THE EFFECT OF SCANNING PARAMETERS ON ACCURACY OF REFLECTIVE PARTS INSPECTION

by

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DEDICATION

I dedicate my dissertation work to my beloved family Mahsa and Armon.
A special feeling of gratitude to my loving parents, Mohammad and Afsaneh who light up the way of my life.

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L'effet des hyper paramètres de numérisation sur la précision de l'inspection des pièces à surfaces réfléchissantes

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RÉSUMÉ

La revue de la littérature révèle que bien que les avantages significatifs des scanneurs laser aient créé une forte tendance croissante à utiliser ce type d’inspection, il existe encore des restrictions fonctionnelles qui influencent considérablement leur qualité de mesure. En raison de l’existence de divers facteurs, qui ont potentiellement un effet sur la performance des scanneurs, leur précision est classée à un niveau inférieur à celui des sondes à déclenchement par contact conventionnelles.

Certains facteurs de numérisation ont été introduits lors de recherches précédentes dont le fait que le processus de numérisation sur les surfaces brillantes est plus problématique. Cette étude se concentre sur la qualité de la mesure par balayage laser sur les pièces réfléchissantes pour évaluer l’influence de certains facteurs de la scannographie, notamment l’éclairage ambiant, la pente de la surface, la forme de la surface et les options de traitement des données logicielles.

L'objectif principal de l'étude actuelle est de présenter une directive technique pour améliorer la précision des mesures sur des surfaces brillantes. La performance de mesure a été évaluée pour le scanneur laser Metris LC50 dans le laboratoire de métrologie ETS et la précision du résultat scanné a été comparée aux valeurs de référence mesurées par les sondes à déclenchement tactile de haute précision sur les machines de mesure de coordonnées Mitutoyo. De plus, le logiciel PolyWorks® a été appliqué pour trouver une méthode optimisée de traitement des données. L'expérience a été conçue en sept phases. Dans chaque phase, l'écart par rapport à la référence est le principal critère de précision.

Les résultats soulignent le rôle des paramètres de balayage et de traitement des données ainsi que le rôle des caractéristiques de surface. Comme résultat principal, cette étude montre que la qualité du balayage laser diminue dans un niveau élevé d'éclairage ambiant et sur des surfaces à forte pente. En outre, une configuration logicielle recommandée a été présentée pour obtenir des mesures plus précises par les scanneurs laser.

Mots clés : Scanner laser, sondes à déclenchement par contact, logiciel PolyWorks®, facteurs de numérisation, éclairage ambiant, métrologie, composants réfléchissants

The effect of scanning parameters on accuracy of reflective parts inspection

Seyed Sajad KAZEMEYNI

ABSTRACT

The literature review reveals this fact that although the significant advantages of laser scanners have created a great growing tendency to use this type of inspection, there are still functional restrictions, considerably effect on their measurement quality. Due to existing a rather large number of factors, which potentially effect on scanners performance, their accuracy is categorized in a lower level than conventional touch-trigger probes.

Some scanning factors were introduced during previous research. This fact is also revealed that the scanning process over shiny surfaces is more sensitive. This study focuses on the quality of laser scanning measurement over reflective parts to assess the influence of some scanning factors including ambient lighting, surface slope, surface form, and software data processing options.

The main objective of current study is determined to present a technical guideline to improve the accuracy of measurement over glossy surfaces. The measurement performance was evaluated for Metris LC50 laser scanner in ETS Metrology Laboratory and the accuracy of scanned result was compared to the reference values measured by the high-accurate touch-trigger probes on Mitutoyo Coordinate Measuring Machines (CMM). Also, The PolyWorks® software was applied to find an optimized method of data processing. The experiment was designed in seven phases. In each phase, the deviation from reference is the main accuracy criterion.

The results emphasize the role of data scanning and processing parameters as well as the surface characteristics. As the main result, the quality of laser scanning reduce in a high level of ambient lighting and over surfaces with a high slope. In addition, a recommended software setup was presented to achieve more accurate measurement through laser scanners.

Keywords: Laser scanner, touch-trigger probes, PolyWorks® software, scanning factors, ambient lighting, metrology, reflective parts

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LIST OF ABREVIATIONS

CMM	Coordinate Measuring Machines
GUM	Guide to the Expression of Uncertainty in Measurement
ISO	International Organization for Standardization
GD&T	Geometric Dimensioning and Tolerancing
FOV	Field of View
DOF	Depth of Field
QC	Quality Control
RMSE	Root Mean Square Error
RMSD	Root Mean Square deviation
CCD	Charge-Coupled Device
TIN	Triangulated Irregular Network
DEM	Digital Elevation Model
RGB	Red, Green and Blue
PDE	Partial Differential Equation
RPS	Reference Point System
CAD	Computer-Aided Design
Min	Minimum
Max	Maximum
AAD	Average absolute deviation

LIST OF SYMBOLS

d	Stand-off distance or scan depth
θ	Incident angle
α	Incident angle
u	Standard uncertainty
u^2	Estimated variance
ur	Relative standard uncertainty
r	Correlation coefficient
u_c	Combined standard uncertainty
${u_c}^2$	Combined variance
d_i	Deviation
ε	Error

INTRODUCTION

Dimensional measurement, inspection and quality control (QC) are fundamental parts of manufacturing processes. However, the setting up a measurement process needs comprehensive consideration to various related aspects. Having a precise evaluation of the data acquisition systems capabilities and weaknesses as well as identifying the factors which have potential influences on their efficiency is a significant aspect of choosing an appropriate measurement system. Following the recent and rapid development of industrial processes and producing parts with high complexity, using an accurate and flexible inspection approach has found a key role, especially in this day's dynamic manufacturing environment. In order to promote and adapt metrological methods, it would be necessary to recognize potential uncertainties which could occur in the production and inspection procedure (Zhao, Xu, Kramer, Proctor, & Horst, 2011).

An ideal inspection system would be a fast and automatic system (without any reproducibility error) which could accurately gather data and work as a part of the production line. Such this real-time inspection system improves the performance and minimize costs. However, the complexity of product shape and the surface specifications (e.g. gloss, roughness) are important factors which affect on choosing an appropriate inspection approach (including the data acquisition, data treatment and features extractions).

Common data acquisition systems could be classified as contact and non-contact approaches. Conventional methods using touch probe instruments are sufficiently accurate in case of regular shaped products. The resolution of contact based inspection instrument is adequate (around 1µm) for measuring primitive features such as planes, spheres, and cylinders. In these cases, capturing only few points data could be adequate (with the hypothesis that the form error is neglected). However, the touch probes have some restrictions to measure on corners, edges, pockets, and spikes of prats (Hosni & Ferreira, 1994).

The interest in using vision-based 3D measurement is increasing in manufacturing industries as a part of their development process in automation, digitalization, and optimization area. The benefits of this method give the capability to capture the information on product geometry, surface finish (e.g. waviness), and surface defects (e.g. bumps) as well as the dimensional data, which is an advantage in detecting deviations in the parts geometric shape. Measuring process could be more complicated in case of free-form surfaces where the vision-based instruments might be helpful in a non-contact approach, because of their ability to acquire data from thousands of points per second (Milroy, Weir, Bradley, & Vickers, 1996). In order to extend the scope of the inspection and diminish the restrictions, the manufacturers of 3D scanners tried to improve the technology of these instruments as a non-contact alternative to the contact probes on Coordinate Measuring Machine (CMM). The vision-based method provides additional functionality regarding measuring various features of possible products shape. Moreover, the 3D scanning method speeds up the production process using the computer to gather and analyze captured data (Matache, Dragan, Puscasu, Vilag, & Paraschiv, 2015).

In spite of all mentioned benefits for laser scanners, there is some considerable problem regarding their measurement accuracy. According to some performed research, the accuracy of the industrialized 3D scanners is still lower in comparison with the tactile probe (Matache et al., 2015). In particular, measurement over shiny surfaces is a serious challenge in this type of inspection, due to the key role of diffuse reflection. Moreover, some factors regarding ambient conditions, scanner features, or part characteristics can impact on the validity of results. Therefore, the assessment of measurement uncertainty and recognizing its sources is significantly important in these systems. The data processing, using developed software, could significantly improve the quality of scanning results. Appling appropriate software algorithm reduces the influence of outliers and provides an optimized fitting for primitive features.

Therefore, this study aimed to investigate the effect of some important factors on laser scanning performance, during the inspection of reflective parts. The results can offer some recommendations to promote the accuracy of laser scanning measurement.

CHAPTER 1

LITERATURE REVIEW

1.1 Classification of data acquisition methods in metrology

Data acquisition approaches have been classified in different ways based on the criteria that were considered by researchers. One of the most referred classifications was done by Varady et al. (Várady, Martin, & Cox, 1997). The main considered term for this classifying is the used technical principle in each method. The diagram in Figure 1.1 demonstrates that the inspection systems are generally categorized into contact and non-contact.

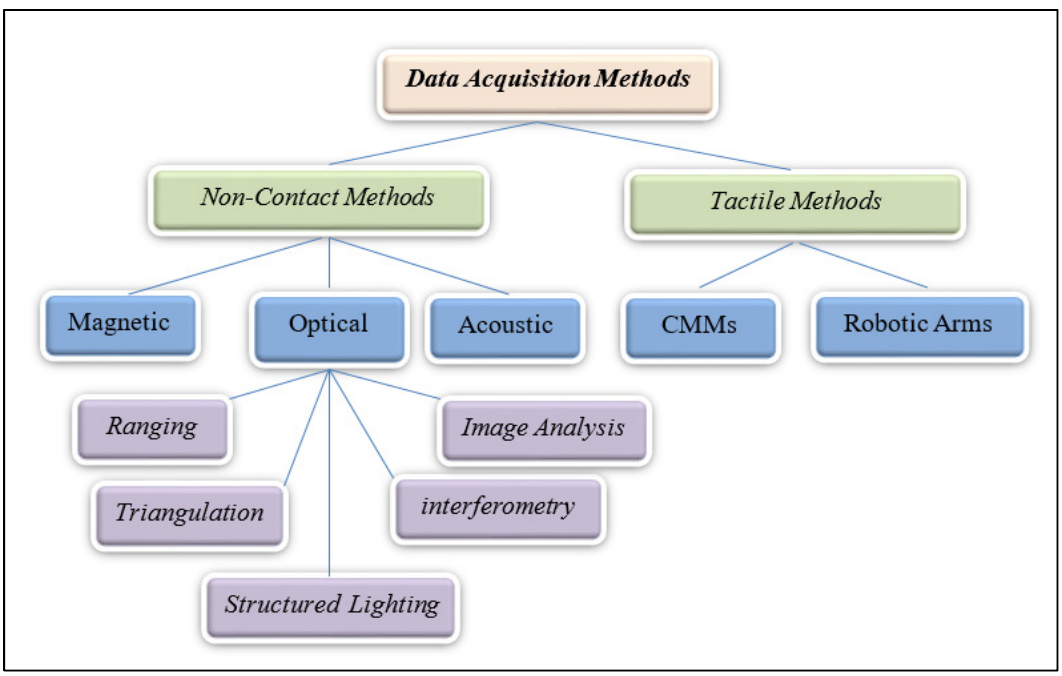


Figure 1.1 Classification of data acquisition devices
Taken from Várady et al. (1997, p. 256)

In contact systems measuring instruments use tactile methods, in the way that usually a mechanical probe mounted at the end of a robotic arm, during a touching process on the product surface, achieves data related to the position of surface points. On the other hand, a contact system takes the advantages of a media such as light, sound, or magnetic fields to scan part's surface. The obtained records in all types need to be analyzed by specific processors. According to Isgro et al. viewpoint, non-contact approaches could be classified into passive and active systems (Isgro, Odone, & Verri, 2005). Passive systems are based on images which are captured by light reflection from a natural or artificial source, in lack of using energy to active sensors. In the active methods, a kind of energy such as light pattern or sonar pulse is projected onto the object surface and the measurement is usually carried out by detecting controlled changes of sensor parameters (Cuesta, Alvarez, Martinez-Pellitero, Barreiro, & Patiño, 2019).

1.1.1 Passive Systems

In a passive system, shape-from-shading, shape-from-motion, or passive stereo vision is applied to capture data in three-dimensional space (Bi & Wang, 2010). In using the shape-from-shading vision, only one camera is necessary to scan the part under various conditions. The information related to depth is obtained by evaluating the variations in surfaces brightness and adjusting the surfaces in certain orientations. Shape-from-motion considers the object motion sequences by moving the object or the camera. Passive stereo vision scans the object by two or more cameras, and 3D data are acquired through triangulation.

A passive system has some advantages including its less sensitivity to ambient condition and its capability for a mobile vision progress without the necessity of external energy source. Shape-from-shading as well as shape-from-motion approaches are sensitive to the lighting and reflectance features of the scanned surface. Moreover, both of these methods have low performance in scanning non-uniform surface textures and measuring absolute depth. Therefore, according to mentioned weaknesses, these two approaches could not be appropriate for general 3D data acquisition.

In a passive stereo vision, finding the pixel correlations of different images plays a key role. To deal with this issue, extracting and matching of features, such as edges and points, should be correctly done. Generating an accurate model need a considerable time due to the complexity of computation in both extraction and matching process (Bi & Wang, 2010).

1.1.2 Active Systems

In the active systems, physical principles which are employed in device function were considered as a base for their classification. These terms contain triangulation, time-of-flight or laser pulse, and interferometry.

In the case of triangulation, the main concept is the principle of triangulating a measurement spot on the surface from a physically separate camera optical source and detector (Bi & Wang, 2010). This approach uses simple geometry to calculate the (x, y, z) coordinates of the illuminated spot (Scott, Roth, & Rivest, 2003). Sensors in this type of active system can be used single point or slit, as it is demonstrated in Figure 1.2 and Figure 1.3 a Set of data are captured point by point in a single-point sensor. However, a slit scanner projects a laser line on the object, so that provides the ability of a simultaneous scanning of a complete profile of points. In this way, compromising between the field of view and depth resolution is needed, and the immunity to environmental lighting is low (Francois, 2003).

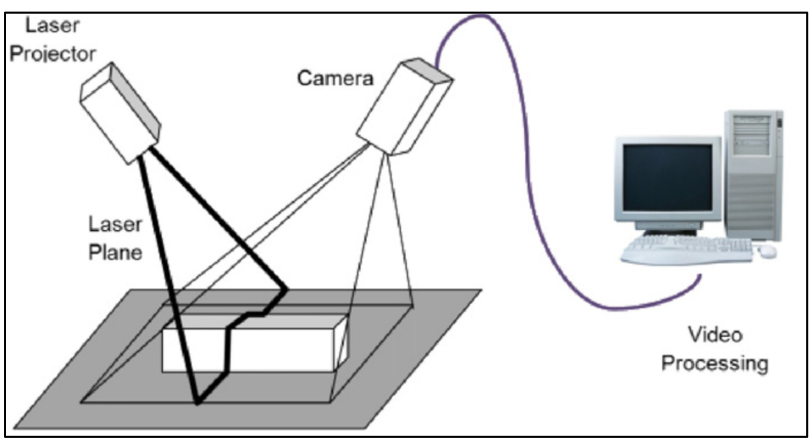


Figure 1.2 Slit Scanner
Taken from Francois (2003, p. 234)

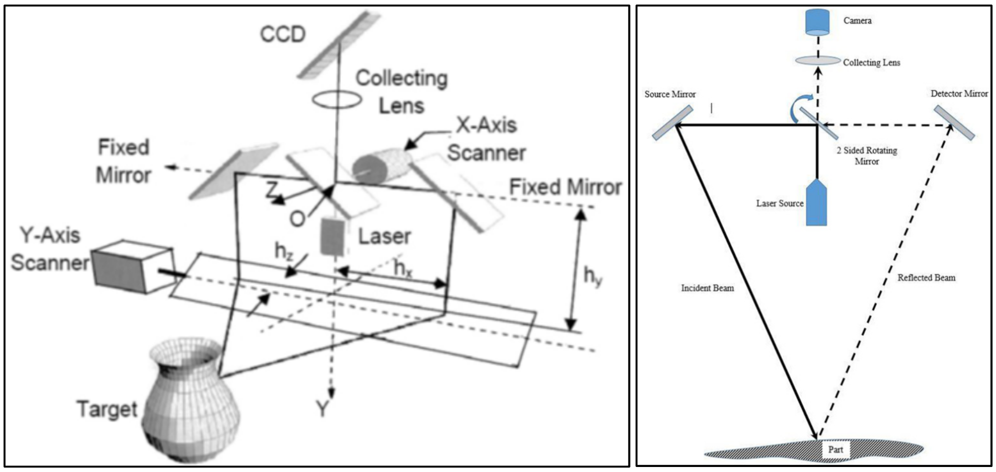


Figure 1.3 Single-Point Scanner
Taken from Francois (2003, p. 233)

The basic principle in the time-of-flight or laser pulse systems is that the scanned surface reflects light back towards a receiver, and then the interval (time or phase difference) between transmission and reception would be measured. The timing accuracy has an important role in a time-of-flight scanning and the offered resolution for longer-range applications is usually modest (normally centimeter or occasionally millimeter). This method is an appropriate approach for distance measurement and medium to long-range modeling (Wulf & Wagner, 2003).

In Interferometry systems, multiple stripes are projected on the surface, at the same time. In order to spatially amplitude modulates the projected light, two pairs of gratings, which are accurately coordinated, are employed. Also, the camera grating is used to demodulate the pattern and generate interference fringes, while its phases are proportionally related to the range. This type of scanning is especially recommended in the inspection of object surfaces including large flat segments and small depth variations. In spite of less accuracy of these scanning methods in comparison with the laser scanning, using the incoherent light in these systems could remove the speckle noise associated with lasers and promote the ability to acquire color texture. Aim to select an appropriate scanning system for a specific project some factors take a significant role, including accuracy, speed, resolution and spot size, range limits and influence of interfering light, the field of view, registration devices, and imaging cameras (Bi & Wang, 2010).

1.2 Definition of the Scanning Parameters

In this section, some scanning factors that may affect the quality of data acquisition in laser stripe systems, as the most common triangulation scanners, are mentioned. Laser stripe scanning, which works according to the triangulation principle, are commonly used in metrological purpose due to their high accuracy and cost efficiency in comparison with other approaches. Moreover, the mobility of the scanners using this method enables them to acquire parts on site. This type of scanner projects a laser beam with a certain angular width on the object surface, and the Charge-Coupled Device (CCD) sensor is applied to detect several points of the stripe which is generated on the surface and reflected. Finally, the system obtains 3D coordinates of the surface points using the principle of triangulation (Gerbino, Del Giudice, Staiano, Lanzotti, & Martorelli, 2016).

Some important geometrical parameters in scanning operation of this kind of non-contact active systems are mentioned in Figure 1.4.The parameters which are in connection with the adopted optics, lens, and focus distance might change depend on scanner models. The definitions of some of these parameters are presented in Table 1.1.

Table 1.1 Some Scanning parameters
Adapted from Gerbino et al. (2016, p. 1789)

item	Parameter	Unit	Definition
1	Field of view (FOV)	mm	3D region within which the CCD sensor can acquire points on the scanned surface. It is defined by the depth of field and the scan width. It may vary a lot depending on the adopted optics and the lens focus.
2	Depth of field (DOF)	mm	the range of distance from the laser source within which the CCD sensor can acquire points on the scanned surface. It is related to the lens focus.

3	Scan width or beam width	mm	width of the laser beam measured in the half position of the depth of field. Only the portion within the field of view is measured.
4	Stand-off distance or scan depth (d)	mm	distance from the laser source to the reference surface located in the half zone of the field of view. It depends on the optics and lens focus.
5	Incident angle (θ)	deg	the angle between the incident laser beam and the projected surface normal of the scanned point in the scanning plane (Prieto, Lepage, Boulanger, & Redarce, 2003).
6	Projected angle (α)	deg	the angle between the scanning plane and the normal (minimum) at the surface in the scanned point(Prieto et al., 2003).

Parameters 4 to 6 are related to the relative positioning of the object and sensor. In the case of mobile scanners, setting a certain orientation would be difficult in comparison with laser scanners on Coordinate Measuring Machines (CMM).

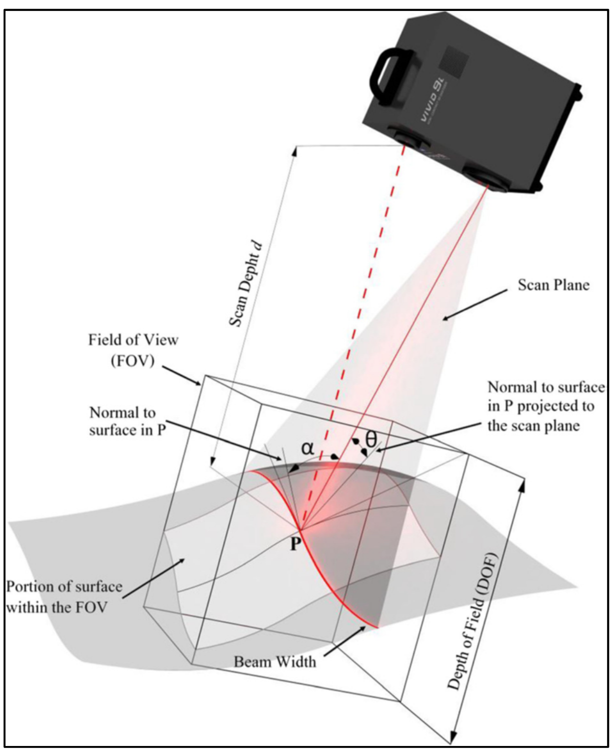


Figure 1.4 Some geometrical parameters of a laser stripe 3Dscanner
Taken from Gerbino et al. (2016, p. 1790)

1.3 Expressing Measurement Uncertainty

In this study, the Guide to the Expression of Uncertainty in Measurement, abbreviated as GUM, was referred to review terms and methods using in evaluation and expression of measurement uncertainty. GUM was published by the International Organization for Standardization (ISO) in 1993 and corrected and reprinted in 1995 (ISO, 1995). The concepts and 1 methods offered in the GUM are summarized in this chapter with a focus on 3D data acquisition. The used terminology and notation in the GUM are defined in the field of metrology (the science of measurement) which has its own terms, symbols, and approximation approaches besides using the statistical methods (Birch & ISSN, 2003). Figure 1.5 demonstrates the required steps for calculating the uncertainty documented by GUM.

1.3.1 Measurement, Error, and Uncertainty

The main aim of a measuring process is the estimation of a particular quantity subject to measurement which is called the measurand. The error in measurement is defined as the difference between the measured and actual value of the measurand. The repeated measurements may have different measured results and errors, while no change has been made in the measurand actual value.

Random or systematic effects in the measurement process could make a measurement error. Both of these effects are generally existent in a measurement process. Random effects can unsystematically make changes in the repeated measurement result. On the other hand, the changes in the measured value, caused by systematic effects, are created by a constant absolute or relative amount in a non-random way. The systematic and random errors are respectively the measurement errors created by systematic and random effects, also a systematic error might be called a bias. It should be considered that a random error in a specific measurement process may emerge as a systematic error in another, depend on measurement condition (Ellison & Williams, 2012).

Moreover, spurious errors are the other kind of possible errors could be created by human mistakes and instrument defects. Although the spurious errors are not a part of statistical uncertainty evaluation, it would be essential to reduce these type of errors by controlling the measurement conditions, through taking the advantages of quality assurance and quality control systems and employing accurate tools. The error is generally a theoretical term because determining the error needs knowing the true value of the measurand, while this quantity is not accessible in a usual measurement process.

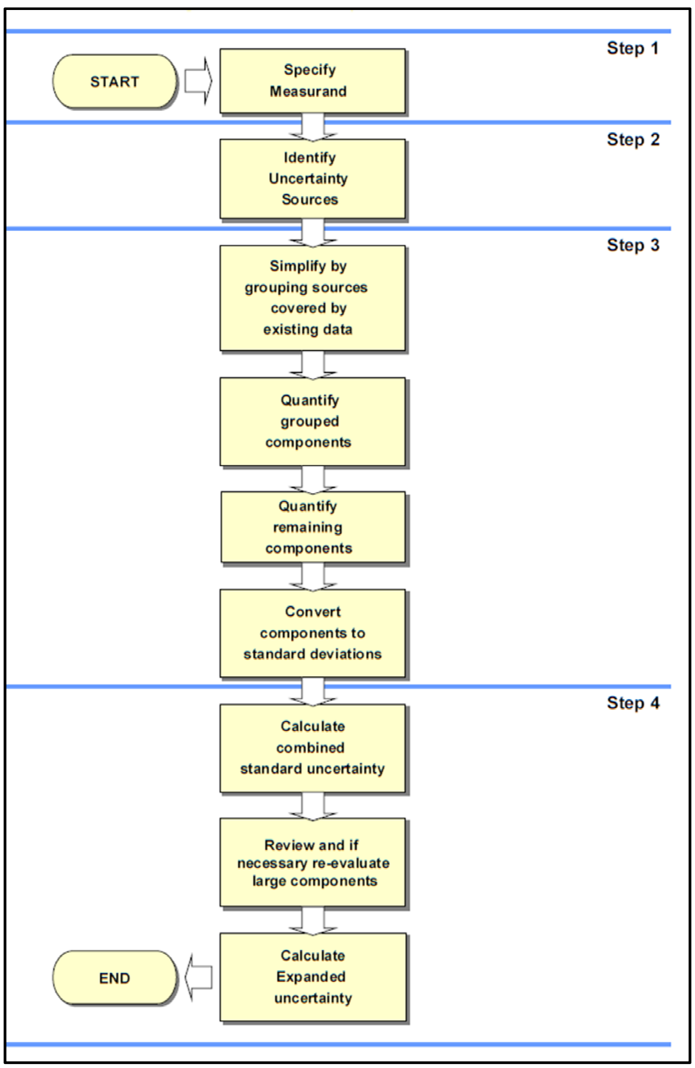


Figure 1.5 The uncertainty estimation process
Taken from Ellison & Williams (2012, p. 11)

However, the concept of uncertainty is practically useful. This concept, regarding the measurement results, indicates a factor which determines the dispersion of the values that may reasonably be assigned to the measurand. In other words, the measurement uncertainty designates a bound contains probable error values in the specific measurement. In fact, what every measurement report needs to be contained in is the uncertainty, whereas the error of measurement is presented occasionally.

1.3.2 The Measurement Process

A measurement process could be defined as an analytical method of specified structure in the state of statistical control, in a condition that the measurement bias and imprecision are static. Due to the importance of an accurate estimating the realistic uncertainties, the requirement of statistical control is a fundamental aspect of the measurement process.

Statistical control is used to indicate that the measurement is stable with a predictable distribution of results. It is also an essential part of the uncertainty estimation and process performance assessment, such as detection and quantification capabilities. Implementing proper quality control (QC) techniques could keep the measurement process in the state of statistical control. In addition to ensuring the stability of the process, statistical QC Techniques can be aimed to provide data for use in the assessment of process uncertainties.

In order to define a measurement process, firstly, the measurand needs to be defined as clear as necessary for the planned data purpose. Also in a highly accurate process, some ambient conditions should be specified.in practice, the measurand is mostly measured indirectly, in the way that the other input quantities, which have an identified mathematical relationship to the main measurand, are initially measured, and then the estimate of measurand could be calculated through using measured values in the function.

Hence, the mathematical model is the other essential part of the measurement process, using to express how the value of the output quantity (y) depends on the values of the measurable input quantities, x_1, x_2 …x_n. Often in practical measurements, a set of equations is needed to describe the current relationship. As it is mentioned, the estimated value of the measured, y, is calculated through the relationship $y = f(x_1, x_2 \dots x_3)$, where xi measured value for each input quantity, thus due to the existence of uncertainty in each input measurement (x_i), estimation of the output (y) also contains an uncertainty. A comprehensive estimation for the uncertainty of y needs a model including all input quantities which may have a considerable effect on y.

1.3.3 Analysis of Measurement Uncertainty

In order to obtain the uncertainty of the output estimate, it would be necessary to determine the input uncertainties and represent them in the comparable forms. In order to represent the uncertainty of input estimate x_i, two following forms usually are used:

- Standard uncertainty (one-sigma uncertainty) which is estimated standard deviation form and denoted by $u(x_i)$.
- Estimated variance which is the square of the standard uncertainty and denoted by $u^2(x_i)$.

The relative standard uncertainty of xi, denoted by $u_r(x_i)$, is defined to indicate the ratio $u(x_i)/|x_i|$. In the condition that there is a possible correlation among input estimates, determining covariance estimates $u(x_i, x_j)$ is necessary. The role of covariance $u(x_i, x_j)$ is usually shown in the form of an estimated correlation coefficient, $r(x_i, x_j)$, defined as the proportion $u(x_i, x_j)/u(x_i)u(x_j)$.

The combination of standard uncertainties and estimated covariance forms the combined standard uncertainty of y, which is denoted by $u_c(y)$. The combined variance is defined as the square of the combined standard uncertainty, denoted by $u_c{}^2(y)$. The mathematical operation to reach the combined standard uncertainty of the output estimate, y, is defined as uncertainty propagation.

In the frequent repetition of measurement, random measurement errors mainly generate the standard deviation; however systematic errors remain constant during repeated measurement. On the other hand, the combined standard uncertainty of a result is designated to cover the effect of both random and systematic errors; consequently, it is reasonable that the combined standard uncertainty is relatively larger than the standard deviation which is identified in repeated measurements.

There are two common approaches in order to estimate the standard uncertainties u(xi) which are named as type A and type B. The base of type A, as a statistical method to evaluate standard uncertainties, is repeated observations. In an ordinary way for using this type of evaluation, a series of independent measurements of a quantity, x_i, is generated and arithmetic mean as well as the experimental standard deviation of the mean is calculated. The obtained arithmetic mean and experimental standard deviation of the mean are respectively employed as the input estimate, x_i, and the standard uncertainty, $u(x_i)$. Type A could be applied in other ways, even though the common feature in all approaches is repeated measurements. The other methods for evaluation of standard uncertainty, which could not be considered as a Type A evaluation, are called Type B. In some approaches of type B, guessing based on all accessible information and professional judgment is considered as a part of the evaluation procedure. Although this type of evaluation could not be an ideal, having an informed conjecture about an uncertainty factor would be better than absolutely neglecting it. Depend on the used evaluation approach u(xi) may be named type A or type B. standard uncertainty, even though both of them are observed the same in uncertainty propagation purposes.

1.3.4 Corrections for Systematic Effects

In the case of measurement which a systematic effect is recognized and quantified, it is necessary that the mathematical model contains a quantity, which is called a correction (additive) or correction factor (multiplicative), to modify this effect. This quantity brings its uncertainty, so evaluating and propagating process for this uncertainty would be necessary. On every occasion of detecting a new systematic effect in the measurement process, firstly, the effect must be recognized, and then it needs to be mathematically corrected or a procedurally removed.

1.4 Identifying Sources of Uncertainty

The first step in the uncertainty evaluation procedure is to make a complete list of potential uncertainty sources in the process of measurement. In practice, usually, there are still more new quantities to add to a designed mathematical model after a precise revising. Although the influence of some sources of uncertainty is more considerable than others, all sources need to be recorded in the list. A quantitative evaluation is necessary for each possible uncertainty which may have a considerable effect (Ellison & Williams, 2012).

There are some sources of uncertainty that must be considered always, even though they may not have a significant role, such as instrument calibration, laboratory subsampling, interferences, atmospheric condition, and approximation errors in simplified mathematical models. Although expending a great effort on the assessment of low-impact sources of uncertainty are not recommended when much more effective sources are identified to dominate the combined standard uncertainty of the measurement. However, a small component of uncertainty which could be ignored in one process may play a key role in another (e.g. quality control of measuring instruments). Moreover, the combination of a large number of small uncertainties may significantly affect on uncertainty of the process.

1.5 Digitizing Errors in a Laser Scanning Process

Laser scanners are classified as electro-optical measurement tools. The scanner's CCD sensor captures the laser image. Using this image and following the optical triangulation principle, the 2D coordinates of captured points are obtained in the scanning plane. Regarding this function of laser scanners, the quality of measurement could be affected by the scanning factors which have a potential influence on the CCD photodetector outcome including focused area, intensity, etc. The function of a laser photodetector which works based on triangulation principle is depicted in Figure 1.6 (Pathak & Singh, 2017; Smith & Zheng, 1998).

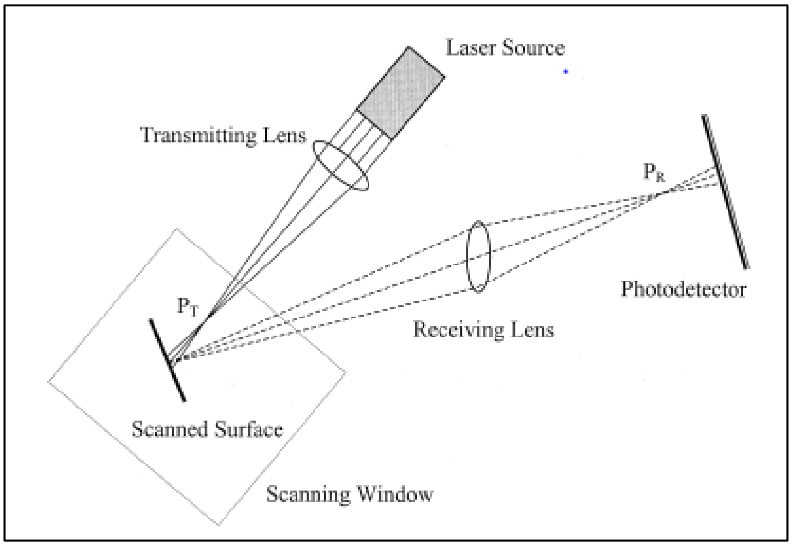


Figure 1.6 The triangulation-based function of a laser scanner
Taken from Feng et al. (2001, p. 187)

The laser source emits the laser beams, and concentrates them at a specific point PT. This point is normally located on the scanning window of the laser range sensor. The beams are reflected from the object surface and a lens is applied to focus the reflected laser beams to create the laser image on the sensor. Any variation of the scanned object position within scanning window could change the zone of illuminated spot as well as the intensity of the laser. In addition, the variation of relative distance between the object and lens could shift the focus point of reflected beams through receiving lens (PR). Combination of the two mentioned factors together is the source of variations in the intensity and the detected laser image area. The other effective factor on the intensity and the zone of CCD laser Image is the orientation of the object surface against the incident laser beams. In other words, the quality of scanning process is under influence of the position of object surface in the scanning window (Feng, Liu, & Xi, 2001; Pathak & Singh, 2017). The other important scanning factor is the scan depth which has a direct relationship with the object surface position. The incident angle within the scanning plane and the projected angle out of this plane indicate the relative orientation of the object's surface and the incident laser beams. (Figure 1.7).

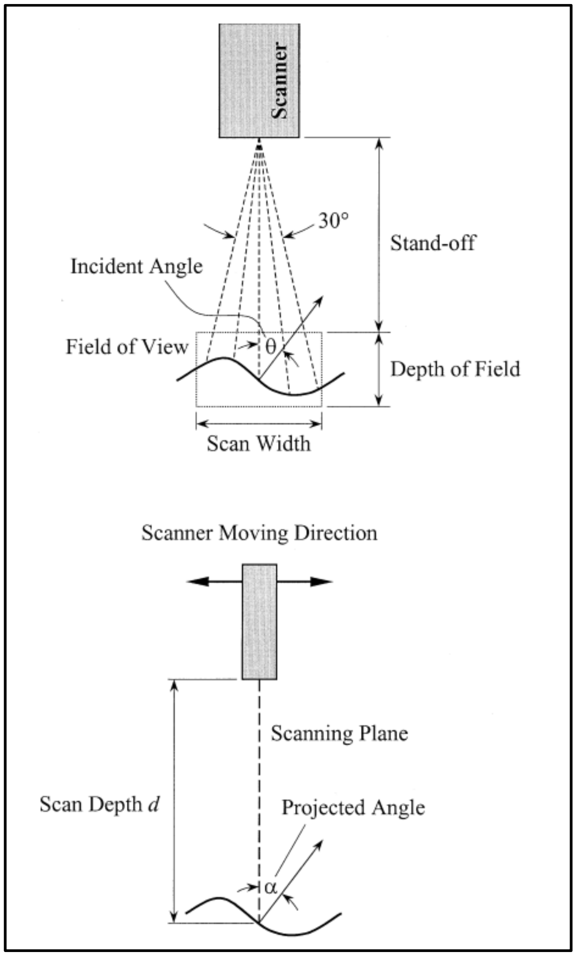


Figure 1.7 Scan depth, projected angle, and incident angle as scanning factors Taken from Feng et al. (2001, p. 187)

Every captured point, during the scanning process over a surface, is acquired based on a specific set of scanning parameters related to the geometry of the object surface including incident angle, projected angle, and scan depth. The producers of laser scanners have provided some standard calibration procedures to diminish the influence of the scanning incident angle on the quality of inspection. However, the role of the projected angle and the scan depth which could be significant are mostly neglected in these procedures.

There is a combination of digitizing error types for the acquired data during scanning process, including random error and systematic error. Hence, the experimental analyze is necessary to investigate and minimize them.

1.5.1 Random Error

There are several factors could be considered as the sources for random error in the captured data in the laser scanning. Hence, taking them under control will be a tough task. One of the important factors recognized as the source of random error in triangulation laser scanners is the speckle noise due to the concentrating of light waves on the photodetector (Baribeau & Rioux, 1991). The summation of light waves usually causes random phasors which may strengthen or weaken each other and some bright or dark speckles could be created because of this interaction effect. This mentioned function, which is occurred randomly, is the uncertainty source to accurate detect of the laser image centroid coordinates in photodetector, consequently, this uncertainty affects the digitized coordinates calculations. The other source for the random errors in the measured data obtained by laser scanners is the repeatability of the translation system of CMM, even though it usually has a low effect (Feng et al., 2001).

1.5.2 Systematic Error

As systematic error is a repeatable sort of the digitizing error, its rate remains constant during the all laser scanning process with the same conditions. In the case that involved random error is small, a mathematical method could be applied to calculate a relatively accurate value as a prediction of the systematic error. This approach can provide the capability of promoting the measurement accuracy.

The misinterpretation of laser images created on the CCD sensor, which is a repeatable defect, is the cause of the systematic error. Therefore, the scanning factors, including scan depth, incident angle, and projected angle, are recognized to be the main sources of the systematic error, due to their significant role on creating the laser image. However, the manufacturer of laser scanners usually reduces the role of the incident angle down to a minimum level, optimizing the system setup. Some experimental procedures have evaluated the effect of the scan depth and the projected angle on the systematic error.

1.6 Uncertainty Sources in Laser Scanners

Although the vision-based system of 3D scanners is significantly developed, many factors may still impact on their measurement accuracy. These factors are in connection with either internal elements of the scanning systems, such as scanner resolution and accuracy, or external conditions, including chosen scanning parameters, ambient lighting, features of the part surface (such as surface texture, color, glossiness, roughness, shape), and the orientation of the sensor in relation to object surface. Figure 1.8 depicts some scanning factors classified in four categories.

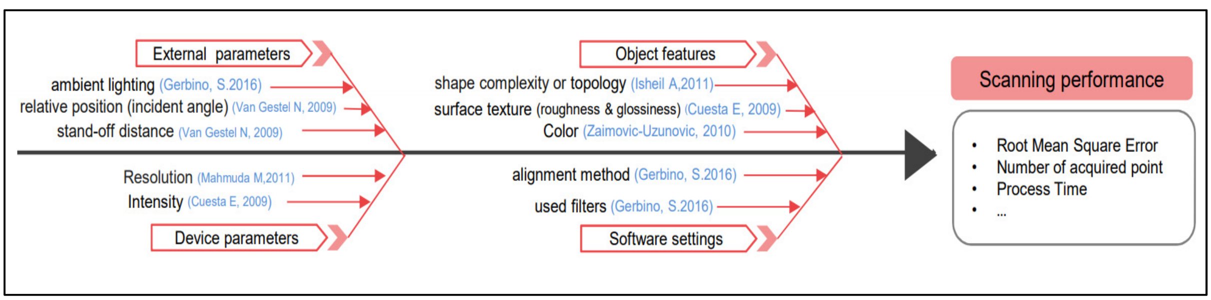


Figure 1.8 Cause and effect diagram: effect of various parameters on scanning result

In order to improve the quality of 3D inspection in industrial processes, the scanning factors have been considered and some guideline was provided for users to help them to set effective parameters properly.

1.6.1 Scanning Factors

As mentioned before, there are several factors which have a possible effect on scanning performance, such as the ambient light [lx], the intensity of laser [W/cm2], the complexity of the part shape (object topology), the part material (e.g. surface texture, color, glossiness) and some internal settings of the scanning device. In multi-scans capturing which the alignment of data sets is important as well as the whole alignment to the reference model, the processing accuracy of used software tools and algorithms may influence measurement results (Martínez, Cuesta, Barreiro, & Álvarez, 2010).

The relative location of the object to the scanner represented by the scan depth (d) is recommended to set as the minimum available distance to achieve higher accuracy. The reason is that, according to the principle of triangulation, setting a higher distance reduces the triangulation angle and consequently increases the measurement noise (Van Gestel, Cuypers, Bleys, & Kruth, 2009).

Two most effective parameters in the scanning process are the incident angle θ and the projected angle α which are respectively measured in the laser plane and out of that (Feng et al., 2001). These angles determine the orientations of the object surface with respect to the incident laser beams. The intensity of the reflected laser beam which effects on CCD sensor performance is dependent on the value of these angles, in the way that there is less measurement uncertainty in the smaller incident angle, when other factors are kept constant (Mahmud, Joannic, Roy, Isheil, & Fontaine, 2011). In addition, the standard deviation of measurement is influenced by both projected angles and incident angle, due to the concentration of measurement noise in the depth direction of the scanner (Van Gestel et al., 2009). According to some experimental research, the recommended angles θ and α are $-35° \leq \theta \leq +35°$ and $-15° \leq \alpha \leq +15°$, and in order to set an optimum orientation of surface in relation to the sensor, an algorithm was suggested regarding these angles, based on CAD model of part as a reference (Isheil, Gonnet, Joannic, & Fontaine, 2011).

Choosing a proper relative positioning of the scanner-to-object can to some extent reduce the positioning error. The normal position sensor-to-surface is commonly the best choice (Vukašinović, Možina, & Duhovnik, 2012). Base on Van Gestel et al. research, the systematic and random errors of the laser line scanner on CMM are significantly influenced by the scan depth d (Scott et al., 2003). Some research showed that the systematic error could also be modified by controlling incident and projected angles in laser scanners (Isheil et al., 2011).

In addition, the random error, as an uncertainty source in laser scanning is in connection with the speckle effect which is related to surface's roughness (Dorsch, Häusler, & Herrmann, 1994). Regarding this effect, because of surface roughness some potential changes are made on the reflected beam and on CCD sensor, it means that there is a probability of elimination or reinforcement for the wave amplitude of the captured signal in the scanning process.

This error, which is related to reflected signals, can make a problem for detecting the correct center point on CCD and consequently reduce the accuracy of 3D measurement of the digitized point. In the scanning process which the laser wavelength is close to the roughness in one of the objects surfaces ($\approx$1/10 μm) the probability of this error is more.

CHAPTER 2

PROBLEMS AND OBJECTIVES OF THE STUDY

Nowadays, using laser scanners has become increasingly more popular because of their advantages compared to touch-trigger probes on CMMs. However, there are several effective factors which can affect the accuracy of laser scanning process. On the one hand, the key benefits of laser scanning systems, compared to current tactile probes, are the ability to acquire several points in a considerable short time in a contactless approach. These capabilities enable them to be extremely beneficial for measuring free form surfaces.

On the other hand, the quality of digitization in laser scanning could be affected by some object characteristic such as the surface glossiness. Then, this study considers on the probable effective factors which can impact the laser scanner performance.

2.1 Problems

In current laser scanners, the limited accuracy and the significant influence of surface quality on the scanning performance are the major challenges. Measuring reflective parts, such as machined steel, could be very problematic, because in this inspection approach diffuse reflection has a key role on the camera function to capture the projected laser beam. In order to tackle this challenge, the most recent scanners are enhanced, even though the accuracy of acquired data in case of reflective surfaces will still be in a lower level. Thus, in order to improve the scanning quality in shiny metal surfaces, the objects are usually coated by some specific powders which are sprayed on the glossy surface before the measurement. In some cases, this method makes a considerable difficulty and in addition the surface translucency could have a negative impact on the quality of measurement.

Moreover, there are some other considerable factors in the laser scanning process which could have negative influence on its results. For instance, ambient lighting, as an important external factor, can affect the performance of measurement. The object topology is also a main factor. Existing of complex surfaces forms with different slopes, corners, edges, pockets, and holes could be some restrictions for measuring by a laser scanner. Finally, in order to improving the quality of point clouds, obtained from laser line scanners, a powerful software is required. Choosing an appropriate filtering and fitting methods play a key role in the quality of the inspection process.

It is undeniable that existing laser scanners are less reliable than common tactile probes by at least one order of magnitude. Due to fundamental differences between the two measurement approaches, standard guidelines for assessing touch-trigger probes are not reasonable for laser scanners. In fact, laser scanners function is based on optical contactless probes, whereas tactile probes use mechanical touch probes and tactile sensors. Therefore, it would be hard to determine the reliability and accuracy of laser scanning process. Regarding the growing use of laser scanners, providing a reliable technique to evaluate and optimize the accuracy of the scanning process has become more essential.

2.2 Objectives

The present work attempts to analyze and characterize the digitizing errors of a commercial laser scanner. The objective is to identify the primary scanning process parameters that contribute to the digitizing errors and to establish an empirical relationship to accurately predict the digitizing errors for typical laser scanning operations.

This experiment was designed to evaluate the effects of some scanning factors and ambient conditions on accuracy of the scanning measurement on glossy surfaces. Influence of ambient lighting, geometric features, and some filtering and fitting software options are considered in this study. It is aimed to identify the role of these parameters on acquisition and digitization process. The final goal is to find the optimum inspection conditions and parameters using laser scanners. The main objectives of this research are presented as follows:

- Identifying some factors which have the greatest impact on scanning reflective objects
- Checking The role of coating reflective surfaces with anti-reflection powder, on the laser scanning quality
- Evaluating the influence of ambient lighting on the accuracy of the scan
- Assessing The role of software options, such as fitting, filtering and meshing options on measurement
- Comparing the accuracy of captured point clouds obtained from different forms of object surface such as a cylinder, hole, slopes flat plane, and non-uniform surfaces.

CHAPTER 3

METHODOLOGY AND EXPERIMENTAL SETUP

Regarding the scanning problems explained in previous chapter and based on defined objectives for this study, the experiment plan was designed. The methodology and material of this study as well as a brief description of used equipment is presented in this chapter.

3.1 Methodology

In this research the scanning accuracy of Metris LC50 is evaluated in comparison with point cloud acquired by touch-trigger probes on Mitutoyo CMM at the ETS Metrology Laboratory. The obtained point clouds (by laser scanner and contact probe) were modeled and analyzed through Polyworks® software.

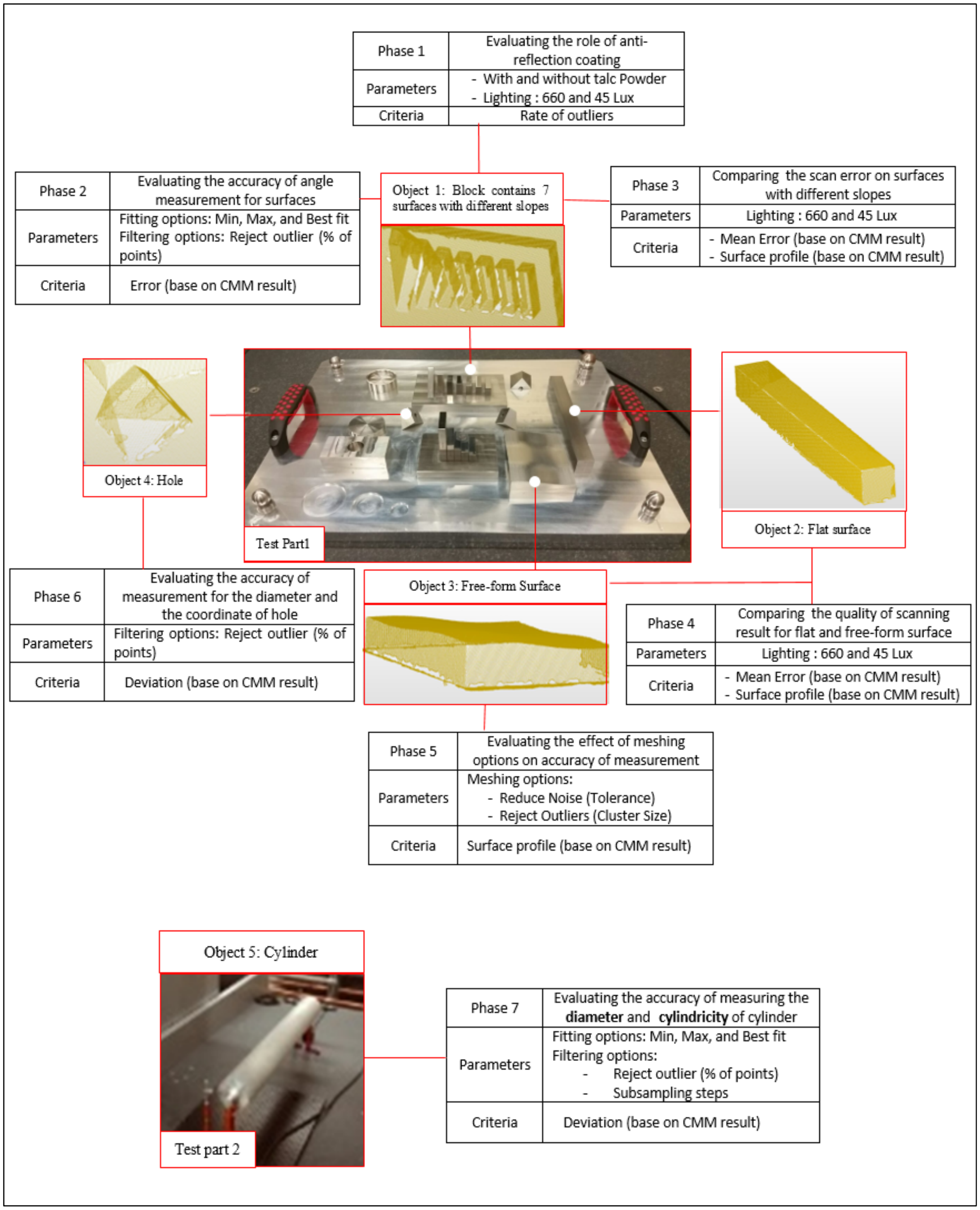
Among various factors which potentially effect on scanning quality, this experiment is focused on influence of **ambient lighting**, **software fitting algorithm** and **filtering options** as well as the object's **surface shape and angle**. For this purpose, scanning process was designed for a multi-shape sample and different lighting conditions. Moreover, different set of software options were applied for point clouds treatment. Scanning process is performed in two different lighting conditions and illuminance was measured each time with a lux meter (45 lux and 660 lux).

The Polyworks® software suggests three (3) fitting methods including maximum, minimum and best fit (Gaussian fit). Some steps of this experiment were designed to compare the measurement obtained from these three fitting methods to find a guideline for applying appropriate one in each possible case. In addition, applying several sets of value for filtering and meshing options were considered to evaluate the effect of this option.

In order to performance evaluation of scanning process, the deviations (d_i), mean error ($\bar{\varepsilon}$), Root Mean Square Error (RMSE), and surface profile was calculated and used as comparison criteria between different digitized model.

The datum in each measurement was assumed to be the obtained reference plane, created based on point clouds which captured by the contact probe on CMM. Surface profile is equal to twice the absolute value of the maximum error.

According to main objectives of the research, the experiment was designed in several steps. Following the experimental plan, scanning process in each step was done on the designed object in the specified condition. Finally, the obtained point cloud in each phase was used for measurement under applying different software options to find the most accurate settings. Figure 3.1 illustrates the defined scanning factors for each phase.



Phase 1	Evaluating the role of anti-reflection coating
Parameters	- With and without talc Powder - Lighting : 660 and 45 Lux
Criteria	Rate of outliers

Phase 2	Evaluating the accuracy of angle measurement for surfaces
Parameters	Fitting options: Min, Max, and Best fit Filtering options: Reject outlier (% of points)
Criteria	Error (base on CMM result)

Phase 3	Comparing the scan error on surfaces with different slopes
Parameters	Lighting : 660 and 45 Lux
Criteria	- Mean Error (base on CMM result) - Surface profile (base on CMM result)

Phase 6	Evaluating the accuracy of measurement for the diameter and the coordinate of hole
Parameters	Filtering options: Reject outlier (% of points)
Criteria	Deviation (base on CMM result)

Phase 4	Comparing the quality of scanning result for flat and free-form surface
Parameters	Lighting : 660 and 45 Lux
Criteria	- Mean Error (base on CMM result) - Surface profile (base on CMM result)

Phase 5	Evaluating the effect of meshing options on accuracy of measurement
Parameters	Meshing options: - Reduce Noise (Tolerance) - Reject Outliers (Cluster Size)
Criteria	Surface profile (base on CMM result)

Phase 7	Evaluating the accuracy of measuring the **diameter** and **cylindricity** of cylinder
Parameters	Fitting options: Min, Max, and Best fit Filtering options: - Reject outlier (% of points) - Subsampling steps
Criteria	Deviation (base on CMM result)

Figure 3.1 The selected test parts and designed experiment phases

Also, Figure 3.2 depicts a general view of the experiment carried out, and contains references to the performed assessment based on outcomes obtained from two measuring systems. This figure provides the reference for next presented details.

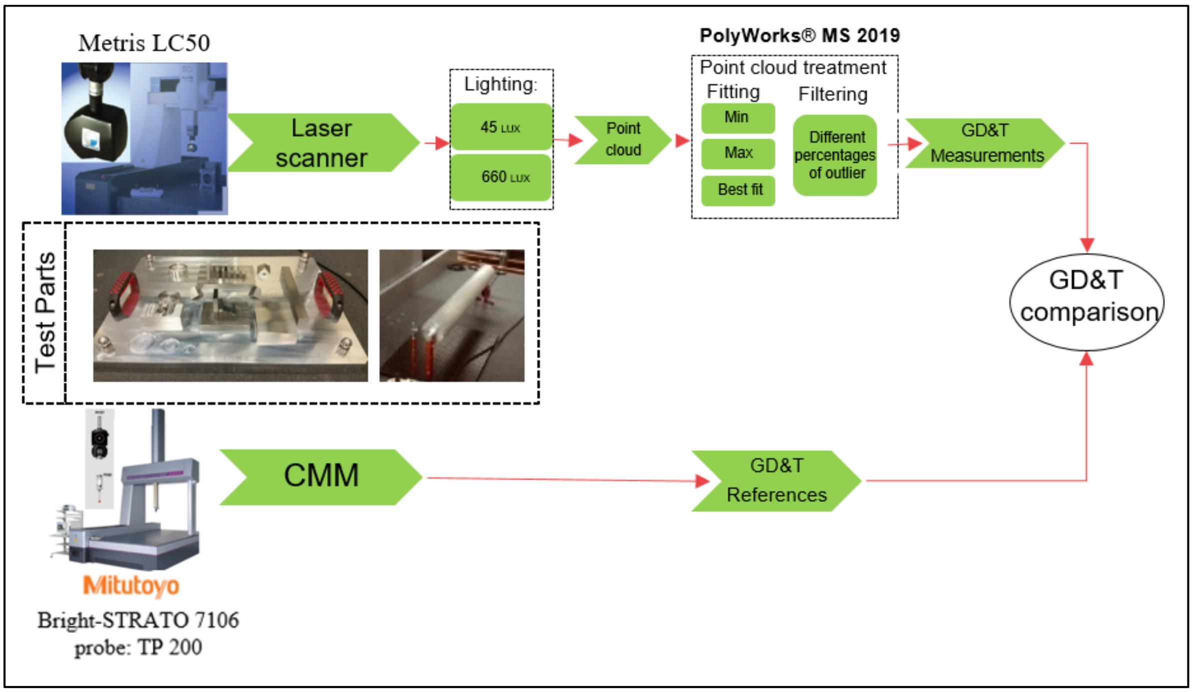


Figure 3.2 Experimentation Methodology

3.2 Select the test parts

In order to carry out the experiments, two test parts were designed. As this study is aimed on evaluation of scanners ability for industrial inspection context, these artefacts were dimensionally characterized and produced to provide appropriate geometric characteristics.

Using objects with various dimensional feature could help us to identify the errors of the laser scanner in comparison to the contact system. Test parts are manufactured with glossy metal surfaces to analyze the effect of ambient light, part geometry, and software options on scanning accuracy of reflective parts. The roughness (Ra) is around 0.01um for gage blocks and 0.3 um for machined surfaces.

The first artefact was designed as a complex object with various canonical surfaces such as the cylinder, pocket, hole, and free-form surface as well as horizontal, vertical and sloped planes. The dimension of this part is $508\ mm \times 381\ mm \times 70\ mm$. Four (4) reference spheres were located in its four corners to use for an accurate alignment. The second test pat is a cylinder with a diameter of $\emptyset 100\ mm$. Figure 3.3 shows the drawing plan of the complex object used in this work.

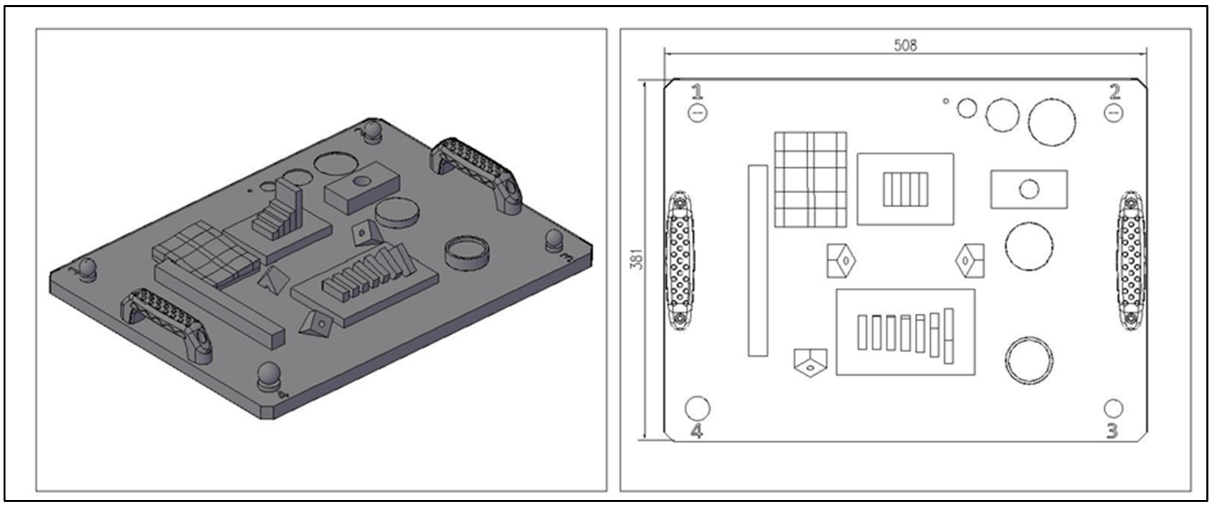


Figure 3.3 The drawing plan of the designed complex object

3.3 Obtain the data points

3.3.1 Touch probe and CMM as the contact system

As mentioned before, the reference value for the measurements in this experiment was designed to be obtained by a contact system. The existing Mitutoyo C.M.M. at the ETS Metrology laboratory, which is a high accuracy measuring device in the 1µm class, was applied to this aim. Also a probe with 4 mm diameter (TP200) was selected for the measuring process. Table 3.1 and Table 3.2 give some information about the CMM and the used probe, respectively.

Table 3.1 Some technical specifications of Mitutoyo CMM

Item	Bright-STRATO 7106	
Measuring range	X	27.76“ (705 mm)
	Y	39.57“ (1005 mm)
	Z	23.82“ (605 mm)
Resolution		.000004“ (0.0001 mm)
Maximum drive speed		16.93“/s (430 mm/s)
Maximum drive acceleration		0.17 g
Work table	Material	Granite
	Size (table surface)	33.07“x63.78“ (840x1620mm)
Work piece	Maximum height	29.13“ (740 mm)
	Maximum mass	1,764 lbs. (800 kg)
Machine mass (including the stand and controller)		3,605 lbs. (1635 kg)
Air supply	Pressure	0.4 MPa
	Consumption	50 L/min typical (100 L/min max)

Table 3.2 Some technical specifications of used touch probe

Main unit accuracy ISO 10360-2 (2001), 10360-4 (2003)		Unit (µm)
Probe used	Maximum permissible displacement error (MPEE)	Maximum permissible probing error (MPEP)
TP200 (Stylus: Ø4×10 mm)	1.4+3L/1000 (4.8+5L/1000)*	1.8

*Z=59.25”(1505mm) models

3.3.2 Laser scanner in this experiment

The laser scanner designated to be evaluated its performance in this study is the Metris LC50. This scanner provides a high speed, contactless, and fairly accurate approach for industrial inspections which is appropriate for a various kinds of Coordinate Measuring Machines. The LC50 laser scanner is enabled to capture around 19200 points per second. Although its accuracy (15 µm) is less than conventional touch-trigger probes, it is still acceptable for a wide range industrial aims. All scanning process was done at the ETS Metrology laboratory. Some of the technical specifications of the Metis LC50 was presented in the Table 3.3.

In this experiment, the head's angles during scanning process for each step are (0, 0), (30, 90), (45, 0) and (45, 180). The density is also 0.1 mm for points distance and 0.2 mm for the strip distance.

Table 3.3 Some technical specifications of Metris LC50 laser scanner

Specification	
Width of field of view	50 mm
Depth of field of view	Minimum 65 mm
Accuracy *	15µm (1σ sphere fit)
Stand-off **	Approximately 100 mm
Points output	up to 19,200 points/sec
Laser	Class 2 or 3R (Visible Red)
Overall dimensions of the head	110x70x105 (without tube and autojoint)
	110x70x150 (with tubes and autojoint)
Weight	315g

*Accuracy according to Metris procedures
** Distance between sensor head and start of FOV

3.4 Process the Data points

3.4.1 Software

Polyworks® is known as one of the most popular software in data processing of laser scanning point cloud. This integrated software is developed by Canada Norma software Co. As its key advantage, Polyworks® has the ability to process point cloud data acquired by different types of 3D scanning device or tactile probes on three coordinates CMMs, in a fast and accurate process. This software has presented in two main functions software packages including Polyworks® Modeler and Inspector. Polyworks® Modeler is specified to point cloud modeling, and Polyworks® Inspector is suggested for point cloud processing and measurement. Polyworks® provides strong tools to merge, combine, section cut, and analyze a huge amount of data. Then this powerful point cloud processing software can significantly improve data inspection using its delivered comparison ability (Mangan, Whitaker, & Graphics, 1999; "PolyWorks|Inspector Reference Guide ", 2019; Xiao & Li, 2014).

Polyworks® also offers several options to choose appropriate method for point cloud processing such as fitting, filtering and meshing options. This study has tried to test different values for these options and provide a comparison between the outcomes to conclude which approach could be more accurate.

3.4.2 The Polyworks®-Inspector surface inspection methodology

The methodology of surface inspection through Polyworks®-Inspector is presented in Figure 3.4. the inspection is based on the calculated deviation of captured data points from reference model.

Alignment as a first step of data processing plays a key role in validity of next steps. Polyworks® offers several methods to align the point clouds along the reference surface. After an appropriate alignment, when the points are located in a right position, various techniques, such as oriented distances, shortest point-to-surface distance, and point-to-boundary distance, could be applied to measure the deviation of obtained points from reference. In the case of measuring a tolerance-based deviation, there is this possibility to assign global tolerances for objects and detailed tolerances for CAD model ("PolyWorks|Inspector Reference Guide ", 2019).

Polyworks® also provides different methods of measurement including the comparison point in a local measurement and cross-section approach.

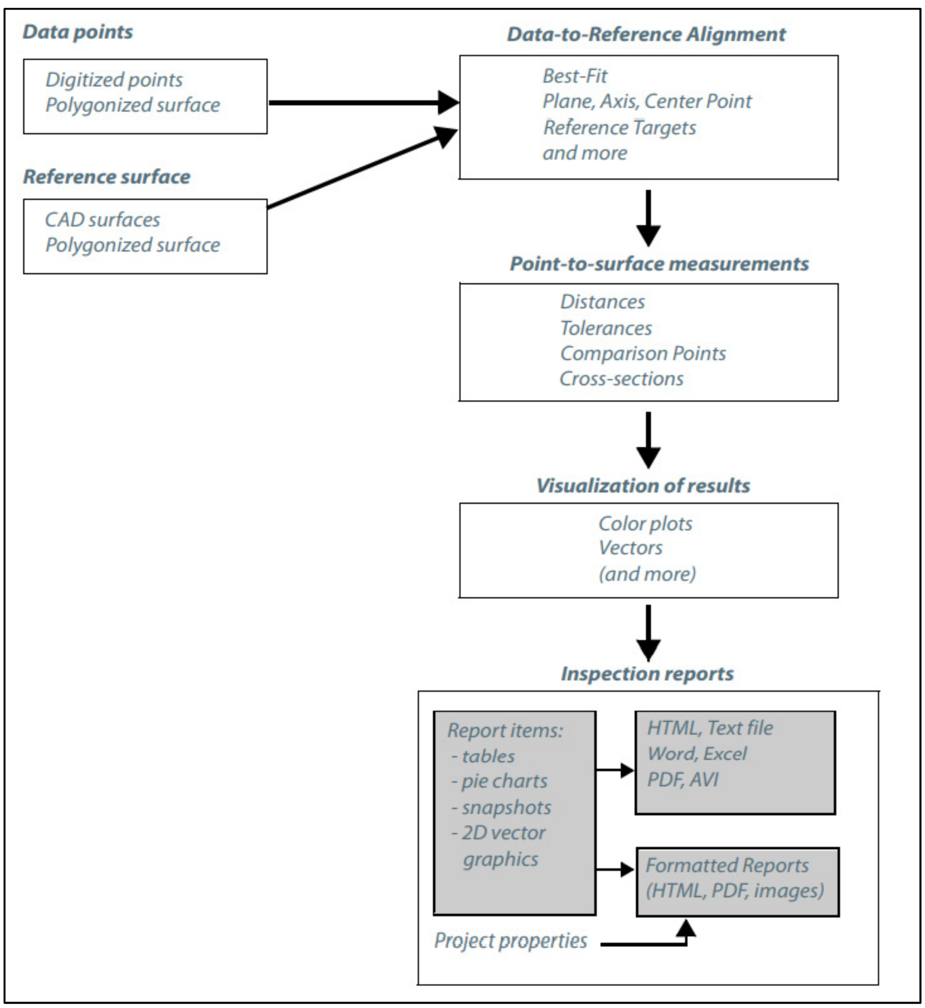


Figure 3.4 The Polyworks® surface inspection methodology
Taken from PolyWorks|Inspector Reference Guide (2019)

3.4.3 Software Alignment Techniques

The proposed approaches to align data points with respect to reference model is presented as follows ("PolyWorks|Inspector Reference Guide ", 2019):

- **Best-fit point-to-surface alignment**

This technique has this ability to automatically recognize the areas which have a high level of deviation and use this information to perform alignment with a higher accuracy. Through this method of alignment, it is possible to only optimize certain degrees of freedom. This type of alignment uses the best-fit method to match acquired points to the reference surface. The high-discrepancy areas are automatically recognized to achieve an alignment with more accuracy.

- **Manual Alignment**

This alignment method makes available to accurately translate and rotate the models manually.

- **Point Pairs Alignment**

During this method of alignment, a pair of points or several pairs of selected points between the acquired points and reference surface are matched.

- **Plane, Axis, Center Point**

In order to perform alignment in this method, reference features such as planar feature, axial feature, or center-point-based feature are matched to corresponding feature on the destination.

- **Perpendicular Planes**

A method that three perpendicular planes of measured surface are matched to three perpendicular destination planes.

- **Reference Targets Alignment**

This method of alignment, same as Reference Point System (RPS), works based on reference targets. It matches acquired points to reference target points or lines, which are specified by user. It is also possible to limit the displacement of the data objects with configuring he reference targets.

3.4.4 Fitting Method in Polyworks®

In order to processing captured point cloud and create feature based on them, three types of fitting method were proposed by Polyworks®, including maximum, minimum and best fit. In case of best fit method, the software uses the average of the captured data points to create the features. In minimum fitting approach, the features are modeled based on the obtained points with biggest negative deviation and the maximum fitting consider only the captured data which have the biggest positive deviation. Figure 3.5 illustrates the planes generated based on these three fitting methods while all approaches use the same point cloud ("PolyWorks|Inspector Reference Guide ", 2019; Xiao & Li, 2014).

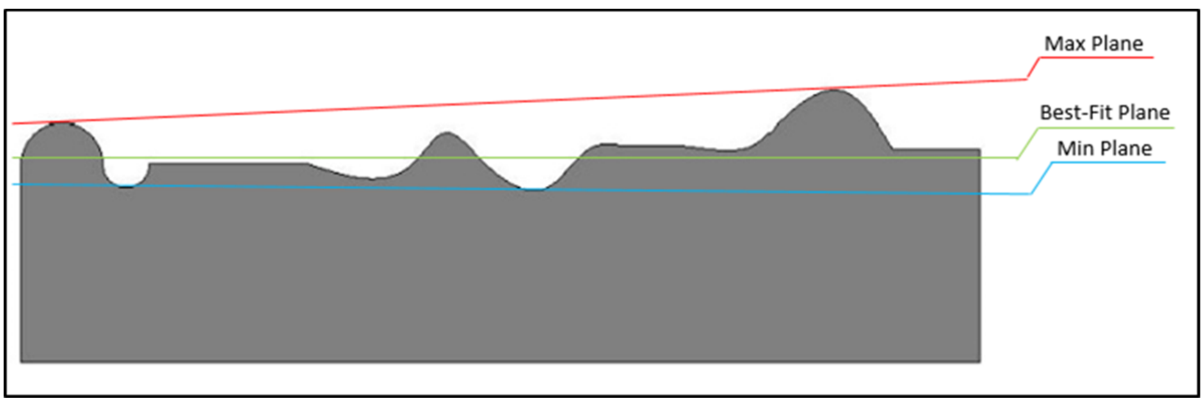


Figure 3.5 The planes generated based on three fitting methods of Polyworks®

3.4.5 Filtering Options in Polyworks®

Polyworks® provides the following filtering options to develop processing data when a feature should be created based on captured point cloud:

- **Subsampling Step**

This option makes available subsampling process for original data points to create more accurate feature. In order to use this option, a value greater than 0 mm should be determined as the subsampling step (software default is 1 mm). Using subsampling method, the software can filter the point cloud to produce a data point with uniform space, in the way that the space between each two points will be as close to the specified step value as possible.

- **Max Angle**

This option gives software this ability to omit the unrelated points. The removed points are captured from surface areas other than the desired feature area. The specified angle for this method, illustrates a maximum acceptable angle between a normal vector of acquired points and the normal vector of features at the feature point closest to the acquired points. This value can be selected between 0° and 180°.

- **Reject Outliers**

This option enables software to reject specific proportion of points as outliers. The data points located in a relatively far distance from the average of acquired points are recognized as outliers. Two following approaches is offered by PolyWorks® to determine the outlier rejection strategy:

- **Standard Deviation Factor:**

In this approach, the standard deviation of the points could be applied to recognize outliers, through selecting a value greater than zero as standard deviation factor. At the first step of this method, the acquired points are used to fit the feature and software calculates the standard deviation value. Then, PolyWorks® rejects points located outside of the standard deviation which is multiplied by the selected factor value. Finally, the fitting process is repeated over the data points remained after outlier rejection.

- **Percentage of Points**

During this approach, a specific percentage (between 0% to 100%) of points is determined to be rejected as outliers. The software firstly fits the feature over all captured points and calculates the average deviation between the points and the created feature. in the next step, it rejects the selected percentage of points, in the way that the rejected points are located furthest from the average distance. Finally, the software fits the feature over the rest of data points.

3.5 Mathematical Basis

In each step of this study, the deviation, indicated with di, is calculated as the shortest distance between $i-th$ data point captured by laser scanner and the reference surface modeled by result of tactile-probe measurement. Then, the root-mean-square deviation (RMSD) or root-mean-square error (RMSE) was used to determine the accuracy of measurements. RMSE over n data points is obtained using equation 3.1 (Barnston & Forecasting, 1992).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2} \qquad 3.1$$

According to this equation, the calculated RMSD value is proportional to the squared value of each error. Hence, it is a sensitive criterion to outliers, in other words, the outliers with a larger error can significantly impact on RMSD.

The other parameter which are calculated by Polyworks® software is surface profile. This parameter suggests a tolerance zone around a reference surface, considering the captured point with maximum distance from reference. In current study, the surface profile is considered as a criterion to compare the accuracy of obtained data point. Equation 3.2 presents mathematical definition of surface profile.

$$Surface\ Profile = 2\ Max|d_i| \qquad 3.2$$

3.5.1 Circle Fitting Calculations

As one of the designated objectives in this research, the accuracy of scanned points over circular shapes (the cylinder and hole) is taken into consideration. In order to achieve this aim, the deviation between acquired data points and actual value needs to be calculated.

To fit circles over captured data points, various fitting strategies are offered. The software algorithm in each fitting method determines the best fit circle correspond to the scanned points, through a set of calculation. The obtained circle should have the closest approximation to the point cloud. In fact, a fitting method applies a mathematical algorithm to optimize a specific parameter, respecting some specific limitations for degrees of freedom. In case of circles, the diameter and center coordinate are considered as the “floating” variables (Janeshewski, n.d.). It means that the value of these parameters are firstly adjusted, then the specific criteria is used to optimize the deviations. The priority of these fitting methods depends on the rate of calculated deviations. In each method, the deviation for $i-th$ data point could be calculated by equation 3.3.

$$d_i = \frac{D}{2} - \sqrt{(X_i - X_O)^2 + (Y_i - Y_O)^2} \qquad 3.3$$

Where D represents the diameter of determined circle, X_O and Y_O indicate the coordinate of the circle center, and X_i and Y_i are the coordinates of the $i-th$ data point.
The Average Absolute Deviation (AAD) of a set including n data points is obtained from equation 3.4.

$$\text{AAD} = \frac{1}{n}\sum|d_i| \qquad 3.4$$

- **Least Squares Circle**

In most software, the Least Square's algorithm is recommended as the software default. This algorithm firstly determines the average circle that is located in the middle space of the acquired points. A circle determined through this algorithm is depicted in Figure 3.6. The result of this algorithm is stable and outliers have less effect on that in comparison with two other methods. In the Least Squares method, the only criterion for optimization is that the sum of the squared deviations ($\sum d_i^2$) be minimized (Janeshewski, n.d.).

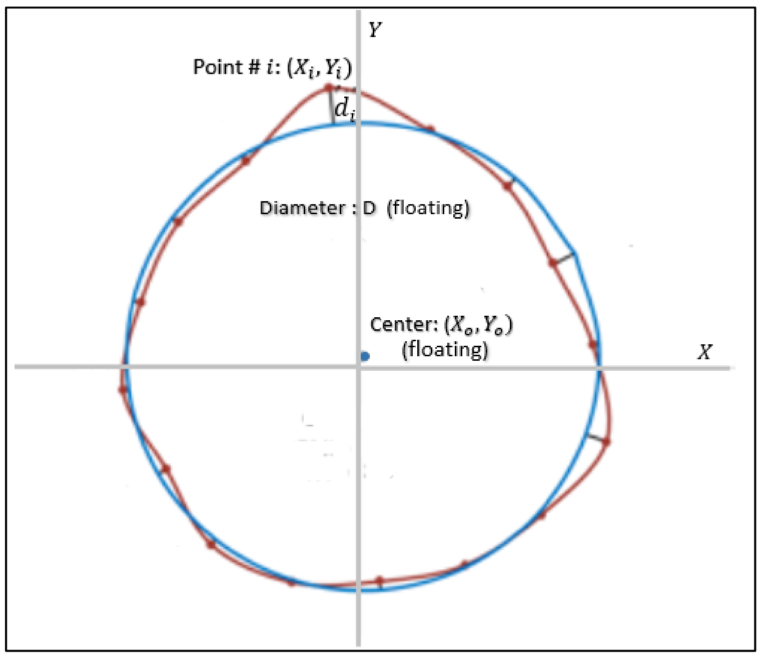


Figure 3.6 A sample of Least Squares Circle
Adapted from Janeshewski (n.d.)

- **Maximum Inscribed Circle**

This algorithm determines the largest circle which could be fitted totally inside the acquired points. Most of the time, at least 3 points are exactly located on the determined circle, so that their deviation is equal to zero. Figure 3.7 shows a sample of maximum inscribed circle determined through this method. Finding a maximum size for this circle reduces the interval between the surface and determined circle, and as a result, decrease the average deviation. There are two following criteria for optimization of this method:

- The average absolute deviation ($\frac{1}{n}\sum|d_i|$) be minimized
- The minimum deviation be zero

In Maximum Inscribed Circle, the most extreme low data points are used in calculations; therefore, unlike the Least Squares algorithm, this algorithm is sensitive to outliers.

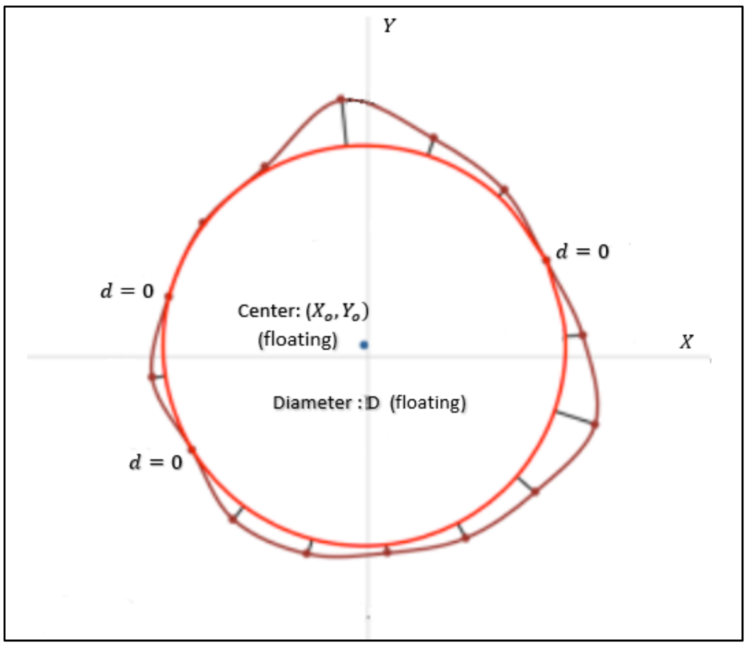


Figure 3.7 A sample of Maximum Inscribed Circle
Adapted from Janeshewski (n.d.)

- **Minimum Circumscribed Circle**

The algorithm in this approach determines the circle which has the smallest size and is totally located outside the captured points. Same as previous method, at least 3 points are usually located on the circle with zero deviation. Figure 3.8 depicts a sample of minimum circumscribed circle. The distance between the surface and determined circle (the average deviation) is in the minimum rate when the circle size is minimized.

There are two following criteria for optimization in this method:

- The average absolute deviation ($\frac{1}{n}\sum|d_i|$) be minimized
- The maximum deviation is zero

In minimum circumscribed circle, as the most extreme high data points are used in calculations; therefore, the outliers play role on the result of the algorithm (Janeshewski, n.d.).

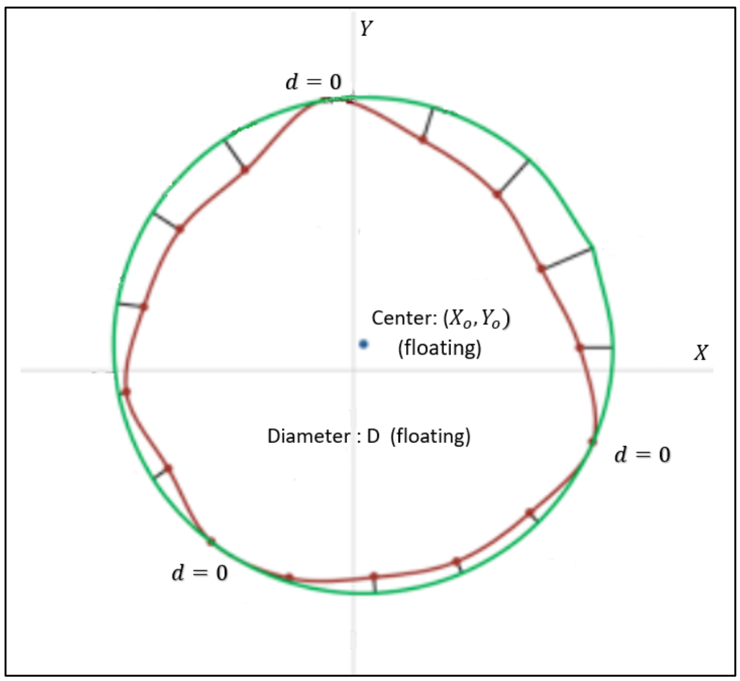


Figure 3.8 A sample of Minimum Circumscribed Circle
Adapted from Janeshewski (n.d.)

CHAPTER 4

RESULTS

The designed experiment in this study contains several phases with different sets of scanning parameters to investigate influences of scanning factors on inspection accuracy (Figure 3.1). The quality of measurements was assessed in each step based on the deviation of result from reference, while the reference was assumed to be the value measured by touch-trigger probes on CMM. The results of each stage along with the selected parameters and conditions on that step were explained in following sections. In case of test part 1, around 1164990 points were captured by laser scanner, and 18600 points by contact probe. Also, test part 2 was scanned with 450400 points, while it was measured by touch probe with 100 points.

4.1 The role of talcum powder on the laser scanning of reflective parts

As mentioned in previous chapters, because of the important role of diffuse reflection on capturing the projected laser line in laser scanners camera, measuring reflective parts is a complicated challenge. Although developing features in modern scanners have helped to solve this problem, there are still considerable defects in scanning result for shiny surfaces. As a common solution, anti-reflection coating for glossy surface with talcum powder is strongly recommended.

To depict the role of coating in quality of captured point cloud, the block including different slopes was scanned in four different conditions, at the first step of this experiment. The object was scanned with and without spraying talcum powder on its surface, and in each case the scanning process was repeated in two illuminance conditions (660 lux and 45 lux). Figure 4.1 shows the obtained point clouds in each condition.

As is observed at first glance, the quality of point clouds has significantly improved after coating with talc powder. In fact, there are huge amount of outliers in scanning results when the powder was not used. Thus, due to this amount of point scattering around scanned model an accurate measurement is challenging. This observation led us to use talcum powder for the all next cases during this study. Also, a comparison between accuracy of results obtained in two different ambient lighting is presented in next section.

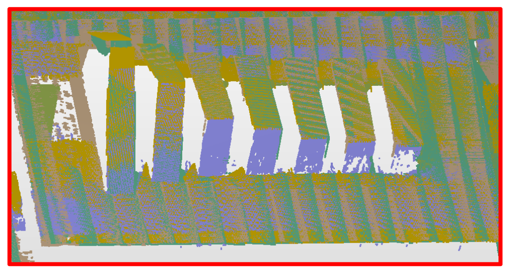
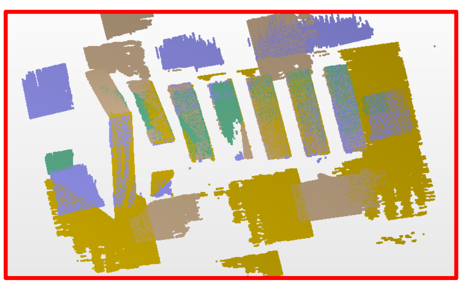
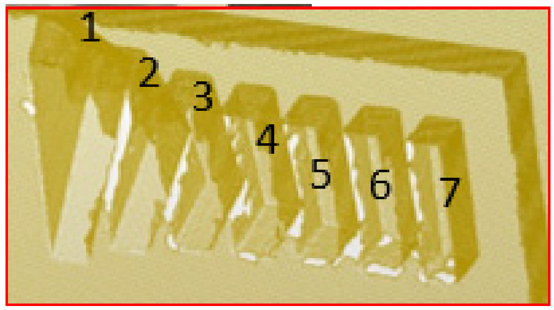
	Illuminance	
	660 lux	45 lux
With Talcum Powder		
Without Talcum Powder		

Figure 4.1 The obtained point clouds in different conditions of coating and illuminance

4.2 Evaluating the role of the incident angle on scanning process over the object with different slopes

To evaluate the influence of the incident angle on performance of the scanning process, 7 smooth surfaces which designed with different angles were selected to scan (Figure 4.2). These angles were specified from 0.8 to 45 degrees to the test part horizontal level as the datum.



surface number	1	2	3	4	5	6	7
angle (degree)	45	30	15	10	5	3	0.8

Figure 4.2 The point cloud of the block including 7 different slopes

In this step, to evaluate the scanning accuracy, the deviation of point clouds acquired by laser scanner was calculated from the datum which was the modeled plane obtained from the tactile probe outcomes. Surface profile and $RMSE$ were calculated to make a comparison between the surfaces with different angles. Moreover, to investigate the effect of illuminance on laser scanning outcome, the scanning process was performed in two different lighting conditions, and illuminance was measured each time with a lux meter (45 lux and 660 lux).

Figure 4.3 and Figure 4.4 depict respectively calculated $RMSE$ and surface profile in each case, in two different lighting conditions. The graphs show this fact that both $RMSE$ and surface profile as scanning accuracy criteria have higher values in the surfaces with higher slopes, it means that to achieve an acceptable result for all slopes it is necessary that incident angle be adjusted according to each slope. In addition, the results obtained in 45 lux are mostly more accurate than the scanning result in 660 lux.

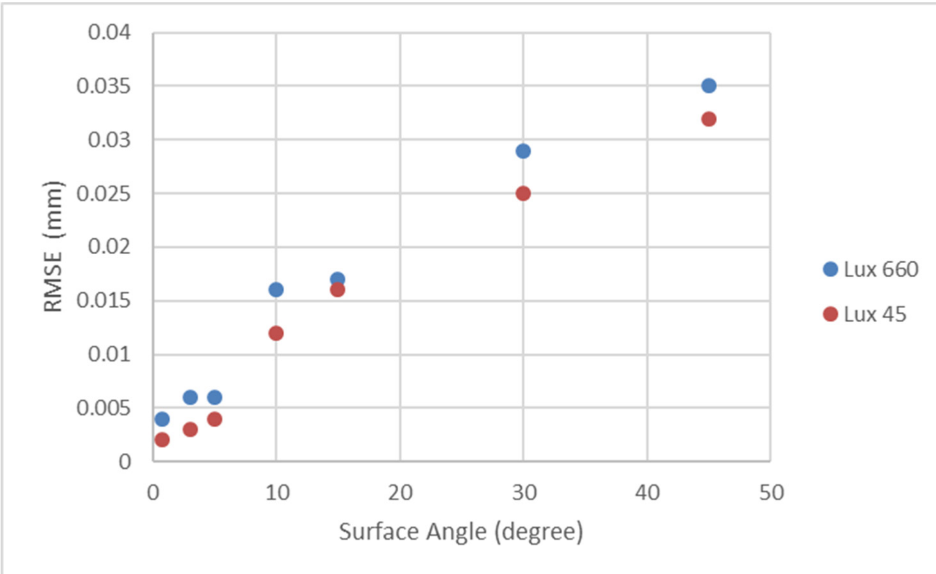


Figure 4.3 Calculated $RMSE$ in 7 surfaces with different slopes on two specified ambient lighting

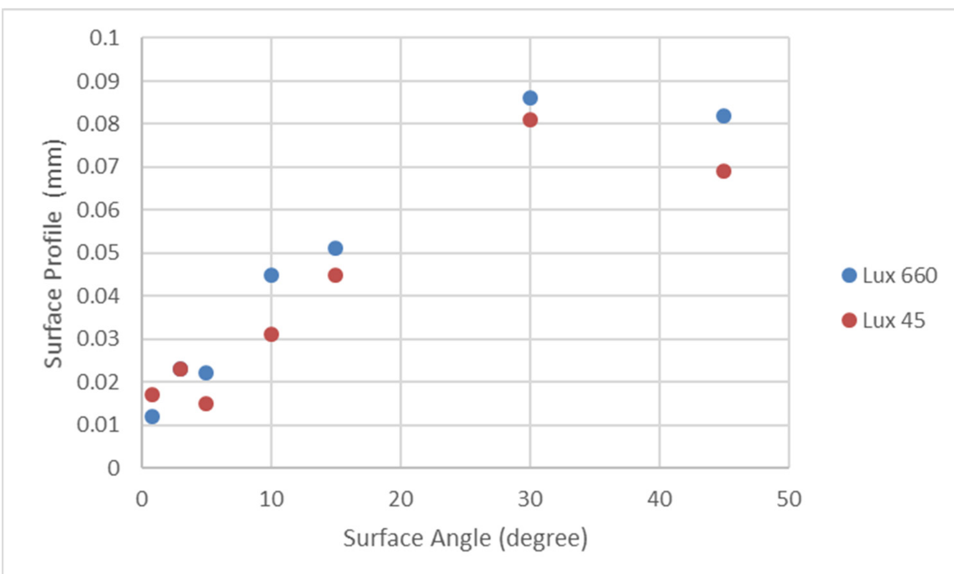


Figure 4.4 Calculated surface profile in 7 surfaces with different slopes on two specified ambient lighting

4.3 The role of software options on measurement of surface angles

To assess accuracy of measurement for surfaces angle, some plans were created based on scanned point by Metris Scanner, then the errors of these planes' angles compared to the reference planes, modeled by contact probe on CMM, were calculated. In this approach, the planes were created on Polyworks® through different types of fitting method (Max, Min, and Best-fit) to compare their outcomes, and also modeling was repeated based on various percentage of points as outliers to reject.

The given graph in Figure 4.5 demonstrates the error calculated in 7 surfaces with different slopes while three different fitting methods were applied to make a comparison. According to this graph, the results delivered through the three fitting methods have almost same rate of error, however, there are a higher level of error in angle measurement of the surfaces with more slope.

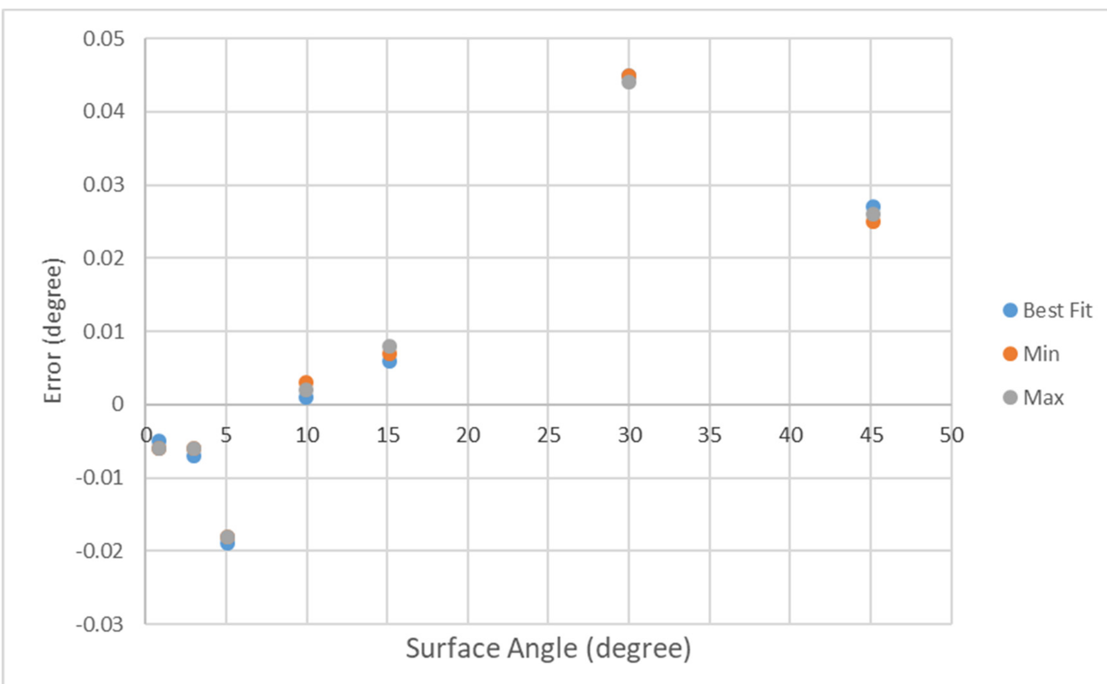


Figure 4.5 Calculated angle measurement error in 7 surfaces with different slopes using three methods of fitting

The provided graph in Figure 4.6 depicts errors of the measured surfaces angles obtained through rejecting different percentage of points as outliers. Using this filtering option on Polyworks® shows the minimum error accrue when this percentage is selected around 5.

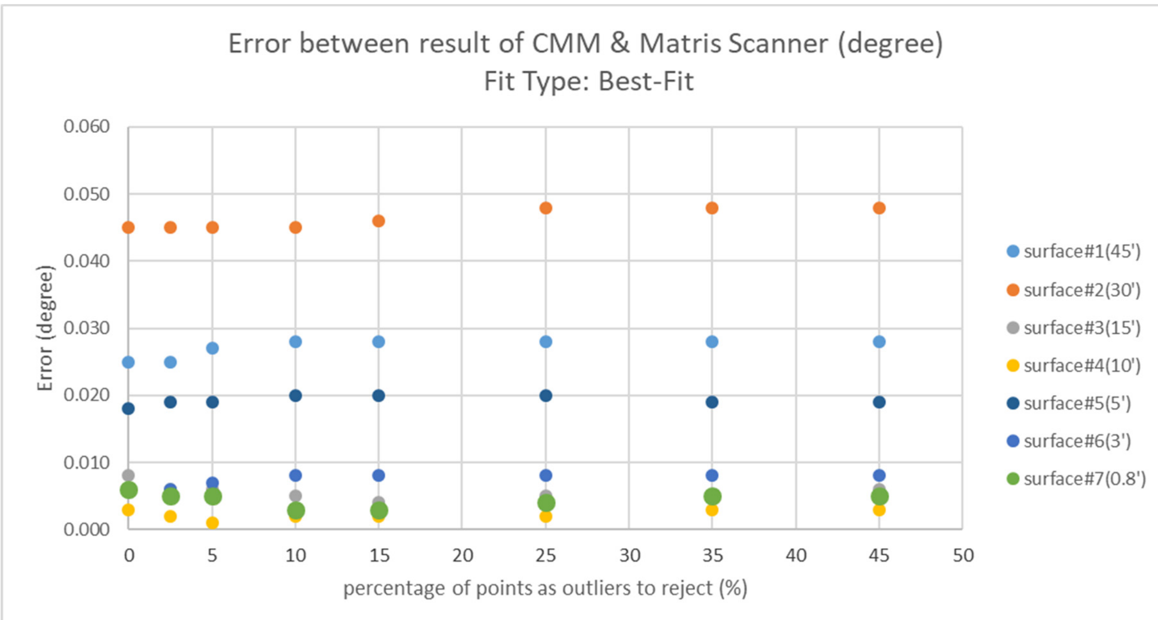


Figure 4.6 Errors of the measured surfaces angle obtained through rejecting different percentage of points as outliers

Figure 4.7 to Figure 4.10 shows the effect of using both filtering and fitting options of software simultaneously, which were depicted for each slope separately. Regarding this information, applying best-fit method and rejecting 5 percent of points as outliers are recommended to achieve an appropriate quality of scanning. However, it should be considered that the accuracy in surfaces with a higher slope is in a lower level.

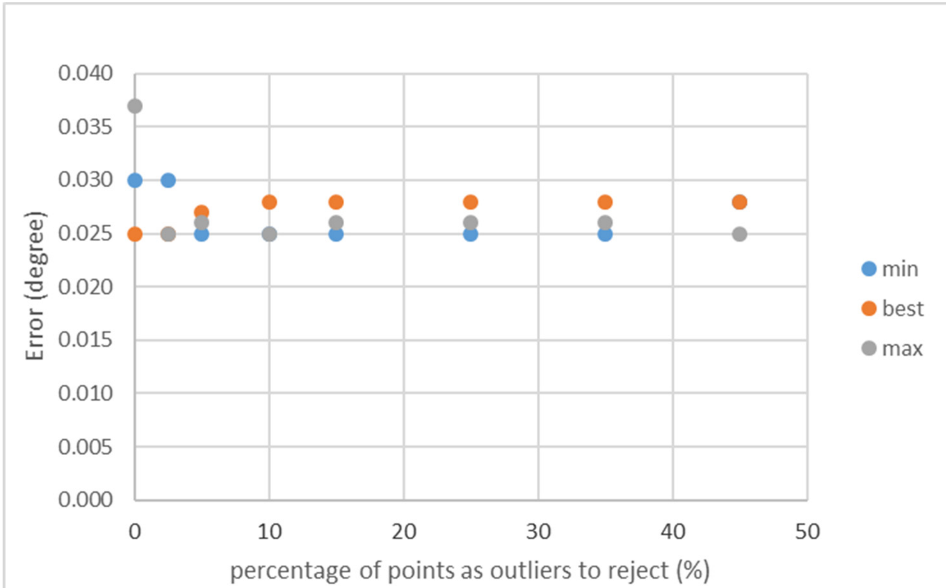


Figure 4.7 Errors of the measured angle for surface number 1 obtained through using both filtering and fitting options simultaneously

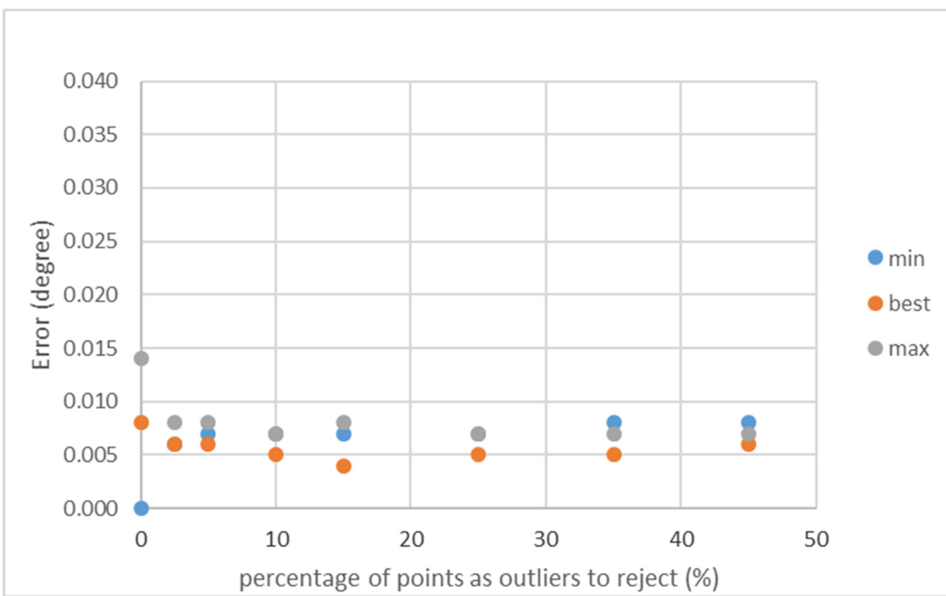


Figure 4.8 Errors of the measured angle for surface number 3 obtained through using both filtering and fitting options simultaneously

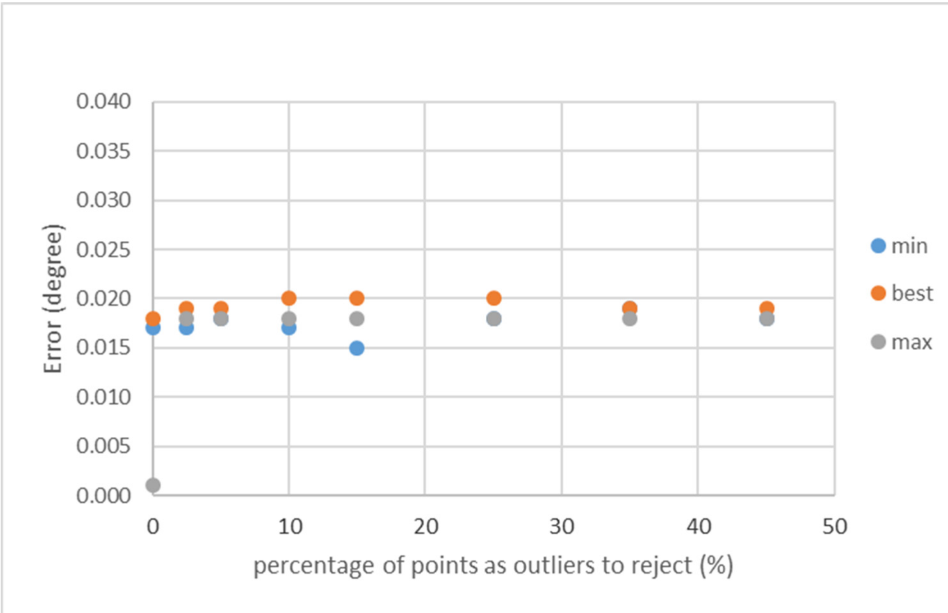


Figure 4.9 Errors of the measured angle for surface number 5 obtained through using both filtering and fitting options simultaneously

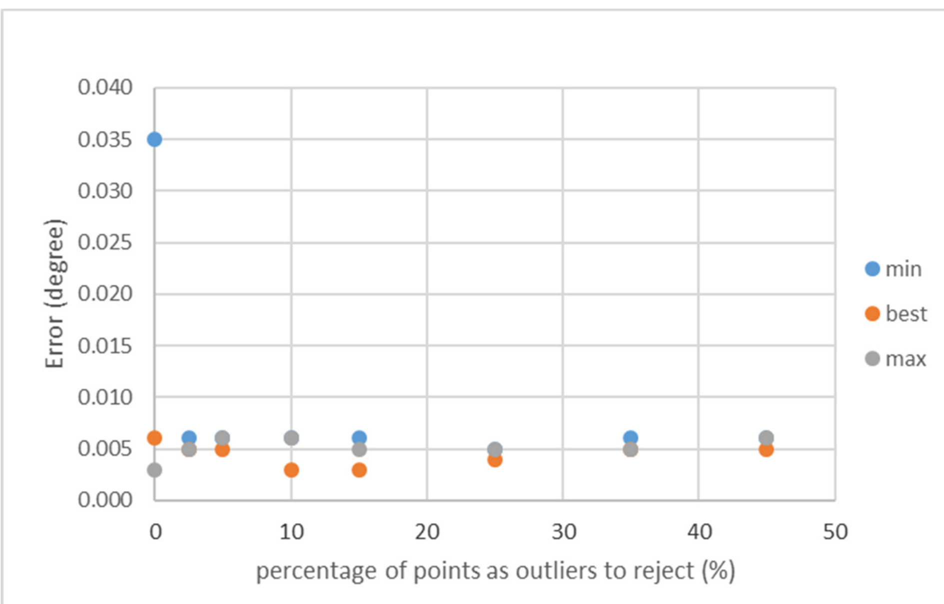


Figure 4.10 Errors of the measured angle for surface number 7 obtained through using both filtering and fitting options simultaneously

4.4 The quality of laser scanning over flat and non-uniform surfaces on different lighting conditions

In order to investigate the influence of the surface form on quality of measurement, scanning process was done over the flat and non-uniform surfaces, manufactured in complex test part. Figure 4.11 depicts the point clouds captured from these two surfaces. In each case, a reference plane was modeled through the points acquired by tactile probe on CMM. Then, the point cloud captured by the laser scanner was used to calculate Max, Min, and Mean Error as well as Surface Profile. These calculations were based on the obtained reference plane, as the datum. In the case of surface profile, it was assumed to be equal to twice the absolute value of the maximum error.

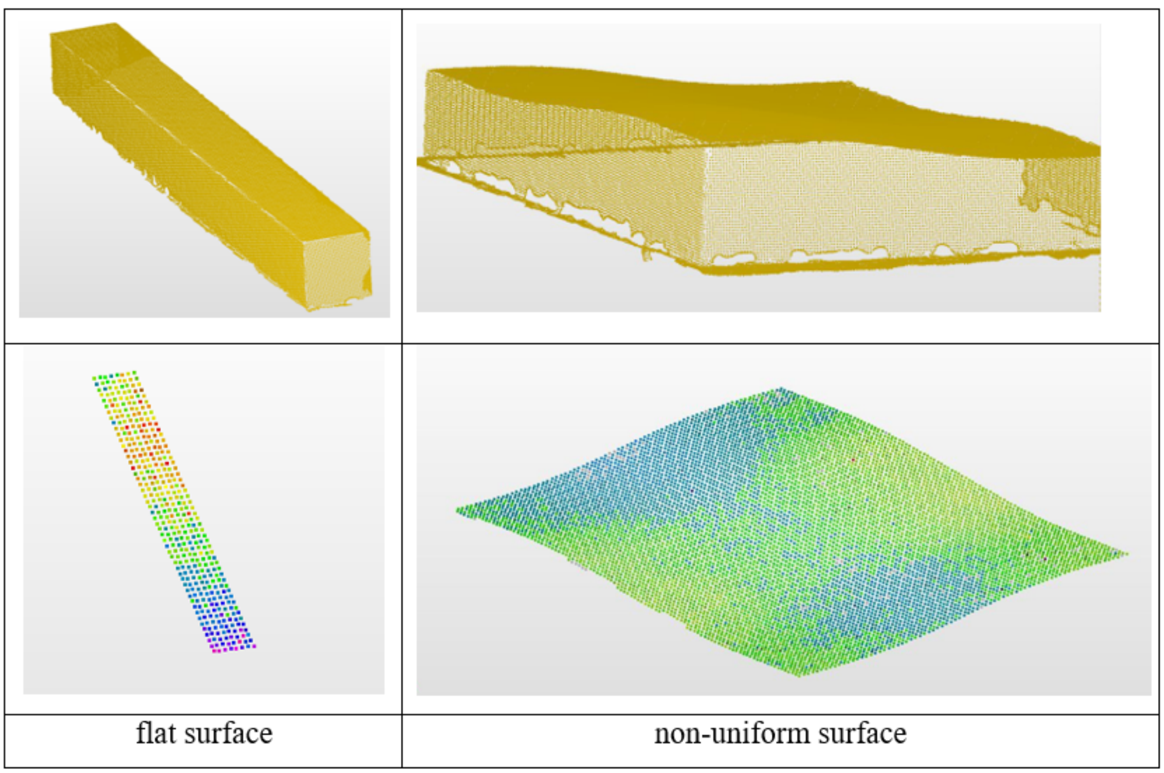


Figure 4.11 The point clouds captured from the flat and non-uniform surfaces

The bar charts in Figure 4.12 and Figure 4.13 respectively illustrate the rate of mean errors and surface profiles calculated by Polyworks® from captured point clouds in two lighting conditions. Although the mean error among points captured from non-uniform surface is lower than the flat surface, the surface profile in this surface is wider than flat one which means maximum error measured in non-uniform surface is bigger. In addition, the results are slightly more accurate when scanning process was done in a dark condition (45 lux).

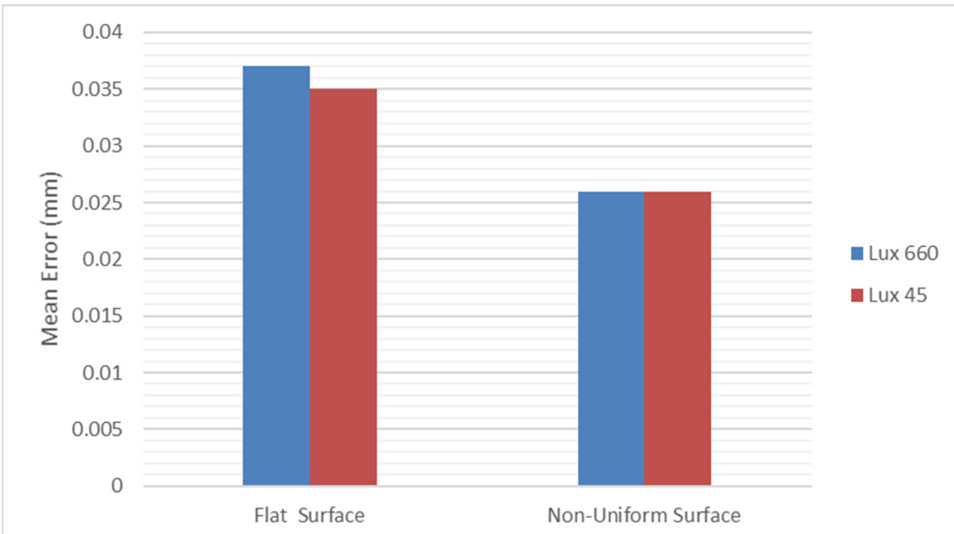


Figure 4.12 Calculated mean error on captured points from the flat and non-uniform surfaces for two specified ambient lighting

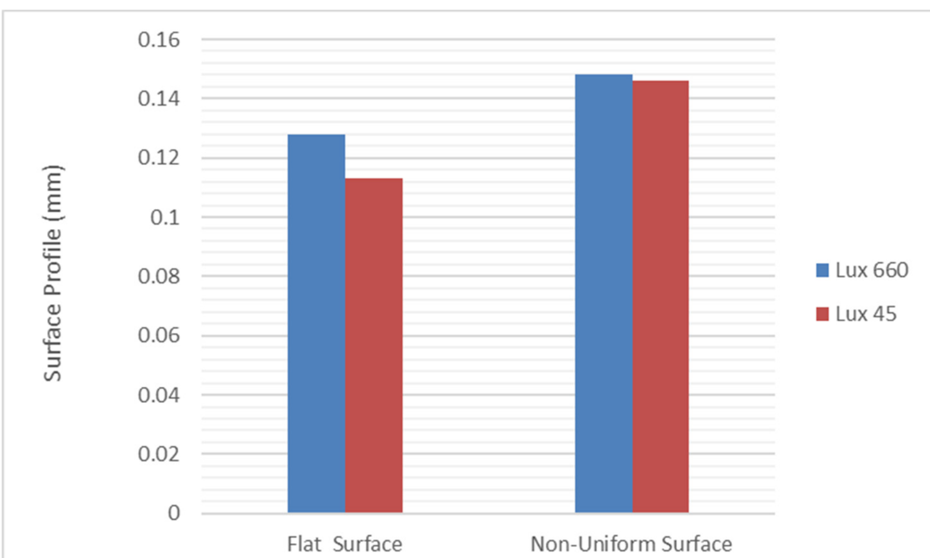


Figure 4.13 Calculated surface profiles on captured points from the flat and non-uniform surfaces for two specified ambient lighting

During meshing process, Polyworks® offers some options including “Reduce Noise” and “Reject Outlier”. Through these options the rate of tolerance and cluster size could be selected. In this experiment, meshing options were checked to assess their effect on the result. Figure 4.14 depicts the measured surface profile for captured points over non-uniform surface. In general, adjusting appropriate meshing setup could improve measurement. However, the experiment shows in case of reduce noise, only choosing small rate of tolerance (less than 0.5) can affect on accuracy.

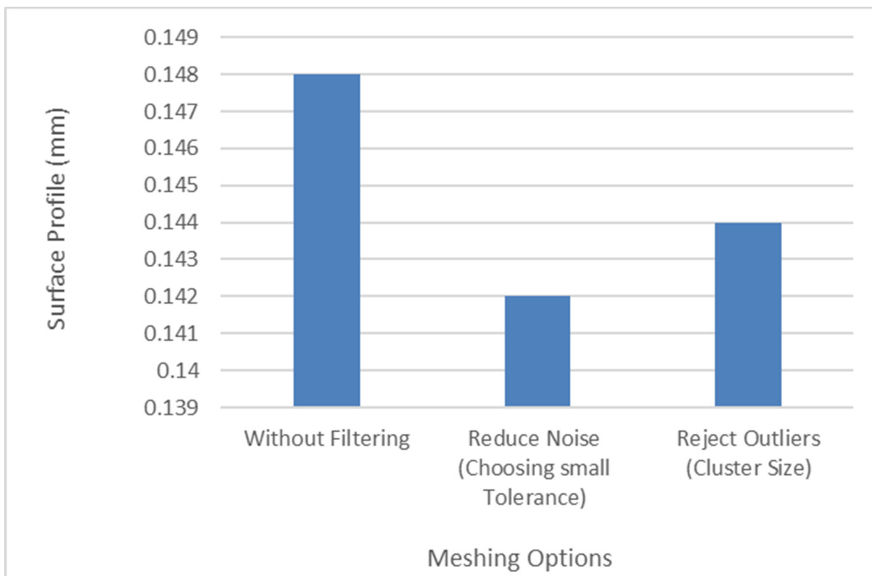


Figure 4.14 The role of meshing options on calculated surface profiles for captured points from the non-uniform surface

4.5 Evaluating the accuracy of measurement for the diameter and the coordinate of holes

The hole located in sloped surface was determined to evaluate the measurement capability of laser scanner. The object was scanned in a normal lighting condition (660 lux). Figure 4.15 depicts the hole and its captured point cloud. The point cloud captured by laser scanner was used to measure the diameter hole as well as the coordinate of hole center. Moreover, in order to assess the influence of filtering option on measurement accuracy, measurement was done with different percentages of rejected points as outliers, where the best-fit method was applied to create the model in Polyworks®. As a reference value to make comparison, the diameter of the hole and its center coordinate were also measured based on point cloud obtained by contact probe on CMM. Finally, the deviations from reference values were calculated.

As literature review reveals, there is this possibility that the capture points from deeper area has less accuracy. Hence, the parameters were measured twice to make comparison; using all scanned points and with neglecting the points captured from deeper area.

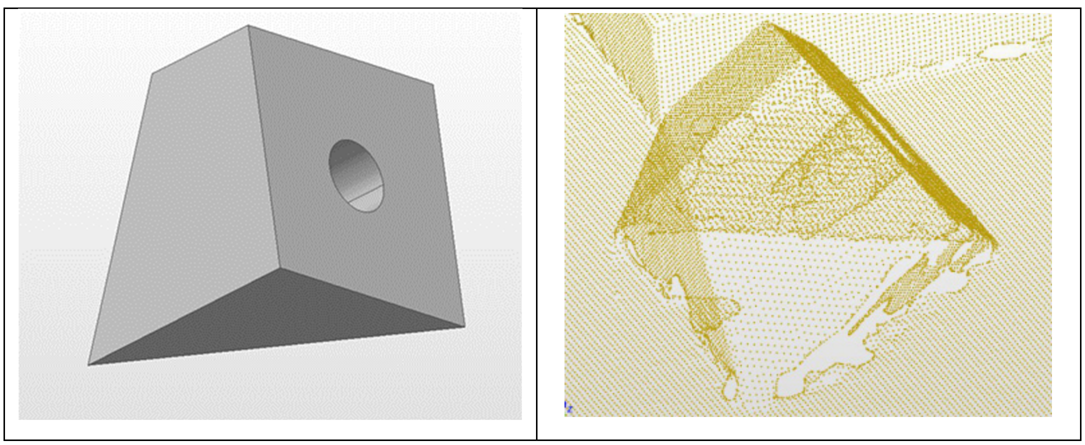


Figure 4.15 The hole and its captured point cloud

The presented graph in Figure 4.16 shows the deviation of measured diameter for the hole when different percentages of points were selected to be rejected as outliers. Regarding the results, the measurements with neglecting the deeper points have lower rates of deviation. Also, different percentages of reject outlier do not have a significant role on accuracy of measurement.

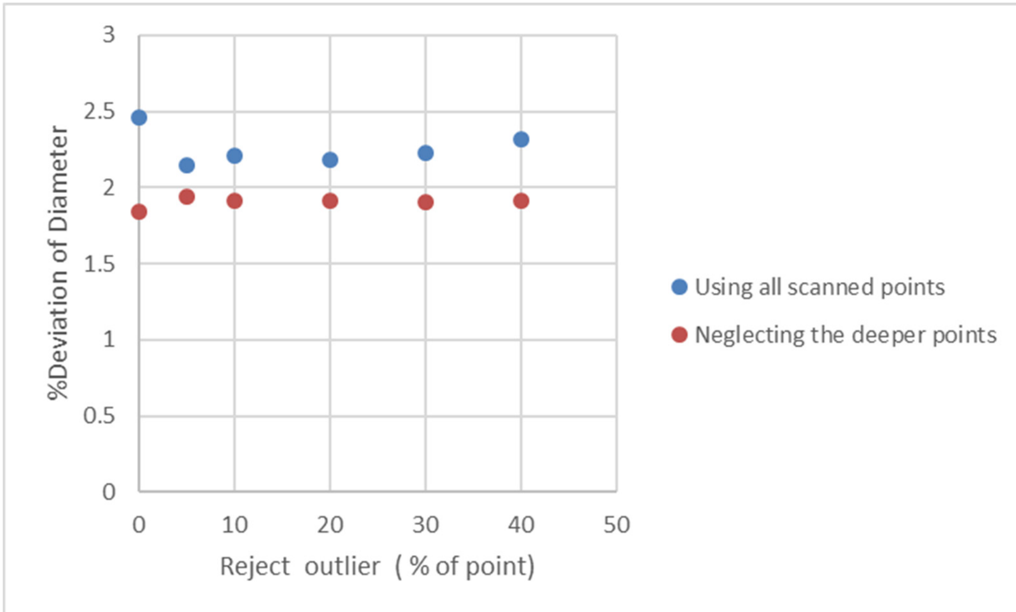


Figure 4.16 The deviation of measured diameter for the hole when different percentages of points were selected to be rejected as outliers

Figure 4.17 to Figure 4.19 represent the calculated deviation of the hole center coordination in X, Y, and Z axis, respectively. According these three graphs, the best result was generally occurred when 5 percent of points were rejected as outlier and deeper captured point were neglected.

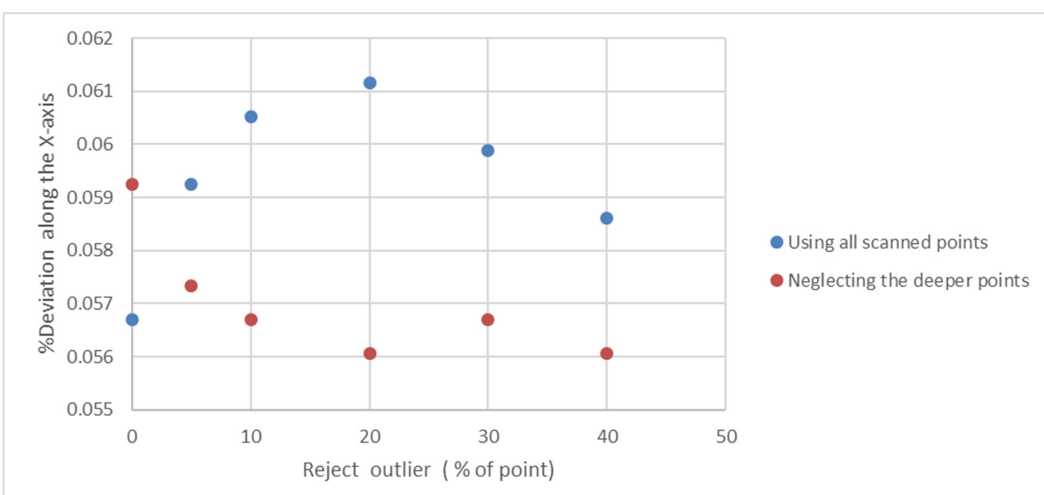


Figure 4.17 The calculated deviation for the coordination of the hole center along X-axis

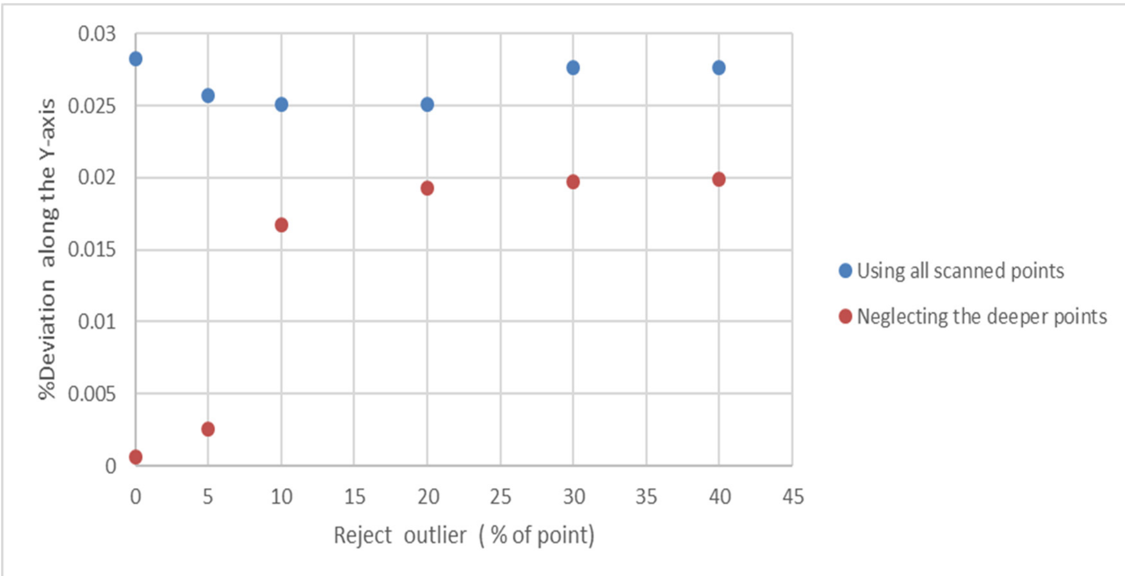


Figure 4.18 The calculated deviation for the coordination of the hole center along Y-axis

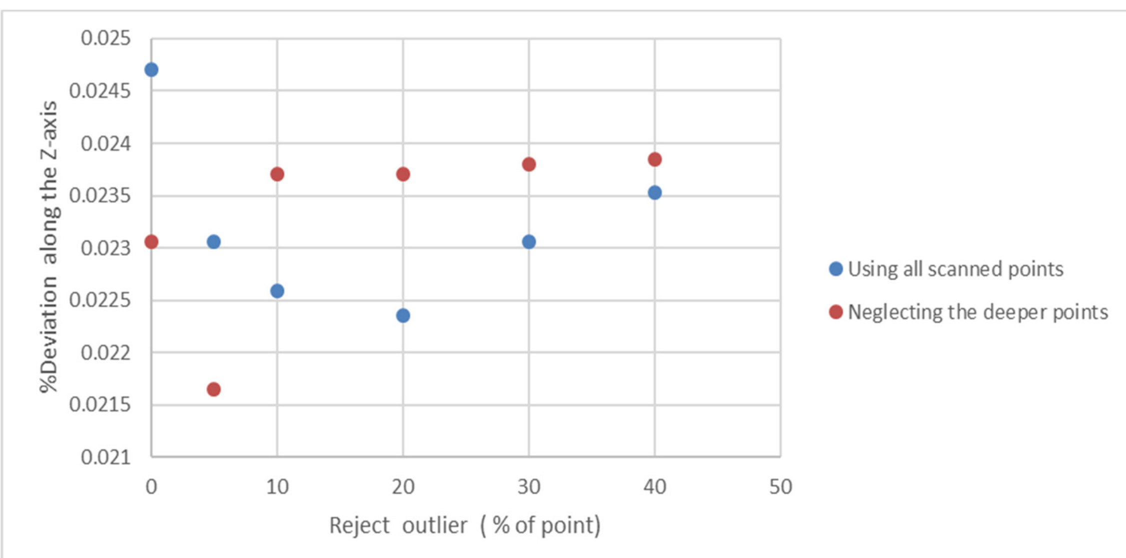


Figure 4.19 The calculated deviation for the coordination of the hole along Z-axis

4.6 Effect of software options on measuring diameter and cylindricity

In this step, the cylinder with a reflective surface was selected as the laser scanning object. Figure 4.20 depicts the point cloud of cylinder captured by laser scanner. The cylinder diameter and cylindricity were determined as the measurand and the reference values were measured based on points acquired using touch probe on CMM. Then, the cylinder was scanned in a normal lighting condition (660 lux). The deviations from reference value were calculated while different values of software filtering and fitting options were applied to evaluate the effect of these parameters on measurement results. The obtained point clouds were fitted through three methods including Max, Min, and Best Fit, then the results were compared. Polyworks® also offers different filtering options such as Reject Outliers, Subsampling, and Max Angle. In this study different values for each of these software parameters were applied. However, results show that choosing various values for Max Angle has no effect on measured Diameter and Cylindricity.

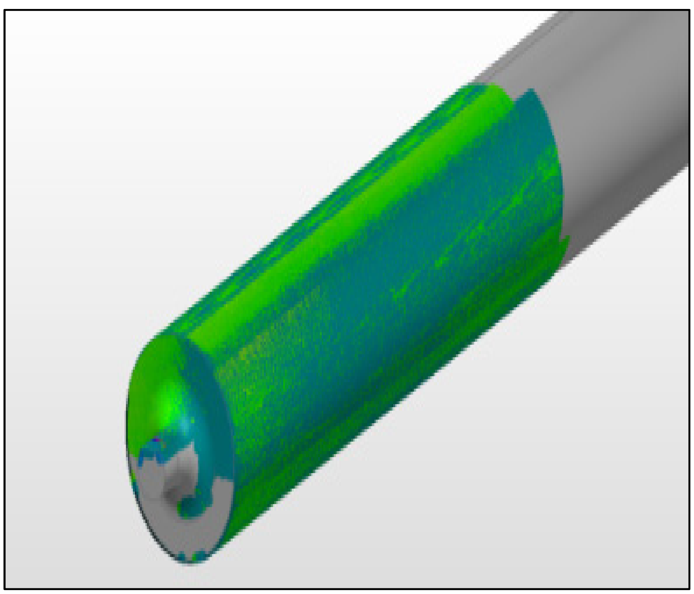


Figure 4.20 The captured point cloud of cylinder

The bar chart presented in Figure 4.21 compares the measured cylinder diameter in three different data processes setting; without filtering, with Reject Outliers (5% points), and using two steps of subsampling. Each measurement was done with three fitting methods (Max, Min, and Best Fit). Also, the reference value for diameter obtained by touch probe (99.957 mm) is shown in the bar charts. Figure 4.22 shows the calculated deviations for these results. According to these results, the most accurate results were measured when best-fit method was selected. Although, the deviations decrease in the case that two steps of subsampling were applied as the filtering method compared to the measurement without filtering, the best accuracy is related to the case which rejecting outlier was used.

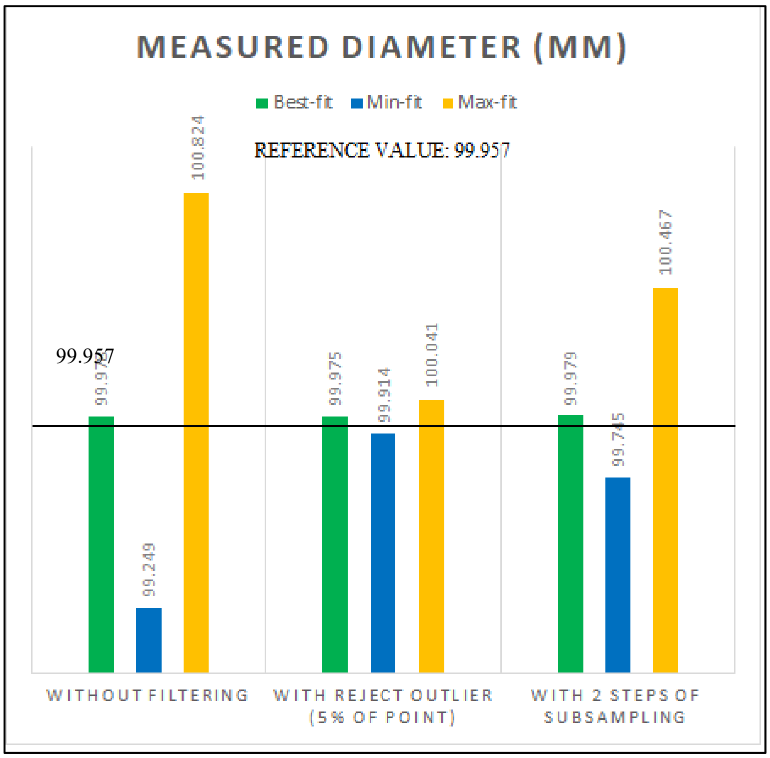


Figure 4.21 The measured cylinder diameter using different set of filtering and fitting options

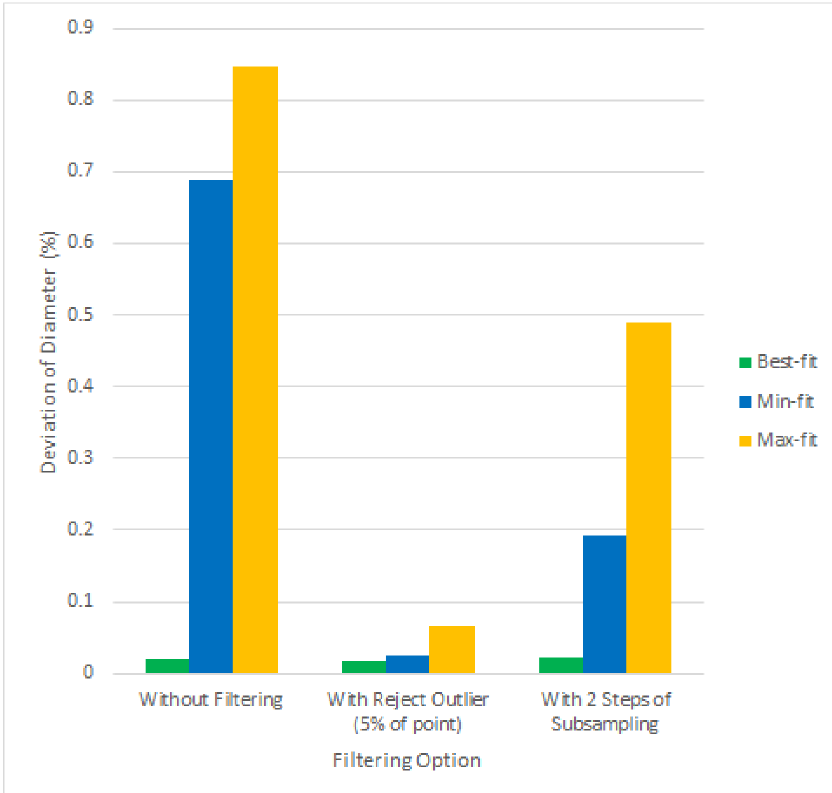


Figure 4.22 The deviations for measured cylinder diameter when different values for filtering and fitting options were selected

The measurement of diameter was repeated several times using different values for the percentage of rejected outlier points as well as different steps of subsampling to check the effect of these options on quality of measurement.

As is observed in Figure 4.23, increasing the percentage of rejected outliers has a significant positive effect on accuracy of measurement for min and max fitting method. However, the deviations of results remain almost unchanged with different percentages of outliers, when best-fit method was used. According to information in Figure 4.24, although using the subsampling steps (more than 1) has positive influence on accuracy of min and max fitting method, there is no pattern to help us to choose the best setup for these two fitting approach.

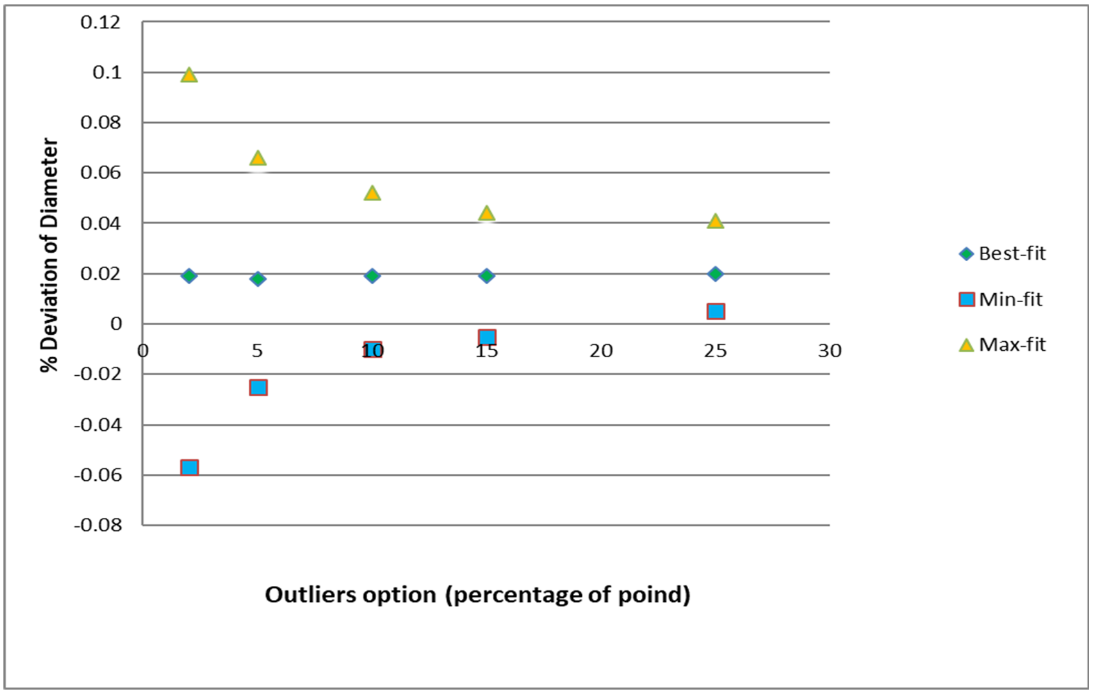


Figure 4.23 The deviation of measured diameter for the cylinder when different percentages of points were selected to be rejected as outliers.

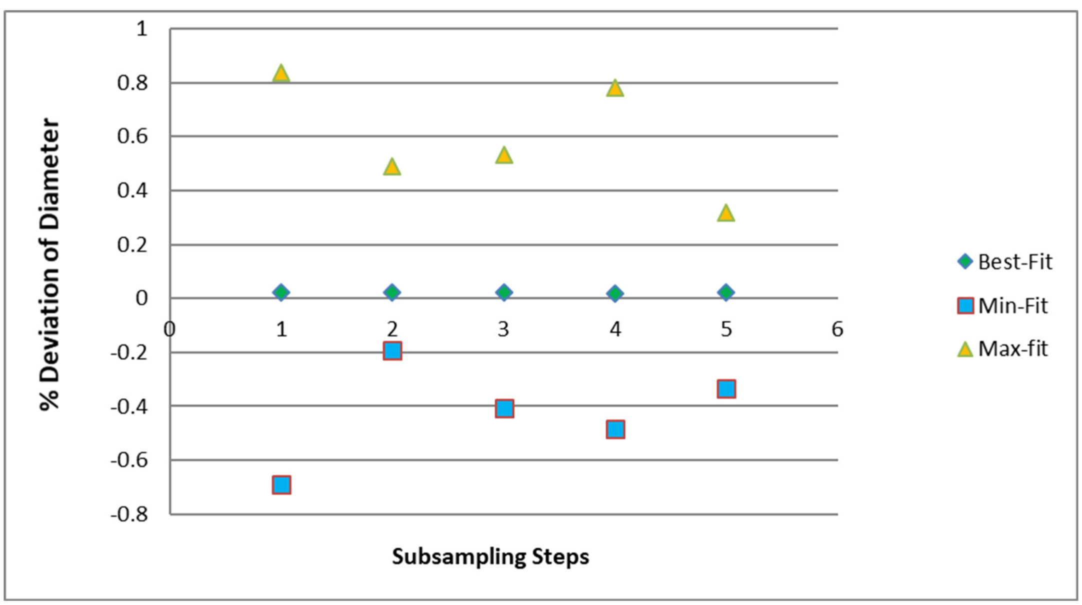


Figure 4.24 The deviation of measured diameter for the cylinder in different subsampling steps

The same process was done to measure the cylindricity. Figure 4.25 to Figure 4.27 depict the measurement results. The reference value for cylindricity obtained by contact probe on CMM (0.018 mm) is depicted in the bar charts. The bar chart in Figure 4.25 shows the most accurate results were measured when 5 percent of outlier points were rejected, however, using 2 steps of subsampling had a positive effect to reduce the error. Regarding all results, there is not considerable difference between results of max, min, and best-fit methods. Figure 4.26 illustrates a downward trend for deviation of measured cylindricity when the percentage of rejected points as outliers was increasing. Despite the lack of a clear pattern in provided graph in Figure 4.27, it is still noticeable that using more than 1 subsampling step improved the accuracy of measurement.

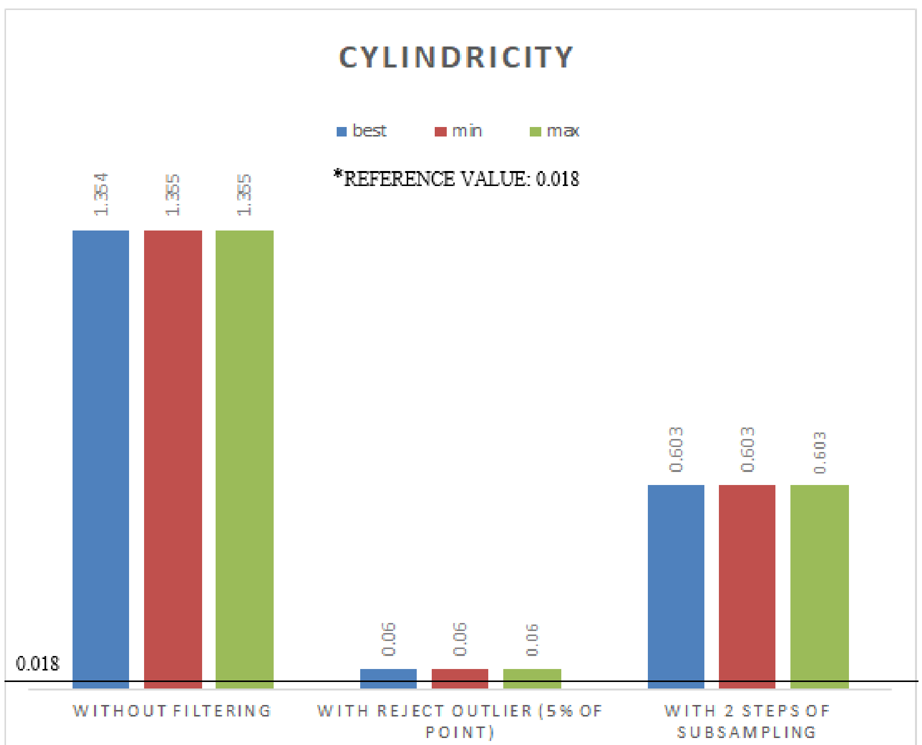


Figure 4.25 The measured cylindricity using different set of software data process: selecting different values for filtering and fitting options

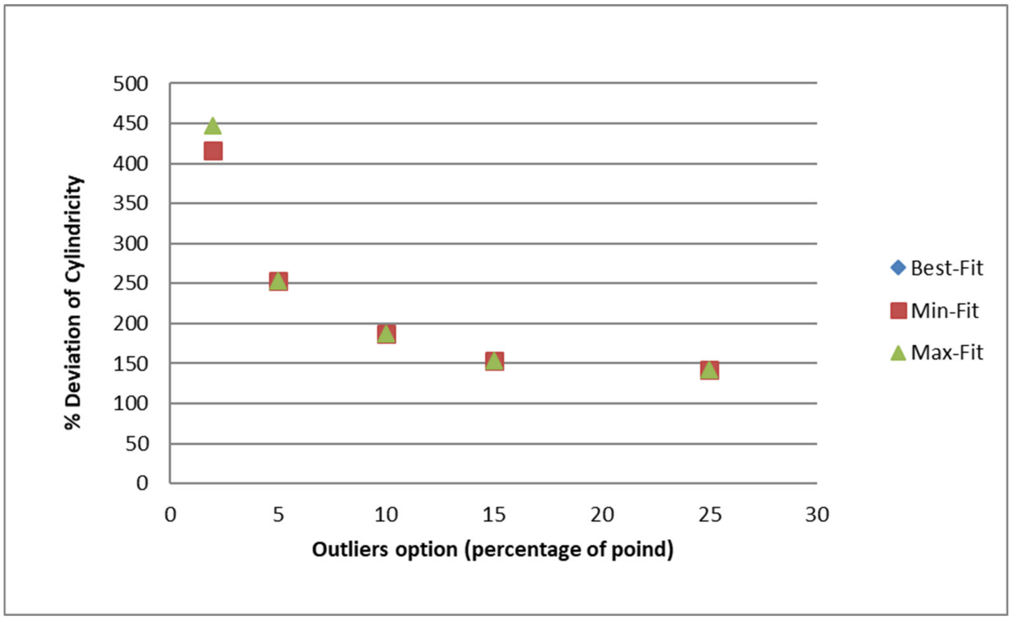


Figure 4.26 The deviation of the measured cylindricity when different percentages of points were selected to be rejected as outliers

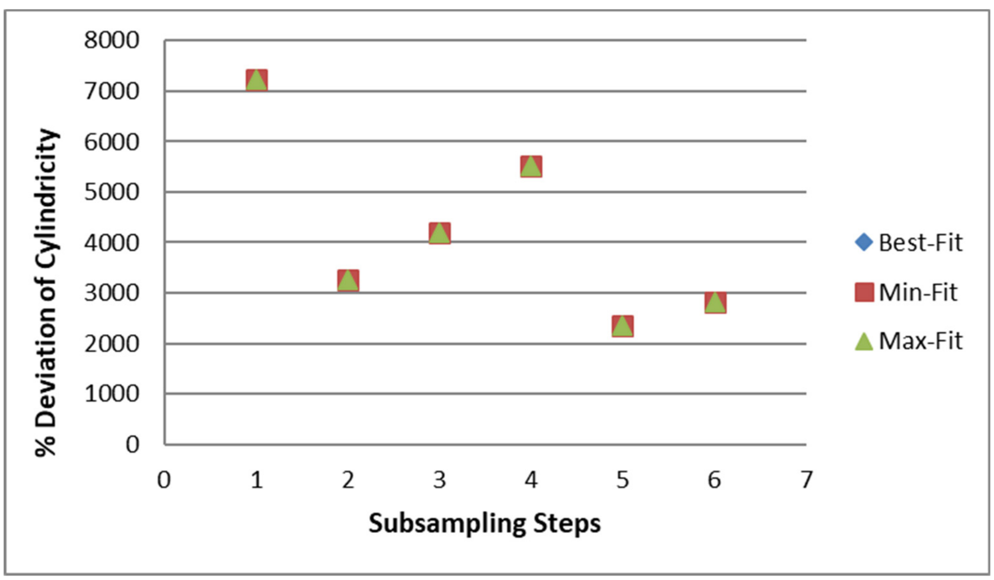


Figure 4.27 The deviation of the measured cylindricity in different subsampling steps

CHAPTER 5

DISCUSSION

Previous works have introduced some possible factors that could have influence on the accuracy of laser scanning process and this study performed some experiments to assess some of these parameters' effect. In this chapter, the experiment results are firstly discussed and classified under some categories of scanning factors, then through analyzing them, some recommendations are provided to improve the quality of laser scanning process. Finally, at the end of chapter validity of the study is explained.

5.1 Ambient Lighting

The influence of illuminance on the accuracy of measurement were investigated in some different steps of this work. The scanning process over flat and free-form surfaces as well as the block, contains 7 surfaces with different slopes, were performed under two ambient lighting; in a normal illuminance when laboratory lights were on (660 lux), and in a dark condition when the lights were off (45 lux).

Overall, as is observed in results, the measured deviations for all surfaces reduce in a dark condition. It means that the less ambient light can improve the accuracy of measurement during an inspection by the laser scanner. This general conclusion about illuminance influence is confirmed by previous works.

The study conducted by Lemeš et al. shows this fact that the ambient light could decrease quality of scan especially when reflective surfaces are scanned (Lemeš & Zaimović-Uzunović, 2009). This research explored the effect of the ambient light intensity and the surface colour on the quality of laser scanning. The criteria for this investigation was the number of captured points. The experiment was performed based on scanning outcomes for objects with different colours while each object was scanned under two lighting conditions including normal daylight and dark condition (respectively, 120 and 20 lux). Their work illustrates that the performance of laser scanners will be affected by the rate of ambient light. In particular, he concluded that in case of glossy surfaces the number of usable captured points decreases due to reflected ambient light.

In current study, the calculated deviation was determined as the evaluation criterion. In case of a flat surface, the mean error has declined by 0.002 mm when the object was scanned in dark condition. Also, the reduction of reflected light decreased surface profile by 0.015 mm. For non-uniform surface, the measured mean error in two states of ambient light is equal. However, the surface profile had a slight decline, around 0.002 mm.

Reviewing results of the block including 7 different slopes, there are the lower levels of RMSE in all slopes when the scanning ambient is dark. The same pattern was occurred for most measured surface profiles. However, the rate of reduction is more significant for the surfaces with more slope. As figures 4-4 shows the maximum rate of reduction for surface profile (0.013 mm) occurred on result of 45-degree surface which has the most slope.

5.2 Software Options to Data Process

During current experiment's data process, different fitting methods as well as various sets of filtering and meshing parameters, offered by Polyworks®, were applied, separately and in combination. The influence of using these software options on measurement results is presented in following sections.

5.2.1 Fitting Methods

This work investigates the role of using different fitting methods including maximum, minimum, and best fit, on the performed inspection for cylinder and surfaces with different slopes. In some steps, the effect of these methods were studied in combination with using different set of filtering options.

In general, presented results in previous chapter depict that although in some tests one specific fitting method has meaningfully improved accuracy of measurements, it was changed on the other situation, for instance in case of applying the other set up of filtering options.

The previous study on the Polyworks® fitting methods, presents this conclusion that minimum fitting method will provide a higher quality of measurement results(Xiao & Li, 2014). This conclusion is based on the comparison between the measured values obtained with minimum and best-fit methods in X and Y directions. But there is no reference in this study to the status of filtering options. Whereas, the result of current study shows this fact that there is not a fixed priority for fitting methods and using filtering options could change the answer.

During current study, in measurement of cylinder diameter, when filtering options were inactive, there are a significant difference between measured diameter through each fitting method, where the best-fit has resulted the most accurate measurement. The measured diameter, in case of using best-fit method, has 0.02% deviation from reference value, while maximum and minimum methods have measured the diameter with 0.84 and 0.68 % deviation, respectively.

However, this gap between results has decreased when each of the filtering options including reject outlier or subsampling step was active. Although the results in case of using best fit method remained constant for different percentages of rejected points as outliers, rejecting more portions of outlier points reduces the absolute value of deviation for two other approaches. In using maximum and minimum methods, the deviation dropped down respectively to 0.05 and 0.01 % in rejecting 10% of points, while in the case of using best-fit method it remained unchanged at 0.02%. It means, in the case that more than 10% of points were rejected, the result of minimum method has been more accurate compared with using best-fit approach.

According to the given graph in figure 4-26, applying subsampling steps as software filtering options has enhanced the quality of measurement in only minimum and maximum approach. In two steps of subsampling, the obtained results through three methods have the least amount of difference and the best-fit method has the most accurate outcome with 0.02 % of deviation, where minimum and maximum approach have made 0.21 and 0.51% of deviations. However, this improvement does not follow a reasonable pattern related to the selected value for this option.

In the measuring cylindricity, there is no significant difference between accuracy of results in these fitting methods. This similarity is repeated when various filtering options were used. Regarding measured Angle of surfaces, there is not a noticeable priority for any of the fitting methods, even though the difference between the results of these methods is slightly greater at surfaces with more slope.

5.2.2 Filtering Methods

Some objects features were measured by the laser scanner in this study to investigate effect of filtering methods. The measured characteristics contain the hole diameter, its center coordination, the cylinder diameter, its cylindricity and the angle of surfaces.

In measuring diameter, as mentioned before, increasing rejected points as outliers has a positive effect on accuracy, only when minimum or maximum fitting approach were applied. The measurement results of the hole diameter also confirm that the accuracy was not under influence of rejecting outliers when best-fit method was applied, same as the inspection of cylinder diameter. Considering results of measured cylindricity in figure 4-25, rejecting outliers has a great influence on the scanning outcomes. The graph shows the increasing the chosen percentage of points to reject from 2 up to 25 makes a considerable reduction on deviation of result by 270%.

In a general review of results related using reject outlier method in measurement of the surfaces angle and the hole characteristics, although there is not a clear pattern to recognize and predict the rate of its influence, it seems that in most cases choosing 5% of points to reject as outliers could improve the accuracy of measurement. Also, in case of using maximum and minimum fitting method, Appling filtering algorithm is necessary.

In case of using subsampling steps as filtering method, in spite of the positive effect of this option on the obtained diameter and cylindricity, this effect was less than the effect of rejecting outlier, and also no pattern was found to predict the optimum setup for that. Figures 4-23 and 4.26 illustrate how using this option can reduce the deviation of measurement.

5.2.3 Software Meshing Options

In inspection process over free-form surface, several sorts of meshing setup, offered by Polyworks®, were applied. However, the only considerable change was occurred with reduce noise when the tolerance value was selected less than 0.5. Selecting this range of tolerance could reduce the surface profile by 0.006 mm.

5.3 The Surface Form

The scanning performance was evaluated on various forms of surface such as the cylinder, hole, and different slopes as well as flat and free-form surface. Providing a comparison between these results could be helpful to investigate the capability of laser scanners in inspection of surfaces.

5.3.1 The Sloped Surfaces

The scanning outcomes for the block including 7 different slopes provide a base to assess the quality of measurements in relation to the surface slope. These slopes were manufactured from 0.8 to 45 degrees to the main level of the test part. The effect of the surface slope on the accuracy of measurement was evaluated during two approaches which finally confirmed each other.

Overall, according to both methods of assessment, the measurement on surfaces with lower slopes were more accurate which shows the importance of the incident angle adjustment. In the first method, the deviation of captured points by laser scanner was calculated from the reference plane created by contact probe outcome. Results show the maximum value of $RMSE$ and surface profile belonged to surfaces with 30 and 45 degrees. For instance, the $RMSE$ for 45-degree surface was measured 0.035 mm, while that is around 0.004 mm for 0.8-degree surface. Second method firstly creates planes based on points clouds captured by laser scanner and also by tactile probe, then compares the measured angles of created planes. This method confirmed the overall conclusion obtained by the first method.

5.3.2 Flat and Free-Form Surfaces

As is mentioned in literature review, the ability of laser scanners on inspection of free-form surfaces is one of their most important advantages. In order to evaluate this capability, the scanning result of the designed free-form object was compared with a flat surface. In general, there is no meaningful difference between their measurement quality. In other words, although the calculated surface profile for the point cloud of the flat surface is smaller than that of the free-form surface, the measured mean error in flat surface is higher (around 0.011 mm).

5.3.3 The Hole

As is claimed in literature review, one of the weaknesses of laser scanners is their low accuracy in the case of scanning deep areas of objects such as holes and pockets. The results of this study could confirm this claim. The measured deviation in the case of hole is considerably more than other cases. Moreover, using captured points from deeper areas increased the percentage of deviation.

An explanation for this effect could be this probability that because of using a higher incidence and projected angles for the scanning process of deeper areas, a higher level of noise could be produced.

5.4 Validity of work

In this work, combinations of different devices, including laser scanner, probe, and CMM, were used, while each of them has their probability of error. Moreover, the possible error due to user performance should be considered. Therefore, some measures were designed and performed to improve the validity of work.

The obtained results of scans were compared with results of highly accurate contact measuring system and regarding presented accuracy of each used devices, the deviations of results were located in permissible range of error.

CONCLUSION

This study attempts to identify some important scanning factors and evaluate their role in the inspection accuracy of reflective objects. The main goal is to reduce the existing gap of quality between laser scanners and tactile probes, with recognizing possible sources of error, to taking the benefits of this high-speed inspection approach. Hence, the current work firstly classifies and clarifies some of the recognised factors that have a considerable impact on the scanning quality.

Regarding the role of diffuse reflection in the laser scanning function, especially for reflective surfaces, the illuminance was identified as an important parameter. This experiment results show a higher level of ambient light could cause a higher rate of error. Also, consider to the obtained point clouds in the first step of this work, using an anti-reflection coating could strongly improve the quality of outcomes.

In case of surface forms, lower levels of accuracy were measured for captured points from surfaces with more slope. The measurement results for the hole confirm the claimed weakness of laser scanners in capturing accurate data from deep areas. In comparison between results of flat and free-form surfaces, no meaningful difference is observed.

Regarding data process on Polyworks® software, although the measured results through best-fit method are mostly more reliable, using an appropriate set of filtering options could result a more accurate measurement through applying minimum method in fitting process.

This research work recommends some general guidelines to improve performance of laser scanners, especially during the inspection process of glassy objects:

- Reflective surfaces need to be coated with an appropriate anti-reflection powder. However, the thickness of the applied layer should be considered.
- A lower level of ambient light is recommended to improve scanning quality

- In case of objects including different slopes or in some deep features such as holes or pockets, a higher level of uncertainty should be expected.
- To process data with Polyworks® software, the recommended fitting method is Best-Fit, however minimum fitting approach could be applied when more than 10 percent of the point is determined to be rejected as outliers.
- The optimum values for filtering options in Polyworks® are 5 to 10 percent of points to be rejected as outlier and also 2 steps of subsampling.
- In case of meshing process in Polyworks® software, the selected tolerance value for the option of reduce noise should be selected less than 0.5.

RECOMMENDATIONS

To achieve a more accurate and comprehensive guideline for laser scanning inspection, this research should be expanded to evaluate a wider range of scanning factors such as the level of glassiness, laser beam colour, method and type of anti-reflection coating, laser intensity, incident angle, etc. In addition, performing the same experiment by other types of laser scanners and different ambient conditions could provide a good comparison opportunity to assess the presented guideline.

This study is limited with only two levels of illuminance and few objects which could be repeated for more variety of objects and lighting levels. Also, in case of data processing, the capability of other software could be compared with Polyworks®.

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