Original citation:

Kiraci, Ercihan, Franciosa, Pasquale, Turley, Glen A., Olifent, Alan, Attridge, Alex and Williams, M. A. (Mark A.). (2016) Moving towards in-line metrology : evaluation of a Laser Radar system for in-line dimensional inspection for automotive assembly systems. International Journal of Advanced Manufacturing Technology.

Int J Adv Manuf Technol
DOI 10.1007/s00170-016-9696-8

ORIGINAL ARTICLE

Moving towards in-line metrology: evaluation of a Laser Radar system for in-line dimensional inspection for automotive assembly systems

Ercihan Kiraci[1] · **Pasquale Franciosa**[1] · **Glen A. Turley**[1] · **Alan Olifent**[2] · **Alex Attridge**[1] · **Mark A. Williams**[1]

Received: 9 August 2016 / Accepted: 3 November 2016

Abstract The increasing interest towards intelligent systems has led to a demand for the development of zero-defect strategies, with a paradigm shift from *off-line and dedicated* to *in-line metrology* with integrated robotic systems. However, a major barrier preventing the systematic uptake of in-line metrology is the lack of evaluation of system capability in terms of accuracy, repeatability and measurement time, when compared to the well-established coordinate measuring machine (CMM). In this study, a robotic Laser Radar (LR) solution is assessed in the context of automotive dimensional inspection of Body-In-White (BIW) applications. The objective is both to understand the effect of robot re-positioning error on measurement accuracy and repeatability and to compare measurement results against a CMM. Eighty-one surface points, six edge points, twenty-five holes and sixteen slots were selected from an industry standard measurement plan. Whilst LR exhibits a lower measurement accuracy than twin-column CMM, its repeatability is well within the specification limits for body shell quality inspection. Therefore, as a real-time in-line metrology tool, it is a genuine prospect to exploit. This research makes a significant contribution toward in-line metrology for dimensional inspection, for automotive application, for rapid detection and for correction of assembly defects in real time, with subsequent reduction of scrap and number of repairs/re-works.

Keywords CMM · Laser Radar · Dimensional metrology · In-line measurement · Process control

1 Introduction

In recent years, there have been significant cycle time reductions for production technologies, especially joining technologies, to improve right-first-time (RFT) capability with a minimum waste of resources and reduced product defects in pursuit of zero-defect manufacturing (ZDM). This method aims to minimise waste of material and resources although there is no clear and effective solution for that goal. In order to reach ZDM, not only is data collection sufficient but also that data mining methods are critical because of the inherent variation of manufacturing processes. Statistical process control (SPC) is used to identify and eliminate defects during the new product introduction (NPI), but SPC and similar tools do not prevent defects from occurring/recurring; thus, they need to be enhanced by developing intelligent control systems. This will help manufacturers to eliminate/prevent defects in real time. Metrology cycle times have not improved to the same extent as those of production technologies. Traditional Body-In-White (BIW) inspections have been performed in a coordinate measuring machine (CMM) room where a sample of parts and assemblies is sent to be inspected off-line. By using off-line measurement (taking off the assembly line), for car manufacturers, it is more difficult to predict defects before they occur or identify trends in the production line due to limited sample size. Not only is this time consuming, but also it cannot identify the root cause of any faults. There is a growing desire to move away from off-line sample measurement to in-line data collection, and this will only be possible with fast, accurate measurement technologies. This leads to a common trend in Europe (but also worldwide) regarding research into in-line

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✉ Ercihan Kiraci
e.kiraci@warwick.ac.uk

[1] WMG, The University of Warwick, CV4 7AL Coventry, UK

[2] Whitley Engineering Centre, Jaguar Land-Rover Ltd, Abbey Road. Whitley, CV3 4LF Coventry, UK

metrology and smart manufacturing with real-time data gathering, such as Industry 4.0 and Factory of the Future (FoF) in Europe. The potential benefits of using in-line metrology solutions are continuous monitoring of process quality, capability for fast detection and correction of defects in real time and faster cycle times, hence allowing rapid increase of data being generated and captured during NPI, production and in-service. This also leads to a number of developments involving process monitoring, data mining and its application for quality improvement. In recent years, in-line metrology solutions are becoming increasingly advanced and more frequently used in manufacturing systems. However, there are a number of challenges:

- Accuracy and repeatability: tolerances are becoming higher, so accuracy is a big challenge and most systems are relying on robot accuracy, which is not adequate for error compensation.
- Calibration: standards are not well-established for measurement uncertainty
- Environmental noise: it is difficult to control lighting, temperature, and vibration and so the production line, which have an effect on accuracy and repeatability.
- Accessibility: in-line sensors' accessibility is limited due to robots' geometrical limitations by comparing it with CMM, which has an extensive range of probe and stylus extensions.
- Material conditions: non-contact measurement sensors have sensitive colour, surface roughness and reflectivity which have an effect on measurement uncertainty.
- Scanning time: in the automotive production line, process cycle time is around 70 s and less, so performing measurement within this time frame is important.
- Cost: a cost analysis needs to be completed when considering alternatives in process control equipment; an in-line measurement system configuration plays an important role in its performance aspects and lifetime costs (initial and operating cost)

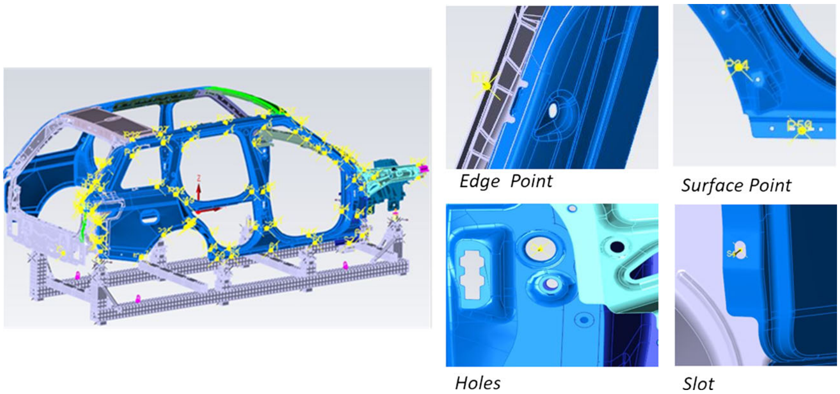
The potential opportunities of such in-line measurement technologies are clear, but there are a number of areas that need further investigation in order for the capabilities of the system to be fully realised in a production environment. Tolerances are becoming tighter so the first challenge with in-line metrology is accuracy. Second is the process cycle time, so most processes in the automotive production line are around 70 s or less. In-line measurement sensors needed to maintain the same speed without reducing the number of measurement features. Thirdly, most in-line measurement systems are relying on robot error compensation which requires frequent calibration, or a two-step calibration, to eliminate robot error, for example using tooling balls in the case of the Laser Radar (LR). Fourthly, given the speed of turnover and number of parts, data storage becomes an issue with significant amounts of data captured and requiring verification by an experienced operator. Fifthly, robots embedded with sensors have less accessibility than CMMs so a number of critical features might be unmeasurable. Finally, the sensor's sensitivity to a production environment such as temperature and humidity can affect results. For example, using the triangulation method for measurement is highly sensitive to the local light conditions.

There is a large number of uncertainty sources for any given in-line measurement (by comparison with off-line), so the uncertainty estimation for any measurement must include issues such as gauge error sources, environmental conditions, sampling strategy and part form errors. Consequently, there is a need to identify potential measurement technologies and investigate their capabilities in order to evaluate the measurement errors. The LR is a non-contact large volume metrology system that has the potential to measure in-line. It has been mainly used for assembly inspection as a closed-loop metrology system and reverse engineering applications in the aerospace industry. It is used for assembly verification and dimensional inspection by comparison with nominal CAD data, and then the results are used to verify and support other machining activities such as drilling and loading [1, 2], for example, the alignment of fuselages as a closed loop system for the multi-stage assembly process [3]. Unlike a CMM, the LR is capable of high-speed measurement to fit with short production cycle times. In this paper, an industrial demonstrator is used to assess the suitability of LR in the automotive dimensional inspection of an automotive BIW as part of an in-line solution. The objectives of this paper are both to understand the effect of robot re-positioning on measurement accuracy and repeatability and to compare measurement results with CMM based on the feature type measured.

In this study, 81 surface points, 6 edge points, 25 holes and 16 slots were taken from the manufacturer's measurement plan for measurement based on critical features as seen in Fig. 1. However, 59 features could not be measured by the LR because of its accessibility and the experimental set-up. These would normally be resolved by different positioning of the Laser Radar (i.e. from the front, rear or opposite side of the vehicle). From the 30 sets of measurement for each system, comparison of means and standard deviations and their correlation, 2σ and 3σ repeatability and mean difference were calculated for both the touch trigger probe and the LR based on feature type.

2 Background

In the automotive industry, the inspection process of parts has traditionally been carried out off-line using a CMM, which is used to check whether the dimensions of manufactured part assemblies conform to the design intent. The inspection data is used for the continuous control of the process to detect and address any process variations. Currently, CMMs are the



Edge Point

Surface Point

Holes

Slot

Fig. 1 Measurement points on BIW

benchmark technology for process monitoring by automotive manufacturers due to their high accuracy and repeatability and well-recognised international standards (ISO: 10360) [4] for calibration and measurement uncertainty.

Touch trigger probing systems are frequently used on CMMs, thanks to the well-established determination of measurement uncertainty and calibration [5, 6]. CMMs acquire discrete points on the surface of the workpiece (contact measurement), and hence, they have a low measurement speed [7]. CMMs are often considered a bottleneck in the quality process due to the ever-increasing product complexity, leading to an increase in the number of measurement points and the measurement time and in some cases only providing partial information on the measured area rather than the full product data.

More recently, the introduction of non-contact measurement sensor technologies can lead to a significant reduction in measuring time. This can be considered the biggest advantage of those systems as well as the ability to collect full product information without local part deformation during the inspection [8, 9]; hence, CMM systems with laser scanners are more frequently being used [6, 10]. The use of laser scanners is well-established in the context of reverse engineering, but they are currently unable to achieve the accuracy and repeatability offered by touch trigger probes. Also, factors contributing to laser scanner measurement uncertainty include the surface finish of the workpiece, product colour, the finished condition of the material and the lighting within the environment [7]. Given the number of potential issues, the challenge is to understand measurement uncertainty. Overall, contact measurement methods can be complemented or partially replaced by non-contact measurements depending on the required accuracy and surface properties [8, 11]. Therefore, the utilisation of CMMs is of particular interest due to a significant investment required and the temperature-controlled working area. Future challenges for using multi-sensor technology on CMM lie in the combination of inhomogeneous data from different measurement sensors and uncertainty standardisation of those non-contact systems.

New non-contact measurement systems, such as the LR technology, have the potential as an in-line metrology system to address the requirements identified for automotive applications. Whilst not a new technology in itself, it has previously been used for aerospace applications over very large distances (up to and beyond 50 m) [1–3], but more recently the technology has been identified as a potential competitor to traditional CMM measurement for automotive BIW applications. Over a range of a few meters, the accuracy of LR could be used with the advantage of being portable, on a robot on rails, for automotive BIW applications. The most recent iterations of the LR hardware and software also offer very fast measurement paths, enabling rapid feature characterisation. Different applications (in-line confirmation, off-line detailed measurement and so on) may benefit from different strategies, which might include the use of multiple units, robotic manipulation of the system and the processing and reporting of measurement data in real time.

The LR technology is a large-scale metrology system, whose errors could be categorised into ranging errors and geometric errors, which come from optical and geometric misalignments within the system. Over the years, ranging errors of large-scale metrology systems have been improving but still larger than geometric errors; hence, the compensation of these errors will become important in the execution of accurate measurement [12]. Large volume systems, such as laser tracker, are verified using ASME B89.4.19, and calibration certificates as a traceability evidence is provided. The uncertainty of point-to-point length measurement and the manufacturer's speciations might be considered as an upper limit, but determining the uncertainty of a particular measurement task is complex [12, 13].

3 Materials and methods

An LK HC90 Horizontal Arm CMM and MV330 LR (Nikon Metrology, UK) were used in this measurement study. The CMM was equipped with a PH10MQ motorised indexing head (Renishaw, UK) enabling both touch trigger probe inspection and laser scanning. The twin column CMM is commonly used in the automotive industry for BIW inspection and provides measurement access to the exterior, interior

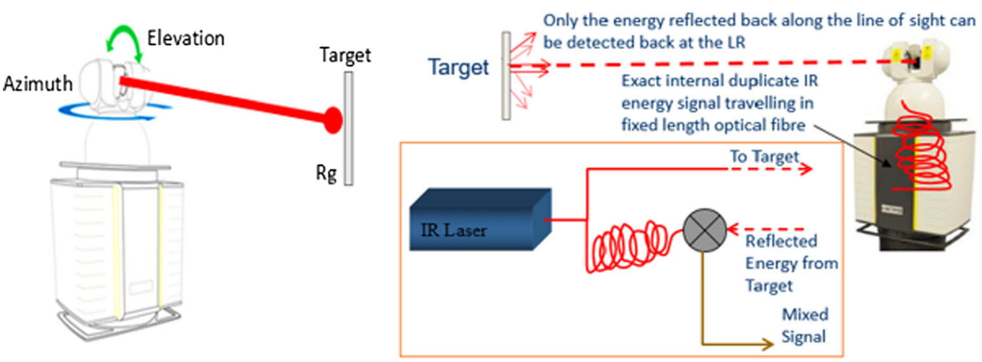


Fig. 2 LR measurement axis and its technology

and underbody of the vehicle. A TP20 five-way kinematic standard force touch trigger probe (Renishaw, UK) was used with 140 mm extension and 2 mm tip diameter, in conjunction with the measurement software Camio 8.2-Feature pack 1 (Nikon Metrology, UK). The CMM measuring arm accuracy was verified in accordance with ISO10360-2 [14] with an expanded measurement uncertainty (k = 2) of ±1.0 μm + 1.0 μm/m as stated by the manufacturer.

The MV330 LR is a non-contact ranging technology, capturing up to 4000 points per second. It consists of two rotary axes, for elevation and azimuth, controlled by a separate encoder feedback and a unique range measurement achieved by comparing two waveforms of an infrared laser beam with a frequency modulated "chip". The waveforms are generated by splitting the beam internally; one part is sent through a calibrated length of the optical fibre and the other out through the mirror to the part then reflected back through the mirror as shown in Fig. 2. The signals are superimposed and the range calculated by phase shift (frequency) as opposed to time of flight. The instrument "focuses" by measuring at the point of maximum return energy.

The range is calibrated by using laser interferometry according to ASME B89.4.19 [15]. PolyWorks 2015 software (InnovMetric Software Inc., QC, Canada) was used for the LR measurement programme. This system has a distance measurement of resolution 1 μm and an expanded uncertainty (k = 2) of 10 μm + 2.5 μm/m. For angular measurement, its resolution for azimuth and elevation is 0.018 mm and 0.039 arcsec respectively as seen in Fig. 2, with an expanded uncertainty (k = 2) of 6.8 μm/m. The automotive artefact selected for this study was an aluminium vehicle body shell located on an underbody CMM fixture (Jaguar Land Rover Limited, UK) as seen in Fig. 3. The Laser Radar was fitted on a FANUC R-1000iA/80F robot with an R30iA controller, running on a 6-m industrial robot rail.

3.1 Experimental set-up

The automotive artefact was located on the fixture for the duration of the study in a temperature-controlled environment at 20 °C ± 1 °C. To define the alignment of the artefact, three measurement points were manually taken on the CMM bed to construct a plane as the primary datum, a line used as a secondary datum was constructed using two references on the fixture, with spheres labelled H1/S1 and H2/S2, and a point was taken as tertiary datum at the H1/S1 sphere with their location shown in Fig. 4. The Reference Point System (RPS) alignment was used in order to manually align an initial local coordinate system with the CMM coordinate system, and this was followed by two iterations in the autonomous mode.

The LR required two levels of alignment. Seven measurement points on the CMM bed, seven tooling balls (stainless steel, grade 25, spherically 0.6 μm and ±2.54 μm diameter tolerance) and the H2/S2 and H1/S1 spheres on the fixture were measured. The locations of H1/S1, H2/S2 and the z-plane on the nominal CAD were known. To transfer the coordinate frame of the LR into the local part coordinate frame of the artefact (car-line alignment), seven measurement points next to the tooling balls on the CMM bed were taken to construct the z-plane (primary datum), H1/S1 and H2/S2 were used to construct the y-line (secondary datum), H1/S1 was used to construct an origin point and then a 3-2-1 alignment was performed as shown in Fig. 4. The seven tooling ball positions were then determined relative to the local coordinate system and set as secondary nominals. With the secondary alignment completed, the LR could be moved to any location and locked back into the same

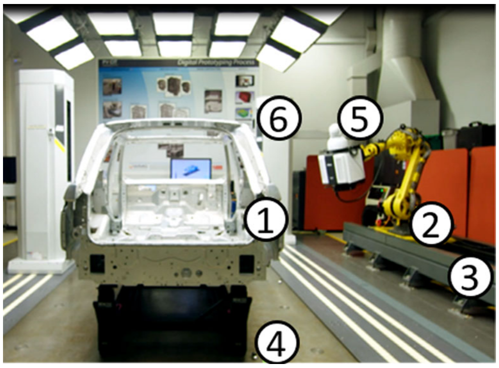


Fig. 3 Experimental set-up (labels: *1* workpiece, *2* robot, *3* trail, *4* tooling balls, *5* LR, *6* CMM

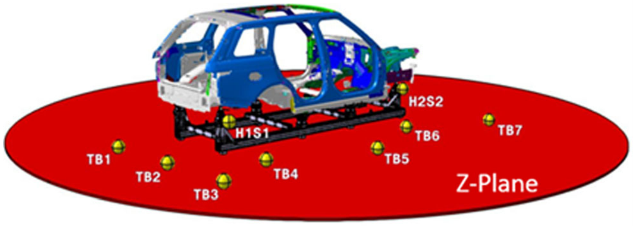


Fig. 4 Illustration of the automotive artefact alignment, tooling balls (TB) and fixture sphere locations

alignment using just the tooling balls. A minimum of four tooling balls were measured in each LR location with the alignment performed before each measurement. The tooling balls remained in the same location on the CMM bed throughout the entire experiment. The only difference between the CMM alignment and the LR alignment was the construction of the primary datum; for the CMM, three measurement points were used whilst seven measurement points were used for the LR.

3.2 Experimental procedure and statistical analysis

A standard touch trigger measurement programme from the vehicle manufacturer was performed with the CMM, after alignment had been completed. For this experiment, 81 surface points, 6 edge points, 25 holes and 16 slots were measured based on a feature critical build. The LR utilised four different robot positions in order to measure all of the features at less than 45° incident angle. A measurement cycle consists of moving to each of the four positions shown in Fig. 5, in turn with an alignment to the tooling balls at each position.

For the LR measurement plan, surface points were measured by the surface vector intersection (SVI) method [16]. Most surfaces use nominal CAD vector input. SVI measures a small surface patch to find and record the point on the actual surface that is normal to the CAD nominal point. This allows measurement of nominal points on the part surfaces in order to achieve the most accurate measurement from the workpiece. Edge points are measured by creating a point vector on the edge surface. The LR then goes back along the direction of the point, to the local surface, and searches in the vector direction for the surface (the perpendicular to the edge) and then outputs the theoretical edge location. Lastly, holes and slots were measured by a number of scan passes over the circle. A fitting algorithm then calculates the feature orientation. The following settings were used to refine the best circle in the software which were as follows: sheet metal, maximum distance to the nominal primitive, 2; constraining plane using the surface scan, tangent offset, 2; width, 5; height, 4 and minimum fit. Note that the settings used on Laser Radar were for a balance of accuracy and speed for in-line inspection. If more time were available, more scan data would be acquired to improve measurement capability further, but this is at the expense of time. The measurement routines were repeated 30 times for both the CMM touch trigger probe and the LR.

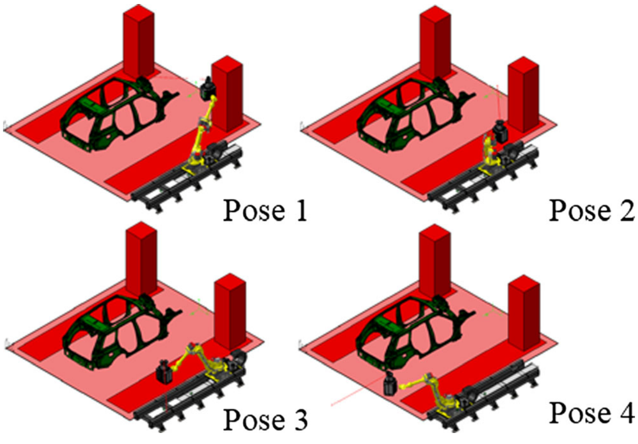


Fig. 5 Experiment pose positions for LR

To compare the systematic error between the horizontal arm CMM and the LR, the mean position, the standard deviation and correlation were calculated from the 30 sets of measurement. Repeatability (random error) was also evaluated using the calculated 2σ and 3σ for both the touch trigger probe and LR. To evaluate the overall measurement agreement between the two systems, paired *t* test for mean difference, chi-squared variance test for standard deviation and correlation analysis for the measurement result were performed. All calculations were performed in MATLAB R2013b (the MathWorks Inc., Natick, MA).

4 Results

For different feature types, there is a significant statistical difference between the LR and touch trigger probe results. For example, data for two of these measurement systems when applied to surface measurement points are shown in Fig. 6a, c, to determine whether there is any difference (on the average) for the systems. Apart from the three measurement points, the *P* value of the remaining points is less than 0.05; therefore, these two measurement systems yield statistically different results. Specifically, the data indicate that the LR produces, on the variance, greater results than does the CMM. However, there is a significant reduction in measurement cycle time. The LR and CMM touch trigger measurement cycle times were 6 and 40 min respectively.

The alignment of each pose in LR was shown to have a significant effect on accuracy of measurement. Table 1 shows the standard deviation for each pose. Although the LR does not rely on the robot repeatability as it is often the case for other in-line measurement systems, the effect on the resulting measurements is not negligible. Also, the consequences of the robot position due to robot repeatability could have an effect

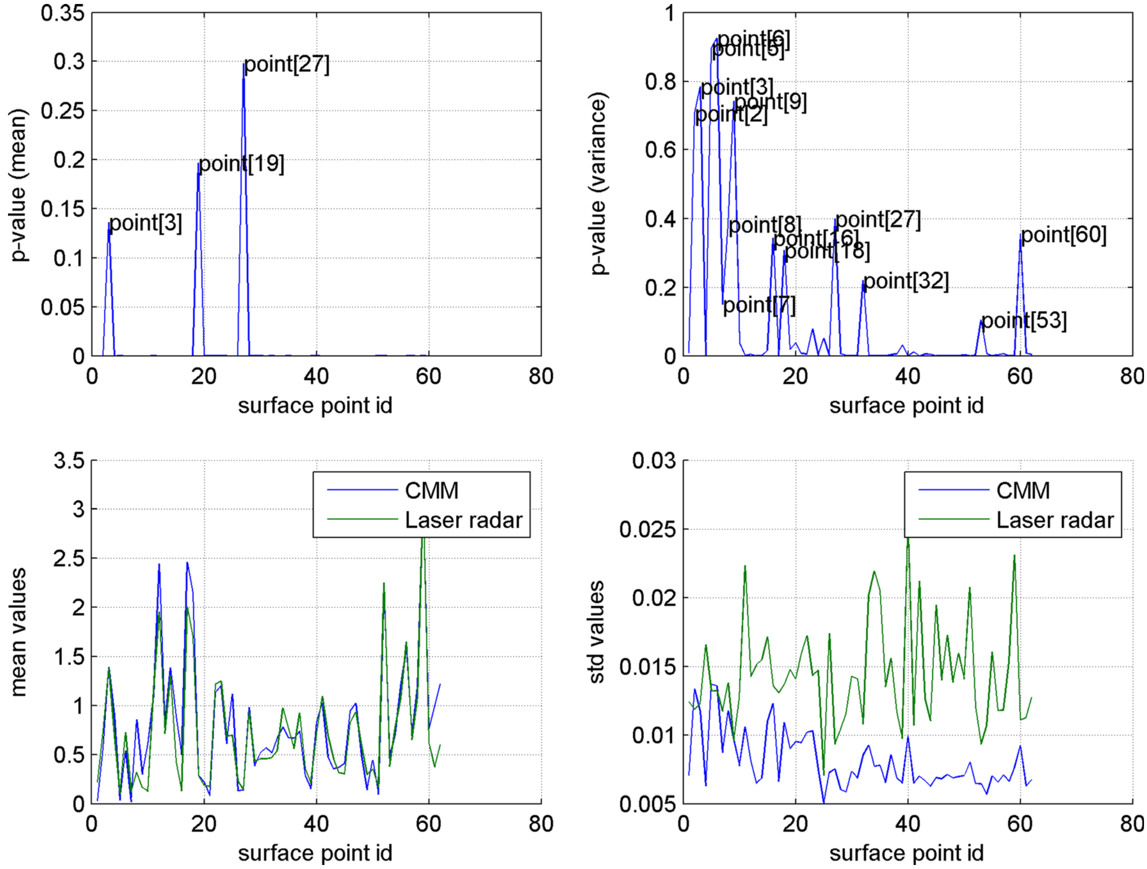


Fig. 6 Comparison of mean and standard deviation of CMM and LR point results

on the incident angle of measurement, hence the alignment results. This should be a topic for future research to identify the errors due to the LR and the ones due to the robot. For example, the FANUC robot repeatability is ±0.2 mm used in this study so this value is not adequate; hence, a calibration process was performed for each LR position to negate the robot inaccuracies. In this study, the LR alignment results are at least four times better than the robot alignment.

Figure 7 shows repeatability values derived from 61 surface point measurements and mean differences. It can be seen that more than 80% of surface points show better than 50 μm repeatability at 2σ. There is agreement between the reported deviation values; 80% points of the measured deviations were within 200 μm when with the LR and CMM as seen in Fig. 8.

For edge points, six edge points were measured in this experiment. The average repeatability 2σ and 3σ for the LR were 35 and 52 μm compared to the values for the touch trigger probe of 14 and 21 μm respectively, as shown in Fig. 9.

For hole measurement, eight holes were measured in this study. It can be seen that over 70% of holes have better than 50 μm repeatability at 2σ as shown in Fig. 10. If categorised into threaded and non-threaded holes, those without threads were measured with better repeatability and agreement with the touch trigger probe. The average repeatability of non-threaded and threaded holes for the LR was 49 and 98 μm respectively. Similarly, the mean difference of non-threaded holes is around three times better, as shown in Fig. 11.

For round slot measurement, three round slots were measured. The average repeatability 2σ and 3σ for LR were 61 and 91 μm compared to touch trigger probe values of 13 and 20 μm respectively, as seen in Fig. 12. The average mean difference between the LR and CMM was 380 μm as shown in Fig. 13.

5 Discussion

Car manufacturers have been moving their attention from off-line to in-line measurement in order to collect process data rather than product data [17], which allows them to extend quality control and process optimising strategies. For example, closure fits (i.e. doors systems) significantly impact on the

Table 1 Standards deviation of each pose

	Pose 1	Pose 2	Pose 3	Pose 4
$\sigma_{\text{repeatability}}$	18 μm	40 μm	21 μm	49 μm

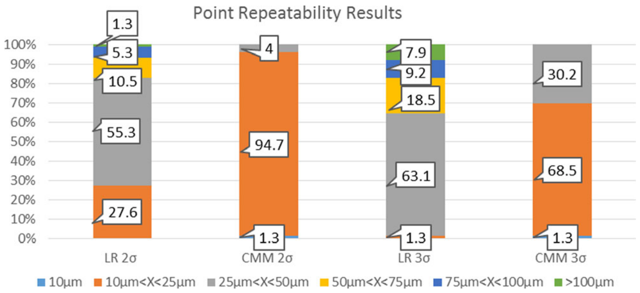


Fig. 7 Repeatability of surface point measurement results

customers' perception of quality. According to the JD Power and Associates Vehicle Dependability Study 2016, wind noise, water leaks and hard door closing are identified as leading causes of warranty claims and around one third of quality problems in total [18]. This affects overall brand image and quality and increases warranty costs. Therefore, it is becoming critical to collect measurement data from every vehicle produced in order to control manufacturing variability.

There are many available technologies capable of in-line measurement, and many of them rely on robot accuracy and repeatability, as well as environmental sensitivity such as lighting and temperature. It is a complex task to evaluate an in-line measurement station due to its applicability as a measurement system and its measurement process capability. In order to determine the capability of an in-line measurement system, repeated measurements of workpieces are performed. These workpieces have to be calibrated on the CMMs. The benefit of using calibrated workpieces is that it does not necessitate any measurement standards or laser tracker but the calibration of body parts includes a higher uncertainty. This is performed to verify the capability of the measurement processes of in-line measuring systems [19]. Based on the results, corrective adjustments on the in-line measuring station might be taken. The correlation between a relative in-line solution with a CMM does allow for trend analysis—but variances need investigating back in the laboratory on CMM. One of the strengths of the LR is that it is an absolute measurement system (comparable to a CMM) and can do detailed in-line inspection, which has been shown by some manufacturers to be particularly useful through NPI. For example, this helps to measure the first production line of 3D-printed cars but the LR can help to support build quality in full production.

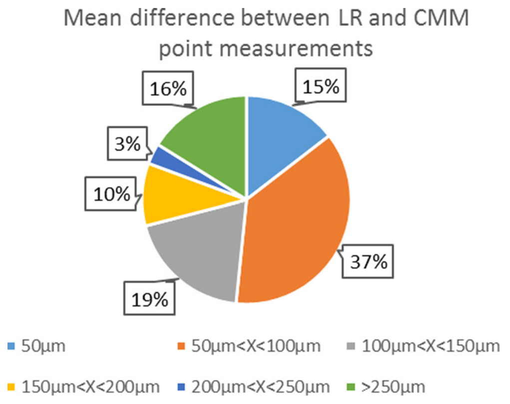


Fig. 8 Surface point mean difference between LR and CMM

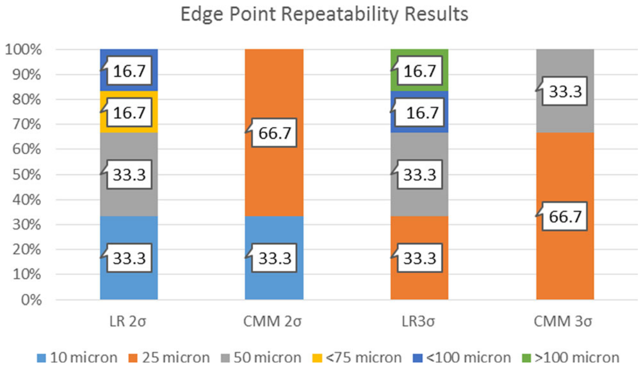


Fig. 9 Repeatability of edge point measurement results between LR and CMM

The LR is less sensitive to the environment in which it operates than a typical CMM so less emphasis can be placed on controlling temperature and humidity. This is because the optics in the LR are inside a temperate-controlled chamber, meaning negligible degradation due to environmental effects through the measurement cycle. Thermal effects are the biggest single source of apparent non-repeatability and inaccuracy in CMMs [20]. The LR can operate between 5° and 40 °C with little variation repeatability so it is therefore better suited to operating in a production environment. Also, LR is more flexible than a touch probe CMM in measuring different surfaces and finishes, such as soft surfaces, because of the range of measurement technology, without compromising measurement accuracy.

Manufacturing tolerances are becoming smaller in the automotive industry largely driven by tighter tolerance specifications in the design and hence require smaller process variation. A number of standards and guidelines require the measurement system to be evaluated by means of capability studies. Process capability studies are also required by ISO/TS 16949 [4], but the procedure to be followed is not specified. Measurement system analysis (MSA) is used, predominantly by the American automotive industry, whereas Verband der

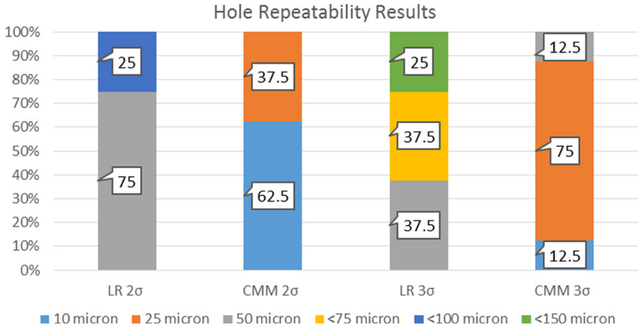


Fig. 10 Repeatability of hole measurement results for LR and CMM

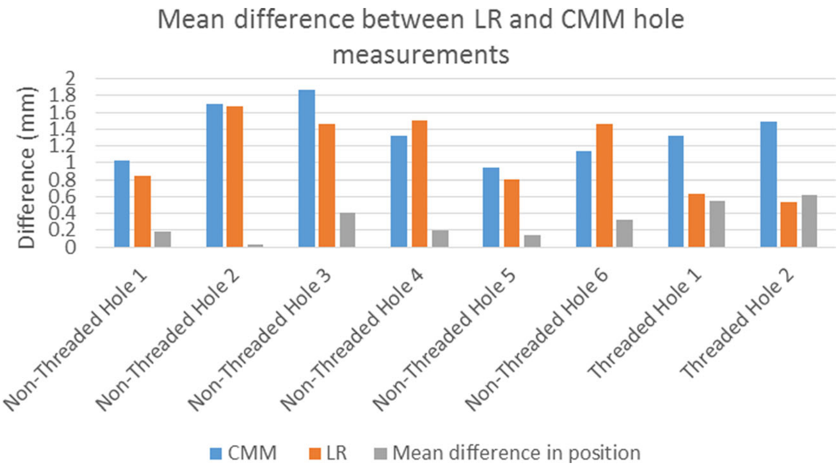


Fig. 11 Hole mean difference between LR and CMM

Automobilindustrie (VDA) is commonly used in Germany and across Europe [21]. Depending on the applied firm standards, the minimum value of percentage of the characteristic tolerance or 6/8 σ_{process} (the process variation) is selected as a reference. In addition, the requirement for the minimum value of the capability ratio Cg and Cgk may also vary (Cg >1.0/1.33) depending on the applied company standard [21]. The capability ratio, as seen in Eq. 1, is defined as the total specified tolerance divided by six times the standard deviation of the measurements (all the guidelines available use a variation range of 6*S_g for the measurement system, but some guidelines use a 4*S_g variation range for the measurement range).

The manufacturer defines the product specification range as 1/6. This is approximately 0.15; the constant is observed in Eq. 1. Also, the variation of measurement instrument could contribute to a maximum 15% of the total observed variance of measurement. Table 2 shows the capability indices (Cg) and variation percentage of the CMM and LR. Typically, in the automotive industry, the limit value for the evaluation of capability, Cg, must be bigger than 1.33.

$$Cg = \frac{0.15*T}{6.*Sg} \quad \text{and} \quad \text{Variation}\% = \frac{15}{Cg} \qquad (1)$$

The LR is capable of measuring all four different types of feature selected, and the variation percentage is consistently lower than 15% as specified by the manufacturer, as shown in Table 2. For the test application chosen, which is representative of automotive practice, it can be concluded that the LR could be used with confidence in the context of BIW inspection process in the automotive industry.

The term *alignment* is used to define the creation of a coordinate system on the workpiece [22]. LR alignment is a two-step process. First, the same reference points on the fixture (spheres) are used to transfer the coordinate frame of the LR into the local part coordinate frame of the artefact (car-line alignment). The second step is to determine the tooling ball positions (seven balls in this study) relative to the local coordinate system and set as secondary nominal. A minimum of four tooling balls are measured in each location with this alignment performed before each measurement. This alignment procedure eliminates any dependency on robot accuracy and allows the measurement of more features using the same systems. A number of methods could be used to improve the alignment process and reduce re-alignment time, but this depends on the range, angle of incident of the laser and angular encoder usage of the tooling target points based on the set-up

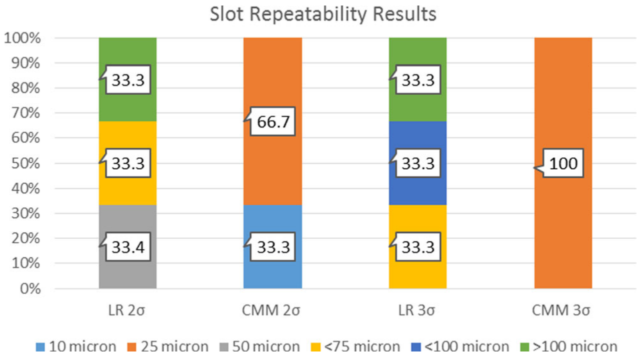


Fig. 12 Repeatability of slot measurement results for LR and CMM

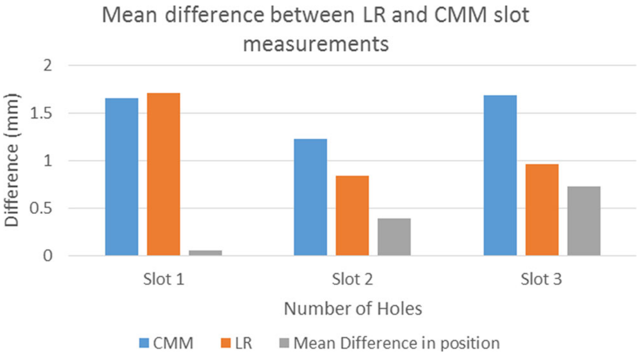


Fig. 13 Slot mean difference between LR and CMM

Table 2 The results of Cg and variation percentage of LR and CMM

	CMM *Cg*	LR *Cg*	CMM Variation%	LR Variation%
Surface points	9.56	4.22	1.56	3.55
Edge points	10.50	4.25	1.42	3.52
Holes	14.76	3.62	1.01	4.13
Slots	12.18	2.45	1.23	6.10

Cg capability ratio (0.15), *T* tolerance (±1.5 mm as specified by the manufacturer), *Sg* standard deviation of 30 measurements

of the workpiece. Alternatively, a rotary table could be used to measure the workpiece following the same alignment procedure. Wing et al. [23] have used two different alignment methods, frame-to-frame transformation and tooling ball best-fit alignment, to evaluate error sources of alignment procedures. They concluded that frame-to-frame transformation is the most accurate form of alignment: 30 μm compared to 53 μm when using the tooling ball best alignment.

There is a need to investigate the effect of alignment repeatability and its subsequent effect on the measurement results. For instance, the repeatability of pose 2 and pose 4 was 40 and 49 μm respectively, which included all tooling ball measurement results. If measurement results greater than 150 μm were excluded, the repeatability of pose 2 and pose 4 would be 26 and 41 μm respectively. Although this has a small effect on the measurement results, the effect of any individual point needs further evaluation.

In the automotive industry, vehicle measurement programmes are becoming more comprehensive, increasing the cost and time associated with inspection. More effective inspection preparation is required to reduce the inspection time [23]. Many researchers have focused on reducing the number of points for CMM measurement and better path planning in order to reduce inspection cycle time [23, 24]. For this experiment, the inspection time of CMM and LR was 40 and 6 min respectively. The LR can significantly reduce measurement speed and environmental sensitivity in comparison with CMMs with touch trigger probes but only if the measurement accuracy is acceptable for the specific application. The most time-consuming operation when performing the LR measurements was the movement from one pose to another, which took around 35 s including alignment measurements and accounted for 39% of the total measurement time. The number of poses could be reduced by using more than one LR or using a mirror to access measurement points and features outside the line of sight, which would reduce this problem. Currently, the LR measurement solution is used in a limited number of automotive companies in USA as an in-line solution, but there is great potential to expand this application globally.

There is still a major challenge for multi-sensor CMM systems (contact and non-contact) to develop the methodology to plan measurement strategies [10]. Both tactile probing and optical sensors typically have less than 100 mm stand-off, and it is quite possible to hit the workpiece with the probe if any programming mistakes occur. However, the LR requires around a 2-m stand-off from the workpiece so, even on a robotic arm, it is far less likely to collide with the workpiece compared with CMM sensors. It is also difficult to measure parts, whose features are a significant distance from their nominal positions, as is often the case for prototype parts, using either touch trigger probes and laser scanners on CMM as they may not fall within the specified search area and may, therefore, fail to evaluate.

6 Conclusion

The objective of this study was to evaluate the capability of the Laser Radar solution in the context of the automotive dimensional inspection of automotive BIW applications in comparison to conventional CMM solutions and to understand both the effect of robot re-positioning on measurement accuracy and repeatability. The results showed that the LR accuracy and repeatability are well within the specification limits of typical automotive BIW inspections. The results show a significant reduction in measurement cycle time, reduced by 83% to 6 min. The greatest time-consuming part of the LR measurement process was the movement from one pose to another one, which took around 35 s each time including alignment measurements. The alignment of each pose has an effect on feature measurements, so its results are not negligible even though LR does not rely on the robot repeatability as is often the case for other in-line measurement systems. In this experimental set-up, both systems were able to measure 91 individual features. The CMM was able to measure a further 59 features due to its span which could be extended beyond the LR set-up.

Based on these case study results, the use of the LR in production is viable and automotive manufacturers can have data for each vehicle. In recent years, a number of car manufacturers used from USA, such as Tesla and BMW USA, have begun using the LR as an in-line measurement solution. It also does not require re-calibration with CMM at regular time intervals. The LR is less sensitive to the environment in which it operates than a CMM. Since its stand-off distance is a few meters, it is less likely to collide with the workpiece by comparing with CMM sensors. On the other hand, tolerances are becoming higher so accuracy is a big challenge for in-line systems. In addition, it is a difficult task to perform the uncertainty calculations for a specific measurement task; hence, improving the accuracy of in-line systems and the development of documentary standards is critical. Although CMMs have slow measurement speed, it has a better accuracy with well-established standards for performance evaluation so they will be still extensively used in the manufacturing industry.

Further work needs to be done to evaluate the effect of incident angle on different type features and to compare the effect of alignment on feature accuracy and feature algorithms.

Acknowledgements This work was carried out as part of the Product Evaluation Technologies Group, within WMG, in part funded by the High Value Manufacturing Catapult. The authors would also like to acknowledge the support of Paul Peterson at Jaguar Land Rover and Martin Bishop, Roger Holden and Simon Andreou at Nikon Metrology UK.

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