Comparison of in-line and off-line measurement systems using a calibrated industry representative artefact for automotive dimensional inspection

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Abstract

Manufacturers should understand measurement system performance to identify and control measurement errors due to changes in the quality standard and actionable measurement data in the age of Industry 4.0. This study evaluates the capability of three measurement systems, determining their feature-specific suitability for automotive inspection. A touch-trigger probe CMM and a laser scanner CMM are compared as off-line measurement systems, against a laser radar as an in-line solution. Representative common automotive features were assessed using a calibrated industry artefact. The study shows the laser radar provides the comparable accuracy to off-line systems. If tolerances are smaller than ±1.5mm, the capabilities of non-contact systems are considerably dependent on the measured feature type. This study provides improved understanding of the non-contact measurement system that would enable automotive manufacturers to implement fast measurement strategy based on feature definition and tolerance limit without reducing the quality of measurement.

Keywords: Industry 4.0, Measurement System Assessment; In-line Measurement; CMM; Laser Scanner; Nikon Laser Radar; Process Control

1. Introduction

In the manufacturing process, metrology is often seen as a cost factor but rarely as a value-adding activity, even though measurement data is key to producing reliable information about the product [1]. Manufacturers face the dilemma of minimising the cost of measurement while balancing the respective needs of quality functions and management. With the recent shift of manufacturing technologies towards smart and connected factories, metrology has become recognized as an enabling factor [2, 3]. New generation measurement sensors should sense the process and be connected while provide intelligence throughout the entire product lifecycle in order to address manufacturing shift [4,5]. This process involves not only inspecting a part, but also optimising manufacturing processes in real time. In the era of Industry 4.0, firms will not survive without implementing this strategy efficiently. They must not only capture the current manufacturing state and adapt it (automatically, if possible) but also make new plans which take the changed requirements into account throughout measurement technology [6]. The main challenge remains, therefore, to use 'right' measurement system to collect the 'right' measurement data in the 'right' place at the 'right' time.

The VDI/VDE-GMA roadmap (2011, 2015) [7] covered a manufacturing metrology roadmap that was updated in 2015 to meet the current production trends. The roadmap covered the measurement challenges based on the trends of production under the topics of fast, accurate, reliable, flexible and holistic. Fast and accurate measurement are self-explanatory. Reliable measurement is not about reducing the measurement uncertainty but is more concerned with methods of determining and communicating it. Measurement technologies are becoming more flexible and agile by combining different measurement systems such as the combination of different sensors. The aim of holistic measurement is to evaluate product quality as a whole rather than reporting measurement values individually and processing the collected data for product characteristics separately.

In the automotive industry, the Coordinate Measuring Machine (CMM) with touch probe provides a robust, and long-lasting measurement solution, with well-established determination of measurement capability and uncertainty, enabling critical control across the entire manufacturing process [9]. However, CMM touch probe measurement is slow and sensitive to the environment, and therefore, would not be suitable for futuristic in-line or near in-line measurements. However, the role of the CMM is changing, with non-contact scanners becoming increasingly common [8, 9]. These non-contact measurement systems have the ability to measure fast and adapt to different measurement tasks under different environmental conditions by overcoming the issues of off-line CMMs. However, one of the main problems of using non-contact sensor is that the measurement uncertainty statement of certain features, which are commonly measured in the automobile manufacturing industry, is limited or unattainable [8, 30, 31]. This limited information is not sufficient to move from touch-trigger (off-line) measurement process to non-contact in-line measurement solutions with associated measurement risks, especially during new product development. For example, a non-contact sensor such as laser scanner might be good in measuring surface points with higher accuracy and repeatability. However, the same level of performance may not be achieved when measuring trim edges or slots. Without prior knowledge of this, the measurement planning decision might be suboptimal and ultimately affect measurement decisions. Therefore, the 'off-the shelf' accuracy, and reliability of non-contact measurement systems should be investigated further under different conditions in order to understand their performance capability although they have addressed the fast and flexible measurement of 'metrology roadmap trends' as aforementioned [7]. Evaluation of these systems helps the manufacturers to improve their understanding about the measurement system capability at different conditions. Also, it will help to find a spectrum of the measurement system performance with a given tolerance criteria when measuring different feature types. This will eventually help to make a feature specific measurement plan for fast, accurate and reliable results, and ultimately prepare a better position for Industry 4.0 because of the big data collected through measurement. Currently, majority of the car manufacturers measure one car per shift (circa 8 hours) that is often too late to find out a problem by the time CMM touch-trigger probe measurements have been completed. 75% of occurring errors and quality defects are in early stage of new product development (NPD), called fuzzy-front end [20] but the majority of these errors are fixed in later phases. With the help of non-contact measurement systems, more data can be captured either off-line or in-line. It will eventually help to identify and analyse root cause faster. It is essential for car manufacturers to thoroughly understand and identify these issues. This facilitates manufacturers to have a proactive approach rather than a reactive mode.

There is a larger number of uncertainty sources associated with an in-line measurement system in comparison with an off-line systems. This is due to the environmental conditions and system set-up including robotic applications. The accuracy and reliability of these systems should be verified in accordance to international standards. In addition, it is also important to design and perform an interim test for accuracy and reliability in accordance with internal quality standards such as ISO 10360-2 [15] to check the measurements system health. There are limited range of artefacts available, such as one-dimensional ball standard [7, 16, 17] and tetrahedron-spatial reference systems [18, 19]. Furthermore, each manufacture has their own artefact for verification, and to the best of the authors' knowledge, there is no international guide and practical application of these systems published by any national institutes. These calibrated artefacts are useful for reverification and interim tests for CMMs but they do not represent typical features on automotive parts or sub-assemblies (such as trim edge points, holes, slots etc.). Consequently, an industry representative calibrated artefact, which fully represents an automotive sub-assembly body part with actual features measured in a typical body in white application, would help to verify feature specific measurement system capabilities when used for automotive dimensional inspection.

The aim of this paper is, therefore, to investigate the measurement capabilities of three different measurement systems: (a) CMM touch-trigger probe, (b) CMM laser scanner (L100), and (c) laser radar (LR), using a fully industry representative and certified artefact, which includes standard features measured in the automotive sector. The majority of the research in this area often compared two similar measurement systems such as comparing off-line systems [8, 31, 34, 43] or only use of the LR [11,12, 14] .However, this study evaluate three different systems which are in high demand for automotive industry [33]. The CMM touch trigger probe is the benchmark off-line measurement with well-established determination of measurement capability and uncertainty. The laser scanner used in this study (Nikon L100) is more accurate in comparison with the other laser scanners currently available on the market as identified by the specifications provided by manufacturer [38, 39, 40]. Therefore, the L100 systems, used in this study, can be considered as the benchmark in terms of accuracy and repeatability, and can be viewed as a representative of other laser scanner systems. Besides, this laser scanner is also compatible with the laboratory's CMM set-up. In case of LR, Nikon is the only manufacturer. This system has been used extensively in aerospace manufacturing because its calibration and verification process is well- defined using the ISO 10360-10 [42]. It captures comparatively smaller data and works fast in comparison with other non-contact technologies including laser scanners or structural light systems. Therefore, the LR has the potential to fulfil automotive industry needs (a tack-time of most processes in the automotive production line are around 70 seconds or less and have been a number of applications) [14,41]. It has been already implemented as in-line solution by different car manufacturers in USA. In addition, LR system is less sensitive to robot accuracy and the environment such as lighting and temperature. Also, the artefact, used in this study, was utilised by an original equipment manufacturer (OEM) to verify their measuring equipment periodically between annual calibrations, as well as investigating new measurement technologies from vendors. The artefact features a tailgate form as this is often a region on a Body-In-White (BIW) that experiences matching surface challenges against the remaining panels of a vehicle. Therefore, to the best of author's knowledge, the measurement systems used in this study are the-state-of-the-art systems and also one of the best in the market as recognised from the reported accuracy and repeatability specifications. The authors believes that the results and the conclusions can be used for similar product types (i.e. laser scanner) as the physics of the measurement for individual measurement system will remain similar amongst different manufacturer, and would follow similar results.

Therefore, the novelty of the work is twofold: firstly, a detailed measurement system capability study, as has previously been undertaken on 'gold standard' CMM touch-trigger probes (off-line) and CMM laser scanner, is reproduced on an in-line LR system. Secondly, the study was performed with an artefact contains all the representative features generally measured in the automotive industry. Therefore, it helps to explore the feature specific performance of the measurement system. This improved understanding of the non-contact measurement system would enable automotive manufacturers to implement fast measurement strategy based on feature definition and tolerance limit without reducing the quality of measurement. This will enable them to proceed for feature-specific in-line measurement.

2. Materials and methods

In this study, the measurement capabilities was investigated for the following three different measurement systems: (a) CMM Touch-Trigger Probe, (b) CMM Laser Scanner (L100), and (c) LR, using a fully industry representative and certified artefact. The following sections details the description of the measurement systems and artefact following experimental procedure.

2.1 CMM touch probe measurement system

To evaluate the capability of a multi-sensor probing system, a LK HC-90 Horizontal Dual Arm CMM was utilised *(LK Metrology)* (Figure 1a). The accuracy of twin column CMM was verified in accordance with ISO10360-2 [15] with an expanded measurement uncertainty (k=2) of ±1.0µm + 1.0 µm/m as stated by the manufacturer. This set-up is commonly used in automotive BIW and sub-assembly inspections. It was equipped with a PH10MQ motorised indexing head (*Renishaw*) enabling both touch-trigger probe inspection and laser-scanning. In this study for contact measurement, a TP20 5-way kinematic standard force touch-trigger probe was used with 300mm steel extension bar (PAA3) and 20mm long by 2mm diameter stylus *(Renishaw*). Both touch–trigger probe and laser scanner measurement programmes used Camio 8.5 software (*LK Metrology)*.

2.2 Laser Scanner (L100) measurement system

For non-contact measurement, a L100 laser scanner (*Nikon Metrology*) was used on the HC-90 CMM, in place of touch-trigger probe and extension (Figure 1b). The L100 scanner is a single-line scanner, which has a scan depth of 60mm, a standoff distance of 105mm and can capture up to 200,000 points per second. The accuracy of the laser scanner stated by the manufacturer is comparable to EN/ISO 10360-2 and EN/ISO 10360-5 with probing error (MPE_p) 6.5µm and multi-stylus test length (MPE_{AL}) 6µm. The L100 sensor was calibrated with specified measurement uncertainty of MPEp= 5.2µm and MPE_{AL}= 2.1µm. This L100 scanner is one of the best available in the market and can be considered as the representative laser scanner for other manufactures.

2.3 Laser radar (LR) measurement system

The LR used in this study was an MV331 (*Nikon Metrology*) that provides automated, non-contact measurement capability for medium to large-volume applications of up to 30m with a scanning speed of up to 2000 points per second. It applies a Spherical Measurement System (SPS) returning range by the help of two rotary axes (elevation and azimuth) and converts

Cartesian coordinates relative to the LR. The expanded uncertainty of the MV331 is (k=2) of 10 µm+2.5 µm/m over the measurement range of 2-30m. The measurement programmes were developed and run in Polyworks 2018 software *(InnovMetric Software Inc., QC).* The LR was fitted on a KUKA KR90 R3100 extra HA six-axis industrial robot, mounted on a KUKA KL4000 linear track with booster pedestal with one corresponding KUKA KRC4 robot controller (Figure 1c). LR was calibrated in comparable to ASME B89.4.19 [21] that prescribes methods for the performance evaluation of laser-based spherical coordinate measurement systems and provides a basis for performance comparisons among such systems.

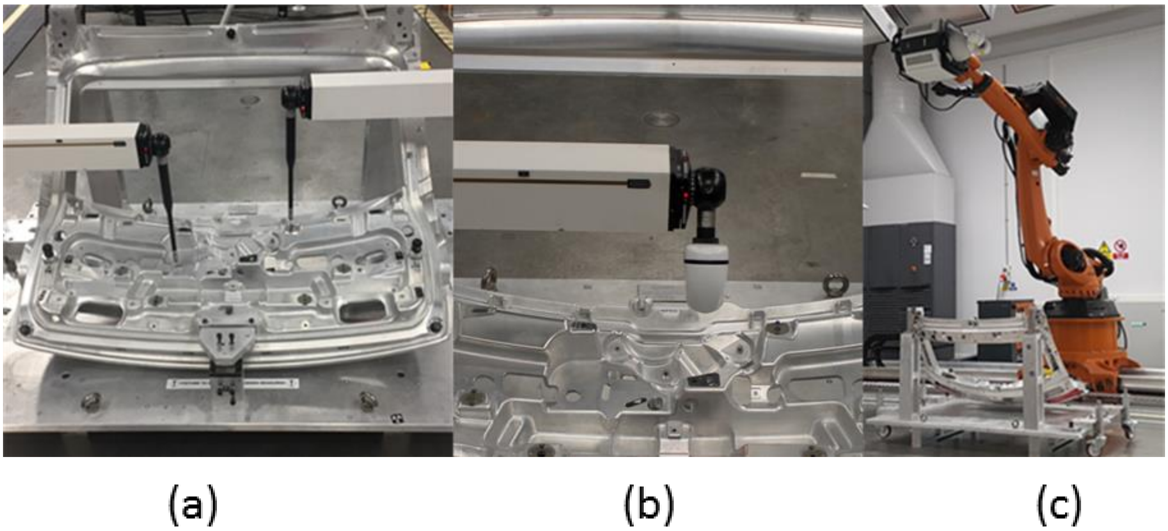

Figure 1: The measurement systems used in this study (a) touch-trigger probe, (b) L100, (c) LR

2.4 Industry representative artefact:

The objective of this study was to use a calibrated artefact which is a physical representation of a manufactured sub-assembly to assess the feature-specific capability of in-line and off-line non-contact measurement systems in the dimensional inspection of automotive assemblies. The artefact comprises of an aluminium machined representation of an automotive tailgate, mounted using a three-sphere, and flat alignment to a bespoke holding fixture as shown in Figure 2. The artefact was generally used by an OEM to verify their measuring equipment periodically between annual calibrations, as well as investigating new measurement technologies from vendors. The artefact features a tailgate form as this is often a region on a BIW that experiences matching surface challenges against the remaining panels of an automobile assembly. The artefact contains 119 features comprising of surface points, trim edge points, circular holes and slots, which are generally measured in a typical Body in White (BIW) measurements. The dimension of the artefact is 1094mm X 583mm X 888mm. Hexagon Metrology UK, a UKAS calibrated laboratory, certified the features from the measurement plan. The measurement was performed by a highly accurate Hexagon DEA Global 12.XX.10, MPE = 2.7+ L/333µm. Each measurement point/feature was measured 30 times by hexagon and the mean value, associated with each feature was considered as the target/benchmark value for the measurement comparison. The following sections detail the experimental set-up, the measurement methodology and statistical analysis procedures of this study.

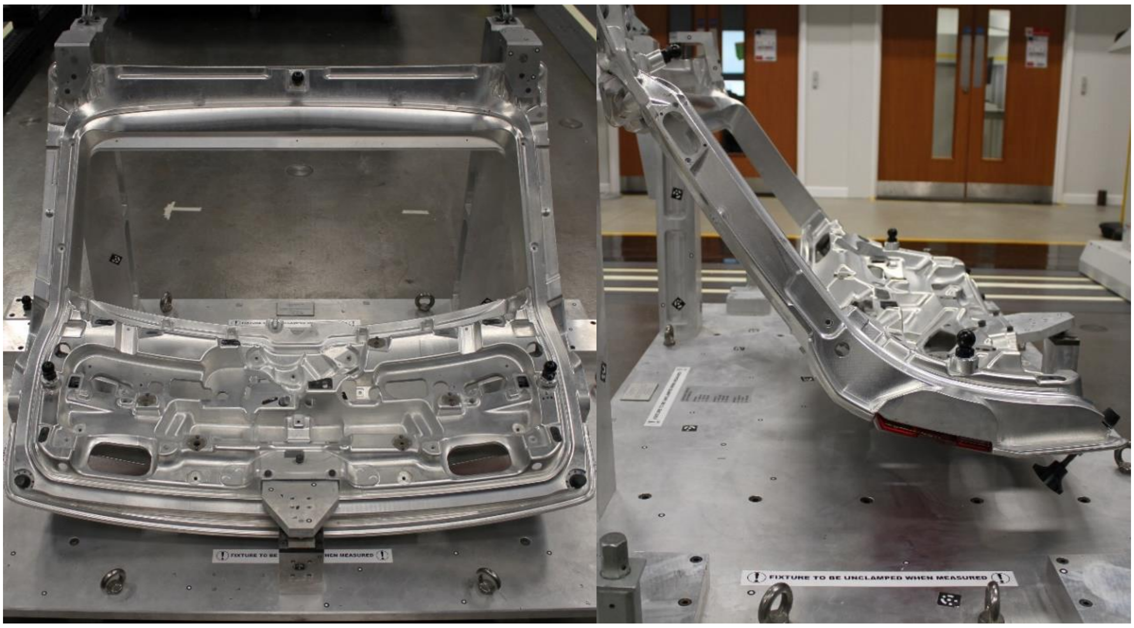

Figure 2: the calibrated tailgate artefact (1094mm X 583mm X 888mm)

2.5 Experimental procedure

The artefact selected for the study, as detailed in the previous section, was located and secured using magnetic clamps on the CMM measurement bed. It remained on the measurement bed for the duration of the study in a temperature controlled environment at 20°C ± 1°C [22, 23]. The average temperature was 19.8°C with an average humidity of 62.3% during the period of the study. The measurements were performed after a 48 hour soaking period [24, 25]. The alignment for the artefact used the three part spheres, (Figure 2) and Reference Point System Alignment (RPS) was performed [9], allowing the artefact to be measured in a car-line coordinate system.

Three separate measurement procedures were carried out for each of the three measurement system options proposed: Laser Radar (LR) on robot, , and Twin-Column CMM with TP20 touch-trigger probe and 300mm extension (Figure 1a), Twin-Column CMM with L100 laser scanner (L100) (Figure 1b) and Laser Radar (LR) on robot (Figure 1c).

The measurement plan included the use of five robot positions to provide the necessary line of sight to measure all points and features on artefact. An example of one of five poses is shown in Figure 1c. The LR application for the measurement of the artefact was completed in a cycle time of 6 minutes, including realigning to the tooling ball network at each of the five positions. The measurement routine repeated thirty times.

Before performing CMM measurements, all touch-trigger probe angles and laser angles were calibrated and four extra features (2 surface points, 1 slot, and 1 sphere) were added to the measurement plan in order to assess the systematic error between the two columns. The same RPS alignment procedure was followed using the two horizontal arms and this was followed through two iterations in the autonomous mode. This is common practice as the points measured in direct computer controlled mode are more accurate and a repeated set of measurements can be used to further refine the coordinate system [2]. The alignment was saved and used for both the touch-trigger and laser-scanning probes. For evaluation of the three measurement systems, all 119- features were measured 30 times. It was not possible to measure all the features with the laser scanner because of the experimental set-up, accessibility and standoff distance of the laser head. Therefore, there were only 90 features, which were measured by all the three measurement systems, and therefore, used for comparison. Most of the features could have been measured using a single column CMM instead of using twin column but this is a still limitation of laser scanning technology due to limited stand-off distance, and thus accessibility. Automotive measurement set-ups typically use a twin-column CMM as this allows auto manufacturers access to both sides of the vehicle to identify any dimensional issues with a single setup. Although it was not the purpose of this study to compare measurement speeds, the measurement time would be approximately double if using a single column.

2.6. Measurement Analysis

In order to evaluate the performance of the CMM touch-trigger probe, laser scanner and LR the following comparisons were performed for each of the feature types: (a) bias (i.e. mean position) (b) repeatability (random error) using 6σ, (c) Capability indices (Cg) considering only gauge variation, (d) Capability indices (Cgk) considering both gauge variation and bias, and (e) minimum tolerance (Tmin) which could be measured using the measurement systems considered in this work.

As explained in 'Experiment Procedure' section, each feature was measured 30 times using each measurement system. The X, Y and Z components of the position of each feature were captured and were then used to calculate the aforementioned statistics. Bias for each component (B_X, B_Y and B_Z) was calculated using Eq. 1, and thereafter the total bias was calculated using Eq. 2

$$
\begin{aligned}
&B_C = \bar{C} - C_R \qquad \text{where, } C = X, Y, Z \text{ component} \\
&\bar{C} = \frac{1}{n}\sum_{i=1}^{n} C_i = \text{mean of the n measurements} \\
&C_R = \text{Reference value}
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
&Bias = \sqrt{B_X^2 + B_Y^2 + B_Z^2} \\
&\text{where, } B_X,\ B_Y, B_Z \text{ are the X, Y, Z component of Bias resepctively}
\end{aligned} \tag{2}
$$

The standard deviation (SD) was calculated for each component using Eq 3 and subsequently, total SD was calculated using Eq. 4. In this work, the results for repeatability was represented with 6*SD to represent 99.73% of the measurement.

$$
\begin{aligned}
&SD_C = \sqrt{\frac{\sum_{i=1}^{n} (C_i - \bar{C})^2}{n-1}} \qquad \text{where, } C = X, Y, Z \text{ component} \\
&\bar{C} = \frac{1}{n}\sum_{i=1}^{n} C_i = \text{mean of the n measurements}
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
&SD = \sqrt{SD_X^2 + SD_Y^2 + SD_Z^2} \\
&\text{where, } SD_X,\ SD_Y, SD_Z \text{ are the X, Y, Z component of SD resepctively}
\end{aligned} \tag{4}
$$

Capability indices (C_g) considering only gauge variation was calculated using Eq. 5. In this work, *k* was defined as 20, this value depending on the applied company standard % of the characteristic tolerance [2,26] and ±1.5mm *Tolerance* was considered as representing tolerances that are typically applied to the dimensional analysis of automotive BIW.

$$C_g = \frac{\left(\frac{k}{100}\right) * Tolerance}{6 * SD}$$
$$\text{where, } k = \text{percent of Tolerance}$$
$$SD = \text{standard deviation} \qquad (5)$$

Capability indices (C_{gk}) considering both gauge variation and bias was calculated using Eq. 6. In this work, *k* was defined as 20 and ±1.5mm *Tolerance* was considered as it was an assembly application.

$$C_{gk} = \frac{\left(\frac{k}{200}\right) * Tolerance - Bias}{6 * (SD/2)}$$
$$\text{where, } k = \text{percent of Tolerance}$$
$$SD = \text{standard deviation} \qquad (6)$$

The minimum tolerance (Tmin) which could be measured using the measurement systems was calculated using Eq. 7 [26] where 1.33 is the limit value (accepted value) of Cgk i.e. if Cgk value is more than 1.33, the measurement system is considered capable.

$$T_{\min} = \frac{1.33 * 3 * SD + Bias}{\left(\frac{k}{200}\right)} \qquad (7)$$

3. Results

The evaluation of the system's accuracy, repeatability, and suitability for application was determined using the calibrated tailgate artefact. All the features were categorised into four feature types: (a) surface point, (b) trim edge point, (d) hole, and (d) slot. All the results were calculated, and summarised for each of the feature types. The following sections detail the comparison of the three measurement systems in terms of (a) bias/accuracy (i.e. mean position) (b) repeatability (random error) using 6σ, (c) Capability indices (Cg) considering only gauge variation, (d) Capability indices (Cgk) considering both gauge variation and bias[27], and (e) minimum tolerance (Tmin) which could be measured using the measurement systems.

3.1 Accuracy/Bias comparison

Figure 3 compares the measurement bias amongst different features for each of the three measurement systems. The bias was divided into six categories which is represented in the horizontal axis of Figure 3. The number of features was then counted based on the category they belonged to. The percentage of the features was then calculated by dividing them with the total number of features within each feature type. It was observed that the LR system returned the best bias results for all the features, with all the bias less than 100µm. In particular, more than 70% of surface points, trim edge points and slots had bias less than 50µm. In contrast, bias results from the touch-trigger probe and L100 laser scanner system were more evenly distributed across bias categories than the LR results. Specifically, bias for the trim edge points was quite spread for both touch probe and L100 system.

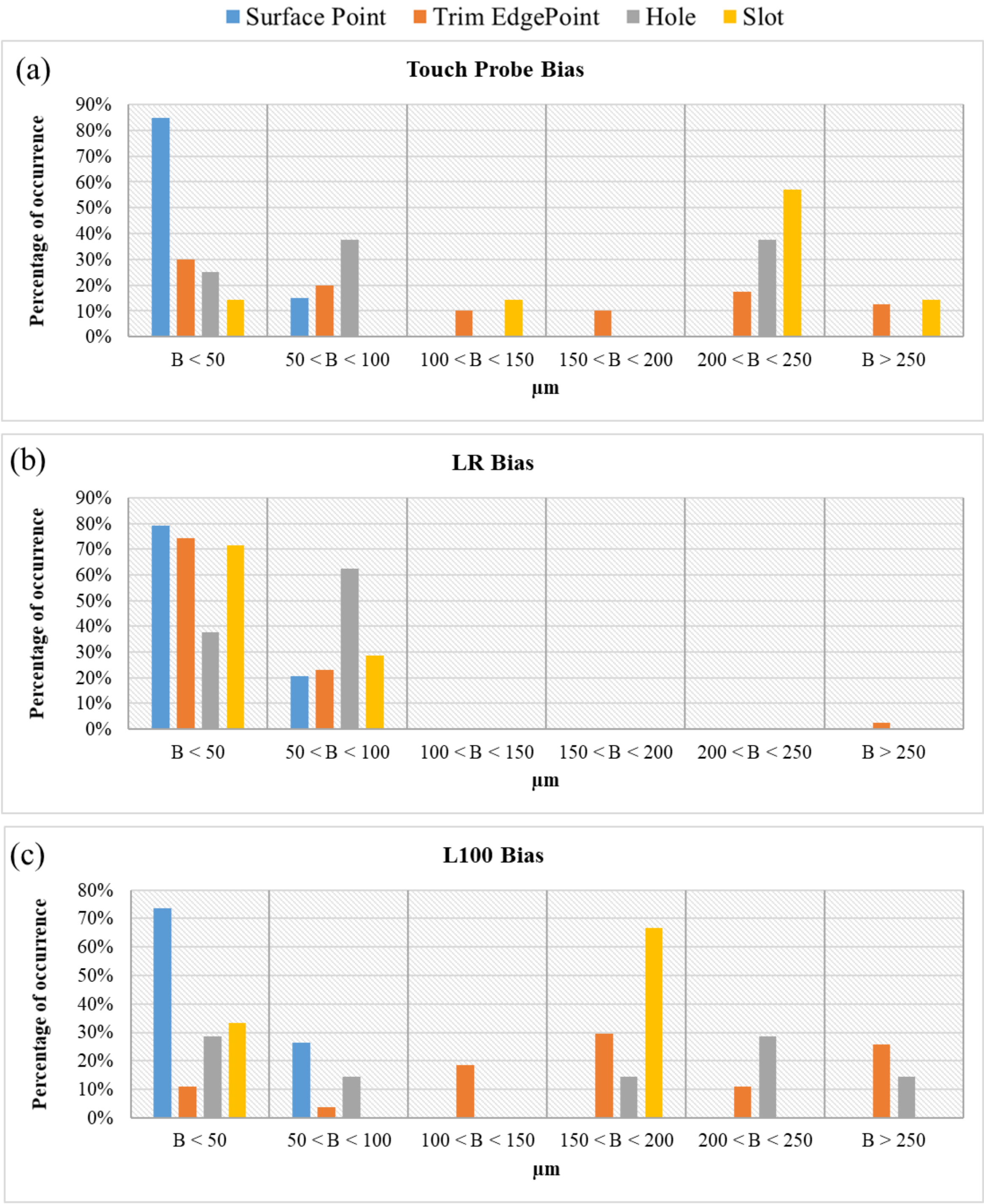

Figure 3: Comparison of measurement bias amongst the four different features for each of the three measurement systems considered in the study

On the other hand, Figure 4 represents the comparison of measurement bias for three measurement systems (Touch Probe, LR and L100) for each of the four feature type. Measurement bias for LR was the least for all the feature types, although it has few outliers for surface and trim edge points.. The median bias for touch probe and LR was similar for surface points, trim edge and hole feature types. The bias for the touch probe measurement system for surface points showed a broad distribution as the inter-quartile range (IQR) was higher compared to LR but is better than other two systems. The number of outliers for trim edge point measurement was quite higher for L100 in comparison with LR and touch probe. Although the IQR was quite narrower for LR for trim edge point measurement (even in comparison with touch probe), there were still few outliers for LR. For hole measurement, touch probe bias was smaller than L100 whereas for slot, it was opposite.

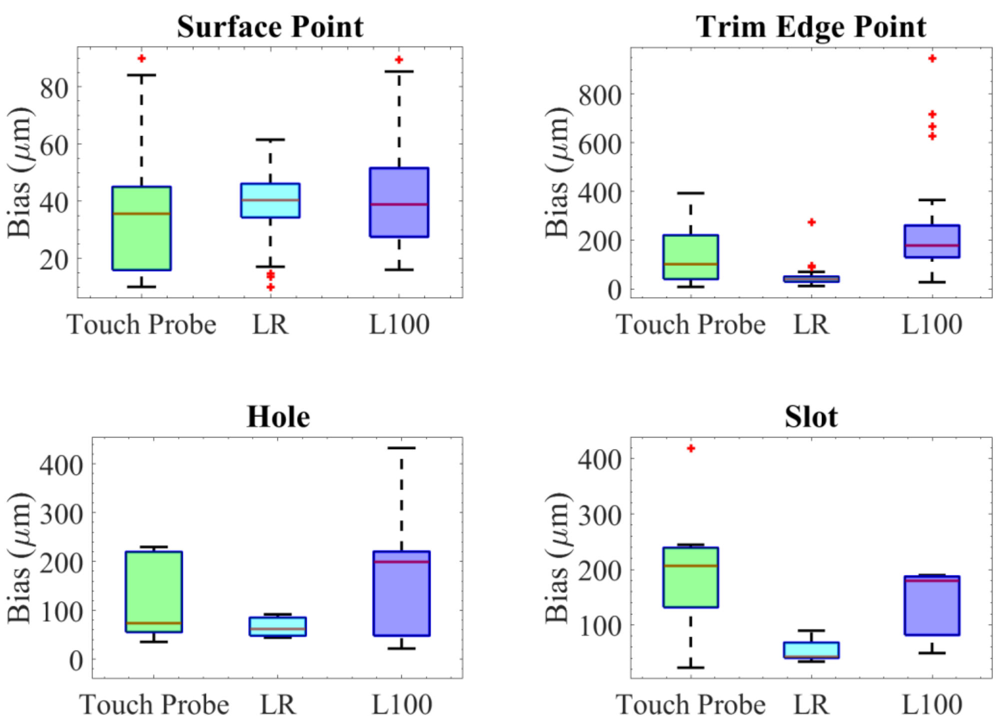

Figure 4: Comparison of measurement bias amongst three measurement systems for each of the four feature types considered in the study

3.2 Repeatability comparison:

The 6SD repeatability results were also grouped into six categories as shown in the horizontal axis of Figure 5. The number of features was then counted based on which category they belonged to, and the percentage of the features was calculated by dividing them to the total number of each feature type. It was observed that the touch-trigger probe repeatability results were the best for all feature types, and all features were below 75µm. The repeatability of measuring the holes and the slots were not acceptable at all for the LR system as the 6SD repeatability of measuring the holes and slots were greater than 75µm and 100µm respectively. The L100 performed better for slots and holes as 6SD repeatability was less than 75µm for all slots, and for 85% of the holes. Repeatability for trim-edge measurement was superior for LR compared to L100. The 6SD repeatability was less than 100µm for 85% of the trim edge features when measured with LR system. This was in comparison to only 48% of trim edge features falling into this category when measured with L100.

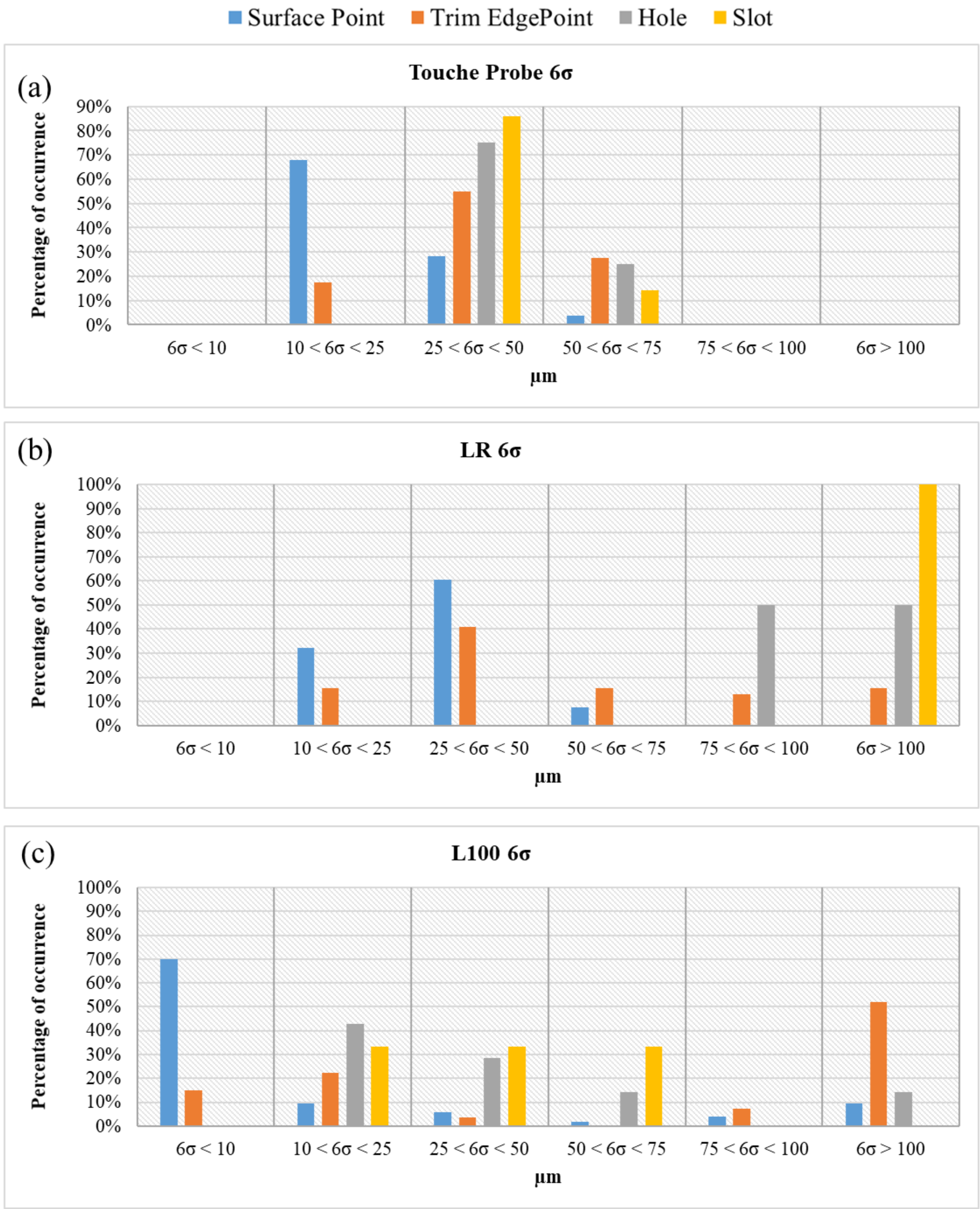

Figure 5: Comparison of 6SD repeatability amongst different features for each measurement system

On the other hand, Figure 6 represents the comparison of measurement repeatability for three measurement systems (touch probe, LR and L100) for each of the four feature type. As would be expected, the 6SD repeatability results were the best when measured using the touch probe. For surface points, the median and IQR of 6SD were smaller for L100 compared to touch probe and LR. However, L100 produced many outlier that were almost negligible for touch probe and LR. The repeatability of trim edge point measurements using the LR system was much better than using L100. On the other hand, the L100 outperformed the LR system in the case of hole and slot measurements.

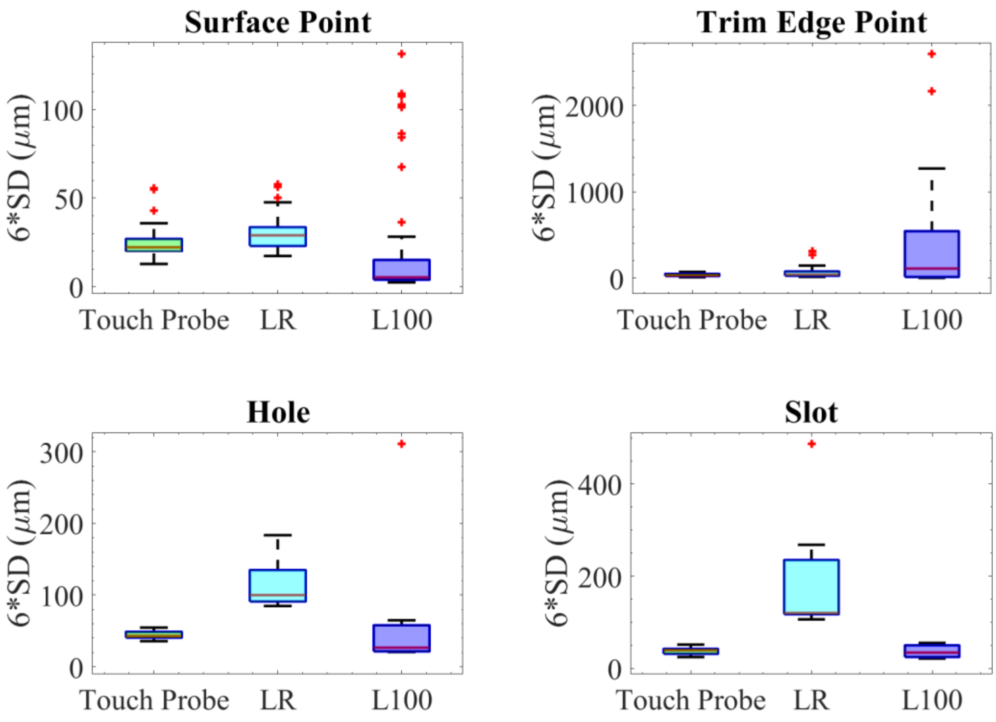

*Figure 6: Comparison of measurement repeatability (6*SD) amongst three measurement system for each feature type*

3.3 Cg and Cgk Comparison:

Figure 7 and 8 compare Cg and Cgk values of the three measurement systems for each of the feature types respectively. Although the median Cg value for each feature type (except trim edge) was always higher for L100 system compared to touch probe and LR, the Cg values were quite widely spread for L100. The Cg values distribution was similar for touch probe and LR systems for surface point measurements. However, the Cg values for the LR system for holes and slots were significantly worse than the other two measurement systems.

The Cg values only considered repeatability where as Cgk values considered both repeatability and bias of the measurement. The median Cgk values were reduced for L100 for all feature types when compared with their respective Cg values. The IQR of Cgk values for all feature types (except surface point) was higher than the IQR of Cg values for touch probe measurements. Although the median Cg value for each feature type (except trim edges and holes) was always higher for L100 system compared to touch probe and LR, the Cg values were quite widely spread for L100 for all feature types. Cgk values were quite consistent for all feature types for touch probe and LR system.

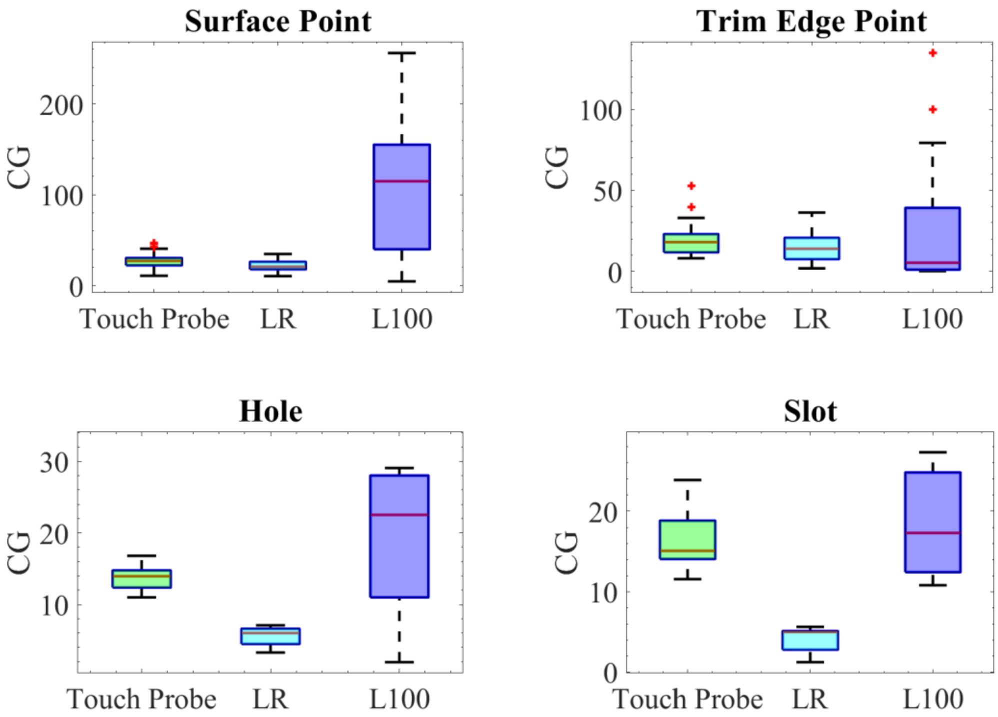

Figure 7: Comparison of measurement Cg amongst three measurement system for each of the four feature types considered in the study

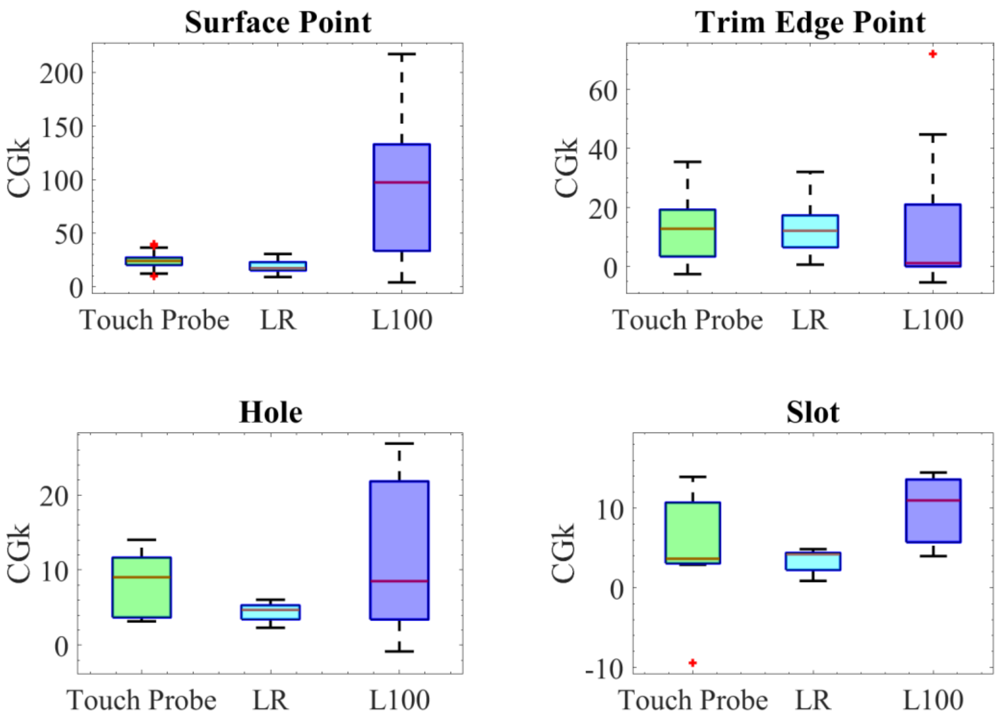

Figure 8: Comparison of measurement Cgk amongst three measurement system for each of the four feature types considered in the study

3.4 Tmin comparison

Figure 9 compares the minimum tolerances that the measurements system would be capable of measuring when the limit of Cgk value was considered as 1.33 i.e. to maintain 8SD (±4SD) measurement repeatability. The red dotted line which is parallel to the horizontal axis of each subplot depicts the tolerance limit of ±1.5mm which is a typical value used in automotive assembly processes [14]. It was observed that all systems would be capable of measuring surface points within the ±1.5mm tolerance values as even the outlying points were below 2.5mm (Fig 9, Surface Point). For the trim edge points, the touch probe and LR systems would be capable as their entire IQR was below ±1.5mm, although the maximum value of Tmin for touch probe and a few outliers for LR were outside tolerance limit. However, most of the IQR and even the median of the Tmin values were higher than 3mm range for L100 system, and therefore the L100 could not be assumed to be capable of measuring trim edge points within ±1.5mm tolerance limit. For holes and slots, all the measurement systems were capable of being used within 3mm tolerance limit measurement.

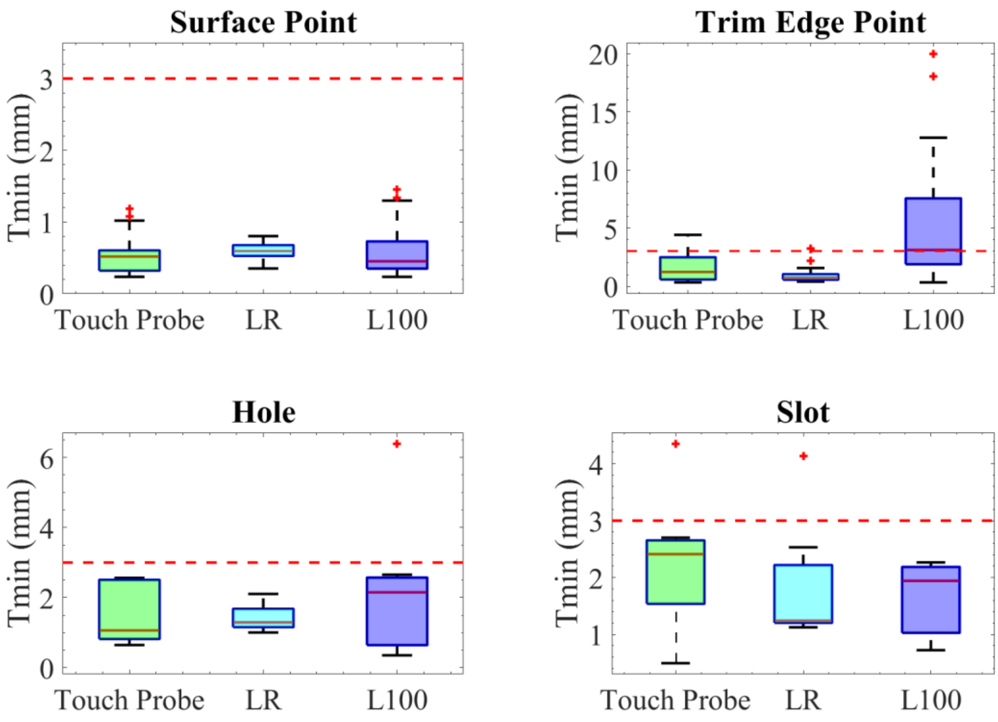

Figure 9: Comparison of minimum tolerance (Tmin) that the measurement system would capable of measuring for each of the four feature types considered in the study

4. Discussion

In this paper, a measurement capability study was performed to compare the capabilities of three measurement systems for an automotive assembly application using a calibrated fully industry representative artefact, with actual features measured in body in white application. The measurement system considered in this study were as follows: (a) CMM with touch probe (Touch Probe), which is a benchmark off-line measurement system, (b) CMM with laser scanner (L100) which is an off-line measurement system, and (c) LR mounted on a 6-axis industrial robot, which could be used for in-line measurement. These three measurement systems were compared with a certified industry representative artefact consisted of actual features. In this study, surface points, trim edge points, holes and slots were measured.. Therefore, there were two novel aspects of the work – (a) a detailed measurement system capability study was undertaken on a ‘gold standard’ CMM touch probe (off-line) in the automotive industry, an advanced off-line measurement system with CMM laser scanner, and an in-line LR system; and (b) the study was enriched by using an industry representative artefact with actual features measured in automotive industry rather than using any length bar or hypothetic features.

There are a number of specific methodologies used to assess measurement system performance. In the automotive industry, Measurement System Analysis (MSA) is commonly used whereas Verband der Autobilindustrie (VDA) is primarily used in Germany and across Europe [28]. The methodology used depends upon the applied company standard, the tolerances required, the process variation (6 or 8 SD) and the requirements for the minimum value of the capability index Cg as a reference. As Figure 9 shows (the capability of the three measurement systems studied according to feature type), all systems would certainly be capable of measuring surface points within the ±1.5mm tolerance values. For holes and slots, all the measurement systems were capable of being used within the 3mm tolerance limit measurement. The L100 laser scanner was not capable of measuring trim edge points within the ±1.5mm tolerance limit for points selected for this study.

As non-contact measurement sensors, laser-scanners (L100) have several advantages over the touch-trigger probing method, including faster measurement speed, higher resolution, prevention of local part deformation during inspection, and hence the ability to measure soft and fragile work pieces [29,30]. The CMM fitted with a laser scanner offers not only improvements in CMM utilisation but also helps accrue more data without significant investment in a new measurement system. By considering the ever-increasing complexity of products and the data required for automotive manufacturers to make business decisions, this improvement (collecting a large set of data as a point cloud) helps manufacturers to visualise the inspected parts in 3D; hence improving communications between different teams and helping to understand root-cause. Whilst the potential opportunities of such non-contact technologies are clear, there are a number of areas that need further investigation in order for the capabilities of the system to be fully understood, particularly measurement uncertainty [31-32]. The laser scanner results were less accurate and repeatable than those of the touch probe system. Laser scanner measurement uncertainties can be categorised as follows: scanning parameters such as scan depth, incident angle, probe head orientation and surface properties [33-34]. The surface of the artefact was shiny and also rough with machining marks. These properties can reflect the laser line towards the camera, thus impacting the accuracy of data acquisition.

Most current in-line measurement solutions rely on robot accuracy and repeatability. These technologies are also sensitive to environment conditions such as lighting and temperature, thus their working and operational conditions must be considered. However in-line measuring stations with robots can be regarded as CMMs as defined by ISO 10360-1 [35]. For this reason, ISO 15530-3 [36] and VDI/VDE 2617-8 [37] describe how to determine measurement uncertainty and verify the capability of the measurement processes of in-line measuring systems. However, manufacturers are requiring to determine associated measurement uncertainties and the relationship between these systems and the laboratory-based CMMs in order to correlate, correct and improve by obtained information. This means an in-line system has to be robust and maintain its calibration performance over time with no degradation. The LR is less sensitive to the environment and is able to operate in a typical production environment where temperature and ambient lighting may not be tightly controlled. The effect of temperature on the robot after running for a certain period of time should not be ignored; robot arm expansion with heat can potentially change the incident angle of the LR towards the workpiece and therefore directly impact measurement results. Overall, it is expected future networked measurement systems, including in-line systems should be capable of performing self-validations and even self-calibrations in the context of Industry 4.0.

Overall, Table 1 demonstrates the applicability of the three measurement systems in accordance with feature type and measurement process variation to guide manufacturers in the context of dimensional inspection for parts /sub-assemblies in the automotive industry. In the table, consider different measurement system variation in terms of sigma values are considered. This is because companies tend to utilise different standards even though they generally use a variation range of 6σ. For each of the measurement system variations, a corresponding Cgk value is used to calculate the minimum tolerance (Tmin) that the measurements system would be capable of measuring. The reason for not using the Cg value is to take into account the effect of mean shift (bias) while calculating Tmin. Each Tmin value is associated with each feature. Therefore, in the experiment, if there are *n* features (e.g. surface points or trim edge points or holed or slots), there would be *n* number of Tmin values, and each associated with each of the features. In Table 1, the maximum value of the Tmin within a feature type is considered as the capability of the measurement system i.e. the worst case scenario is considered. For example, for 53 surface points, there are 53 Tmin values and only the maximum of the Tmin amongst the 53 values is presented in the Table 1, and this is performed for each feature type. The next column in Table 1 shows the range of the Tmin values. Therefore, subtracting the range value from its corresponding Tmin would provide the best case scenario i.e. the minimum of Tmin amongst all the Tmin values associated with their features. For the percentage of feature calculation, the minimum tolerance value of 3mm (±1.5mm) was considered, as it is generally accepted value for assembly measurement [14]. The number of features whose Tmin value was below 3mm was counted as a successful measurement. Therefore, 100% means every surface point considered in this study could be measured successfully if 3mm tolerance value is used under typical process variation. The performance of L100 for trim edge point is drastically reduced if variation range increased from 6σ to 12σ whereas the performance Touch Probe (TP) and LR are comparatively stable.

Table 1: *An effective tolerance standard for automotive manufacturers to assess measurement system capability - Comparison of Max Tmin, Range Tmin, and percentage of features that the measurement system would capable of measuring for each feature type (Tmin and Range Tmin values in mm)*

Surface Point	**Max Tmin**			**Range Tmin**			**Percentage of Features**		
	TP	**LR**	**L100**	**TP**	**LR**	**L100**	**TP**	**LR**	**L100**
6σ (Cgk = 1.00)	1.11	0.76	1.27	0.91	0.45	1.05	100.00	100.00	100.00
8σ (Cgk = 1.33)	1.18	0.80	1.45	0.95	0.45	1.22	100.00	100.00	100.00
10σ (Cgk = 1.67)	1.26	0.89	1.63	0.99	0.50	1.39	100.00	100.00	100.00
12σ (Cgk = 2.00)	1.33	0.99	1.81	1.02	0.55	1.56	100.00	100.00	100.00
Trim Edge Point	**Max Tmin**			**Range Tmin**			**Percentage of Features**		
	TP	**LR**	**L100**	**TP**	**LR**	**L100**	**TP**	**LR**	**L100**
6σ (Cgk = 1.00)	4.30	3.12	15.70	4.03	2.76	15.38	87.50	97.44	51.85
8σ (Cgk = 1.33)	4.42	3.25	19.98	4.09	2.85	19.65	87.50	97.44	48.15
10σ (Cgk = 1.67)	4.54	3.38	24.39	4.16	2.95	24.05	85.00	97.44	44.44
12σ (Cgk = 2.00)	4.66	3.51	28.68	4.23	3.04	28.32	85.00	92.31	44.44
Hole	**Max Tmin**			**Range Tmin**			**Percentage of Features**		
	TP	**LR**	**L100**	**TP**	**LR**	**L100**	**TP**	**LR**	**L100**
6σ (Cgk = 1.00)	2.50	1.80	5.88	1.92	0.94	5.56	100.00	100.00	85.71
8σ (Cgk = 1.33)	2.56	2.10	6.40	1.92	1.10	6.04	100.00	100.00	85.71
10σ (Cgk = 1.67)	2.63	2.42	6.93	1.91	1.27	6.54	100.00	100.00	85.71
12σ (Cgk = 2.00)	2.70	2.72	7.44	1.91	1.43	7.02	100.00	100.00	85.71
Slot	**Max Tmin**			**Range Tmin**			**Percentage of Features**		
	TP	**LR**	**L100**	**TP**	**LR**	**L100**	**TP**	**LR**	**L100**
6σ (Cgk = 1.00)	4.31	3.33	2.18	3.88	2.39	1.51	85.71	85.71	100.00
8σ (Cgk = 1.33)	4.36	4.14	2.27	3.86	3.01	1.54	85.71	85.71	100.00
10σ (Cgk = 1.67)	4.40	4.97	2.36	3.84	3.66	1.58	85.71	85.71	100.00
12σ (Cgk = 2.00)	4.44	5.77	2.45	3.81	4.29	1.61	85.71	71.43	100.00

For CMM touch-trigger probe, there has been considerable progress in developing methodologies to estimate task-specific measurement uncertainties in the past. In this study, automotive industry representative artefact was used. It does not represent all the manufacturing industries such as aerospace industry. Therefore, it could be beneficial to use an artefact which represents a particular industry. Also, different dimensional size and features of an artefact would be beneficial to evaluate the large spectrum of the measurement systems and measurement volumes. Also, further work needs to be done, especially for non-contact measurement systems, not only for evaluating them in the context of BIW measurement applications, but also the effect of different parameters on the results. For instance, software algorithm, or materials of the work piece i.e. composite materials might have effects on measurement results. Moreover, one important priority is how to integrate multiple sensors in systematic way to facilitate the implementation in a complex production environment.

5. Conclusion

In this study, measurement system capabilities of touch-trigger probe and laser scanner (off-line measurement) and the laser radar (in-line measurement) were investigated in the context of the feature-specific automotive measurement processes. It was observed that all the measurement systems were capable of measuring surface points, holes and slots within the ±1.5mm tolerance values. Also, the performance and measurement decisions from CMM touch probe and LR systems did not change considerably if 12σ process is followed rather than 6σ process, and therefore, this systems can still be used even the manufactures improve the process from 6σ to 8σ or more. However, the performance of the laser scanner is poor for the trim edge points even for 6σ process. All three systems can be used for measuring surface points. LR should be used when measuring trim edge points. Touch probe and CMM both can be used for measuring holes whereas laser scanner is the best for measuring slots. This study provided an improved understanding of the non-contact measurement system, which would help the automotive manufacturers to implement fast measurement strategy based on feature definition and tolerance limit without reducing the quality of measurement, and ultimately enable them to proceed for feature-specific in-line measurement.

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