FACULTY OF MECHANICAL ENGINEERING TUL

**Master Thesis**

# Measurement accuracy analysis of the TRITOP photogrammetric system

*Study programme:* N0788A270005 Innovation and Industrial Engineering

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Department of Manufacturing Systems and Automation

Liberec 2023

## Master Thesis Assignment Form

# Measurement accuracy analysis of the TRITOP photogrammetric system

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| *Academic year:* | 2022/2023 |

### Rules for Elaboration:

**The main aim of the thesis will be to assess the influence of various factors on the accuracy, quality and repeatability of measurements of the TRITOP photogrammetric system.**

1. Get acquainted with the laboratory equipment needed to implement the practical part of the work (photogrammetric system TRITOP, SW GOM ATOS, etc.) and the principles of photogrammetry.
2. Research of papers on a similar topic – an overview of the current state of knowledge (will be part of the theoretical part of the thesis). Focus primarily on the issue of accuracy of photogrammetry systems (methods used for its assessment; influencing factors).
3. Formulation and analysis of the solved problem, proposal of a methodical approach to the solution.
4. Experimental part – based on the chosen procedure, perform repeated measurements of suitable artifacts under different input and ambient conditions (e.g. number of frames; measurement positions; camera parameters – focus, aperture, flash; distance from the object; size, quality, number, distribution of reference points; ambient conditions).
5. Processing and evaluation of measured data (SW GOM ATOS Pro), analysis with regard to the assessment of the influence of selected factors on the measurement accuracy of the TRITOP system, discussion, conclusion.
6. Prepare paper on this topic for publication in a technical journal or konference

*Scope of Graphic Work:* according to need
*Scope of Report:* 60
*Thesis Form:* printed/electronic
*Thesis Language:* English

**List of Specialised Literature:**

[1] ZHANG, S. Handbook of 3D Machine Vision: Optical Metrology and Imaging. Boca Raton: CRC Press, 2013. ISBN: 978-1-4398-7219-2.
[2] GOM GmbH. GOM Software 2018: Inspection Basic. Braunschweig (Germany): GOM GmbH, 2018.
[3] GOM GmbH. Acquisition / Inspection Basic, GOM Software 2018, Photogrammetry. Braunschweig (Germany): GOM MbH, 2018.
[4] GOM GmbH. GOM Acceptance Test, Process Description, Acceptance Testaccording to the VDI/VDE Guideline 2634 Part 1. Braunschweig (Germany): GOM GmbH, 2016.
[5] KOTERAS, Robert, Michał WIECZOROWSKI, Piotr ZNANIECKI a Natalia SWOJAK. Measurement strategy as a determinant of the measurement uncertainty of an optical scanner. Archives of Mechanical Technology and Materials [online]. 2019, 39(1), 26–31. ISSN 2450-9469. DOI:10.2478/amtm-2019-0005
[6] LUHMANN, Thomas, et al. Close Range Photogrammetry: Pricliples, techniques and applications. Dunbeath, Caithness KW6 6EG, Scotland, UK: Whittles Pulishing, 2011. p 510. ISBN 978-184995-057-2
[7] KLUS, P. Teoretická a skutečná přesnost měření fotogrammetrického systému Tritop. Brno: Vysoké učení technické v Brně, Fakulta strojního inženýrství, 2018. 91 s.

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Liberec November 20, 2022

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May 21, 2023 Abishake Sakthivel Murugan

## ACKNOWLEDGEMENT

I want to start by thanking my supervisor, Professor Doc. Ing. Radomír Mendřický, Ph.D. for his constant support throughout the entire process. He made this process easy.

Also, I want to thank my department for helping me complete my work successfully. Last but not least, I want to convey my gratitude to my parents, who are the driving force behind everything I do.

## ABSTRACT

The main motive of the thesis is to evaluate the factors that affecting the accuracy, quality and repeatability of the Photogrammetry system Tritop. The object utilized to evaluate the factors is ten calibrated carbon bars, in which two are reference bars and the remaining are measuring bars. All these bars are under VDI/VDE 2634 standard which says its acceptance test. The evaluation is performed in different methods like Photos captured in different distance, Photos captured in four different numbers with same setup, changing the value of flash intensity, Different number of Coded reference points, measured with same bars in different position. The measurement is evaluated in GOM software. The object is measured for three times for each experiment to evaluate its repeatability. The evaluated result is shown in Bar graph for each individual experiment. The values in bar graph are Average, Maximum and minimum for three measurements. Final result will be comparison of each experiment. The result of this work will help to prevent from the uncertainty in accuracy and optimize measurement accuracy of Photogrammetry system Tritop.


**Keywords**: Photogrammetry, Tritop, GOM, Measurement accuracy, Acceptance test


### ABSTRAKT

Hlavním cílem diplomové práce je nalezení faktorů, které ovlivňují přesnost, kvalitu a opakovatelnost měření fotogrammetrického systému TRITOP. K měření je použito celkem deset kalibrovaných uhlíkových tyčí, z toho 2 tyče jako referenční, zbylých 8 tyčí slouží jako měřítko přesnosti při vyhodnocování. Všechny tyče jsou používány v souladu s normou VDI/VDE 2634, která uvádí její akceptační test. Pro nalezení faktorů ovlivňujících přesnost je zkoumáno několik parametrů, jako je změna vzdálenosti od objektu k fotoaparátu, snímání objektu na různý počet fotografií, změna intenzity blesku, změna počtu kódovaných referenčních bodů ve srovnání s referenčním měřením, či změna vzájemné pozice jednotlivých kalibračních artefaktů. Fotografie jsou pořízeny kolem kalibračních tyčí z několika úhlových a výškových pozic. Pro každý parametr byly provedeny vždy tři sady měření. Inspekce byla provedena v software GOM Inspect. Pro každý parametr byla určena hodnota průměru a rozsahu chyby. Dílčí a celkové výsledky jsou porovnány pomocí grafů. Výsledek této práce pomůže předejít nejistotě v přesnosti a optimalizovat přesnost měření fotogrammetrického systému TRITOP.


**Klíčová slova:** Fotogrammetrie, Tritop, GOM, Přesnost měření, Přejímací test

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## LIST OF ABBREVIATION:

3D - 3 Dimension

2D - 2 Dimension

FBM - feature based matching

GCP – Global Coordinate system

MPE – Maximum permissible error

m – meters

mm - millimetres

MPE – Maximum permissible error

RMS – Root mean square

SFM - structure from Moton

# 1. INTRODUCTION

In recent years, laser or optical scanners so-called non-contact technique scanners are highly used for inspection and measurements due to their accuracy and quick measurements. Even though the Contact technique scanners measuring machines provide the most accurate measurements but the problem is that they cannot be used in some cases which has very complex shapes [1]. 3D scanning is process of analysing the real world or environment, which collects the data with its shapes and appearance to construct the 3D model and to analyse the measurements. It also used for reverse engineering [2].

Photogrammetry is a field of science and technology which reproduce its shape, position and sizes of the object on the basis of photogrammetric images. The word photogrammetry comes from Greek word, where photos mean light, grama means a record and metreo means measure.

In late 1990s the photogrammetry measuring system is began to use in some of the industries. But, now a days the development of this system increasing widely. Many industries especially the automobile industry using this photogrammetry system which replaces the Contact Scanners like Coordinate Measuring System [3]. The main advantage of the Photogrammetry system is, if we want to measure the length or size of the object we can measure it, but if we don't have the data and have some images of the objects then it's easy to get the desired data of the object. An image is enough to get the data that we need [4].

The accuracy of photogrammetric system is increasing recent years. However, there are some factors that affect the accuracy of this system. Such as camera resolution, camera calibration or measuring positions, so on. Each of these factors can occur error during the measurements which will analysed in this thesis. The photogrammetry system shown in Figure 1 [5] .

Figure 1 Photogrammetry system [5]

# 2. GOAL OF DIPLOMA THESIS

The main motive of this thesis is to analyse the factors that affecting the accuracy of the photogrammetry system Tritop and to analyse the expected relationship that define the measurement accuracy with the GOM software.

- The photos to be captured with Nikon D-500 for the selected parameters.
- To perform evaluation for each measurement in GOM software and to compare the results of each measurement using graph.
- Describe the factors affecting the accuracy of photogrammetry system for selected parameters.

# 3. SUMMARY OF CURRENT STATE OF KNOWLEDGE

## 3.1. PHOTOGRAMMETRY SYSTEM

Photogrammetry system is defined as art, science & technology used to get accurate information about real world objects and surrounding. It is the technique of capturing and measuring the captured image. It will determine the shape of the object from two or more images. This convert the 2D images to the 3D model, if captured image in different position. The photos are taken in different position which is shown in above Figure 1. The dimension is calculated from the reference point which is set by the user. Photograph is essential thing in photogrammetry measurement. For high accuracy in the measurement the images should be in high quality [6].

The procedure for photogrammetry is first we will take the photos in different position and angle; on the other side the photos are automatically transferred to the software via Wifi. Then the photos are converted to the 3D model shown in Figure 2. From the 3D model it is possible to inspect, document, manufacture and reverse engineering.

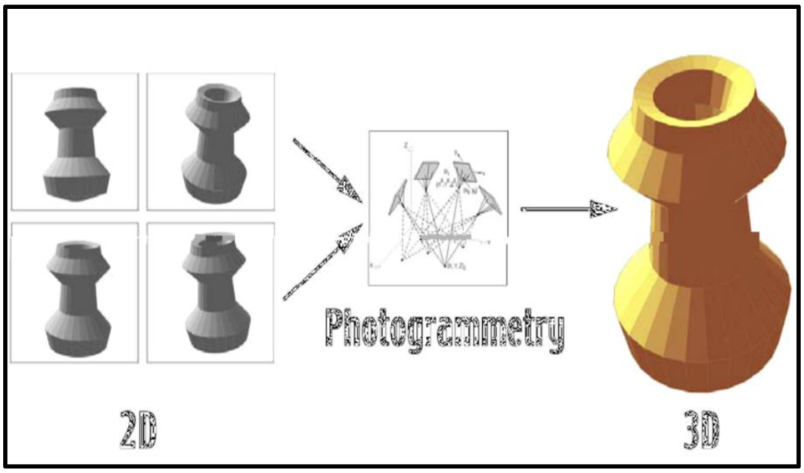



Figure 2 Photogrammetry Process [6]

### 3.1.1. Application of photogrammetry

The photogrammetry accuracy is increasing in recent years, so, this system is used in various application like design and construction, manufacturing, reverse engineering, medicine, etc.,[7].

### 3.1.2. Advantages

- The photogrammetry system is ease to use and highly accurate.
- The photos are enough to measure and reconstruct the real object.
- Convert the 2D image to the 3D model [7].

## 3.2. PHOTOGRAMMETRY PRINCIPLE

### 3.2.1. Geometric Principle 1: Camera Position, Focal length

This principle explains the relation between the length of camera position and object shown in Figure 3.

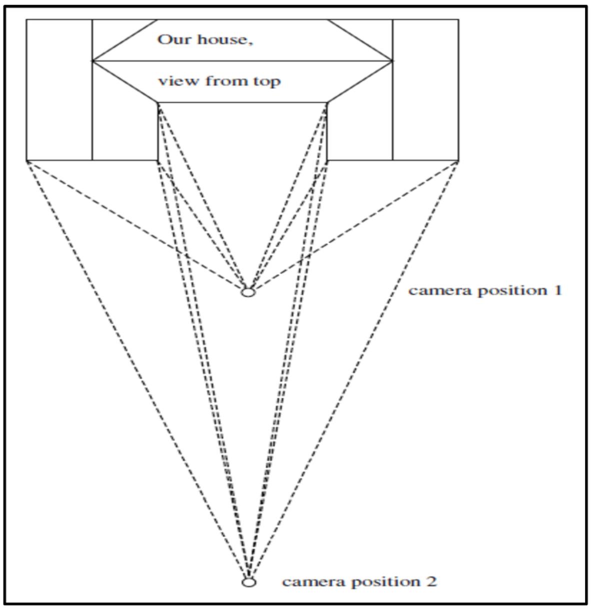



Figure 3 Different camera position and angle lens [4]

The goal is to take the photo of the object. We have many possibilities to do it, we can take from short distance with wide angle lens (camera position 1) and long-distance small angle lens (camera position 2) or from any distance. But the outcome will not be the same result which is shown in Figure 4.

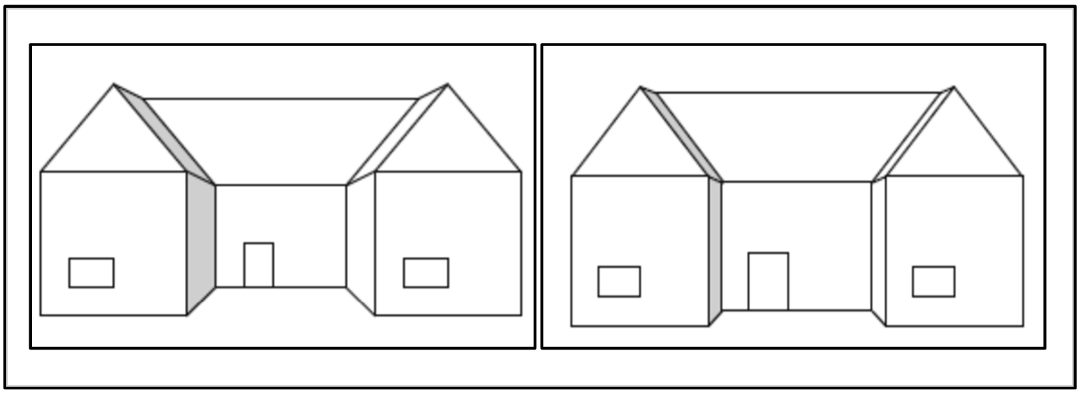


Figure 4 Outcome of Camera Position 1 & 2

From the camera position 1 small position and wide lens where there are displacements are greater. From the camera position 2 long position and small lens where their displacement is smaller.
As a conclusion taking the picture from long distance will have smaller in displacement where there will be good outcome of the image [4].

### 3.2.2. Geometric Principle 2: Image Orientation

First step of the work is reconstructing the orientation of photos, within the object coordination the photos to be arranged. If the coordinates of the projection centre, three rotation angles (X, Y, Z axis), camera focal length are known, then the photo position is unequivocally defined. So, first we set the exterior orientation ($x_0$, $y_0$, $z_0$, φ, ω, k) is shown in below Figure 5.

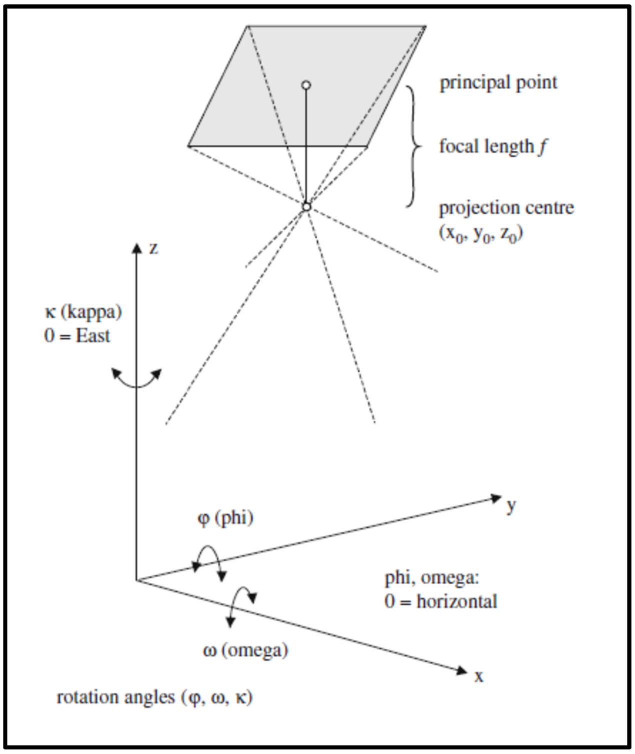



Figure 5 Focal Length, rotation angles and projection centres [4]

The formula of mean photo scale $M_b$ or mean photo scale number $M_b$ is,

$M_b = h_g/f$ or $M_b = 1/m_b = f/h_g$, where $h_g$ is height of the projection centre above ground and f the focal length shown Figure 6.

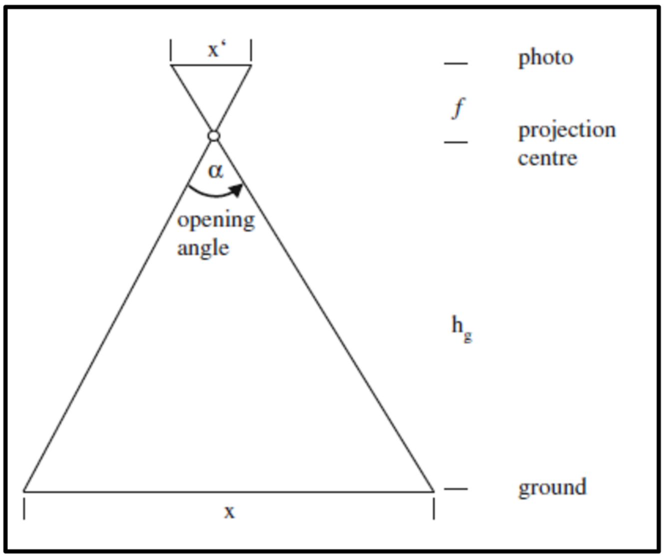



Figure 6 Mean Photo Scale [4]

Depends upon the coordinate system we come to know to which it deals with, first all the photos have 2D coordinate system, that to be converted to 3D coordinate system by changing the angle of φ, ω, k [4]

### 3.2.3. Geometric Principle 3: Relative Camera Positions (Stereo)

To get 3D coordinate of object points, at least two images are required from different views.

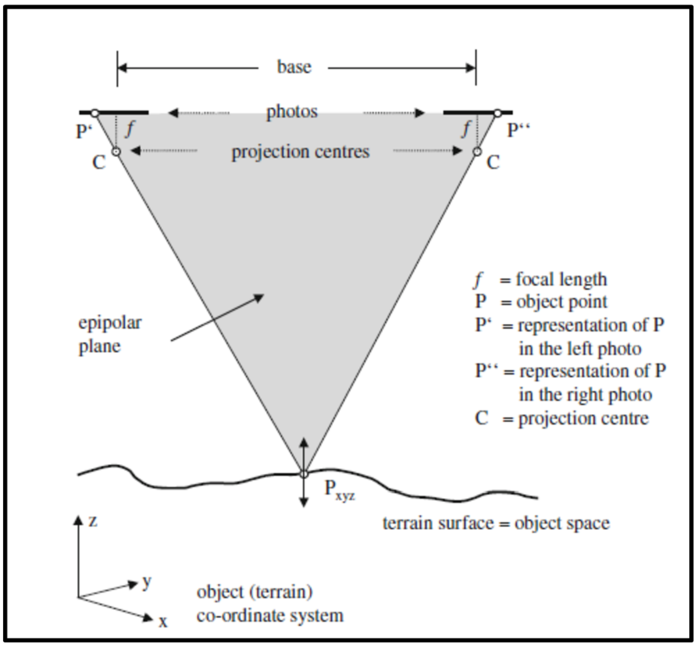



Figure 7 Geometry oriented stereo model [4]

From the above Figure 7, the point P (x, y, z) will be calculated based on the two rays [P′ - P] and [P″ - P]. Depends upon the rays we could say about the accuracy. Smaller angle less accuracy. When the angle is very small in Z axis then there is chance of large error. Besides, to avoid this error, wide angle cameras are best for photogrammetry.

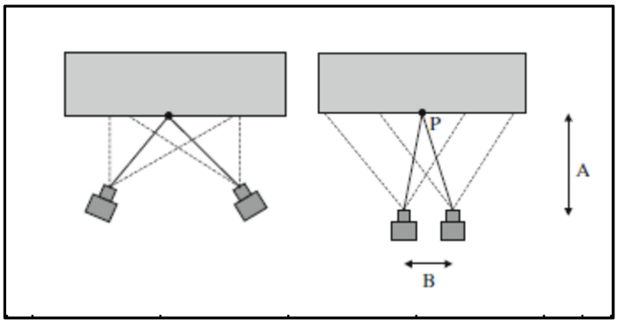



Figure 8 Camera Position Parallel and convergent [4]

From the above Figure 8, let A be the distance between the object and camera. B be distance between two cameras. The accuracy can be increased by changing the position of B. Compare to the convergent B, the parallel B will give good accuracy because of additional perspective distortion in the image. In parallel case, we can expect high precision in Z axis [4].

## 3.3. MATHEMATICAL PRINCIPAL

This chapter is about mathematical principle of photogrammetry in which it will discuss about coordinate system, analysis of internal & external orientation and also the derivation of colinear equation.

### 3.3.1. Coordinate System

The photogrammetry involved in establishing the relationship between the sensor or camera which take images of the object, so to define this relationship it is necessary to know the coordinate system [8].

#### 3.3.1.1. Pixel Coordinate system

The digital image file is defined in the pixel coordinate system. This system coordinates the image with its origin point shown in below Figure 9. where the X axis is denoted as c which is towards the left from the origin and Y axis is denoted as r downwards towards the origin. The file coordinates (c, r) which is also taught as pixel column and row number. The reference of pixel coordinate system is P (c, r) [8].

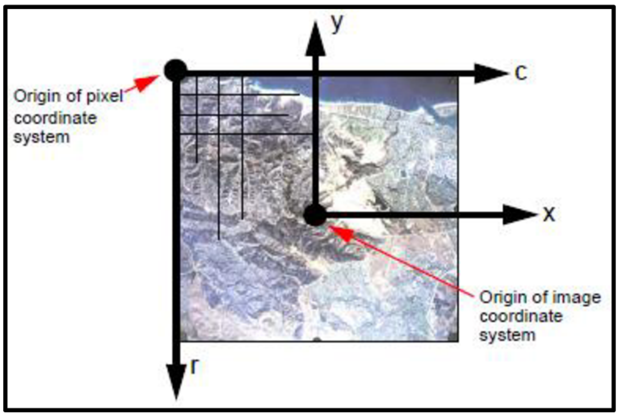



Figure 9 Pixel and Image Coordinates [8]

#### 3.3.1.2. Image coordinate system

The image coordinate system will be in two-dimension x and y, where this axis is from the origin point of image centre shown in above Figure 9. Normally this point is at intersection of fiducial point or principal point. The reference system of this coordinate system is: Image coordinate system (x, y) [8].

#### 3.3.1.3. Image space coordinate system

This coordinate system is same as image coordinate system but the only difference is it has third axis z. The origin of this system is defined as **S** shown in below Figure 10. The axis x and y are parallel to the image plane axis of respective X and Y. The optical axis is z axis, so the value of z will be equal to focal length. This system will describe the position inside the camera. The reference system of the coordinate system is: image coordinate system (x, y, z) [8].

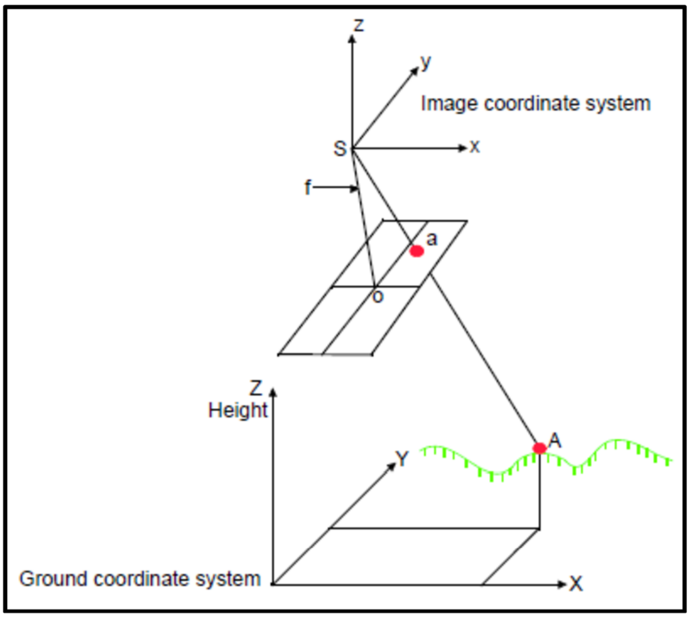



Figure 10 Image space coordinate system [8]

#### 3.3.1.4. Object Coordinate system

The object coordinate system is also called as global coordinate system. This system usually defines the dimension of the coordinate system (x, y, z), where z is elevation of given vertical datum. The reference of this system is: Object Coordinate system (x, y, z) [9].

## 3.4. INTERIOR ORIENTATION PARAMETERS

Interior orientation describes the internal geometry of the sensor or camera which exists during the capture. The variable of image space is defined at the process in interior orientation. This parameter is used for transforming the pixel and image coordinate system to image space coordinate system.

The below Figure 11 shows the variable of the internal geometry during capture. Where **a** represents image point and **o** represents principal point. The internal geometry is defined by four variables they are:

- Principal Point
- Focal length
- Fiducial marks
- Lens distortion [10]

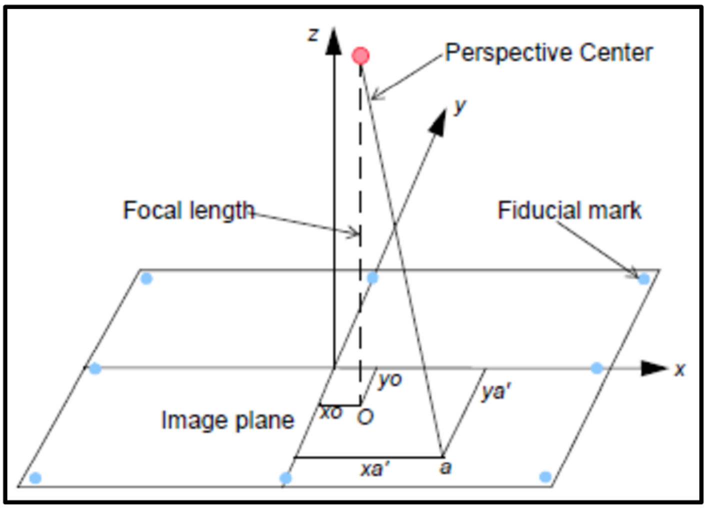



Figure 11 Internal Geometry [10]

### 3.4.1. Principal point and focal length

Principal point is defined mathematically as the intersection line from the perpendicular line to the image centre. The length between the perspective centre to principal point is Focal length [10].

### 3.4.2. Fiducial marks

This defines the image position of principal point for every image. So, the image position of fiducial marks will measure on each image & on other side it is compared with calibrated coordinates of every fiducial marks.

The image space coordinate system is not still defined, the reference of pixel or file coordinate system is measured position of image in fiducial marks. As above discussed, the pixel coordinate has X (column) coordinate and Y (row) coordinate. The origin is defined at the O point of both row and column. The relationship between pixel coordinate and image space coordinate system is defined by 2D affine transformation. The below equation can used to find the coefficients which is required to transform measurement of pixel coordinate to image coordinate.

$$x = a_1 + a_2X + a_3Y$$

$$y = b_1 + b_2X + b_3Y$$

From the above equation, the image coordinate x and y associated with calibrated fiducial marks. The measured fiducial marks in pixel coordinate system X and Y are used to define the six coefficient which is required to transform the pixel coordinate to image coordinate. The quality of affine transformation is defined by root mean square (RMS) error. If the RMS error is large then the quality of the system will be poor [10].

### 3.4.3. Lens Distortion

The lens distortion changes the accuracy of the points located in image plane. This occurs when lights rays pass in bent lens. Radial lens is causing the image points along with radial lines from principal point. At the time of calibration procedure of camera, the lens distortion effect is determined. The lens distortion can be approximate using the polynomial equation (the equation is in below), where we used to find the coefficient of polynomial.

$$\Delta\mathrm{r} = k_0r + k_1r^3 + k_2r^5$$

$\Delta r$ is radial lens distortion along distance r, Using the statistical technique the coefficient ($k_0$, $k_1$, $k_2$) is computed. Once the process is computed then the image measurement is corrected for radial distortion [10].

### 3.5. EXTERIOR ORIENTATION PARAMETERS

The exterior orientation is used to determine the angle and position of the image. The characteristics associated to the image are determined in the exterior orientation during the time of capture. The exterior parameters positional elements are $X_0$, $Y_0$, $Z_0$ from origin to perspective centre O′ shown in below Figure 12.

$$X_0 = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} \text{ Position of perspective centre [11]}$$

The (X, Y, Z) of ground space coordinate system determine the position of perspective centre. The relationship between (X, Y, Z) of ground space coordinate system and (x, y, z) of image space coordinate system are defined by angular or rotational elements of this orientation parameters.

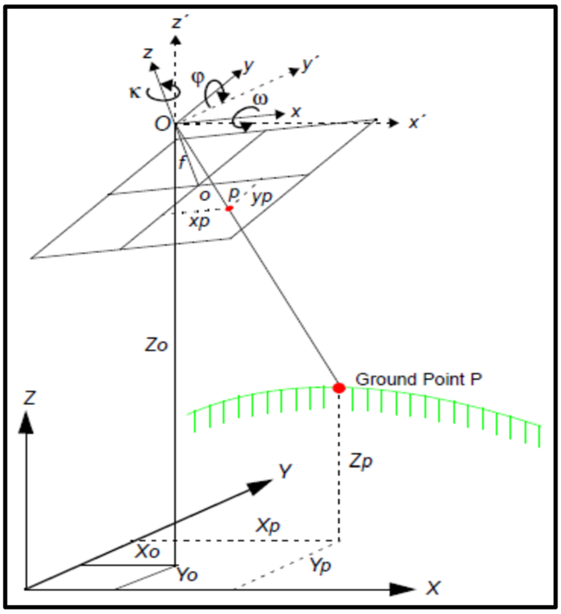



Figure 12 Elements of Exterior orientation [12]

The rotation angle defines angular orientation, the angle is ω – rotation about x axis, ϕ – rotation about y axis, κ – rotation about z axis.

As discussed before the image coordinate position is from origin to perspective centre O′ let's set is as vector $X_0$ the equation is shown in below and R define the angular orientation[12]. The R value can be found using the 3x3 matrix [11].

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

### 3.6. DERIVATION OF COLINEAR EQUATION

The equation determines the relation between the camera, image and ground. Mostly photogrammetry tools use this formula in one form or another. From the above exterior orientation figure 12 the image vector a is from the O to image point P. The ground vector and image vector are colinear and the line interfering from the image point to the ground point is linear.

As mentioned above the ground vector and image vector are colinear, if the one scalar multiple to other then the equation will be,

$$a = kA$$

From the above equation k is scalar multiple. Both the vector image and ground should be in single coordinate system. So, an image vector is comprised to,

$$a = \begin{bmatrix} x_p - x_0 \\ y_p - y_0 \\ -f \end{bmatrix}$$

where from the above form x and y are image coordinate of principal point. Similar to the image vector a, the ground vector A is formulated,

$$\mathrm{A} = \begin{bmatrix} X_p - X_0 \\ Y_p - Y_0 \\ Z_p - Z_0 \end{bmatrix}$$

Both the image vector and ground vector are in same coordinate system, therefore the ground vector is multiplied with the matrix R. The equation is formulated as,

$a = kRA$

So,

$$\begin{bmatrix} x_p - x_0 \\ y_p - y_0 \\ -f \end{bmatrix} = \mathrm{kM} \begin{bmatrix} X_p - X_0 \\ Y_p - Y_0 \\ Z_p - Z_0 \end{bmatrix}$$

The equation will define the relationship between the perspective centre of sensor or camera exposure station and P ground point which appear on the image with image point p. The above equation forms the basic colinear condition which is used in most of the photogrammetry operations,
the exposure station, ground point and image point lie in same straight line being collinear, two equation comprises the above collinearity equation. For each ground point that appear on image, any one set of equation can be formulated. Then equation is [13],

$$x_p - x_0 = -f\left[\frac{r_{11}(X_p - X_{0_1}) + r_{12}(Y_p - Y_{0_1}) + r_{13}(Z_p - Z_{0_1})}{r_{31}(X_p - X_{0_1}) + r_{32}(Y_p - Y_{0_1}) + r_{33}(Z_p - Z_{0_1})}\right]$$

$$y_p - y_0 = -f\left[\frac{r_{21}(X_p - X_{0_1}) + r_{22}(Y_p - Y_{0_1}) + r_{23}(Z_p - Z_{0_1})}{r_{31}(X_p - X_{0_1}) + r_{32}(Y_p - Y_{0_1}) + r_{33}(Z_p - Z_{0_1})}\right]$$

### 3.7. BUNDLE ADJUSTMENT

Bundle adjustment simultaneously calculates both interior and exterior orientation along with object coordinate for subsequent analysis.

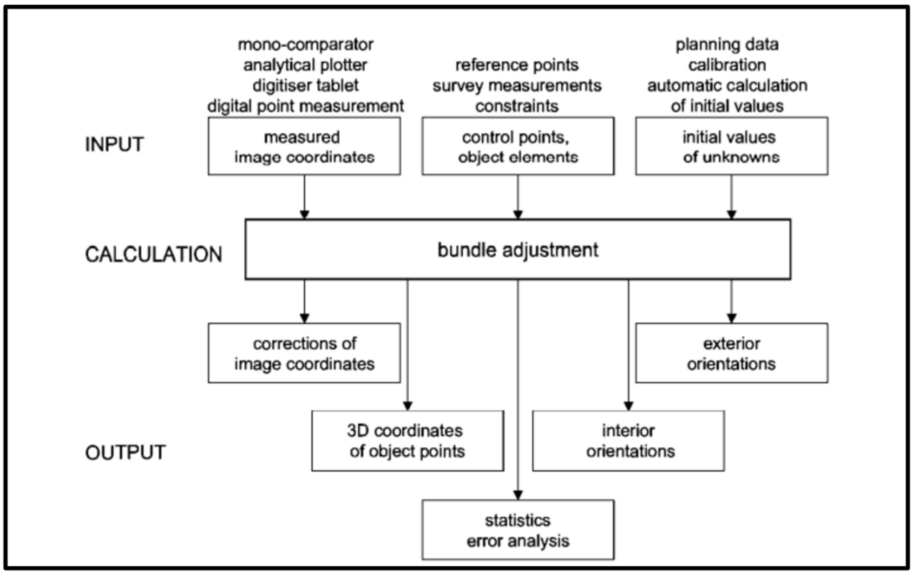



Figure 13 Bundle Adjustment process [11]

The above Figure 13 shows the data flow of bundle adjustment. Input data will be the image coordinate value from the photographs. Each of the image point is saved in unique point identifier and image number. This information is enough to construct the 3D models. The angles, measured length is also taken into account for this process. They provide absolute scale, position and object coordinates. This all above information goes into the system as reference points.

To make the process easy only accurate values are needed, to get accurate information a greater number of photos to be taken, photo quality should be high. The exterior orientation elements for all the image are estimated.

The principal result of this process is 3D coordinate of the object points. They are provided in a coordinate system of object determined by reference point or else free net adjustment [11].

### 3.7.1. Algorithm Principle

The below Figure 14 shows two image one is tie points and known points which is GCP (global coordinate points). The tie points are used to determine the image orientation in space by connecting each image with one another.

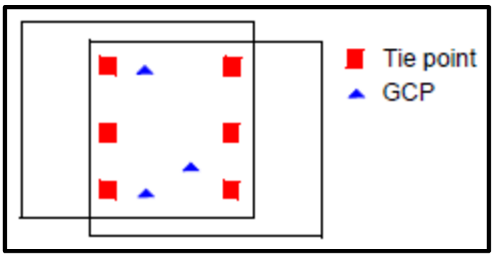



Figure 14 Photogrammetric Configuration [14]

For all the measured known points there will be two corresponding x and y image coordinate. To categories the relationship among ground point image measurement correspond to ground point two collinearity equation is formed which is called as observation equations. From the above Figure 14 there are three GCP points which is known points, there are two know point from that it is possible to form around 12 equations. There are 6 tie points where 24 equations are formulated. Therefore totally 36 equations are formulated which is called as observation equations.

From the above Figure 14 the following unknowns are:

- For the left image (X, Y, Z, ω, ϕ, κ) 6 exterior orientation elements
- For the right image (X, Y, Z, ω, ϕ, κ) 6 exterior orientation elements
- There are X, Y, Z three coordinate system for tie points, from 2 photos 6 tie point present, therefore 6 times the 3 coordinate which 18 unknown points.

There are 30 unknowns. As discussed above there are 36 equations and 30 unknown equations, by subtracting this the redundancy is 6. Which is also referred as degrees of freedom. Once observation equation is formulated then it is solved by non-linear least square method [14].

### 3.7.2. Least square method for Bundle Adjustment

This method is used to find the unknown parameters and minimizing the error within the solution. The least square method is used for:

- To find and adjust values in exterior orientation
- To find and adjust values in interior orientation
- Minimise the error
- To find the tie points X, Y, Z coordinates.

The solution is obtained gradually by iterations. These iterations are stopped once the data of input is minimised. Once the data is minimised the following formula is followed:

$$A_m X_m = L_m + V_m$$

- V= matrix contains image coordinate
- A = matrix contains partial derivatives w.r.t unknown parameters as discussed above
- X= matrix contains correcting the unknown elements
- L = matrix contains input observations like image and known coordinate.

All matrices are directly connected to functional model based on colinear equation. Depends upon the colinear equation the A matrix is formed by differentiating the colinear model. By subtracting the initial results with the estimated new results in iteration the L matrix is formed. The X matrix is correction of unknown value of exterior orientation [14].
There is various algorithm are used to solve this least square method like Newton-raphson method, Gauss-newton method, Gradient descent method and Levenberg Marquardt method (this method is most used method because of its effect).

### 3.7.3. System using Bundle adjustment

In the Tritop system there are number of systems that use this algorithm like Photomodeler, Australis, IGP-ETHZ, V-STARS and others.
The author **Remondino** showed the difference of each software by comparing with one another by using 3D test field shown in Figure 15. The results are in table 1[15].

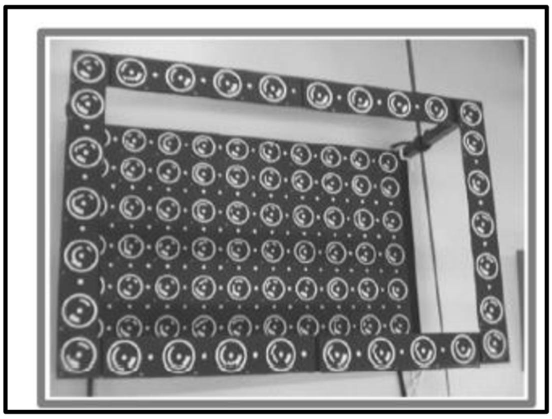


Figure 15 Test field [15]

Form the below table 1 each system tells the mean square deviation of image points. The value differs in each software but the same result in each individual coordinate of the object

Table 1 Accuracy of bundle algorithm in different software [15]

| Software/Algorithm | Root mean square Deviation (x, y) (µm) | Root mean square Deviation (x, y, z) (mm) |
|---|---|---|
| Photomodeler | 0.36 | 0.01/0.01/0.02 |
| Australis | 0.29 | 0.01/0.01/0.02 |
| IGP-ETHZ | 0.30 | 0.01/0.01/0.02 |

### 3.8. ACCEPTANCE TEST & REVERIFICATION

Checking the accuracy is fundamental important thing before starting the measurement. In the field of optical measurement, the standard measurement method is VDI/VDE 2634/1 to 3 it defines the acceptance, reverification and monitoring accuracy measurement of the system. The goal of this test is final proof of accuracy measurement in defined environmental condition. In industry the system is checked with the already calibrated part to make the system to work with accuracy. For photogrammetry VDI/VDE 2634/1 method is used to enable the accuracy of the system. This standard method is focused on point scanning. The below Figure 16 is calibrated rods of dimension 2x2x1.5m. For acceptance test number of photographs are taken in different angle [16].

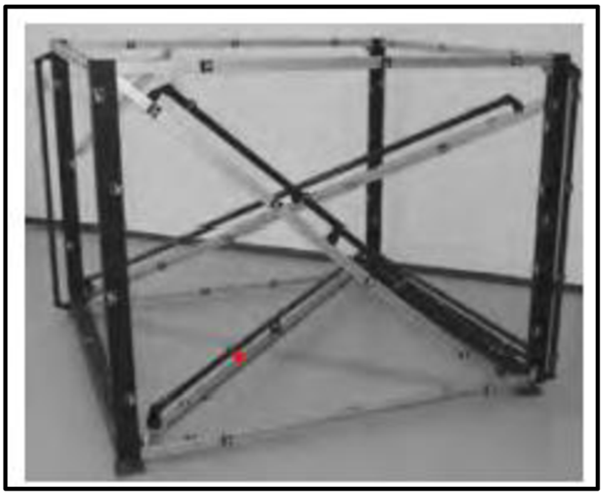


Figure 16 Test Rod for Acceptance Test [16]

The seven scale bars are arranged three bars are parallel to the coordinated axis and other four bars are arranged to diagonal of cuboid measurement volume. To increase the number of reference points in the bars, each bar is subdivided in which it provides 21 different lengths. Once the process is done if the deviation is lies between the given interval, then the process is set to be success and ready for the measurement.

### 3.8.1. Reverification

Reverification is periodical checking of the system after the commissioning. Comparing to acceptance test, reverification process is simple. It is examined by the user [16] .

## 3.9. FACTORS AFFECTING ACCURACY OF PHOTOGRAMMETRY

### 3.9.1. Photogrammetric Method and its effect in accuracy

The photogrammetry system uses cloud points for measuring. There are two methods used in photogrammetry FBM feature based matching and SFM structure from Moton. In the Tritop system the cloud points are known as Coded marks. Atleast, 5 coded marks are need from the image for measurement. The author **Fraser** [17] experienced two photogrammetry methods in his work. In his experiment he compared coded tag and FBM method. The camera used is Nikon D200, totally 11 photographs are taken and 22 coded tags are placed in the object for each experiment. The object is shown in below figure 17. The result is shown in below table 2.

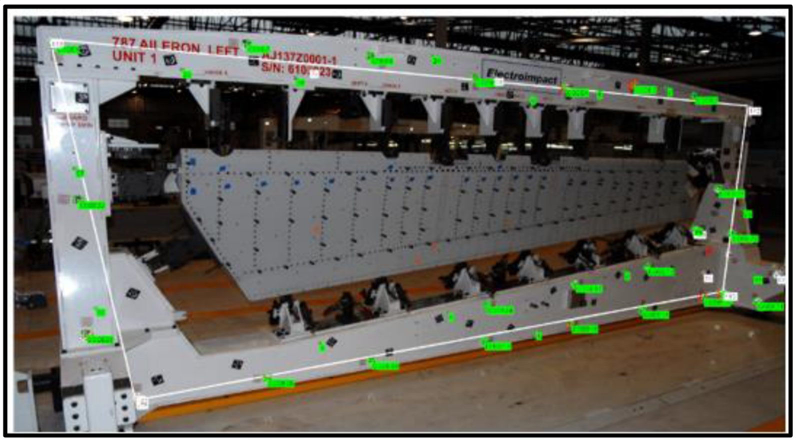


Figure 17 Object used for FBM approach [17]

Table 2 Results for the Measurement FBM approach [17]

| Bundle Adjustment Details | Targeted | Non-Targeted FBM |
|---|---|---|
| No of 3D points | 200 | 490 |
| RMS σx | 0.11 mm | 0.21 mm |
| RMS σy | 0.08 mm | 0.42 mm |
| RMS σz | 0.14 mm | 0.20 mm |
| RMS σxyz | 0.12 mm | 0.30 mm |

During measurement in the FBM method some unnecessary points are detected during measurement. As a result, the coded marks measurement is more accurate compare to the FBM.

### 3.9.2. Influence of Used camera

We know that the camera is very important thing in photogrammetry process, to acquire high accuracy of measurement it is essential to know what camera to be used. The author **Chandler** [18] experienced that accuracy of low resolution camera is high compare to high resolution due to the focus lens used. Use of Quality of lens leads to good accuracy of the system.

### 3.9.3. Influence of Calibration model

In the photogrammetry system the calibration is also plays an important role. The two most used method for calibration is Zhang and Tsai method. The Tsai method of calibration using the test field estimates the all exterior and important interior parameters by solving linear equations. The Zhang method is lies between self-calibration and test field, it is enough for the camera to observe only planner pattern. The author **Feng** [19] compared this method with 9*7 square pattern with Sony Iex-285 camera The results are shown in below table. Compare to the methods Zhang method has best results and validity. The comparison shown in below table 3.

Table 3 Comparison of Zhang and Tsai Calibration model [19]

| Variable | Zhang | Tsai |
|---|---|---|
| Deviation on X axis | 0 | 0 |
| Deviation on Y axis | 6.821 | 7.729 |
| Total Time spend (s) | 80.407 | 23.047 |

### 3.9.4. Influence of Colour spectrum

The influence of colour spectrum also affects the accuracy of measurement in photogrammetry. The below figure 18 shows that all the different colour spectrum is not fallen in same position after it passes the lens this is known as chromatic Aberration. The result of radial distortion is also dependents on the colour spectrum [21].

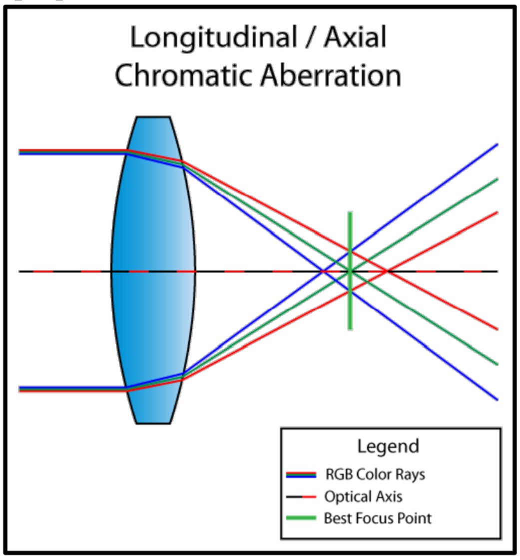



Figure 18 Chromatic aberration diagram [20]

This author **Fraser** [15] examines this problem with SONY DSC F828 camera with 8 Mega pixel and focal length 10mm. The below figure 19 tells the radial distortion for each channel compare to green and blue channel the blue channel has largest distortion the difference is about 10 pixels at sensor edges. For accurate measurement the author tells two possible options one uses the external filter to record single colour image and another possible option is for each image self-calibrate the lens distortion.

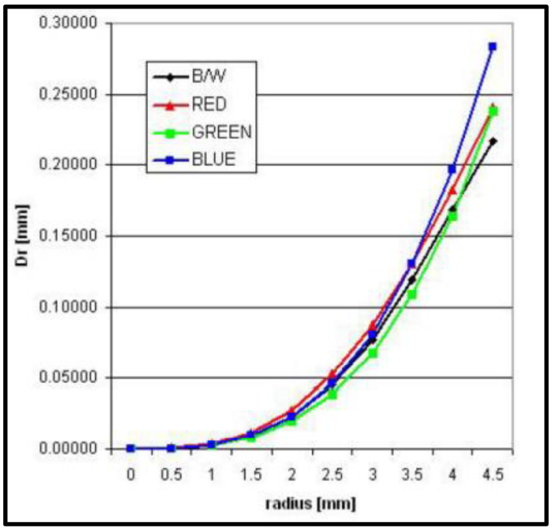



Figure 19 Degree of Radial Distortion in 3 colour channels [15]

### 3.9.5. **Influence of convergent angle between images**

In the photogrammetry process the photographs are taken in different position to reconstruct the object. During the photograph if the position of camera is close to 90° with respect to the object, then the result will cause the small error. From the below figure 20 the camera station 1 is same in good and bad position. Compare to the results the bad position the good position has small error because station 2 position is acute angle to station 1. To avoid this error preferred point should be fixed and from that point 2 or more photos are taken if the position is incorrect in any one of the photo other photos will supress the error which is recommended option [21].

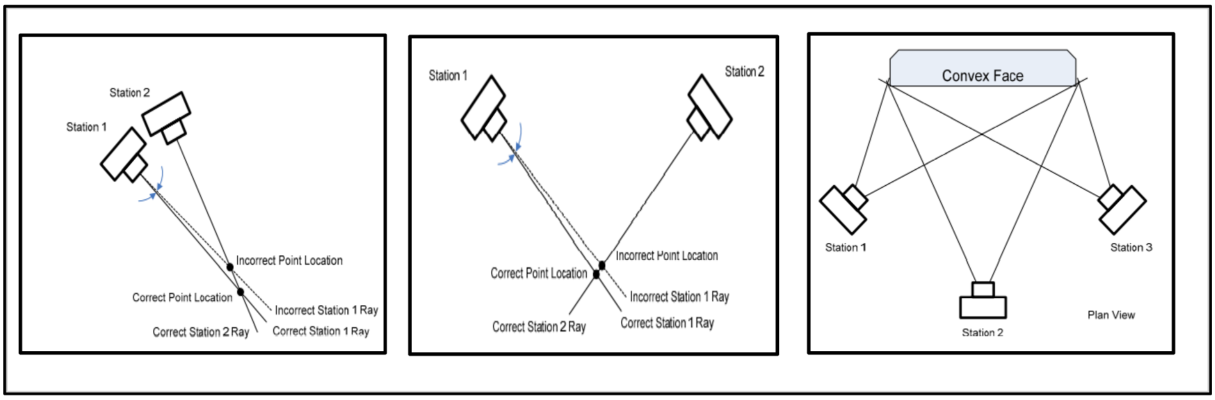



Figure 20 Good camera position, Bad camera position and Recommended Camera position

### 3.9.6. Influence of Redundant images

As discussed above the location of point is found from the image. As we know number of photos make accurate measurement in photogrammetry. The **Fraser**[22] author examines how the quality of photos affect the accuracy of the photogrammetry. The author measured Hobart radio telescope shown in below figure 21. This telescope is measured in camera INCA4 with focal length 18mm. The convergence angle θ depend on curvature reflector 60°-100°, At least four points are needed for measurement. The measurement of V-stars which fall under the category of measurement with coded marks are evaluated.

The standard deviation of points is 0.065. The author limited the measurement up to the angle θ is 50° in which it not scanned in circular path which is shown in below figure 22 the black square indicates the camera position for measurement. Given these difficulties, the author's only choice was to take a huge number of measurements using hyper redundancy, which required low errors. A total of 435 photos were captured, and the telescopes with three different position vertical, 45° tilted, and horizontal were all scanned. He worked the bundle adjustment procedure with a tremendous number of degrees of freedom because there were so many frames, which allowed him to spot significant measurement inaccuracies. Four or more locations were often found in each image that caused a significant mistake into the measurement and were thus eliminated from the calculation. The redundant in photos leads the average measurement deviation was 0.034 mm, satisfying the criteria for maximum errors.

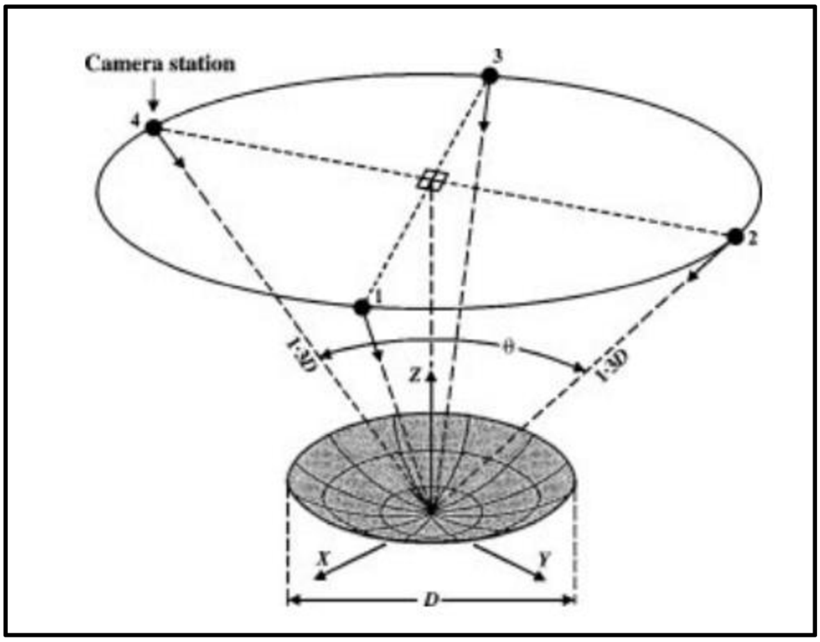



Figure 21 Hobart radio telescope for measurement [22]

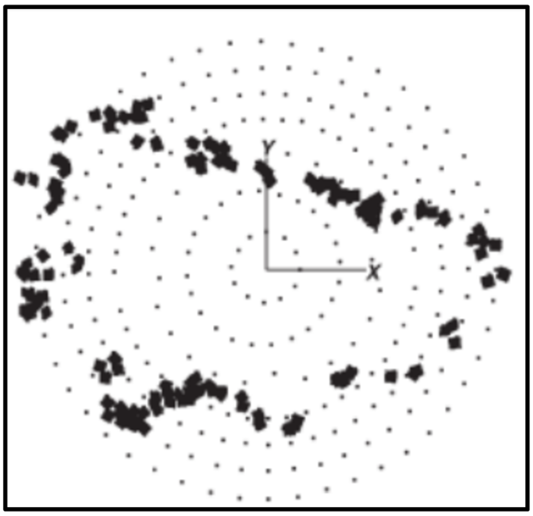



Figure 22 Camera Position during measurement

### 3.9.7. Effect of Lighting and brightness

During the photogrammetry process if there is over lighting in surrounding leads to inaccuracy in measurement. The author **Golparvar** [23] done an experiment using FBM method and geosystem software. He had measured the construction building from outdoor and indoor. During indoor measurement he used artificial lighting which results in good accuracy. At the outdoor measurement the sunlight effect made the result 4% greater inaccuracy compare to the Indoor results. At the time of measurement if the background is dark then we will use the flash light which will end in inaccuracy because the flash light reflects new reference mark, so the system measures the dimension in wrong way. But now the photogrammetry system automatically warns during measurement that the image does not use for calculation.

# 4. TRITOP PHOTOGRAMMETRY SYSTEM

TRITOP Photogrammetry system is a non-contact measuring system used for industrial use. Before the measurement the object is glued with uncoded reference points, and the coded reference points are placed near the object. Once the photos are taken in different position and in different angle the TRITOP software calculates the 3D coordinate automatically based on the reference points. Using the reference points, it is possible to gather different direction images into single image. With the single image it is possible to calculate the 3D coordinate system. Based on the reference points the camera position can be determined. The point rays of line reference point makers shown in below figure 23. The TRITOP software's primary function is the accurate search for ellipses (reference points seen in perspective) in a collection of photos and the spatial fitting of those ellipses. Software called TRITOP makes it possible to identify measurement points in the coordinate system based on measurement images [3]

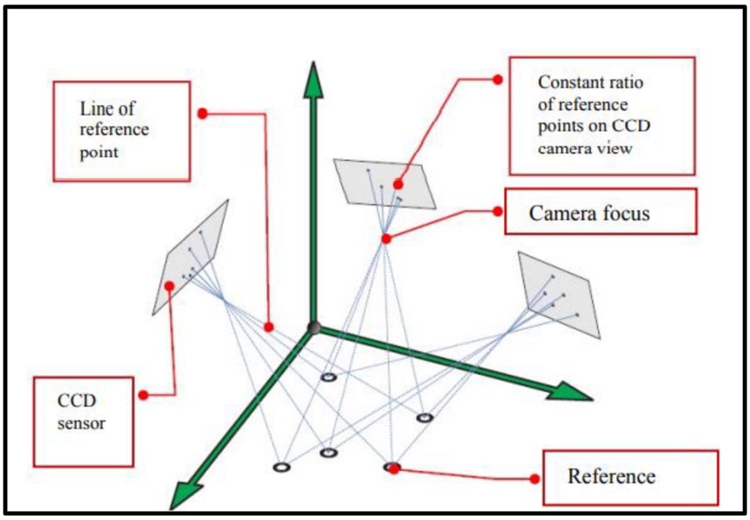



Figure 23 Points rays of reference point makers [3]

## 4.1. THEORETICAL ACCURACY OF TRITOP SYSTEM

### 4.1.1. Accuracy of Tritop System by Manufacturer

According to the regulation of VDI / VDE 2634 the Maximum permissible error specified by the Tritop manufacturer, GOM company is

$$MPE = \pm (5 + L/50)\ \mu m$$

Where, L = Length in mm

MPE = maximum permissible error

The above relationship used only for measure length not other factor entering the measurement [3].

### 4.1.2. Experimental Verification of theoretical accuracy of Tritop system

The author **Grzelka** [3] conducted Tritop Photogrammetric coordinate system accuracy using VDI//VDE 2634 and ISO 10360 standards. Two standard compatibility is maintained. One is measured value length gauge blocks are used and calculated as well as determined maximum permissible error for each sample of the Tritop coordinate system.

$$MPE = = \pm (4 + L/100)\ \mu m$$

Where, L = Length in mm, MPE = maximum permissible error

The author came to the conclusion that the system's actual accuracy is higher than its declared producer. He also noted that the calibres had their maximum length in the measurement of 500 mm, so to corroborate its findings, you would need to conduct a second study to look at calibrated blocks of higher sizes, such as 1000 and 2000 mm.

### 4.2. Accuracy of Photogrammetry system according to several factors

The Company GOM published a theoretical relationship on the basis of several factors which predicts the accuracy of photogrammetry system. The relation is

$$\sigma_C = \frac{d}{f} * \sigma$$

where,

σc = deviation of reference points in mm

σ = accuracy of image in mm

d = object distance in mm

f = focal distance in mm

The parameter is created by multiplying the average deviation of picture points parameter by the pixel size (the size of one of its sides in mm, not the entire area). For accuracy prediction purposes, the user selected the frame point average deviation option based on his prior experience. The Tritop program shows the precise value of this parameter after the measurement. Independent research that would confirm the validity and practical applicability has not yet been produced.

**Fraser** [22] described another relationship predicting the accuracy of the photogrammetric system dependent on the multiyear parameters. The author provides a simplified formula for calculating the standard deviation of a point's coordinates, which depends on the quantity of pictures utilized among other things:

$$\sigma_C = \frac{\sigma}{\sqrt{k}} * \frac{d}{f} * q$$

Where,

σc = average deviation of coordinate in object points in mm

σ = average pixel deviation μm

k = number of photos used

d = distance of object in m

f = focal length in mm

q = factor range 0.5-0.7

The empirical factor varies depending on the convergent angle; values between 0.5 and 0.7 correspond to high convergent angles (60 to 100 degrees). As discussed before the location of the convergent angle between two images gives further details. A graphic representation of the relationship between convergent angles, the quantity of images taken, and the precision of measurements pertaining to the computed coordinates for item X, Y, and Z in figure 24.

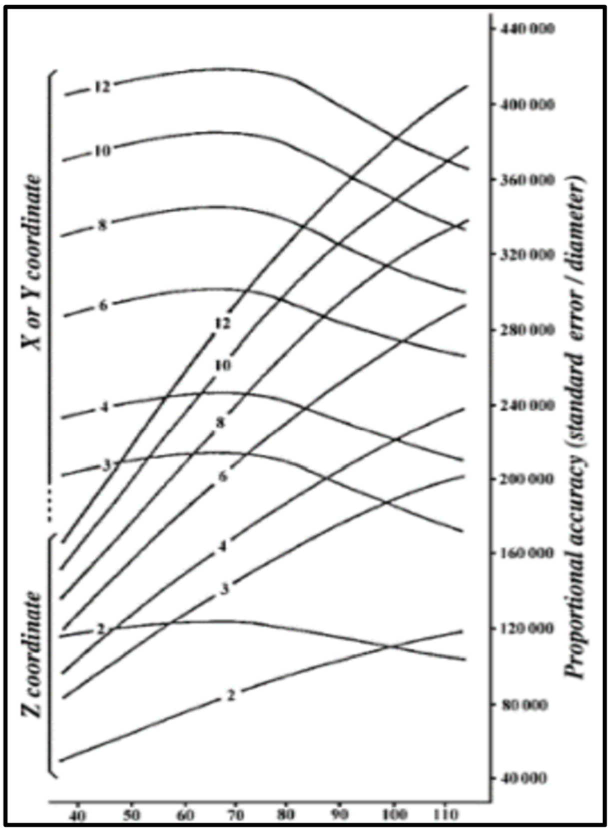



Figure 24 Accuracy of measurement according to convergent angle dependent on no of p
tographs to the object coordinates X, Y, Z [22]

The proportional measurement accuracy (measurement error / average measured item) in relation to the estimated coordinates of the object X, Y, and Z is shown on vertical axis. Convergent angles are described on a horizontal axis. The number of images taken is indicated by the numbers at each curve in the graph.

# 5. METHOD OF MEASUREMENT

## 5.1. Object Used for measurement

The object used for measurement is Carbon calibrated bars. The calibrated bar used since its exact dimensions is known. As a result, the object's deviation may be easily determined during the measurement. A total of ten calibration bars of different sizes are used and from those two bars used as reference bars for all the experiment. These bars are based on the VDI/VDE 2634/1 standards, which describe the photogrammetry measurement acceptance test. The surrounding temperature is 21°C. The components used for evaluation are orientation cross, coded reference points, Uncoded reference Points. The calibrated bars are made of carbon, which has a very low thermal coefficient where there is no possibility of deformation. Each bars have the coded points in it which the software identifies the bar. Detail description about the calibration bars, measurement setup, parameters and evaluation are explained in upcoming topics.

## 5.2. Components Used for measurement

### 5.2.1. Photogrammetry Camera

Different photogrammetry camera systems with various camera resolutions are available from GOM. Based on housings for professional digital reflex cameras, the photogrammetry cameras capture data. These cameras come with a flash and a manual fixed focus lens. Each photogrammetry camera system has been checked and approved in the manufacturing. The accuracy of the measurements is ensured by this process [24]. For this research Nikon D 500 camera us used shown in below figure 25 [24] .


Figure 25 Nikon D500 Camera

### 5.2.2. Scale Bars

The size of the object determines the choice of end gauges. Placement of the pattern should not interfere with the tested element or the reference points. End gauges are outfitted with additional coded reference points at predetermined distances in order to uniquely identify uncoded reference points. The software uses defined and numbered reference points to automatically identify length patterns [3]. The scale bars are shown in below figure 26. The bars have both coded and uncoded points. For this research the scale bars are used which is calibrated under VDI/VDE 2634/1 standards. The distance between the top and lower coded points and the distance between the top and lower uncoded points is used to calculate the length of uncoded patterns.

Figure 26 Scale Bars [24]

### 5.2.3. Coded Reference Markers

The TRITOP system can connect a sequence of measurement images using coded reference points, and it can also use them to locate the camera automatically. Using of more coded reference makers results in high accuracy and these points are spread around the object.

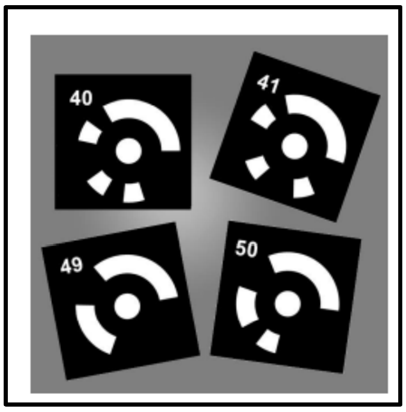



Figure 27 Coded reference Markers [24]

### 5.2.4. Uncoded Reference Markers

With the help of uncoded reference points, coordinates can be determined automatically. The TRITOP program will automatically identify those points. The measurement job determines how they are laid out. Using this uncoded reference makers the object length can be measured. In a semi-automatic mode, TRITOP can also detect 3D points, patterns, and lines drawn on the object. To find the point's location, pictures must be obtained from three separate camera angles [3]. The different types of uncoded reference points are shown in below figure 28.

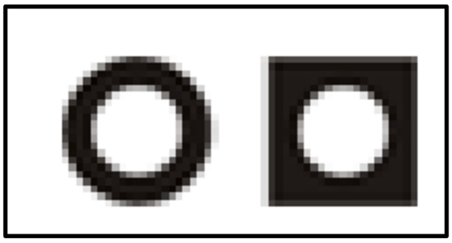


Figure 28 Uncoded Reference Markers [24]

### 5.2.5. Orientation Crosses

An orientation crosses is part of a photogrammetry system. Numerous coded reference point indicators are pre-installed on the orientation crosses during manufacturing. Coded reference point markers can be applied using the orientation crosses for the measurement object quickly and easily. This alignment cross establishes the 3D photogrammetry measurement project's coordinate system (XYZ). The cross bar is kept in middle of the object used to set its coordinate system. The orientation cross is shown in below figure 29 [24].

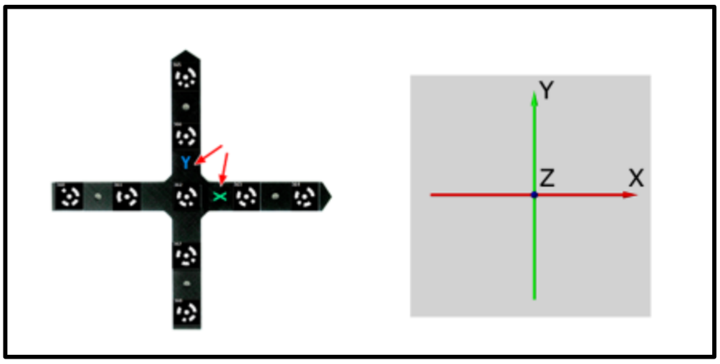



Figure 29 Orientation cross [24]

### 5.2.6. GOM Software

The measuring system images are uploaded to the Tritop Professional program, which analyses the resulting 3D coordinates using the measured points from the bundle adjustment procedure [24].

### 5.3. Calibration bars

The measuring bar used for experiment is four 1m bars (D1, D2, D3, D4), one 0.7m of cross bar (K1 & K2) and two 0.4m bars (D5 & D6). The reference bar for all the experiment is two 0.25m (R1 & R2). All the bars are placed in the floor in different position for the measurement. The exact dimensions of each bar are shown below table 4.

Table 4 Calibration Bar keywords and its length

| Calibration bar | Key words | Nominal Calibrated length of bar (mm) |
|---|---|---|
| 1m bar | D1 | 952.35 |
| | D2 | 951.917 |
| | D3 | 949.051 |
| | D4 | 949.275 |
| 0.4m bar | D5 | 364.901 |
| | D6 | 364.801 |
| **0.25m bar** | **R1** | **223.088** |
| | **R2** | **223.524** |
| 0.7m Cross bar | K1 | 660.105 |
| | K2 | 660.829 |

### 5.4. Procedure for evaluation

#### 5.4.1. Image Capturing method

The image captured using Nikon D500 camera for each experiment is shown in below figure 30, first the calibration image is taken in four different angle 0°, 90°, 180°, 270°. After taking the calibration photos the photos are taken around the object shown figure 30 [24]. The important thing to be seen during taking photos is at least 5 coded reference points should be visible in every image.

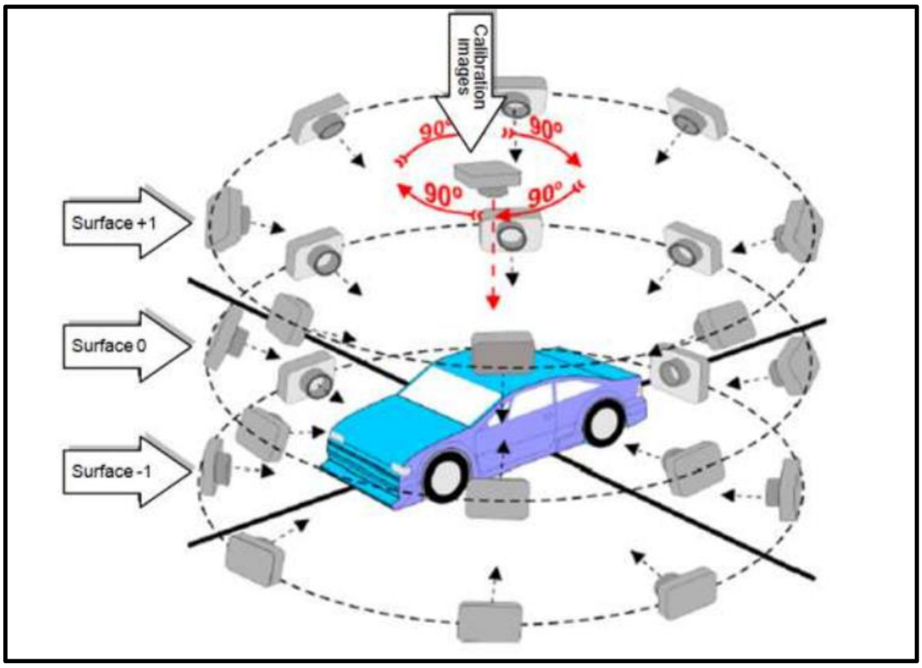



Figure 30 Image taking method [24]

### 5.4.2. Importing Images

To evaluate the object first we need to import the images to the software. When opening the GOM software, screen start is shown in figure 31. After selecting the new project, the captured photos to be imported.

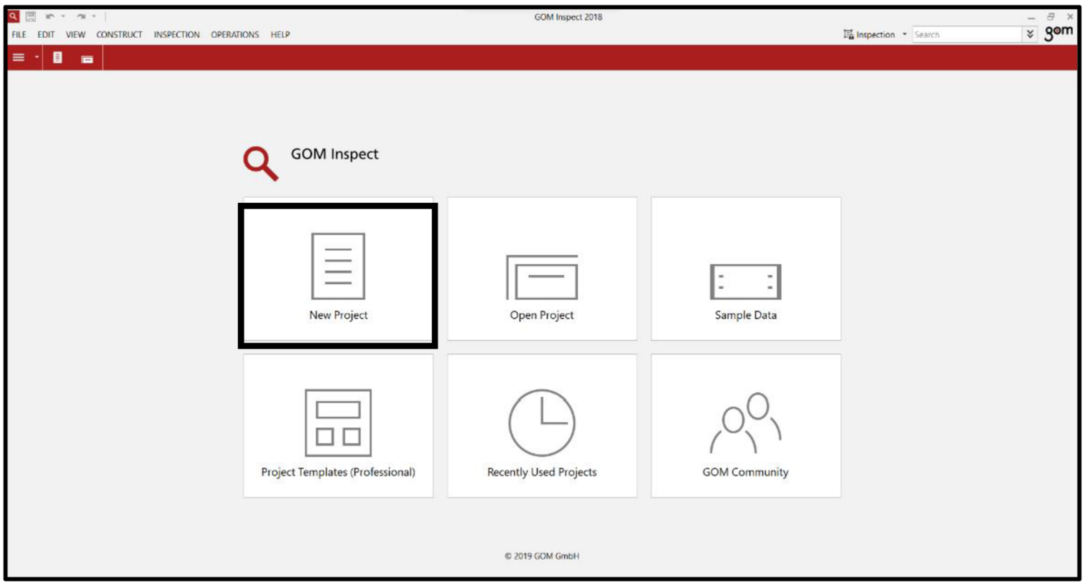



Figure 31 Start screen of GOM software

After the Photos are imported to the software, the import file to be given as Photogrammetry image shown in figure 32. Once the photos are imported then the image to recalculated which the system compute and bundle the capture images.

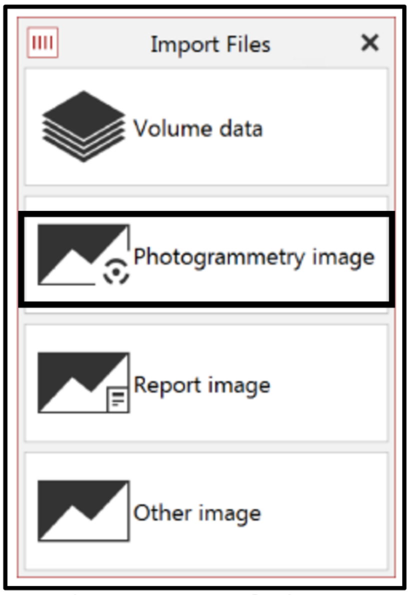



Figure 32 Import Option

### 5.4.3. Image Mapping

In the image mapping it is possible to see the 2D camera image from the different position. We can get the good overview of the object from different position in different view. It is possible to combine the inspection with different images.

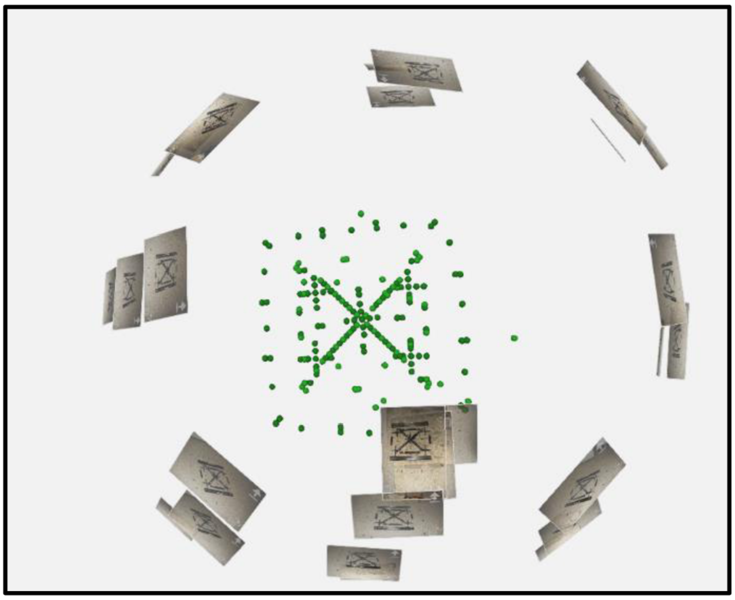


Figure 33 Image Mapping

### 5.4.4. Selecting Dimension

The coded points will not be visible in the captured image, before starting the evaluation it is necessary to enable Inspect coded points in the parameter setting shown in below figure 34.

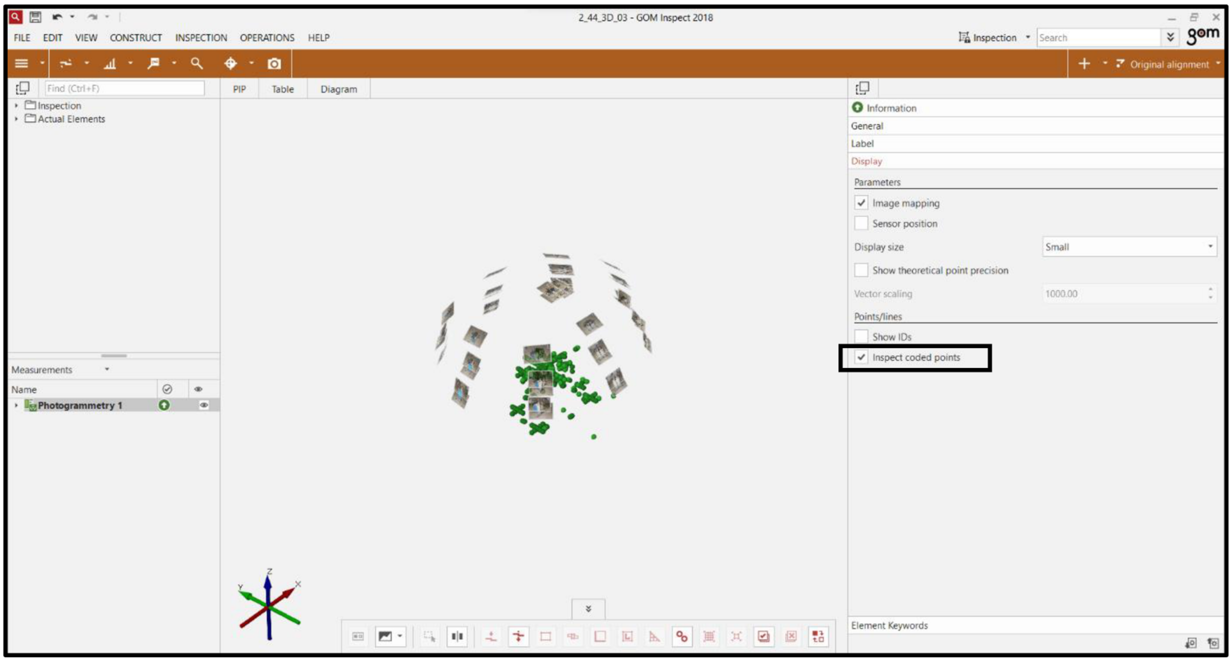



Figure 34 Enable the coded points

For measuring the dimension, on construct option in tool bar the values are calculated shown in below figure 35.

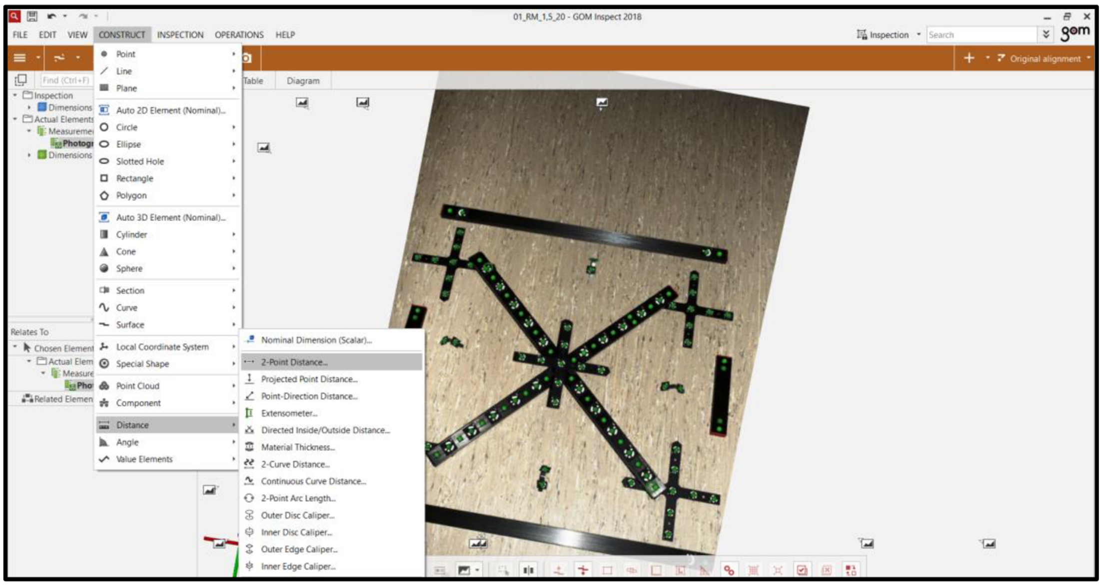



Figure 35 Dimension Construction

### 5.4.5. Inspecting the dimension

To inspect the required parameter, click on the search symbol (I - inspect) shown in figure 36. By clicking that, a pop-up will appear asking for the original length of the selected part; once the value is entered, it will display the actual value of the selected dimension and deviation.

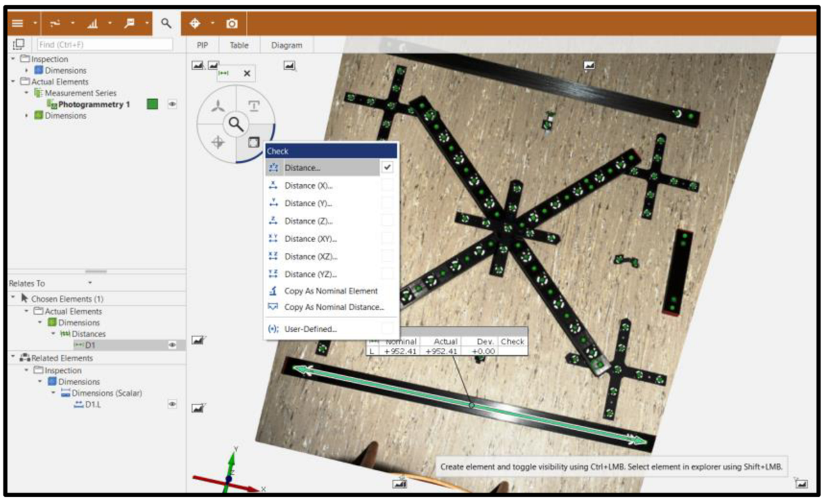


Figure 36 I- inspect Option for giving dimension

### 5.4.6. Graph used for result

As already discussed, the photos are taken in three different sets, for each experiment there will be three deviations. For three deviation the average value is calculated. The bar graph is used for visualizing the results. The X axis is of the graph is Bar for each measurement series and Y axis is Deviation. In the bar graph the value of average is shown in clustered column form, the Maximum and minimum value in Scatter form shown in below figure 37. Let us assume $f(x)$ is average, the equation of average is shown below,

$$f(x) = \frac{\sum_{i=1}^{3} x_i}{3}$$

where,

$f(x)$ = Average value

x = deviation value

i = number of measurements

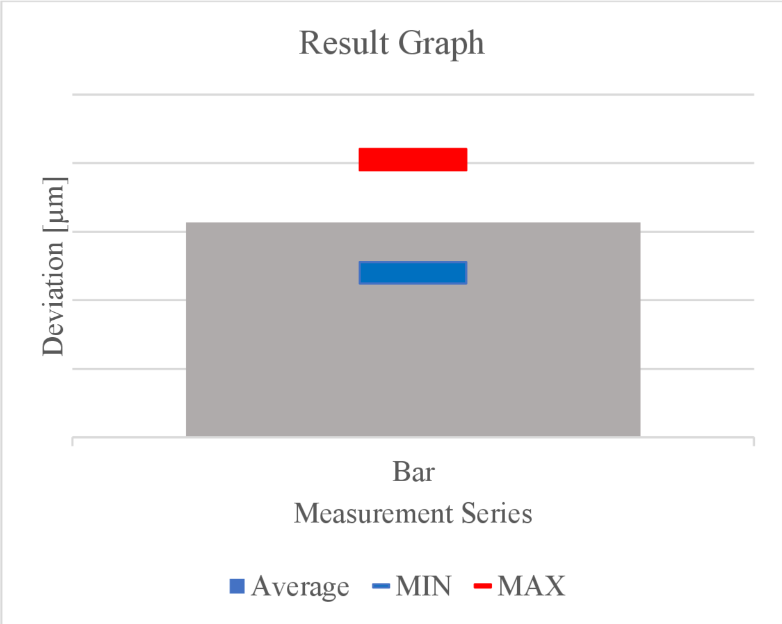



Figure 37 Result for each experiment

### 5.5. Description of Performed Experiments

The evaluation is performed with different experiments and bar positions. The pictures are captured around the bar three times to demonstrate its repeatability. GOM software is used to evaluate the photos. The deviation result is expressed in a bar graph. The experiment is evaluated in:

- Different distance
- Different series of photos
- Different flash intensity
- Different number of coded reference points
- Bar Parallel position and Combination of Horizontal & vertical (H & V) position
- Bar position in 3D Setup

For Distance measurement and parallel and combination (H & V) only four measuring bar (D1, D2, K1, K2) and two reference bars (R1 & R2) are used and remaining experiment all the bars are used for evaluation.

#### 5.5.1. Measurement in Different distance

In the previous chapter discussed about how to take photos for the large object. The coded reference points do not lie only on the one level, that should lie in all the levels. The below figure 38 [24] shows the principle of tiling method. The tiling method is a shooting technique. The total length of the car is 5m the maximum the camera covers is 3m, so the tiling method is used which cover the marginal area that leads to prevent error during the evaluation.

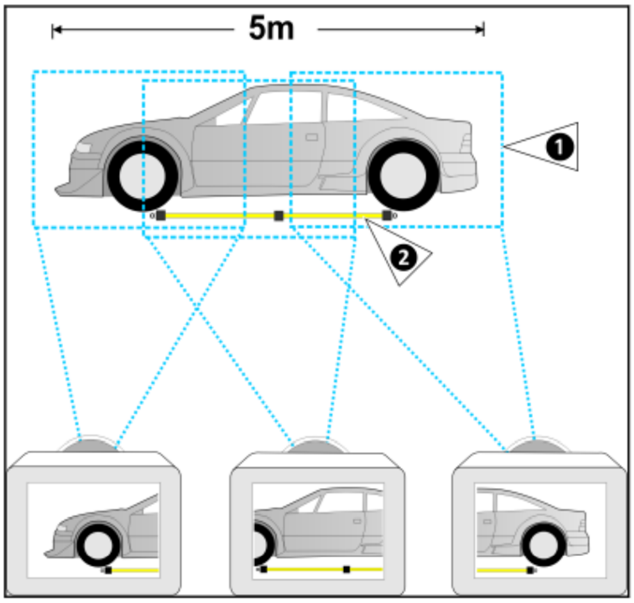



Figure 38 Tiling shooting technique [24]

1. The camera view
2. Scale bar

Whenever the photos are taken if there is good connect with other picture then the result will be good. Even during the evaluation if the required measurement is in single image, then the time of evaluating the object will be less. The author **Grzelka** [3] says that the maximum distance between the object and camera can be up to 10m. For our experiment the measurement is evaluated in three different distances. For each distance 20 photos are captured. The measurement set up for this experiment is shown in below figure 40. The distance between camera and the centre for each set of measurement is 1m, 1.5m and 2m. From the figure 39 we can see the difference in distance clearly.

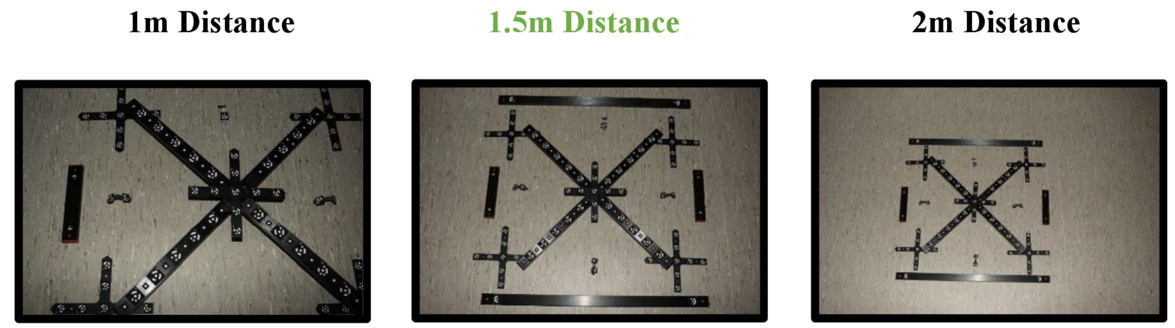



Figure 39 Captured Image for Distance Measurement

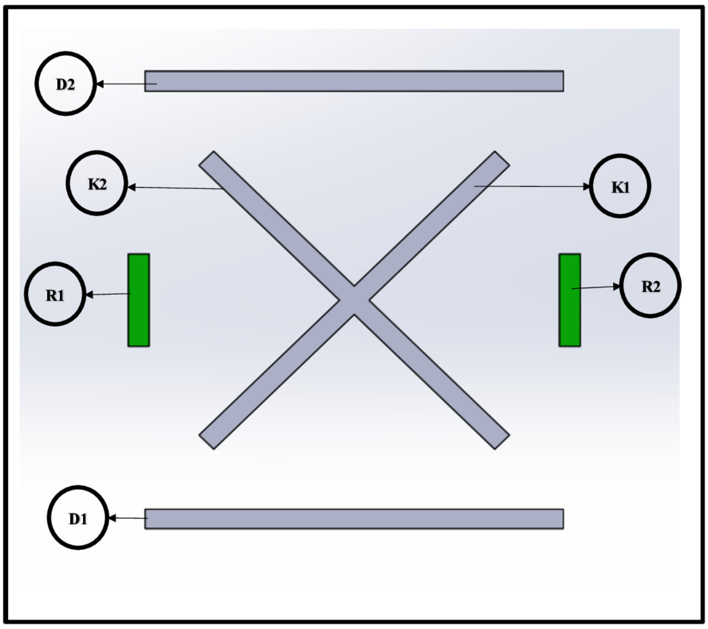



Figure 40 Measurement setup for distance measurement

### 5.5.2. Measurement with Number of Photos

In this experiment the photos are captured in four different series for same setup. The measurement setup for this experiment is shown in figure 41. In this setup we have used 4 more extra bars compare to the above distance measurement. The different number of photos are 40, 20, 12 & 12 Photos (in different position). The image mapping for each 4 series evaluation is in below figure 42. In the table we can see the location of camera around the measuring object.

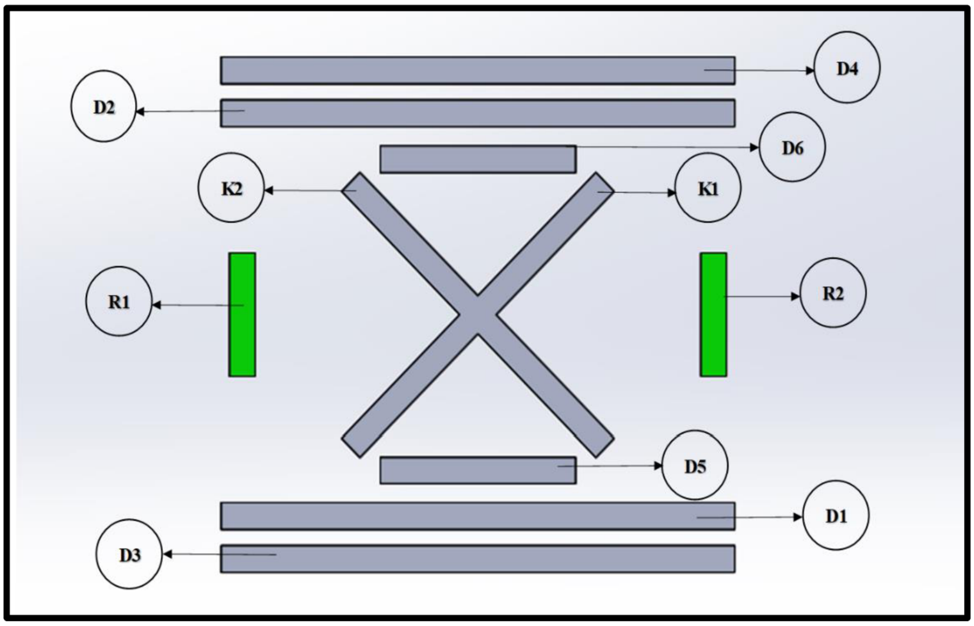
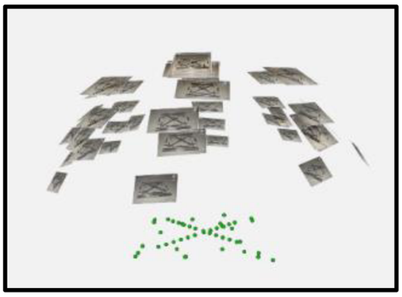
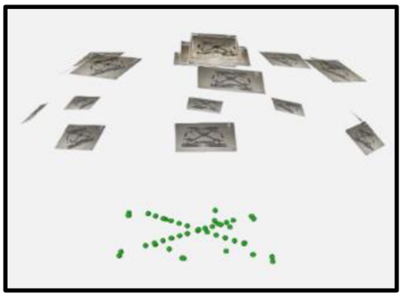



Figure 41 Measurement setup for No of photos, Flash and reference methods

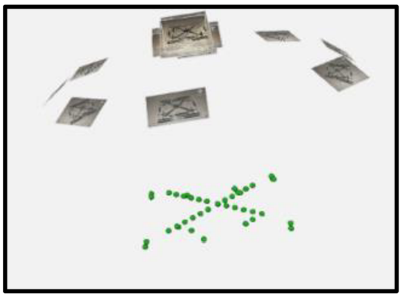
**40 Photos:**



**20Photos:**



**12 Photos:**



**12 Photo:**

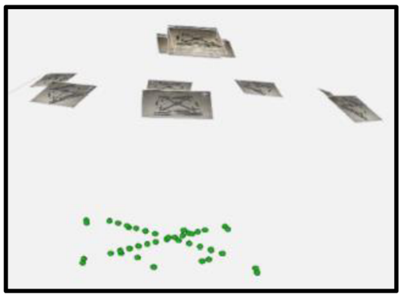


Figure 42 Image mapping view of number of photos experiment

### 5.5.3. Reference Result for Flash and reference point parameters

The result of the 20-photo experiment acts as the reference for the next flash and reference point experiments. The reason for using this 20-photo experiment as reference is that the setup of the experiment is same but only the method of evaluation is differing.

### 5.5.4. Measurement with intensity of flash

The experiment is evaluated by changing its intensity setting in the flash part of the camera. After changing the intensity setting the focal length to be changed as per the requirement. The Photos are captured in under and over exposure of flash. The figure 43 shows the output of captured photo in this setting.

**Reference setup (20 Photos) 1/4 Equivalent to 1.5m** **1/1 Equivalent to 3.8m** **1/32 Equivalent to 0.6m**

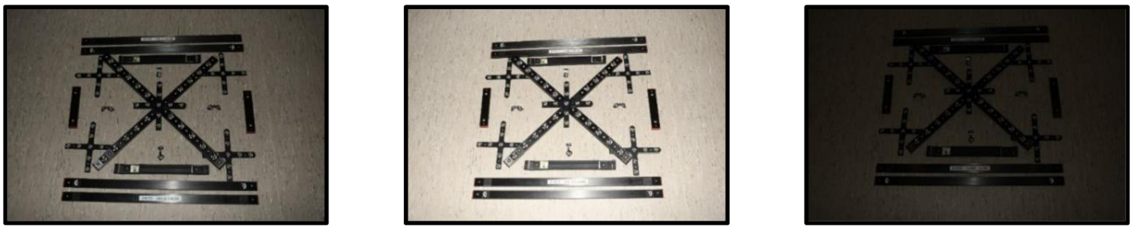


Figure 43 Captured image of Intensity of flash parameter and reference measurement

### 5.5.5. Measurement with Reference point

The coded reference point is used to determine the object in the 3D space. Before taking the image, it is necessary to spread the reference point around the object. In the manual it tells that if the coded reference point is more than the accuracy is high. During evaluation of this experiment more number of coded reference points kept around the object (179 coded points) and 28 images are captured. Then only 43 coded points are kept. Form the figure 44 it shows clearly how much coded reference points are used during measurement.

**Reference setup (20 Photos) 78 coded reference points** **179 coded reference points** **43 coded reference points**

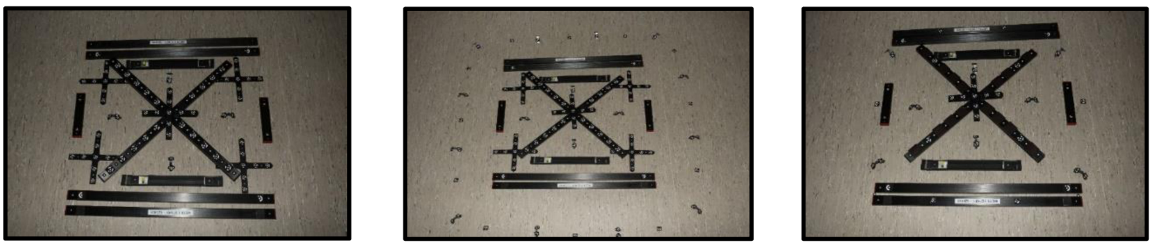


Figure 44 Captured image for reference point experiment and reference measurement

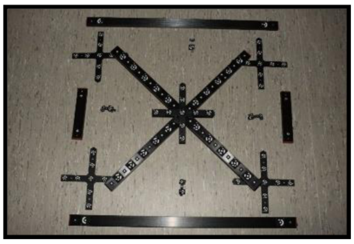
### 5.5.6. Measurement with different setup

This topic is about the position of the calibration bar. The same bars are used for the measurement, but the thing is the bars are kept in different position from the above executed experiment.

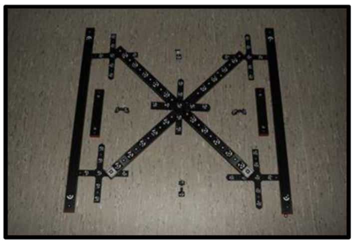
#### 5.5.6.1. Calibration Bar Parallel and Combination Vertical & Horizontal Setup

The experiment is evaluated by changing the position of bars from the distance measurement. In the distance measurement parameters, the bar D1 & D2 are kept parallel and R1 & R2 are kept parallel but horizontal to 1m bars but in parallel setup the 0.25m and 1m bars are parallel to each other and in the horizontal setup D1 & R1 is horizontal, D2 & R2 is vertical. In figure 45 we could see the position of bars in each experiment. The photos are taken from this setup and evaluated. The result for this setup is compared with 1.5m distance measurement result as the scanning parameter are same.

**Reference measurement 1.5m distance**



**Bar Parallel**



**Bar Horizontal & vertical**

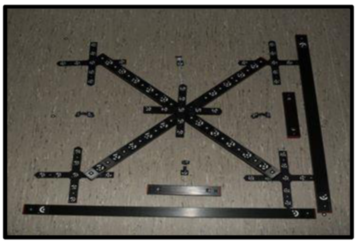


Figure 45 Different bar setup from distance measurement

#### 5.5.6.2. Calibration bar 3D Setup

In this experiment the bars are kept on and around the table. In this 3D setup the position of reference bar is changed in three different areas. From the figure 46 we can see the placement for reference bars.

First the reference bars are kept in top of the table. Then the reference bars are kept on the floor near the table and finally one bar kept on the table and another one in the floor near the table. The photos are captured for each experiment and evaluated.

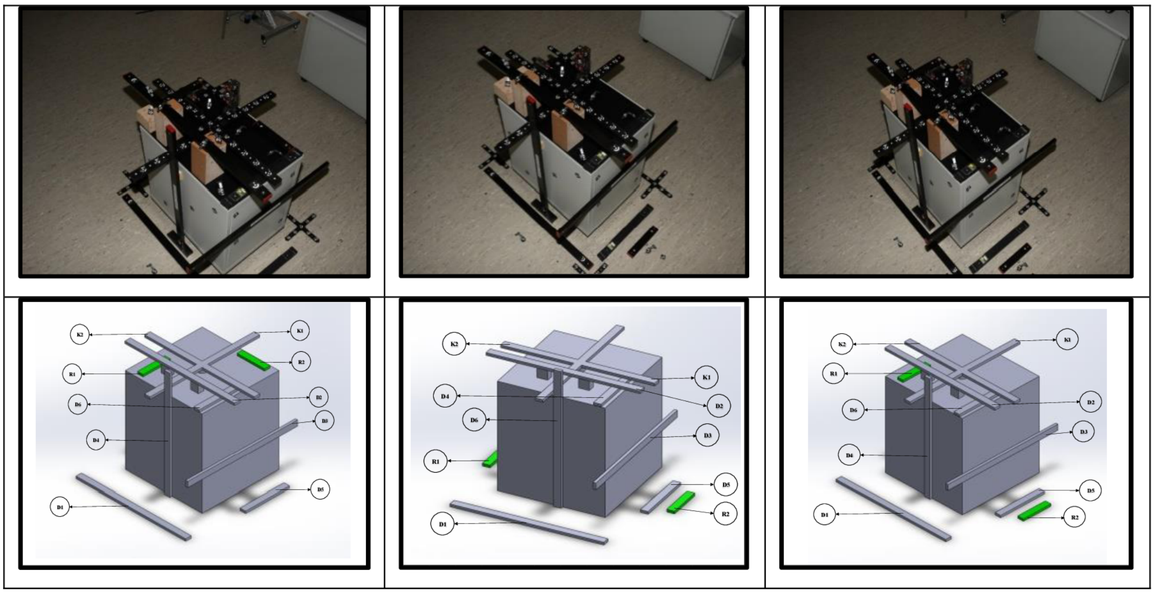


Figure 46 Position of Bars in 3D setup

# 6. RESULTS

As discussed above the average deviation, Maximum and minimum value is shown in bar graph. From the three series the value of average is calculated.

## 6.1. Analysis of results for distance measurement

The scanning parameters for this experiment is shown in table 5. The measurement is done in three different distance which is highlighted in below table. The deviation value is shown in table 6 below.

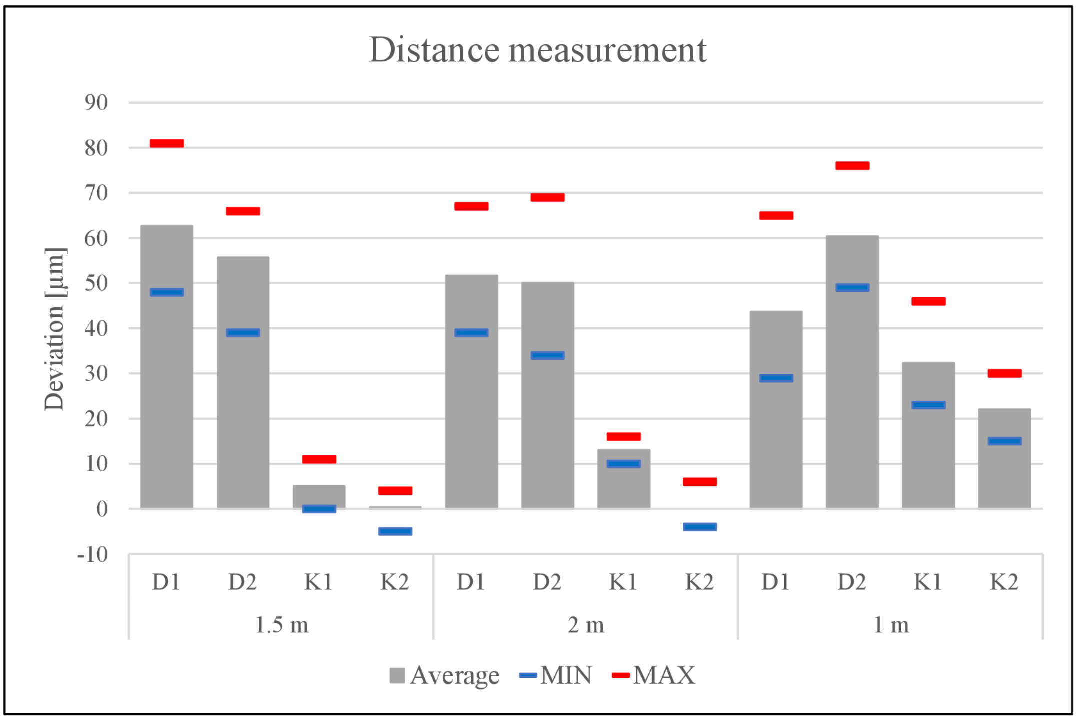
Table 5 Scanning parameters of Distance measurement

| | **Measurement series** | | |
|---|---|---|---|
| **Parameters** | **Distance measurement** | | |
| Distance | **1.5m** | **1m** | **2m** |
| Number of photos | 20 | 20 | 20 |
| Light | 1/4 equivalent to 1.5m | 1/4 equivalent to 1.5m | 1/4 equivalent to 1.5m |
| Number of coded reference points | 78 | 78 | 78 |
| Number of uncoded reference points | 40 | 40 | 40 |
| Number of scale bars | 2 | 2 | 2 |
| Temperature °c | 21 | 21 | 21 |

Table 6 Deviation value for Distance Measurement

| Measurement Series | 1.5m Distance | | | 2m Distance | | | 1m Distance | | |
|---|---|---|---|---|---|---|---|---|---|
| **Bars** | **Average** | **MIN** | **MAX** | **Average** | **MIN** | **MAX** | **Average** | **MIN** | **MAX** |
| **D1** | 63 | 48 | 81 | 52 | 39 | 67 | 44 | 29 | 65 |
| **D2** | 56 | 39 | 66 | 50 | 34 | 69 | 60 | 49 | 76 |
| **K1** | 5 | 0 | 11 | 13 | 10 | 16 | 32 | 23 | 46 |
| **K2** | 0 | -5 | 4 | 0 | -4 | 6 | 22 | 15 | 30 |

The ultimate goal of this experiment is to know about the parameters that influence the accuracy of the system when scanning at different distances. In practice the photos can be captured up to maximum of 10m. In our case, the photos are captured in three different distances (1m, 1.5m, 2m) and evaluated. From the above graph 1 in 2m result the average deviation and repeatability has less compared to other series but not much difference (only 15 to 20 micros).




Graph 1 Deviation result for Distance measurement

### 6.2. Analysis of results for Number of Photos

The scanning parameters for this number of photos experiment and important parameter is highlighted in below table 7 and the deviation occurred during the evaluation is shown in table 8.

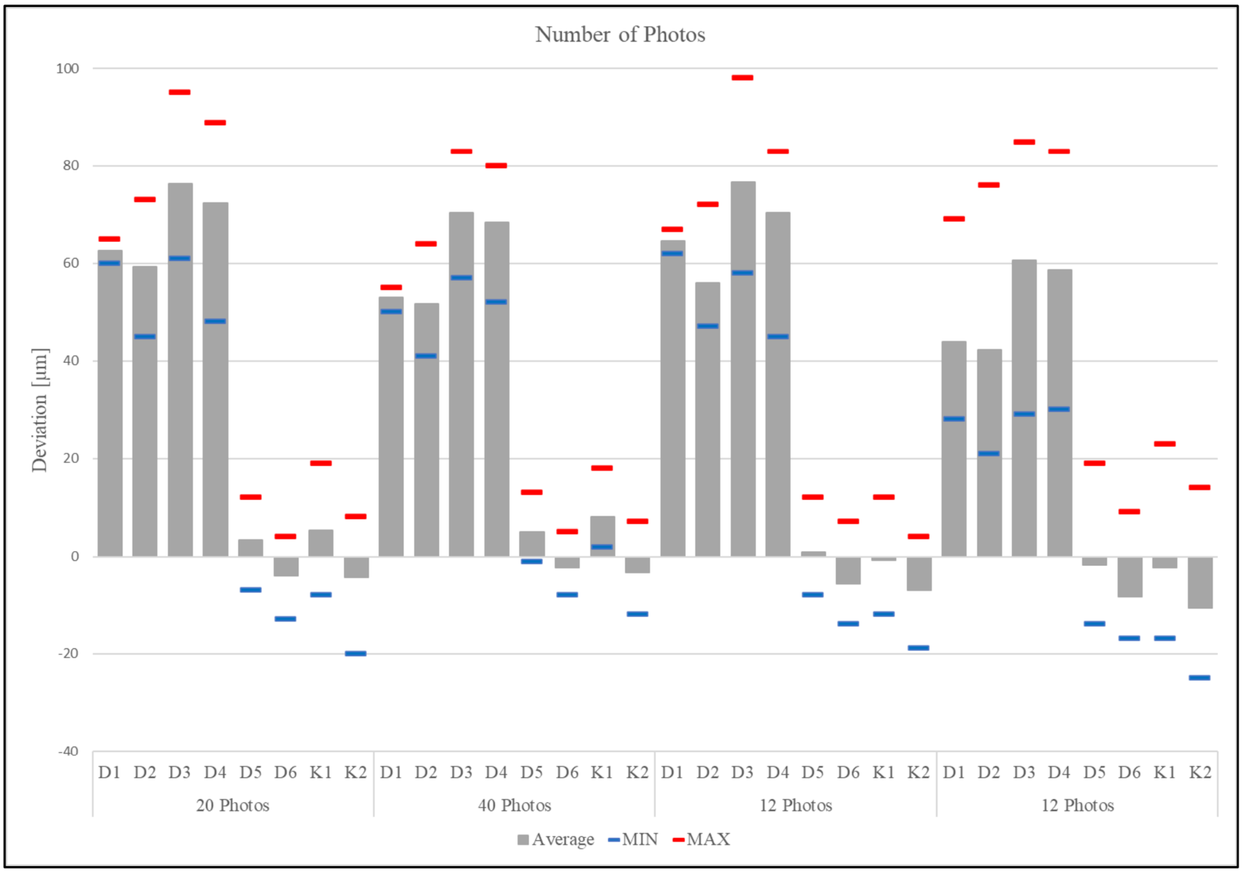
Table 8 Scanning parameters of number of photos

| | Measurement series | | | |
|---|---|---|---|---|
| Parameters | Number of photos | | | |
| Distance | 1.5m | 1.5m | 1.5m | 1.5m |
| Number of photos | 20 | 40 | 12 | 12 |
| Light | 1/4 equivalent to 1.5m | 1/4 equivalent to 1.5m | 1/4 equivalent to 1.5m | 1/4 equivalent to 1.5m |
| Number of coded reference points | 78 | 79 | 77 | 79 |
| Number of uncoded reference points | 49 | 52 | 45 | 42 |
| Number of scale bars | 2 | 2 | 2 | 2 |
| Temperature °c | 21 | 21 | 21 | 21 |

| **Measurement Series** | **20 Photos** | | | **40 Photos** | | | **12 Photos** | | | **12 Photos** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Bars** | **Average** | **MIN** | **MAX** | **Average** | **MIN** | **MAX** | **Average** | **MIN** | **MAX** | **Average** | **MIN** | **MAX** |
| **D1** | 63 | 60 | 65 | 53 | 50 | 55 | 65 | 62 | 67 | 44 | 28 | 69 |
| **D2** | 59 | 45 | 73 | 52 | 41 | 64 | 56 | 47 | 72 | 42 | 21 | 76 |
| **D3** | 76 | 61 | 95 | 70 | 57 | 83 | 77 | 58 | 98 | 61 | 29 | 85 |
| **D4** | 72 | 48 | 89 | 68 | 52 | 80 | 70 | 45 | 83 | 59 | 30 | 83 |
| **D5** | 3 | -7 | 12 | 5 | -1 | 13 | 1 | -8 | 12 | -2 | -14 | 19 |
| **D6** | -4 | -13 | 4 | -2 | -8 | 5 | -6 | -14 | 7 | -8 | -17 | 9 |
| **K1** | 5 | -8 | 19 | 8 | 2 | 18 | -1 | -12 | 12 | -2 | -17 | 23 |
| **K2** | -4 | -20 | 8 | -3 | -12 | 7 | -7 | -19 | 4 | -11 | -25 | 14 |

Table 7 Deviation for Number of Photos

In this experiment, four additional bars are used in comparison to the last scanning distance experiment. The goal of this experiment is to determine what causes the system to be inaccurate when less and more number of photos imported for evaluation. The image is captured in four separate series with the same setup in this experiment. Table 8 is represented visually in graph 2. Visualizing the graph in the fourth column, 12 photographs from different locations have a little variance. Even with fewer photos, the accuracy is not affected, and the values are not significantly different in deviation when compared to other results.




Graph 2 Deviation result for Number of Photos

### 6.3. Analysis of results for Flash Intensity

The scanning parameter for this changing the intensity of flash experiment is shown in below table 9 and important parameter is highlighted. The green colour is reference and blue colour is changes in parameter. The table 10 is deviation of values for this experiment and the reference measurement.

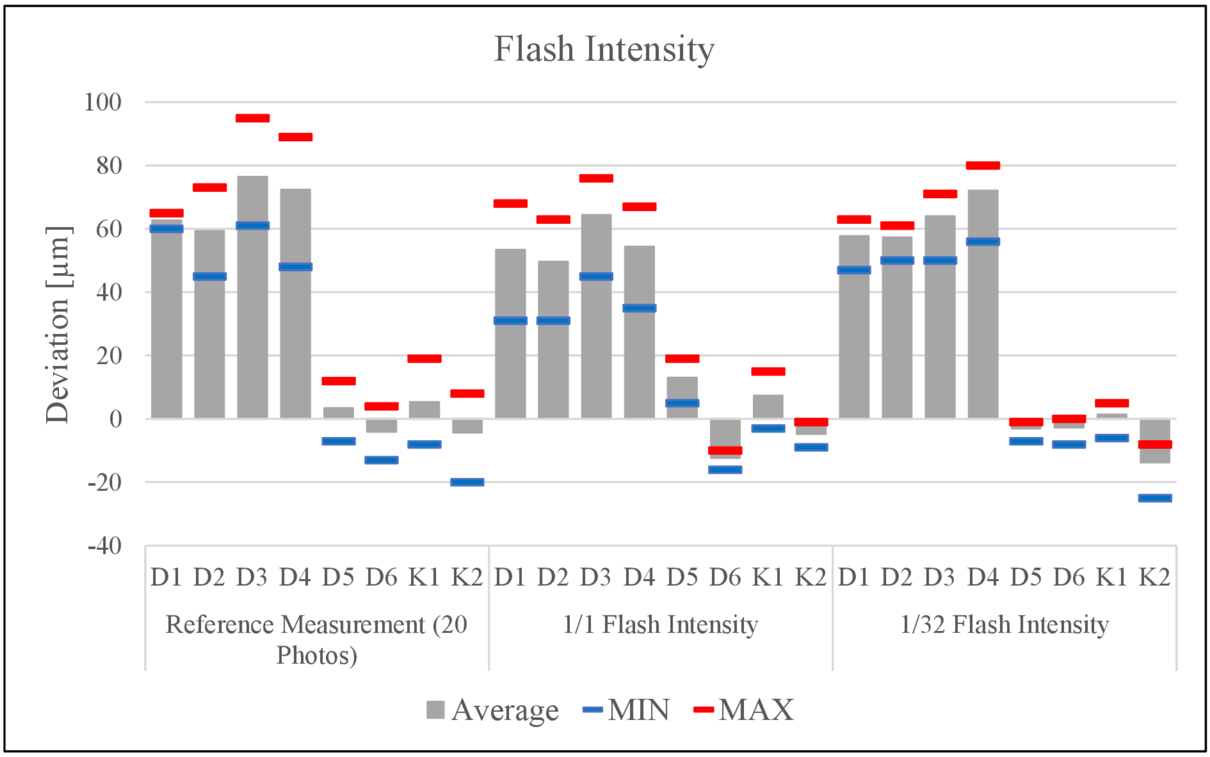
Table 9 Scanning parameters of Flash intensity

| | Measurement series | | |
|---|---|---|---|
| Parameters | Flash intensity | | |
| Distance | 1.5m | 1.5m | 1.5m |
| Number of photos | 20 | 20 | 20 |
| Light | 1/4 equivalent to 1.5m | 1/1 equivalent to 3.8m | 1/32 equivalent to 0.6m |
| Number of coded reference points | 78 | 78 | 79 |
| Number of uncoded reference points | 49 | 46 | 43 |
| Number of scale bars | 2 | 2 | 2 |
| Temperature °c | 21 | 21 | 21 |

Table 10 Deviation value for Flash experiment with reference measurement

| Measurement Series | Reference measurement 20 Photos | | | 1/1 Flash Intensity | | | 1/32 Flash Intensity | | |
|---|---|---|---|---|---|---|---|---|---|
| **Bars** | **Average** | **MIN** | **MAX** | **Average** | **MIN** | **MAX** | **Average** | **MIN** | **MAX** |
| **D1** | 63 | 60 | 65 | 53 | 31 | 68 | 58 | 47 | 63 |
| **D2** | 59 | 45 | 73 | 50 | 31 | 63 | 57 | 50 | 61 |
| **D3** | 76 | 61 | 95 | 64 | 45 | 76 | 64 | 50 | 71 |
| **D4** | 72 | 48 | 89 | 54 | 35 | 67 | 72 | 56 | 80 |
| **D5** | 3 | -7 | 12 | 13 | 5 | 19 | -3 | -7 | -1 |
| **D6** | -4 | -13 | 4 | -12 | -16 | -10 | -3 | -8 | 0 |
| **K1** | 5 | -8 | 19 | 7 | -3 | 15 | 1 | -6 | 5 |
| **K2** | -4 | -20 | 8 | -5 | -9 | -1 | -14 | -25 | -8 |

The parameter that changed in this experiment is the intensity value. The goal of this experiment is to see how over and under exposure flash light settings effect accuracy when compared to standard flash intensity. Table 10 is visualized in graph 3. According to the results, when the images are captured in overexposure, the accuracy is good, but there isn't much of a difference in the results when compared to the other experiment.




Graph 3 Deviation result for Flash intensity

### 6.4. Analysis of results for Reference measurement

In this experiment the number of reference point has been changed which is highlighted in blue colour in below table 12 and green colour is reference scanning parameter. The deviation in values for this experiment is shown below table 13.

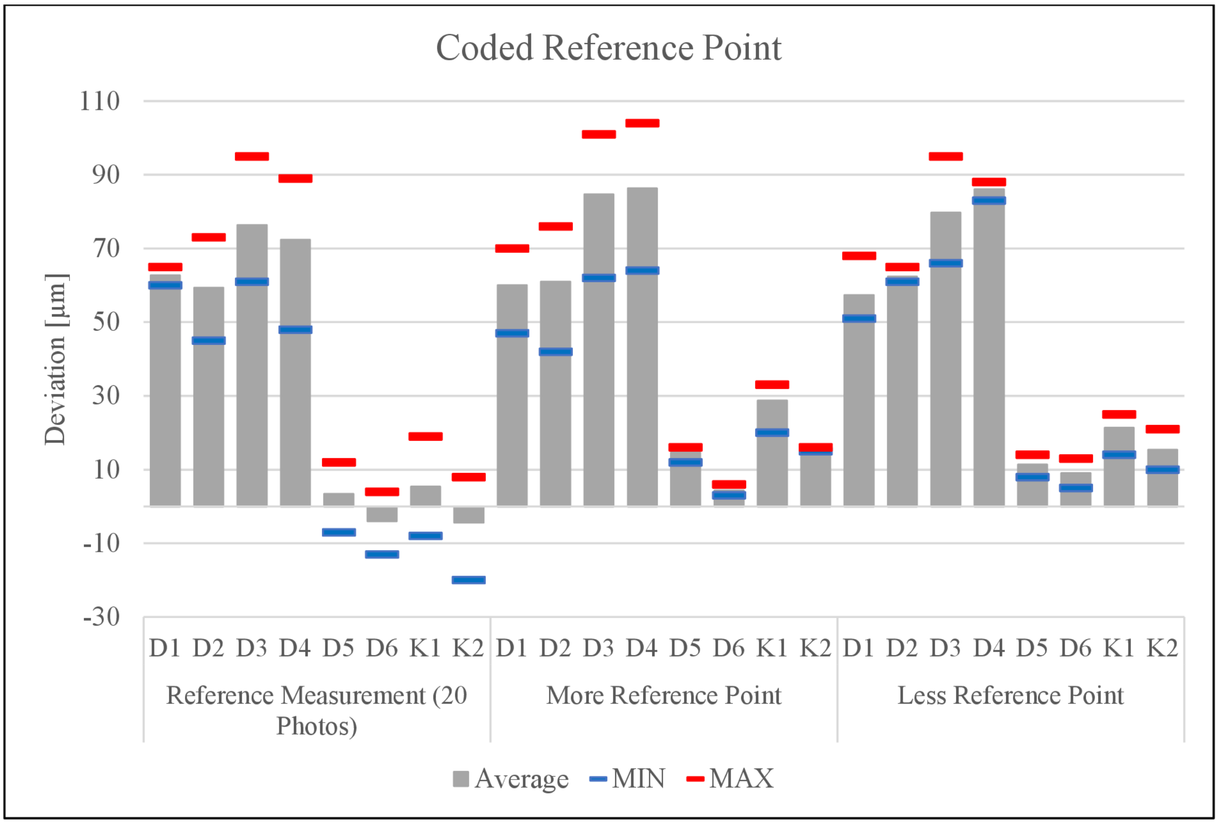
Table 11 Scanning parameter of Reference point experiment

| | MEASUREMENT SERIES | | |
|---|---|---|---|
| PARAMETERS | REFERENCE POINT | | |
| DISTANCE | 1.5M | 1.5M | 1.5M |
| NUMBER OF PHOTOS | 20 | 20 | 20 |
| LIGHT | 1/4 Equivalent To 1.5m | 1/4 Equivalent To 1.5m | 1/4 Equivalent To 1.5m |
| NUMBER OF CODED REFERENCE POINTS | 78 | 179 | 43 |
| NUMBER OF UN-CODED REFERENCE POINTS | 49 | 114 | 48 |
| NUMBER OF SCALE BARS | 2 | 2 | 2 |
| TEMPERATURE °C | 21 | 21 | 21 |

Table 12 Deviation value for Reference Point

| **Measurement Series** | **Reference measure-ment 20 Photos** | | | **More Reference Point** | | | **Less Reference Point** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Bars** | **Average** | **MIN** | **MAX** | **Average** | **MIN** | **MAX** | **Average** | **MIN** | **MAX** |
| **D1** | 63 | 60 | 65 | 60 | 47 | 70 | 57 | 51 | 68 |
| **D2** | 59 | 45 | 73 | 61 | 42 | 76 | 62 | 61 | 65 |
| **D3** | 76 | 61 | 95 | 85 | 62 | 101 | 80 | 66 | 95 |
| **D4** | 72 | 48 | 89 | 86 | 64 | 104 | 86 | 83 | 88 |
| **D5** | 3 | -7 | 12 | 15 | 12 | 16 | 11 | 8 | 14 |
| **D6** | -4 | -13 | 4 | 4 | 3 | 6 | 9 | 5 | 13 |
| **K1** | 5 | -8 | 19 | 29 | 20 | 33 | 21 | 14 | 25 |
| **K2** | -4 | -20 | 8 | 15 | 15 | 16 | 15 | 10 | 21 |

The coded reference point is used more and less in this experiment and is compared to reference measurement. The result shows the elements influencing the accuracy of this experiment. The result is represented in graph 4 of table 12, in which the result for each experiment has little variance, but when comparing to the result, the reference measurement has less deviation.




Graph 4 Deviation result for Reference point and reference measurement

## 6.5. Analysis of results for Different setup

### 6.5.1. Analysis of results for bar Parallel and combination of Horizontal & vertical Setup

In table 13 the scanning parameter is shown for this experiment and the green highlighted is reference measurement and table 14 is deviation value for this experiment.

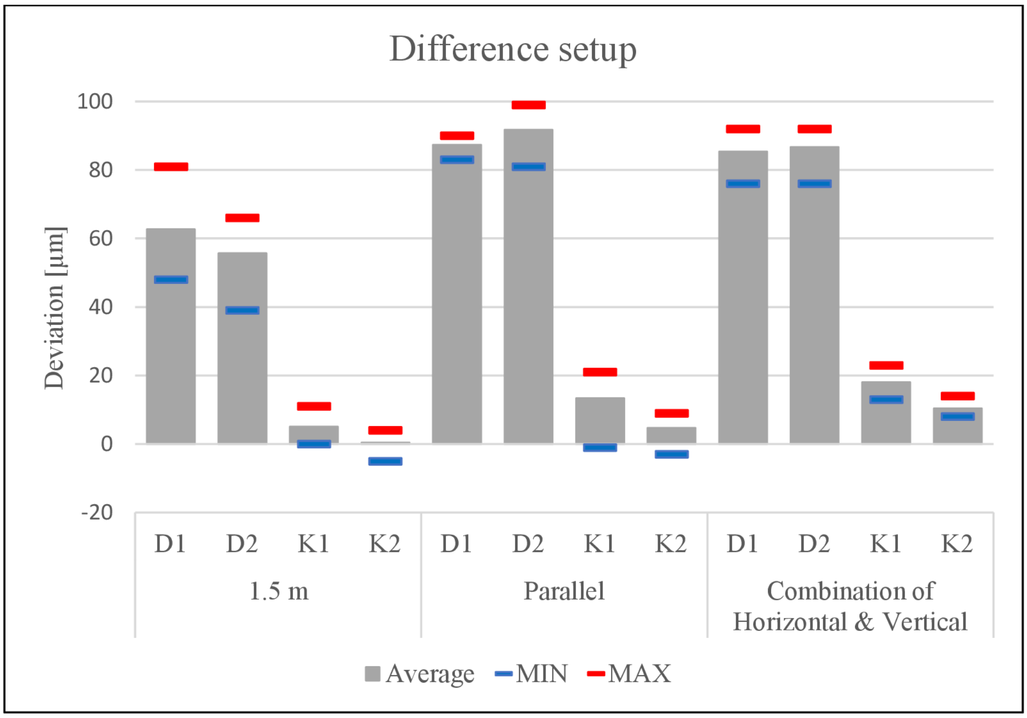
Table 13 Scanning parameter of Reference and parallel, horizontal setup

| | Measurement series | | |
|---|---|---|---|
| Parameters | Bar parallel & Combination of Horizontal and vertical setup | | |
| Distance | 1.5m | 1.5m | 1.5m |
| Number of photos | 20 | 20 | 20 |
| Light | 1/4 equivalent to 1.5m | 1/4 equivalent to 1.5m | 1/4 equivalent to 1.5m |
| Number of coded reference points | 78 | 74 | 76 |
| Number of uncoded reference points | 36 | 36 | 36 |
| Number of scale bars | 2 | 2 | 2 |
| Temperature °c | 21 | 21 | 21 |

Table 14 Deviation for Parallel and Combination of (H&V)

| **Measurement Series** | **Reference measurement (1.5m distance)** | | | **Parallel** | | | **Combination of Horizontal & vertical** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Bars** | **Average** | **MIN** | **MAX** | **Average** | **MIN** | **MAX** | **Average** | **MIN** | **MAX** |
| **D1** | 63 | 48 | 81 | 87 | 83 | 90 | 85 | 76 | 92 |
| **D2** | 56 | 39 | 66 | 92 | 81 | 99 | 87 | 76 | 92 |
| **K1** | 5 | 0 | 11 | 13 | -1 | 21 | 18 | 13 | 23 |
| **K2** | 0 | -5 | 4 | 5 | -3 | 9 | 10 | 8 | 14 |

The purpose of this experiment is to determine how changing positions of the same object affect the system's accuracy. The experiment result is compared to the distance 1.5m result. When the results are compared, the reference measurement shows less variance, even though that the reference bar is far from the measuring bar in this configuration. Yet, when the results are compared with other experiment, there isn't that much difference.




Graph 5 Deviation result for Parallel, Combination H&V and reference measurement

### 6.5.2. Analysis of results for 3D Setup

The scanning parameter for this experiment is shown in below table 15.

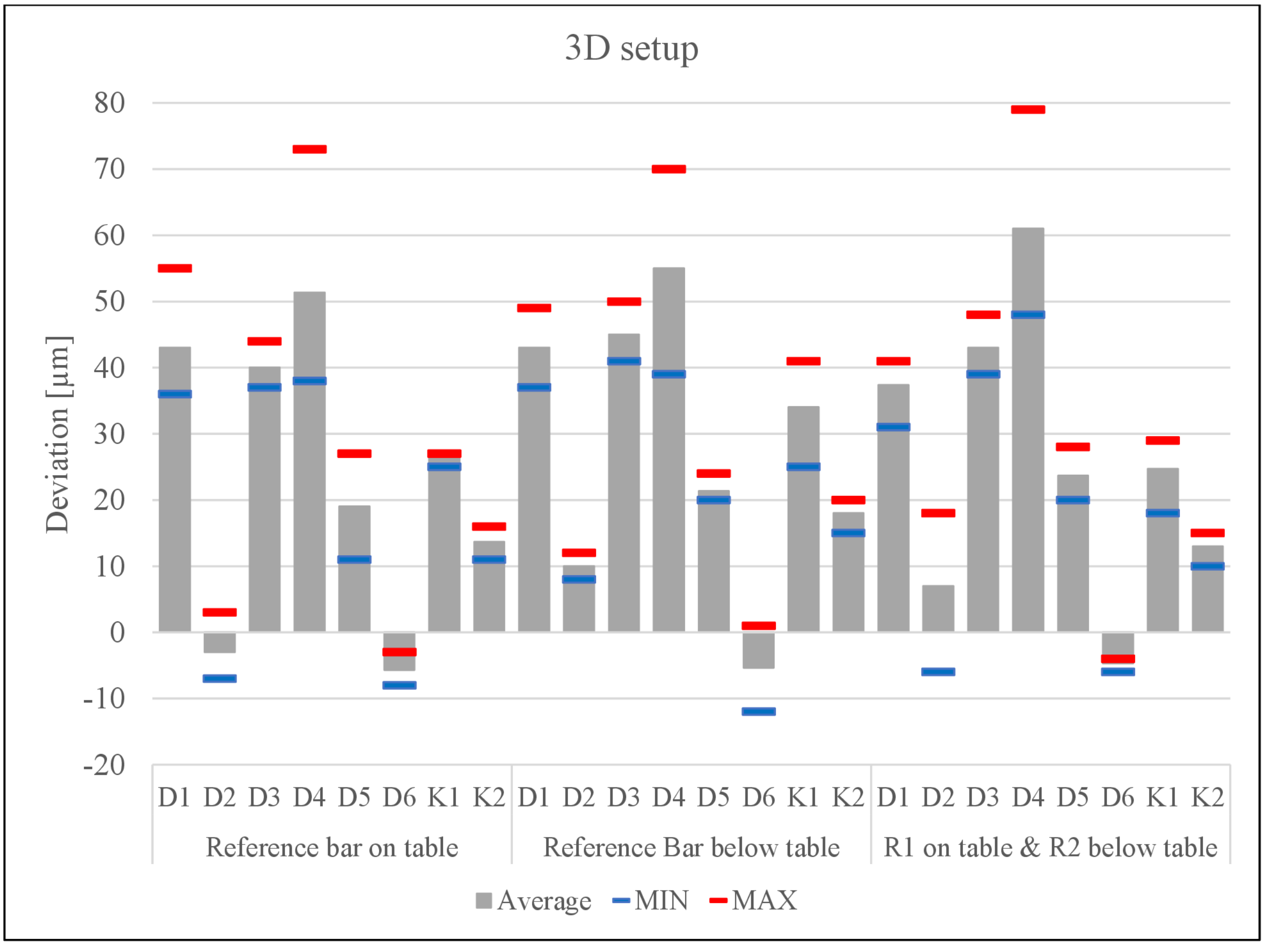
Table 15 Scanning parameter of 3D setup

| | Measurement series | | |
|---|---|---|---|
| Parameters | 3d setup | | |
| Distance | 1.5m | 1.5m | 1.5m |
| Number of photos | 28 | 28 | 28 |
| Light | 1/4 equivalent to 1.5m | 1/4 equivalent to 1.5m | 1/4 equivalent to 1.5m |
| Number of coded reference points | 128 | 129 | 127 |
| Number of uncoded reference points | 153 | 163 | 93 |
| Number of scale bars | 2 | 2 | 2 |
| Temperature °c | 21 | 21 | 21 |

Table 16 Deviation for 3D setup

| **Measurement Series** | **Reference bar on table** | | | **Reference Bar below table** | | | **R1 on table & R2 below table** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Bars** | **Average** | **MIN** | **MAX** | **Average** | **MIN** | **MAX** | **Average** | **MIN** | **MAX** |
| **D1** | 43 | 36 | 55 | 43 | 37 | 49 | 37 | 31 | 41 |
| **D2** | -3 | -7 | 3 | 10 | 8 | 12 | 7 | -6 | 18 |
| **D3** | 40 | 37 | 44 | 45 | 41 | 50 | 43 | 39 | 48 |
| **D4** | 51 | 38 | 73 | 55 | 39 | 70 | 61 | 48 | 79 |
| **D5** | 19 | 11 | 27 | 21 | 20 | 24 | 24 | 20 | 28 |
| **D6** | -6 | -8 | -3 | -5 | -12 | 1 | -5 | -6 | -4 |
| **K1** | 26 | 25 | 27 | 34 | 25 | 41 | 25 | 18 | 29 |
| **K2** | 14 | 11 | 16 | 18 | 15 | 20 | 13 | 10 | 15 |

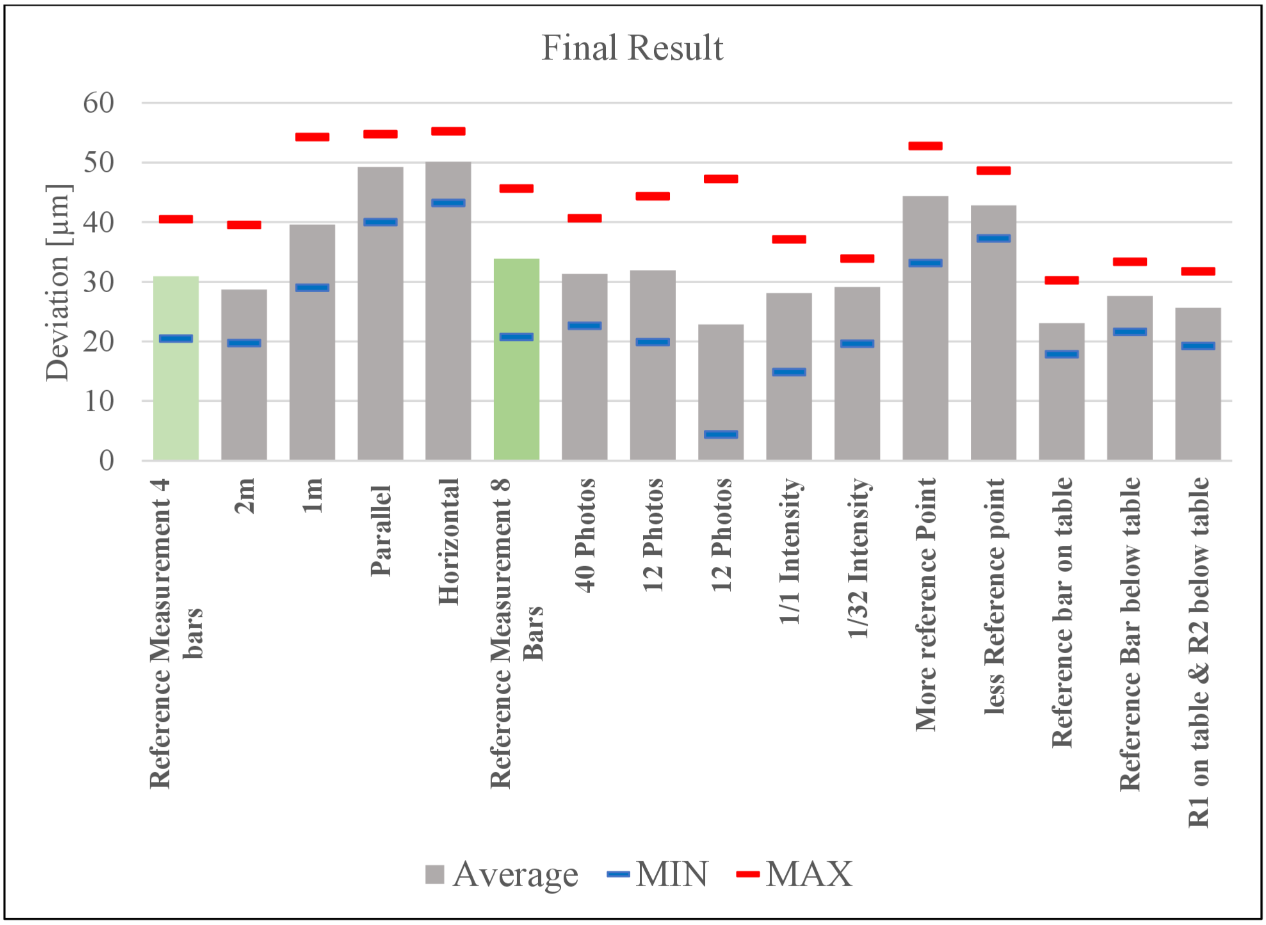
In this experiment, the location of the bars is altered in the same way that the position of the bars is adjusted in the experiment below. In this configuration, the evaluation is performed for three alternative setups where the position of the reference bar (R1 and R2) has been altered. As a result, the variance for each measurement is not much different.




Graph 6 Deviation result for 3D setup

### 6.6. Final Result

The graph for each individual graph is shown above. In this topic all the experiment is combine together and shown in single graph below 7. The average result is found from the total average of each measurement series. The maximum and minimum value is total average of maximum and minimum deviation. With this graph we come to know in which parameter the there is less deviation and good accuracy.




Graph 7 Final result for each measurement series

The green color in the above graph represents the reference measurement for four and eight bar measurements, and the values for 12 photos measurement in number of photos and reference bar on table in 3D setup measurement have less deviation, but when compared to other experiments, the variation has no more effect on the accuracy.

# 7. DISCUSSION

In this chapter I am going to discuss about the results shown in each graph and the reason behind the deviation in results. The thesis is focused on factors that affecting the accuracy of photogrammetry system Tritop and to find possible way to acquire the accuracy of this system. As already discussed, the accuracy of this system can be affected by many possible ways like camera resolution, lighting, brightness, coded points, flash, etc, So, to know its accuracy, in KSA/TUL laboratory the test was performed with difference parameters using the calibrated bars which is VDI/VDE 2634/1 standards.

The photos are taken in Nikon D500 camera for three times for each different experiment to know its accuracy of repeatability. The two 0.25m bars (R1 & R2) are used as reference bars for each experiment. Firstly, the measurement is done in three different distances from the object with four measuring bars. As the result in 2m distance there has less deviation but compare to other distance results the deviation is 10 to 15 micrometer difference each other, which is not much difference. I could say that the distance parameter does not cause the accuracy of the system.

Next the 1m bar position has been changed to parallel to each other and horizontal & vertical to each other with reference bars near to it. While analysing the result for this parameter with reference measurement 1.5m distance result, the difference in this situation has small difference in average with each other. So, changing in position of bars is not affecting the accuracy of the measurement.

Before only 4 bars are used for the measurement and seen the results. While measuring the dimension of 1m bars has constant big deviation for each measurement. So, to cross check the reference bar 0.25m is changed to 1m (D1 & D2) and checked the measurement where there is constant big deviation in 0.25m bars. Then decided to add extra 1m bars for checking the deviation the same constant deviation occurred in 0.25m bars but in 1m bar there is less deviation it is because of length measuring error where the measuring object less than the reference bar. As the bars are not have any support to with stand so the bars are not straight. It can be also the reason for deviation errors in 1m bars.

Now there is 8 bars for measurement and same 0.25m reference bars. The photos are evaluated in four different series with same setup in GOM software as stated above. All the results in graph shows that there is very little changes in deviation. When 12 photos are imported to the GOM

software the deviation is very small compare to other 3 series. I say that even though if less or more photos are imported to the software there is not affecting in accuracy.
Then the flash light intensity is changed to maximum and minimum. The setup is same as number of photos experiment. The 20 photos result for above experiment is used as reference because the setup and number of photos parameter is same only the intensity of flash is changed. The average result is very similar. So, changing in intensity is not affecting the accuracy.

As same as last experiment same 20 photos result is taken as reference for the coded reference point measurement. Comparing the result with reference measurement, the 20 photos result has less deviation values and also only 10 micrometer difference from each other which is very small. So, I could say that if there is increase and decrease in coded reference points does not affecting the accuracy of the system.

In the 3D setup the result for each experiment there is not much in variation, which means changing the position of bar there is not affecting the systems accuracy.

From the final graph 7 the result for each measurement is between 20 to 30 micros which is very small, even the repeatability is not much in variation.

# 8. CONCLUSION

The aim of this thesis is to determine the influence of various factors that affecting the accuracy, quality and repeatability of the photogrammetry system Tritop and finding a possible solution for to define the accuracy of the system using GOM software. For this measurement the calibrated bars have been used in which the nominal values of each bar are known. The calibration bar is under VDI/VDE 2634-part 1 standard which define its acceptance test. Using these bars has very good advantage as the dimension of each value is known, if there is any deviation it is easy to define its deviation.

Several experiments were undertaken with different parameters. The photos are taken in different distances, photos are exported in different series, intensity of flash has been changed, changed number of coded reference points for same setup, changed the setup of bars in different position and all these parameters were evaluated and compared. The experiments are evaluated by subtracting the actual value with the measured value in scale bars. As everything is discussed in the discussion chapter. Let me finally conclude that,

- When there is changing in distance of the camera from the object the results of each bar in each measurement series have minor deviation difference.
- The position of bars has been changed, in the distance measurement the reference bars are not kept near to the measuring object but in horizontal and vertical bar setup the reference bar as kept very near to the measuring bars but as a result the average deviation is little more compare to the distance measurement. So, if the bars are not kept near the measuring object does not influence the accuracy.
- When the photos are evaluated in different series the deviation difference between each bar in each series has less deviation in difference and if less photos are imported the measurement accuracy has come out well.
- As the intensity of flash is changed, the result is very similar and also when compare to reference measurement the value has little deviation.
- As the number of coded reference point is changed and the results are compared with the reference measurement there is small deviation from each result.
- As the bars are kept in the table, comparing to the reference measurement all the bar position kept in different. The result is very small to each other and also with reference measurement.
- The average range also very small which means the repeatability is also good and the actual deviation is comes out near to other values in each parameter.

From the manufacture point of view the maximum error can obtain for all bar is 10 to 25 micro meters the values of deviation are found from the formula which is discussed above. As per author **Grzelka** the maximum errors can obtain is 10 to 15 micrometres [3] but the deviation error was between 40 to 80 micro meters for long bars in each case it is because of length measuring error which means maximum deviation of error of measured bar length with respect to the reference bar and this case also applicable for the other bars [25]. As the size of measuring bar is big then the bar has changed to 1m bar then same average deviation occurs the reason is the measuring bar size is less than the reference bar. So, it is good if measuring object and reference bar has same size then this error can be reduced.

Finally, the results 4 bar reference measurement is compared with other measurement series which has the same 4 bars the average deviation for each measurement is 15 to 20 micrometer difference from each series and for 8 bar reference measurement the average deviation for each measurement is 5-10 micrometer difference from each series. So, there is no much difference in result if the parameter is changed.

**Therefore, the result of each experiment is very similar to each other which means there is good accuracy in the system and there are no factors that influencing the affect of the accuracy of the photogrammetry system Tritop.**

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