is essential. A standardized defect template, such as the one developed for this study, could be used for training and certification of new staff. Ongoing calibration will ensure accuracy and precision.

This technology offers several avenues for future improvement. One could focus on the automation of defect classification—potentially using artificial intelligence—to assist the operator in applying the correct inspection limits based on the defect type. It is also conceivable that collaborative robots could assist the operator when scanning in ergonomically straining positions. Furthermore, there is great potential for introducing blue-light scanning technology to borescope inspection.

## 5. Conclusion

This article aimed to compare the performance of two measuring systems, namely profile projector and 4D InSpec handheld 3D scanner. The results of the 3D scanner show a significantly improved measurement accuracy, reduced operator dependency, and enhanced process efficiency, while meeting aerospace quality standards. Furthermore, it highlights other benefits of modern measurement systems that may be important to industry practitioners and aerospace organizations. Future research could focus on assessing the performance of other measuring systems such as laser scanners, digital micrometers, photogrammetry systems, or stereo cameras, and comparing them with the results presented in this article.

## Conflict of Interest

The authors have no conflict of interest to declare.

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