Evaluate Error Sources and Uncertainty in Large Scale Measurement Systems

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Abstract

Modern manufacturing technologies place increasingly higher demands on industrial measurement systems. Over the last decade there have been rapid developments in 3D measurement systems, with the primary requirement coming from industries such as automotives, aerospace, shipbuilding and power plant equipments for accuracy and efficiency. This paper focuses on the analysis of large scale scanning techniques using a laser scanner; investigating the errors which arise during the measurement process and the uncertainty calculations for the measurements. Both point measurement and surface measurement has been performed and the result shows that the consistency of distance measurements between two points was 65 μm and between two surfaces was 9 μm. The laser scanner requires scans from different positions which have to be aligned. The result shows that reference frame alignment is the best method when compared to the tooling ball best fit method, fitting to 17μm when using the laser scanner.

Keywords: Laser scanner, Measurement errors, Uncertainty, Best fit methods

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1. Introduction

Humans have used measurement in some form since the beginning of existence. Metrology was first analysed in metal machining and cutting workshops where reducing scrap metal had cost benefits [1]. It was however technology such as active feedback control, artificial intelligence and rapid data storage which was the driving force for advances in metrology [2]. Modern metrology have not only restricted its use on finished component inspection, control of manufacturing and assembly process, jigs and fixture verification, it has also opened up new application areas for metrology assisted production, for example for end-inspection process of long, heavy parts such as airframe structures and spars. Large components with tight manufacturing tolerances are often measured by large scale measurement systems include the laser radar, laser scanner, laser tracker, coordinate measurement machine (CMM), theodolite and photogrammetry [3]. The development of these measurement systems and the evaluation of the instrument measurability over the last forty years have been well defined [3, 4, 5, 6, 7, 8, 9]. However the most portable large volume measurement systems have complex structures and do not have simple characteristics. For instance: laser trackers have angle errors and larger than the interferometric distance errors; accuracy of the photogrammetric systems vary and depends on the range, the number of images used and the location of the images [10]. For controlling the measurement quality, an accepted procedure to verify the system and evaluation of error sources and uncertainty is required. There are different recognized methods for determining the uncertainty of measurement made with CMMs [11]. These methods are covered in the ISO 15530 series of standards [12]. Despite the increasing application of the laser scanner [13, 14, 15, 16], common laser scanners are less accurate when compared to touch-trigger probes. Therefore identifying measurement uncertainty and improving digitizing accuracy are the most challenging tasks.

Much of the research efforts on laser scanning have been focused on the development of applicable laser scanning systems and the path planning of commercial laser scanners, only limited research has been carried out to analyze the error sources and uncertainty of the laser scanning systems [17]. The research work presented in this paper attempts to analyse and characterize the measurement uncertainty of a laser scanner. Experimental work has been performed. The objective is to first identify the build up errors within the laser scanner systems. This has been achieved by comparing with the laser tracker on performance measures to see the contributing factors of the uncertainties in laser scanner systems. The second objective is to identify the systemic errors and random errors within the scanner systems. The final objective is to establish the best-fit methods and frame to frame methods to reduce uncertainty for a typical laser scanning operation.

2. Understanding Uncertainty

The uncertainty of a measurement, also called accuracy [18], can be described as the doubt or query which exists around a measurement result. Error was the original way of quantifying a measurement result; it was used to give an indication of the range in which the measured was located.

As the technology has progressed, measurement procedures and standards defining the results have been developed along side. These standards allow manufacturers to produce high quality products which can be clearly clarified. Two major standards are ISO 1101 series [18] and ISO 14253 series [19]. ISO 1101 relates to geometrical tolerancing, it defines general principles of form and positions of the material requirements. ISO 14253 relates to uncertainties in geometrical measurement (GUM); providing guidelines on the expression of uncertainty in measurement. It was officially recognised in the guide that measurements should be expressed in terms of their uncertainty instead of their error. Error of measurement is seen as a range in which the true value lies. Uncertainty gives a range and a probability that the result is within this range, generally SD=2 (standard deviations) is used which represents 95% probability. This recognises that measurement is an experimental procedure and hence results cannot be 100% reliable. Uncertainty shows it is as important to know the quality level of the measurement as the measurement result [20].

Figure 1 shows a graphical representation of how measurements taken under the classical approach relate to the feature being measured [21]. y_{true} is the true value of the measurand and y_i is the individual measured value, then $\bar{y}$ is the average measured value. If a large number of measurement results are taken and plotted, the resultant plot will represent a normal distribution. This distribution can be put down to random errors. Systematic errors have a set of values equal to the difference between $\bar{y}$ and y_{true}. This error represents possible issues such as machine calibration. In a measurement series, systematic error is not observable and does not behave in a random nature, therefore statistical analysis cannot be applied as with the analysis of the random errors.

Modern metrology is moving away from the classical approach towards the uncertainty approach. There are two possible approaches, Uncertainty in Measurement approach and the International Electrotechnical Commission (IEC) approach. GUM states that it is not possible to know the exact value and it accounts for systematic and random errors on equal footing. It recognises in Equation 1 that error is an idealised concept and uses a Gaussian probability density function (*pdf*) to represent it, where $\bar{x}$ is the mean value and σ^2 is the variance.

$$pdf = \frac{1}{\sqrt{2\pi\sigma^2}} e \frac{(x-\bar{x})^2}{2\sigma^2} \quad (1)$$

A measurement result fully defined using uncertainty, would be *x* mm +/- *y* mm *z*σ, where *x* is the measurement result and *y* is the range in which the result lies with a probability of *z* standard deviations (2σ being 95% probability).

The IEC approach has a more operational method; it works on the basis of the true value being both unnecessary and unknowable. It is important that measurements are compatible with each other and the averaging of multiple measurements is encouraged [21]. When single measurements are taken, the measurement systems calibration must be taken into account when working out the uncertainties. When decisions need to be made on whether a measured quantity conforms to a particular requirement, a hybrid of the classic and uncertainty methods is normally used. Examples of this include machine tolerances and legal requirements. A two step process is used, first measuring a calibration result using a high accuracy level system then repeating the measurement using the lower accuracy machine in the measurement process and assessing errors with respect to the classic approach.

When comparing the error form to the uncertainty form, it becomes clear that the random error is closely linked to the standard deviation used in uncertainty, in that both can be modelled using a normal distribution curve. Random error can be related to the range in which the result lies. The problem with splitting into two parts in error measurement analysis is that the best way to represent random error is to use statistical analysis. Whereas the systematic part, as it is individual to each measurement type, should not be represented using statistical analysis.

Within uncertainty there are two categories for generating an uncertainty value, Type A & B. Type A estimates the uncertainty using statistics based on measurement results. Type B calculates the uncertainty based on known data such as calibration certificates, manufacturer specifications and common sense. Equations 2, 3 [22] calculate uncertainty values u, where σ is the standard deviation of the measured data and m is the number of sets of data. The upper and lower limits states (USL, LSL) are related to values quoted either by the manufacturer's specification or the calibration certificate.

Type A: $$\mu = \frac{\sigma}{\sqrt{m}} \quad (2)$$

Type B: $$\mu = \frac{ULS - LSL}{2\sqrt{3}} \quad (3)$$

There are many different areas from which uncertainty can arise. These can be calculated individually using either type A or B more than once. Therefore to cover all the different aspects, they need to be combined as shown in Equation 4.

$$\text{Combined uncertainty} = \sqrt{\mu_1{}^2 + \mu_2{}^2 + \ldots. + \mu_n{}^2} \quad (4)$$

In order to combine the uncertainties calculated in the Equations 2 and 3, the uncertainty type A and type B must have been calculated using the same levels of the standard deviation.

3. Influence Factors

Measurement uncertainty is the key performance indicator for any measurement systems and subject to imperfections. Some of these are due to random effects, such as short-term fluctuations in temperature, humidity and air-pressure or variability in the performance of the operator. Repeated measurement will show variation because of random effects. Other imperfections are due to the practical limits to which correction can be made for systematic effects, such as offset of a measuring instrument, drift in its characteristics between calibrations, personal bias in reading an analogue scale or the uncertainty of the value of a reference standard. The uncertainty influences has been classified into the following categories: measurement method, environment, scanning hardware and processing software. This classification differs slightly from classifications presented in [23, 24, 25, 26].

3.1 Uncertainty Related to Laser Scanner

The laser scanner on which this paper is based uses a Frequency Modulated Coherent Laser Radar (FM, CLR), described in detail in the reference [27, 28]. The Laser radar is a versatile metrology system that offers non-contact and singe operator inspection. As it is offline-programmable, the system is completely automated and unattended in operation. It requires no special environment or expensive tooling. The system works indoors or out, in any lighting and on any material or finish surface with a reflectivity of even less than 1%.

The system was developed for large volume coordinate measurement in engineering, reverse engineering, inspection in CAD systems and calibration of robot units [29,30]. As can be seen in Figure 2, the system is made up of the FM CLR scanner, its mountings, power unit, and a PC is required to run the software which drives the scanning procedure and records data. The software used for point cloud manipulation is Spatial Analyzer (SA).

All measurements are taken with the scanner in a set position and then data points are measured and recorded in SA. The positions are measured using a spherical technique which records the orientation of the scanner head in Azimuth and Evaluation, then takes a range measurement from the scanners mirror to the feature, which is where the laser comes into play. Once measurements are taken they are transferred to SA where the positions are converted into Cartesian coordinates.

Laser radar uses frequency modulation to measure range, this is because it is possible to measure frequency more accurately than time. The frequency is modulated into a saw tooth wave, in this case the wave cycle is two milliseconds with a base frequency of 200THz and the modulation adds up to 86THz at its peak, with the wavelength fixed at 1500nm [27]. The modulated wave is the reason why this system can operate a non-contact measurement, because it is the modulation of the wave that is being measured only a tiny amount of the wave needs to be reflected back along the path travelled to the part, as little as 0.1x 10^6 % of the original signal. This saves time in the measurement process and reduces human error introduced by placement of the reflectors.

There are only a few measurement techniques used in large scale metrology that do not use a light source of some kind. They include a taut wire for alignment and spirit level for levels; however laser alternatives for both of these methods exist. All light source measurement systems are line of sight and require the beam to travel through the atmosphere. The light source within a measurement system is used for distance measurement. Knowledge of how these light sources are used to make a measurement makes identifying where errors came from easier [31, 32, 33, 34].

The simplest form is time of flight, where the time from laser sent to target until it returns to a sensor is recorded. The value is halved and then multiplied by the speed of light to give the distance. This is not an accurate method. Fringe counting is a popular method for high accuracy metrology, but if the beam is broken the system needs to be reset and the sensitivity is dependent on power supply being constant. Fringe counters can also be set up to measure phase shift $\Delta\varphi$ and using a reference distance, it is possible to calculate a distance using Equation 5 [5]. The calculation of phase shift is presented in Equation 6 [5] where c is the speed of light in a vacuum, f is the laser frequency and n is the refractive index which is assumed to be the same in both reference and actual distance.

$$D = D_{ref} \frac{\Delta\varphi}{\Delta\varphi_{ref}} \tag{5}$$

$$\Delta\varphi = \frac{4\pi D n \Delta f}{c} \tag{6}$$

The laser radar instrument directs a focused laser beam to a point on the part to be measured, and recaptures a portion of the reflected light. The single large-aperture optical path maximizes signal strength and stability. As the laser light travels to and from the target, it also travels through a reference path of calibrated optical fibre in an environmentally controlled module. Heterodyne detection of the return optical signal mixed coherently with the reference signal produces the most sensitive radar possible. The two paths are combined to determine the absolute range to the point. Combined with the measured horizontal and vertical laser beam angles, the 3D coordinates of the acquired points are determined in real time.

3.2 Uncertainty related to the Measurement

There are two ways in which error can be stated: absolute error, which is the difference between the true value and the measurement value, and relative error, which is the absolute error divided by the true value, normally given in per thousandths [35]. At the measurement stage, error compensations are normally calculated relating issues which will affect the measurement, such as environmental conditions. Sometimes these compensations can not be put into the measurement process, therefore they need to be compensated for at the analysis stage. Co-ordinate Measuring Machines (CMM) with touch probes work with six different errors, three machine axis errors and three squareness errors. These are used to correct the results and can be used further in the Monte Carlo simulation to evaluate uncertainty [5]. This method is not suitable for systems like the Laser scanner; it has different scales of errors coming from angular encoders and the range finder, making an in situ mapping of uncertainty very complex. Performance tests can be used on systems like the laser scanner and are carried out using calibrated scale bars in a variety of orientations. Task specific uncertainty can be calculated for any given measurement procedure as illustrated in Equation 7. In Equation 7, M is the number of errors; E_j is the value of the individual errors and σ_R^2 is the sample variance calculated from the repeatability data.

$$u(t) = \sqrt{\frac{1}{M}\left[\sum_{j=1}^{M}(E_j - \overline{E})^2 + \sigma_R{}^2\right]} \tag{7}$$

The errors introduced by the use of a robot have been analysed using a tracker and Particle Swarm Optimisation (PSO) algorithm, which assumed the geometric errors of the robot manipulator is zero [36]. This approximation is possible because relative to the robot error, the tracker error is minimal. This theory can be applied to tracker or scanner errors with the use of a more accurate system. The conventional way of improving accuracy is to generate a complete identification model for the measurement procedure. A more generic and practical technique uses prediction functions to estimate expected position errors, thereby no extra data needs to be collected.

The measurement goes through five steps:

- Choosing a type of function
- Deciding on size of function (number of co-efficients)
- Estimating the numerical values of co-efficients using PSO
- verifying the size of function using the experimental data

- Generating a modified joint space or Cartesian space for error correction

The Cartesian errors of the robot used in a PSO algorithm can be stated in Vector form. In Equation 8, where P_{rk} is the true value of the K_{th} measurement and P_{nk} is the corresponding nominal position vector.

$$\Delta P_k = \begin{bmatrix} \delta x_k \\ \delta y_k \\ \delta z_k \end{bmatrix} = P_{rk} - P_{nk} \tag{8}$$

3.3 Uncertainty related to the Environment

As the light source has to travel through the atmosphere in order to register a measurement, it is important to look at how this affects the measurement. It is assumed that when taking measurement the light travels in a perfectly straight line.

We know that the speed of light can fluctuate due to changes in temperature, pressure and humidity. It is possible to calculate a compensation for the humidity by using several different frequencies and look at how the results vary. If the temperature is known it can be fed into an equation used to calculate distance as shown in Table 1. It shows the values of deviation due to the effects of temperature variation compared to another important factor, such as the curvature of the earth. On a small scale feature within a laboratory the earth's curvature has little effect; however on a large scale feature its impact can be significant.

The temperature in Table 1 is given in gradient form because the rate of change of temperature known as Kelvin per metre affects the path of light. Pressure gradients can also affect the measurement by up to -160µm over a 100m path. It has been proven that different wavelengths of light can be refracted different amounts by the presence of an index gradient, the shorter the wave length the stronger the refraction.

To get over fluctuations under environmental conditions, some systems such as a Laser Tracker use a reference measurement to set up the distance calculations. The reference measurement involves putting the corner cube reflector in a holder, which is positioned at a known distance from the tracker.

3.4 Uncertainty related to the Measurement Techniques

Sometimes conditions like temperature and pressure cannot be controlled, so they need to be accounted or adjusted for. There are other factors which affect errors and can be controlled, such as the way a part is dimensioned; this can affect the size of errors based on a cumulative factor. It is better to dimension from the centre, it halves cumulative errors at edges when compared to dimensioning from the edges. This method can also be used when carrying out a measurement procedure, as uncertainty increases with cumulative effect. When assessing the uncertainties, the tolerance level must be considered to the same tolerance level as when producing the part. In an ideal world the same tolerance level would be used throughout design, manufacture and assembly but in real world situations, this is often not the case [37].

For a part to be measured, features have to be created to assign the dimensions to. Simple geometries can be modelled from data points within the SA, but more complex surfaces might require freeform surfaces to be represented. This often means transferring the data to software systems such as Solidworks, which can introduce errors in the conversion of the data. Different programs represent geometries in different ways, a sphere can be represented as a centre and radius, a semi-circle and central axis of rotation, or as a Non Uniform Rational B-spline (NURBS) surface[38]. With large objects like aircraft wings, gravity can have a large deflection effect. If the wing is measured whilst fully supported, it will hold a different shape to when it is only supported at one end or if it is loaded, as in flight.

Considering the system taking the measurements, if a network of different machines is used, linking these machines can introduce errors. SA has a program called Unified Spatial Metrology Network (USMN), this can be used to reduce errors when linking data point clouds together. It can also work out uncertainty for these aligned clouds. The method requires measurement of a point from multiple positions, finding the average location of the point and working out errors in distance (ε_l) and two angles (ε_θ,ε_Φ), as can be seen from Figure 3. The uncertainty is calculated using Equation 9 with the groups of errors being used for r [39].

$$\mu = \sqrt{\frac{1}{M-1}\sum_{M=1}^{M} {r_M}^2} \tag{9}$$

4. Experimental Setup

The key elements of the experimental setup depicted in Figure 4 are the LT500 Laser Tracker unit, reflector, MV220 Laser scanner and tooling balls. Three tests were carried out which represented typical production environment. The measurement process uses more than one system and errors can be split into two distinct areas, hardware and software. A simple way of testing for errors in a system is to analyse test results using a measurement system with a higher level of accuracy. In this section results of a comparison test between the FM CLR scanner and the more accurate Laser Tracker have been analysed.

4.1 The Build Up of Errors

When evaluating the uncertainty, there are two specific aspects to consider, the hardware and the software. The CLR scanner uses a modulated wave comparison so hardware uncertainties would depend on the form of the wave sent out and the measurement equipment. Software or electronic uncertainties are very dependent on the method used. The electronic uncertainty usually equals the resolution of the system, when using a corner cube reflector (tracker) this is half the wavelength [40]. With a FM CLR scanner, uncertainty is dependent on the quality of the modulation and the frequency measurement. There are built-in checks to evaluate these parameters[41].

A method which can be used is known as Peak to Valley surface errors. This evaluates measurement results and as the name suggests, looks at how data points vary above and below the final surface, this can be seen in Figure 4. Uncertainties in these errors are hard to determine and an overestimate of the actual value often occurs because of noise in the measurement process. There are many sources of uncertainty and when combined together a matrix can be formed. The high information density of a matrix is good for use in analysis, and can be used in conjunction with the raw data to give an improved representation of the actual surface [42].

4.1.1 Hardware

The FM CLR's hardware has been designed to reduce errors, the two angular positional measurements (Azimuth and elevation) are taken using encoder technology and the other positional measurement (range) recorded using contactless technology. Sources of errors in this system are related to the:

- Quality of the modulated wave
- Measurement head, mirror and laser alignment
- Background noise/Environmental conditions
- Object properties

The manufacturer quotes an accuracy of 50µm to 2σ (industry standard), if a set of checks which have been built into the system are passed. Errors due to the surrounding environment are minimised in several ways, first the scanner uses an infa-red frequency which is not affected by varying lighting conditions. The base frequency is set at 200THz and then modulated up to 86GHz [27]. This gives the scanner a distinct window of frequencies in which to scan for the reflected signal and this limits noise to frequencies in that range. Background noise in this frequency range is low relative to the signal strength, so a simple signal intensity filter can be applied to make sure that the recorded frequency is the signal reflected from the measurand. The effects of environment have been addressed in section 3.3 and the effect of humidity is minimal to the measurement result. The system can cope with humidity ranging from 10%-90%.

4.1.2 Software

Spatial Analyser (SA) is the software used for manipulating and analysing the data. Physical measurement errors due to software come in the process of converting the raw measurement data into the X, Y and Z co-ordinates which are fed into SA. The way SA introduces errors into the physical measurement process is when compensation algorithms are used to account for properties such as material expansion due to temperature. Or with the introduction of an incorrect set scale, these two features have to be applied by the user making it a human error rather than a software error. Errors which come in the data manipulation stage of the measurement process are due to either the errors within the algorithms used to manipulate the data, geometry generation of point clouds and 'Best Fit' transformations, or the choice of the actual algorithm used. The most algorithms are based on the Least Squares method although different matrix approaches can also be used.

The Least Squares method is a standard approach to the approximate solution of overdetermined systems, i.e. sets of equations in which there are more equations than unknowns [43]. The objective consists of adjusting the parameters of a model function to best fit a data set. A simple data set consists of n data pairs (x_i, y_i), i-1…., n, where x_i is an independent variable and y_i is a dependent variable whose value is found by observation. The model function has the form f(x, β), where m and c are the adjustable parameters held in the vector β. The sum of the squared residuals in Equation 10 could be minimised by using different alignments function. The aim of the Equation 11 is to predict the differences between the data point y_i and the function used to represent the final geometry of the parts being modelled. For a simple straight line, Equation 12 could be the function used, where x_j is the variable, m is the gradient and c is the fixed constant.

$$S = \sum_{t=1}^{n} r_i^{2} \tag{10}$$

$$r_i = y_i - f(x_j, \beta) \tag{11}$$

$$f(x_j, \beta) = c + mx_j \tag{12}$$

The linear function in Equation 12 cannot exactly represent experimentally recorded data. This problem of data representation is magnified when taken into 3 dimensions and the equations get much more complicated. Data representation is the main source of software errors.

Best fit transformations require two sets of points, a reference set and a nominal set (fixed in place) and the relationship between the points within each set needs to be reasonably similar. The method works by reducing the distance between each nominal point and its corresponding reference point. When this orientation is found the reference points take the position of the nominal points and the information connected to the reference points (an instrument or a point cloud) take a new location. A minimum of three points are required for a best fit, but at least four should be used to minimise errors.

There is a feature in SA for bringing together different types of machines such as a CMM and a laser scanner. Each different measurement system will have different error spreads as shown in Figure 5. The Unified Spatial Metrology Network (USMN) program uses a different method than best fit to compensate for this. Instead of the nominal points being fixed, the corresponding sets of data points used to locate the instruments are bundled together[44]. An average position within each bundle is used as the reference once the minimum spread within each group has been found. This leads to more flexibility in fitting these sets of points to each other, which leads to a closer alignment. There are reservations within industry because of the loss of a fixed reference point, this is misleading as the loss does not affect the accuracy as all measurements are taken relative to either the instrument or other points so a better alignment of the instruments or point clouds leads to more accurate results.

4.1.3 Comparison of a FM CLR scanner with a Laser Tracker

The scanner has a built in program for measuring tooling balls. This program can measure the centre of a tooling ball to a higher accuracy, which is why they are used as reference points. The test will comprise of measurements of the distance between points set out in a grid, as shown in Figure 4. The laser tracker can use a 1.5” sphere with a central corner cube as a reflector and the scanner can be set up to measure a 1.5” tooling ball. In order to make sure that both machines are measuring the same positions, 1.5” tooling ball holders will be clamped in place to make up the grid. The test will be run 5 times for each machine to ensure the accuracy and the repeatability of the measurement process is evaluated.

Table 2 shows the results of the distance measurement and Table 3 shows how the two machines compared with each other. The largest difference between the two machines was 0.065mm in this test, which equates to an error of 0.0079%. The consistency of the scanner is most impressive, as the quoted accuracies of the two machines are 50µm for the scanner compared to 10µm for the tracker. Despite this the scanner on this test showed that it could keep the standard deviation to the same order of magnitude as the tracker, less than 0.01mm.

4.2 Identification of Random and Systematic Errors

Errors are defined as the difference between the measurement result and the true value of the measured, for the purpose of this test it is assumed that a true value exists. In section 2 it was shown that errors can be split into two parts, Systematic errors and Random errors. If it is possible to identify and classify these errors then it is possible to account for and even reduce them. Most measurement systems have built in algorithms to account for factors such as temperature or humidity of the surrounding environment.

Of the two types of errors, systematic error is easier to measure. Systematic error is stated as the difference between the true value and the average measured value. This can be due to instrument calibration (dial reading high), software limitations (not a very refined algorithm) or procedure techniques (dirt on the part surface). Using the average tracker measurement as the true value, averaging out of the differences between the true value and scanner measurement results from Table 3 gives a systematic error for the whole system of +0.038mm. Improvement on the true value can be found by using a full contact measurement system and by taking more measurements, the measurement results will produce a normal curve as seen in Figure 1*,* and the centre point is the true value to be used.

Random error is more difficult to evaluate, as there is no consistency; if enough measurements are taken, the results should form a normal distribution curve. There is an uncertainty calculator built into SA, which uses a normal distribution simulation to plot a specified number of points, either 100 or 1000, using the quality of the point recorded to define the normal distribution. Random error is linked to the procedure and/or human error, generally not the equipment or software.

So far these errors have referred to single points but it is also possible to look at errors of a point cloud and the geometry used to represent it. Figure 6 shows a plane generated from the point cloud, using the same theory as for the point error evaluation previously. The distance from the plane to the actual surface would represent the systematic error. Random error can be related to the spread of points either side of the plane. If the distance of each point from the plane created was plotted, the results would represent a normal curve centred on the plane as the plane is generated using a least squares method.

5. Evaluation Test of Laser Scanner

5.1 Creating Standard Geometries

Working purely in SA, geometries are used to turn the point clouds into features which can be measured. These geometries are created using a least square best fitting algorithm. The aim of this algorithm is to create the selected geometry (plane, circle etc.) and fit it as closely as possible to the points selected. In the generation process SA has a tolerancing option which allows the operator to ignore points over a certain distance from the initial geometry and then recalculate the geometry. This helps to eliminate anomalous results which would affect the geometry alignment. SA calculates the Root Mean Square (RMS) of the geometry, which shows in Equation 13 the average spread of data used to form the geometry. x_p being the difference between the data point and the geometry. The operator can use the RMS value to decide if the data points used in the generation of the geometry need a tighter tolerance applying in the creation.

$$\text{RMS} = \sqrt{\frac{\sum_{i=1}^{p} {x_p}^2}{p-1}} \tag{13}$$

5.2 Distance Measurement with Uncertainty using FM CLR Scanner

If the system has a systematic error which can be measured, this must be recorded and compensated for before the uncertainty calculation is carried out. To find out if the FM CLR scanner working with SA to create geometry has a systematic error, a comparison test with a Laser Tracker is carried out using a method similar to that used in section 4.1.3. Instead of using tooling ball reference points, a reference surface and a block with a flat surface are used. The distance from the block's top surface to the reference surface is measured using both measurement systems. To improve the accuracy of the Laser Tracker a mirror reflector was used, as seen in Figure 7, which enables surface points to be measured without the user having contact with the reflector, thus reducing any vibrations introduced by the user, when using a corner cube reflector on a smooth surface. The surfaces were measured five times for each system and the distances calculated. Figure 8 shows how the measurements of the distances between the surfaces compared.

With the adjustment worked out, the uncertainty can be calculated. The uncertainty for the CLR scanner is 0.0015 mm, the uncertainty for the laser tracker based on the same standard deviation is 0.007mm, and therefore the combined uncertainty is 0.0177mm.

5.3 Evaluation of Best Fit Methods

The uncertainty calculation in this section only concerned a single scanner position. In order to get a point cloud which covers the whole part, multiple scans are required. These scans require aligning to each other for the full cloud to be of any use. There are several methods of aligning the point clouds that these scans generated, a tooling ball grid can be set up around the part and then used to position the instruments relative to the part. An alternative method is to use a reference frame transformation to position the instrument relative to the part.

The evaluation test involves measuring a set of four positions on a freeform surface five times as seen from Figure 9. For each set of measurements, the instrument must first be located using the best fit method being tested, either by using a tooling ball or reference frame. A freeform surface is chosen as it is relevant to the type of measurement the FM CLR scanner is to be used for. By using a freeform surface, any misalignment will cause results to be different in all directions, not just along one axis. For a control, the data points will be measured five times without moving the machine, this gives a value of the system's inconsistencies before best fit methods are applied. Results can be seen in Table 4.

5.3.1 Tooling ball best fit method

With the control data recorded, the first best fit method to be tested will be a tooling ball grid around the part in order to best fit the instrument to the part, Figure 10 shows the setup. For each test run, a new instrument is added into SA and the four data points are measured. The reference points for the four data points were measured on the first measurement run. The instrument is then directed using the point instrument as function; this function points the instrument in the direction of the reference point relative to the scanners current location. A measurement of the data point is then recorded and compared to the original reference point. This is repeated for each of the four data points and then a new instrument is added, located and the reference points measured again. This is repeated until five sets of data points have been recorded. The differences between data points and reference points can be seen in Table 4. The standard deviation is calculated, this allows for anomalous results to be ignored. A comparison of the standard deviations of the best fit method with the control data set shows the accuracy of the alignment of the best fit method.

5.3.2 Frame to Frame Transformation

The Frame to Frame transformation is an alternative to the tooling ball best fit method for locating an instrument; this method creates a frame to identify a location. A frame is made up of three axes, each at 90° to each other. Measurements are taken to create features which a frame can be created from; these features can include points, lines and planes. For this method to work the part must possess these features.

To create planes, it uses more points allowing tighter tolerances to be used in the creation of the geometry. If three intersecting planes are created, the frame is fitted to the normal of each plane, as seen in Figure 9. This frame locates the instrument relative to the part and will be used as the reference frame for the future instruments when added. The four reference data points are now measured as in the previous method, a new instrument is added and the part frame is created as before for this instrument. An instrument transformation is carried out on the new instrument using the reference frame of the first instrument as a location and the frame of the new instrument as the source. This aligns the new instrument with the original instrument, to the accuracy of the frame creation. The data points are measured using point instrument at function. The process is then repeated with new instruments until five data sets have been recorded. Results for the difference between reference data points and the transformed instruments data points can be seen in Table 4 and compared with the results for the control and the tooling ball best fit method.

Analysis of the results in Table 4 shows that the Frame to Frame (FtF) transformation provides a group alignment with a smaller positional difference than the Tooling Ball best fit (TBBF) method. The control measurement shows that there is an error in the test process of

0.0165, which means that the error due purely to the alignment methods is actually less than the quoted accuracy level of +/-50µm.

The reason that the FtF method had lower alignment errors could be due to the way in which the references in each method were measured. TBBF uses a built-in program to measure the centre of the tooling ball. It takes multiple measurements of the tooling balls surface and aligns the results with calculated results for the surface of a tooling ball of the stated size. This was repeated for each of the tooling balls, with a set measured. The group is aligned to the nominal group, in a way which minimises the difference between each of the tooling balls and it corresponding nominal point. FtF required the measurement of three planes, a frame was then fitted to those planes. A frame is perfectly aligned to another frame as they both have exactly the same geometry, then any errors must be due to fitting the frame to the part. If the part has three planes and they accurately intersect each other at 90°, then using a large number of points with tight tolerances to create the planes will minimise this error. More points are measured in the FtF method than the TBBF method.

The standard deviation is a more relevant result than the average as the part measured did not have a flat surface and it was partly transparent causing there to be anomalous results. On analysis of these results, the FtF method is still the better method to use. However there are several limitations, the major one being the need for appropriate features which can be measured to generate the reference frame, in addition the extra time taken to measure the plane and create the geometry. The accuracy of both methods can be increased by taking more measurements. In the TBBF method this would require more tooling balls to be placed on/around the part. When more than three tooling balls are used a function can be used which automatically measures tooling ball positions after the first three have been located. The improvements are minimal, when using more than 5 tooling balls, on scans in a volume less than $1m^3$. The FtF method can be improved by taking more measurements for each plane and using a tighter tolerance when fitting the plane.

5 Conclusions

This paper has investigated the function of Frequency Modulated Coherent Laser Radar (FM CLR) and its use in the field of large scale metrology. It includes a review of the development of metrology in terms of physical techniques, the theory behind the techniques and the analysis of their results in terms of errors and uncertainty. The influence factors of the uncertainty during the measurement process have been identified in relation to hardware error, software error, environment and measurement techniques. Both point measurement and surface measurement have been performed to minimise errors and these values are used in the calculation of uncertainty. The results for the distance between two surfaces, when a plan is generated for each surface using one hundred points over five separate measurement runs, show a spread of only 9μm. Using a more accurate machine to check the systematic error and using the observed spread in the calculation would reduce the uncertainty for instrument accuracy by a factor of 5 in this case. In order to generate a 360° point cloud of a part, multiple scans are required and these scans must be aligned to each other correctly. Frame to Frame Transformation is the most accurate form of alignment: 30μm compared to 53μm when using the tooling ball best fit method. However, the part must have features which can be used to create the frames and they must be visible from all directions. This method also requires more user input than other methods to create the frames. The other method is a tooling ball best fit, which requires a grid of tooling balls around the part, but due to functions built into the system it is a quick and easy method of alignment.

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