InDA Software System for Industrial Metrology on Geometry Form Fitting and Deformation Estimation

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ABSTRACT:

Conventional geodetic observation using the electronic theodolite and total station is still valid and suitable for use in deformation monitoring and industrial metrology. Deformation monitoring applications not only concentrate with engineering structure and geotechnical but widely use in machinery and manufacturing. Deformation parameter estimation is the objective of the work of deformation monitoring. The magnitude rate and direction of the deformation or generally known as trend analysis can be determined by using robust estimation or congruency testing. Both methods are the rigorous techniques for estimating the trend of movements for all the common points in a monitoring network. The typical industrial objects such as plane, circle and line usually concerned in geometrical form fitting analysis. Typically, the industrial surveying with geometrical firm fitting analysis is a main concern and the techniques of positioning such as intersection and resection usually applied in this application. With support of recent technology such as servo-motor, the uses of total station were upgraded to a motorized and robotic function. Robotic total station allows an automatic data acquisition procedure. In this paper, observation and data collection can be automatically programmed and controlled by a computer. The control function is applicable where the communication protocol between the computer and robotic total station is applied. It is possible to increase the capability of the geodetic industrial deformation monitoring by integrating the robotic total station as a data acquisition sensor with the complete software system. This software system has a full capability to communicate, controls, collects, process and analysis the deformation estimated parameter and geometry form fitting analysis. Hence, this process involved development of the complete system for automatic data acquisition and analysis. This paper intensively describes the development of the InDA Software System or InDA for industrial deformation analysis. The software system has been developed using Microsoft Visual C++ and using Leica GeoCOM protocol as a communication between sensors and computer. For benchmarking, the InDA System has been evaluated with other commercial system for data integrity during communication and other measurement systems. Several case studies were setup to evaluate the geodetic intersection with photogrammetry and laser scanning. The result showed the method of measurement using geodetic support with InDA System compare to the photogrammetry and laser scanning were within few millimetre.

1. INTRODUCTION

Geomatic incorporate many disparate method and technologies that offer surveying engineering flexibility in the design and implementation of high precision surveying and recording scheme. In this case, deformation monitoring and industrial metrology can be classified as a high precision surveying application.

The traditional task of deformation measurement is the investigation of movement and displacement of an object with respect to space and time (Welsch and Heunecke, 2001). The objective of deformation analysis is the detection, localization and modelling of point movement in measured network. In the deformation studies using geodetic observation, the processes are repeated at different epoch of time. The repeated observations of each epoch are adjusted independently. From coordinate differences between two epochs, the parameters of the deformation model are estimated. The displacement represented as a spatial shift vector or separated into its component in 2D and 3D views. The industrial surveying or metrology normally is to deal with problems such as design, modelling, detection, lofting, quality control and dynamic monitoring related to shape, size and action status of the objects (Feng, 2002). In addition, it is also used to construct, assemble and align a work-piece or component as per the relevant drawing (Fuss, 1993).

Deformation monitoring can be divided into geodetic, structural and geotechnical (Setan, 1995). The structural and geotechnical can be classified together as non-geodetic. Geodetic method can be divided depending on the instrument technology being used, into terrestrial and space methods. Meanwhile, industrial metrology can be divided into two segments, namely contact method and non-contact method. Besides that, geodetic instruments can be classified as non-contact measuring method Non-contact geodetic instrumentations are categorized as terrestrial optical (Motorized Electronic Theodolite-MET, Robotic Total Station-RTS), photogrammetry and laser scanning. These type of instruments widely used for high precision surveying. In addition, non-contact geodetic instruments are difference depends on instruments and target selection. Staiger (2009) classified traditional acquisition methods of MET and RTS as “point-oriented”, while Terrestrial Laser Scanning (TLS) is categorized as an “element-oriented” approach.

Implementation of geodetic method in high precision surveying widely involved 3D coordinate system. The introduction of accurate 3D data from extraterrestrial positioning technique such as Global Positioning System (GPS) in the last decade has resulted in the re-emergence of 3D geodetic network. This paper highlight on the latest surveying technology such as MET and RTS used in industrial metrology. The first part of the paper presents some background information about instrumentations and systems. Establish and latest optical techniques and technology such as motorized electronic theodolite (MET) and robotic total station (RTS) is reviewed. This is followed by a review of data communication and software which is integrated with the MET and RTS. The paper concludes with some comment regarding the survival and potential uses of this type of system in the surveying industry of the future.

2. ROBOTIC TOTAL STATION

Surveying technology allows the determination of 3-dimensional determination and movement. Current technology provides robotic total stations that are able to measure angle with an accuracy of $\pm$ 0.5” (0.15 mgon) and distance with an accuracy $\pm$ 1mm+ppm in standard measurement mode (Leica Geosystems, 2000). Actually, TCA2003 produced by Leica Geosystems AG, was designed for conducting deformation-monitoring survey. Dunish and Kuhlman (2001) have used the TCA2003 model for tracking moving target in setting out rail geometry. Modern technologies are more sophisticated and packaged internally. Certain instrumentations have an active beam sensing capability. With this latest technology, robotic total station allowed the measurement of many points on a surface. Then the points will be monitored within a short period with the approximate coordinate of each target prism stored in memory or database. All the periodic measurement operation were using Automatic Target Recognition (ATR) technology (Leica Geosystems, 2000). The ATR technology takes over the pointing, reading and measuring function completely. Technically, ATR consisted of an external video camera imaging system and a separate servomotor drive (US Army Corp of Engineer, 2002). An emitted IR signal is transmitted to the prism that passively reflects the signal back to the instrument. The return spot is imaged on a high resolution (500x500) pixel CCD camera.

3. CONCEPTION OF InDA System

Industrial surveying commonly referred to:

a) restriction on space area to setup a survey network,
b) intersection measurement from two stations simultaneously,
c) real time processing or on-site processing,
d) an information of reference network before starting the measurement,
e) positioning issues,
f) special software system to analyze,
g) least square estimations.

That mean, we need a system can be integrated and communicated between instrumentation and workstation (computer) To serve for most automation application of the deformation and industrial measurement, Industrial Deformation Analysis (InDA) software system has capability (M.Idris & Setan, 2007, 2009):

- can treat one, two or three dimensional,
- can perform in single or dual instrumentation,
- has communication module to communicate between user and instrument,
- measure the point automatically either order from user or timer system,
- has database module to handle the spatial data,
- has a data processing module for least square estimation, deformation detection and also easy to handle.

The system developed for use on personal computer with the operation system Microsoft Window Me/2000/XP. The software package system installed on a personal computer or notebook is possible to make all computation and analysis in the field or measurement site. The main program for InDA is written from the combination of several programming languages such as in standard Visual C++ based on Microsoft Foundation Classes (MFC) and Microsoft Visual Basic 6. The main InDA is written in standard C/C++ and Visual C/C++ but several modules are written in standard Visual Basic.

4. InDA SYSTEM MODULES

The InDA System contains two main parts, namely the Instrumentation and the System itself. The InDA System consists of three main modules known as Communication (COMM), Data Acquisition (DAQ), and Analysis (ANALY) as shown in Table 1.

Modules	Major Hardware/Software
Module 1 :– Communication (COMM)	- Leica TCA2003/1800 - Portable Notebook - In house developed InDA system - Medium of communication by RS-232 -
Module 2: – Data Acquisition and Database (DAQ)	- Microsoft Visual C/C++ with Microsoft Foundation Classes - PC-based database; Microsoft Access/Excel
Module 3 : –Analysis (ANALY)	- InDA system - Least Square Adjustment - Deformation and Dimensional Analysis. - Result presentation: Microsoft Excel

Table 1**:** Modules of InDA Software System

4.1 Communication Module

InDA System only supported Leica instruments TPS1000 and TPS1100 system software family. This research was conducted on selected Leica robotic total station TCA2003 and Leica electronic theodolite TM5100. These TPS system software is built around the sensor element (simple word: on-bord software), organizes and controls the interplay of several sensor elements (Leica Geosystems AG, 2000). It provides a set of function to access sensors. Figure 1 shows the architecturally communication between TPS 1000/1100 Software System and computer unit. All these functions can be manipulated and controlled from GeoCOM Client. Robotic total stations in TPS1000/1100 family are able to recognize and act on certain sequences of character or commands send via the serial port (Leica Geosystems AG, 1999). Figure 2 illustrates the configuration between computer unit and sensor. The power supply is supported by interface T-Link and data cable GEV86.

The principle here is, on the low level of implementation, each procedure, which is executable on the remote instrument is assigned a remote procedure call identification number. This number is used internally to associate a specific request, including the implicit parameter to a procedure on the remote device (Leica Geosystems, 1999). This level, GeoCOM provides an ASCII interfaces. On the high level, GeoCOM provides normal function interfaces for Microsoft Visual C/C++ and Microsoft VBA.

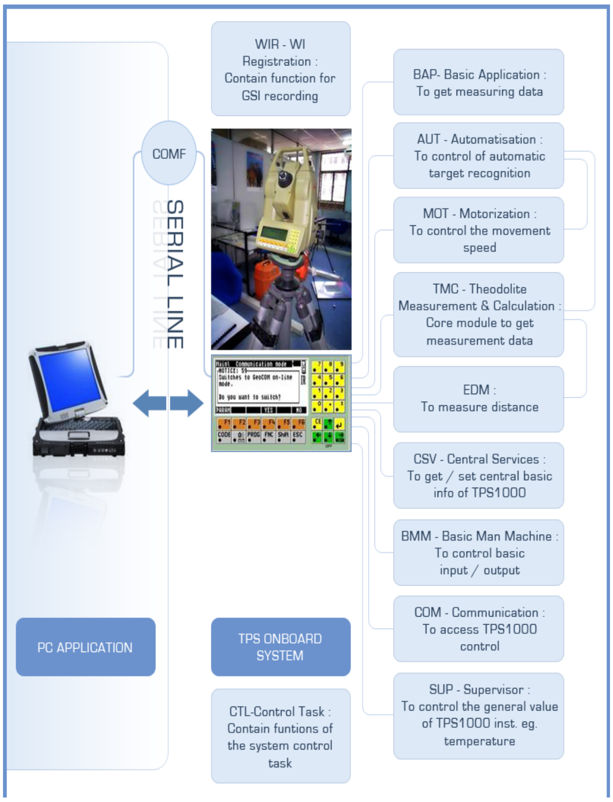

Figure 1: Client/Server Applications and GeoCOM Function

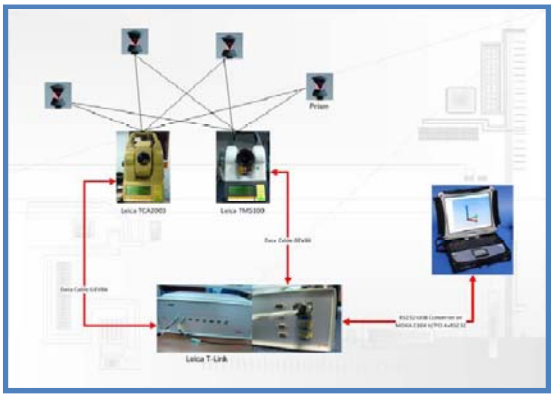

Figure 2: Communication between computer unit and sensors

GeoCOM is implemented as synchronous communication. The request/reply pair may not be interrupted by another request/reply. Instead of that, a communication unit must be completed successfully before a new communication may be initiated. In a synchronous communication, both sender and receiver are exactly synchronized to the same clock frequency (Miller & Beasley, 2004). Other mode is asynchronous, where transmit and receive clock free-run at approximately the same speed. The type of GeoCOM communication is half-duplex. Half-duplex permits transmission in both directions but only in one direction at a time. Others are simplex and full-duplex. Simplex communication is one way where the communication can take place in only one direction. Full-duplex allows information to flow simultaneously in both directions on the transmission line (Bayly, 1989).

4.2 Data Acquisition Module

Programming in C/C++ or Visual C++ is based in the well-know Dynamic-Link Library (DLL) concept. DLL was defined by Microsoft Corporation. The main communication component in developing software system is GeoCOM protocol. To compile a software system successfully:-

i. a header file namely *com_pub.hpp* must be included. This header file contains all necessary constants, data type and functions prototypes.
ii. Library file, *geocom.lib* has to be included in the software system. With this library file, it enables the linker to resolve the DLL exported functions
iii. Dynamic-link library, *geocom.dll* file must be accessible for operating system. It must be located in a directory.

Figure 3 illustrates the architecture of InDA System for data acquisition process. In the Data Acquisition module, it enables the user to select either single measurement (means single robotic total station) or dual measurement (more than one robotic total station). The InDA System consists of following parts which are the way to user (client) communicated with RTS (server):-

i. Step 1st: Set the communication parameter and initialize GeoCOM protocol.
ii. Step 2nd: Open a connection hub to the RTS/server
iii. Step 3rd: Request/reply procedure for one or more GeoCOM RPC's
iv. Step 4th: Close the active connection to the RTS/server
v. Step 5th: Finalize GeoCOM protocol

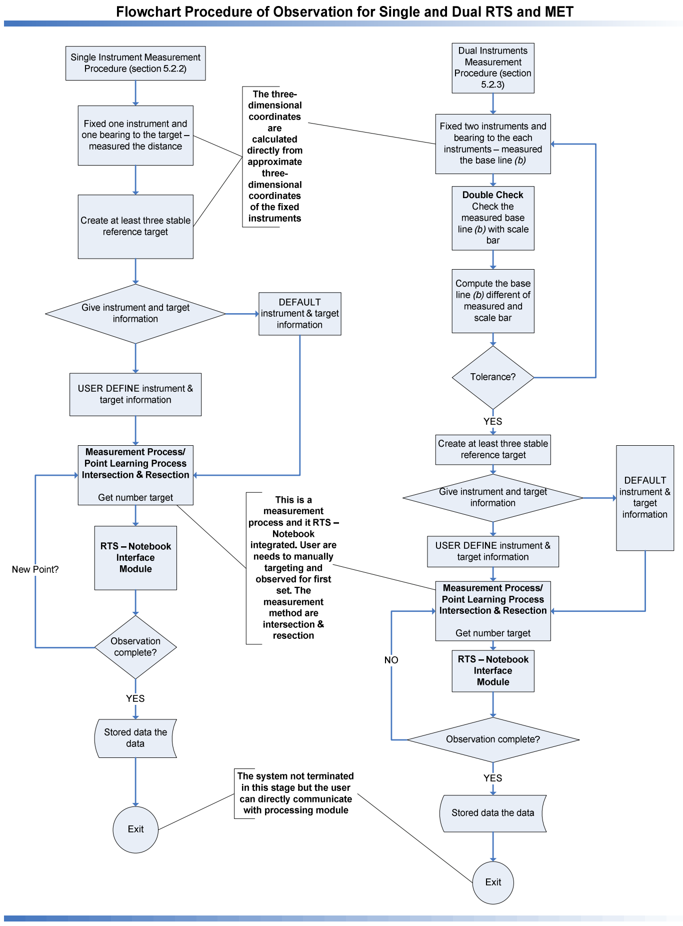

Figure 3: Architecture of Data Acquisition Module

All the data reply from RTS (server) and the data was acceptable, then stored in database. All information from sensor element (TCA2003/TM5100) was downloading. The data is an azimuth, direction, angle, spatial distance, height difference, coordinate, temperature, time and other. The database management system implemented to support huge amount of measurement data. Open Database Connectivity or ODBC have been using for this software system and linked to Microsoft Access. Figure 4 show interface of InDA software system for communication and data acquisition.

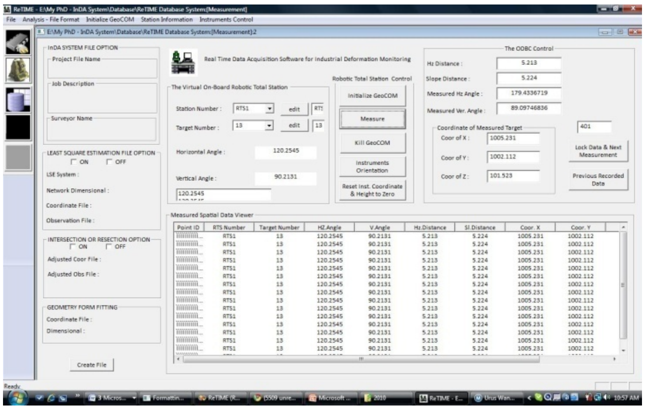

Figure 4: User interface for COMM module

4.3 Analysis Module

4.1.1 Least Square Estimation

All adjustment computation analyses using least square estimation module in InDA System embedded with either commercial software or 'in-house' software. The commercial software used as embedded module is Star*NET. While 'in-house' software supported as embedded modules are 3D-CDS (Sheng, 2002) and MyLSE (Amat, 2007). This module of LSE (Figure 6) capable to computes

- pre-analysis for network planning,
- Simplified Variance Component Estimation (SCVE) to estimate variance of un-weighted observation,
- Least to obtains most possible value (MPV) from redundant observation,
- Determine accuracy and quality of observation,
- Statistical analysis (chi-square),
- Outlier detection using Baarda method,
- Assessment quality of the network,
- Sequential Least Square Estimation,
- S-Transformation for datum re-definition

Least Square Estimation (LSE) is a method to provide a unique solution (of the normal equation) from redundant observations by minimizing the sum of squares of the residuals (Mikhail, 1976; Anderson and Mikhail, 1998). LSE can be implemented either using observation, condition or combine equation. This paper focused on the implementation of LSE using observation equation. The relationship between observation and parameter can be expressed by mathematic model. The mathematical model is comprised of two parts, first is functional model and second is stochastic model. Functional model describes the deterministic relation between quantities (Mikhail, 1976; Anderson and Mikhail, 1998).

$$F(\hat{l}, \hat{x}) = F(l^o + \Delta l, x^o + \Delta) = 0 \quad (1)$$

where $\hat{l}$ = vector adjusted observation
l^o = vector approximate observation
v = vector correction of observation, l or residual
Δ = vector correction of parameter, x^o
Δl= vector correction of the approximate parameter l^o
$\hat{x}$ = vector adjusted of the parameter, x
x^o = vector approximate of the parameter

Stochastic model describes the statistic properties of all the elements involved in the functional model (Anderson and Mikhail, 1998; Mikhail *et al*., 2001). The properties are expressed by either covariance matrix or cofactor matrix:-

$$\Sigma = \sigma_0^2 Q \quad (2)$$

where, σ_0^2 is variance a priori (Wolf and Ghilani, 2002) or reference variance (Mikhail *et al*., 2001). The inverse of cofactor matrix is called the weight matrix, or

$$W = Q^{-1} \quad (3)$$

If variance a priori $\sigma_0^2 = 1$

$$W = \Sigma^{-1} \quad (4)$$

When the random variables involved are uncorrelated, the covariance, cofactor and weight reduce to the diagonal form.

$$\Sigma = \begin{bmatrix} \sigma_1^2 & \sigma_{12} & . & . & \sigma_{1n} \\ \sigma_{21} & \sigma_2^2 & . & . & \sigma_{2n} \\ . & . & . & & . \\ . & . & & . & . \\ \sigma_{n1} & \sigma_{n2} & . & . & \sigma_n^2 \end{bmatrix} \quad (5)$$

The concept of least square is sum of the square of the *n* residual or correction to set of *n* measurement must be a minimum (Mikhail, 1976; Anderson and Mikhail, 1998; Mikhail *et al.,* 2001):-

$$\phi = v_1^2 + v_2^2 + v_3^2 + ... + v_n^2 = \min \quad (6)$$

or in matrix notation

$$\phi = v^T v = \min \quad (7)$$

If the observation has a different weight, the least square concept and criterion becomes

$$\phi = w_1 v_1^2 + w_2 v_2^2 + w_3 v_3^2 + ... + w_n v_n^2 = \min \quad (8)$$

or in matrix notation

$$\phi = v^T W v = \min \quad (9)$$

There are several techniques for least square estimation such as indirect, observation only, combined adjustment, unified adjustment, sequential adjustment, filtering and collocation adjustment (Mikhail, 1976). Combination method mathematic model was generated from indirect and observation mathematical model. Sometimes indirect observation refers to term of parametric method, observation equation and parametric equation (Mikhail, 1976; Anderson & Mikhail, 1998). The observation only sometimes refers to condition method, adjustment of observation, conditional observation, condition equation and method of correlates (Mikhail, 1976; Anderson and Mikhail, 1998). In this research, used term of parametric equation, conditional equation and combined

4.1.2 Geometrical Form Fitting

The main features in this InDA system is module for geometric form fitting analysis. The adjusted parameter from least square estimation process will be used as entry data in geometrical form fitting module. The module shows the adjusted target position for user chooses the subset of the points. Three types of geometric form fitting can be analyses by module of geometric form fitting in InDA System. This module is embedded from 3D-CDS (Sheng, 2002). Three types of analyses, which are line, circle and plane fittings. The mathematical models for line, circle and plane in two or three dimensional can be found in Bayly (1991) and Mikhail *et al*. (2001)

4.1.3 Deformation Detection

Deformation survey is one of the most important activities in engineering survey. The purpose is to determine any movements from an object between ranges of pre-determine time. For deformation detection, we using the software named ADDS (Adjustment and Deformation Detection Software) and is capable of performing deformation analysis with multidimensional data. ADDS was developed using Visual Basic 6.0 (VB6) language and consist of three main modules (Endot, 2007). This system was developed at Surveying Engineering Research Group Lab Universiti Teknologi Malaysia.

A robust method, Iterative Weighted Similarity Transformation (IWST) had been adopted and applied for the deformation detection computation. Three main process of deformation analysis are least square adjustment, deformation detection and graphic interpretation.

The first module is Converter. It acts as a connection for commercial least square estimation software named StarNET via OLE (Object Linking and Embedding). This module is also capable of converting least square estimation output of StarNET to the readable input format for the second module of ADDS. The second module is the deformation detection module. This module will give the results of deformation detection process in numerical result. The third module is the graphical interpretation module. A library that consists lists of graphical assist VB6 objects named Vecad had been used in this module. This module will illustrate the deformation vectors and error ellipses of the deformation analysis that had been done. The graphical results from ADDS can be exported to the graphical commercial software, AutoCad. Figure 5 shows the main component embedded inside InDA software system.

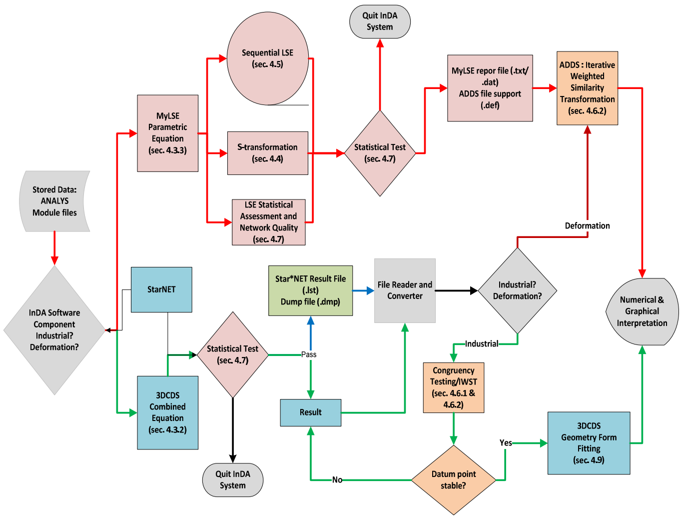

Figure 5: Flow of Analysis Module (Least Square Estimation)

5. REAL OBSERVATION CAMPAIGN

5.1 Hull Model

This industrial object, boat hull (Figure 6) was measured by electronic theodolite (TM5100) and robotic total station (TCA2003) and compare with photogrammetry technique, laser scanning from two type of manufacturer, FARO PHOTON and Konica Minolta. Small network survey was setup indoor. All the observation and measurement was done in 3D Measurement Lab. Several points have been selected to measure it dimension. The result show consistency between geodetic and photogrammetry technique (Table 2). From Table 2 and Figure 7, the biggest different between geodetic(electronic theodolite and robotic total station) and laser scanning (VIivid910) is 4.551mm for dimension line 1 – 11 and 3.695mm for dimensional line 1 – 12.

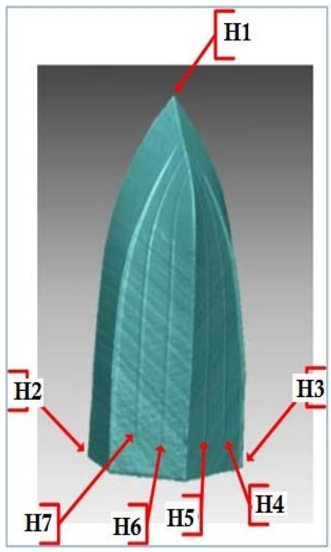

Figure 6: Hull model

No	Object Point	Geodetic – Photo	Geodetic - Faro	Geodetic - Vivid
1	H1-H2	-0.056	-0.309	0.528
2	H1-H3	0.297	1.698	2.716
3	H1-H4	-0.178	-1.266	-0.972
4	H1-H5	-0.806	-2.727	-1.248
5	H1-H6	0.834	-0.452	1.01
6	H1-H7	0.426	-0.316	-0.221

Table 2: Different between geodetic and laser scanning

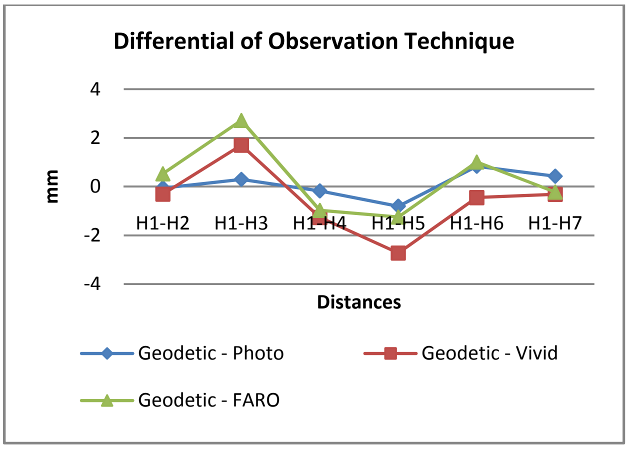

Figure 7: Hull model measurement compared with other technique

5.2 PVC Pipe

For industrial object fitting such as centre of a circle (Figure 8) and its radius, only the points with circle geometry features can be used for adjustment. The parameter of the circle form commonly refers to the unit vector (a, b, c) which is perpendicular to the plane of the circle and (d) is the perpendicular distance from the plane to the origin. The computation includes estimated centre coordinate $(x_0, y_0, z_0)$of the circle and its radius (r_0) (Bayly, 1991).

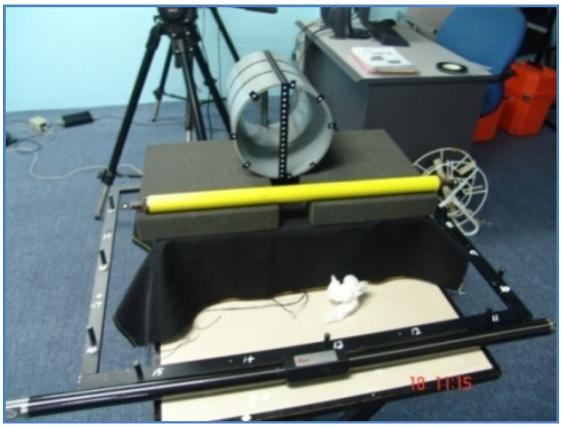

Figure 8: PVC Pipe

Point	X (m)	Y (m)	Z (m)	Common Line (mm)
W1	3.99563	4.24398	-0.49526	0.01808
W2	4.52009	0.07649	-0.18169	0.02295
W3	4.15309	4.39851	0.71643	0.01791
W4	4.36999	1.41962	0.6962	0.04554
W5	4.57227	-1.92913	0.71492	0.00147
F1	1.3057	1.5049	-0.55772	0.01465
F2	1.21524	1.57981	-0.5585	0.01275
F3	1.19129	1.87979	-0.55843	0.00819
F4	1.16783	2.17913	-0.55908	0.00519
F5	1.24632	2.26466	-0.55931	0.0005
SB1	1.17476	1.45692	-0.58313	0.00952
SB2	1.11034	2.3543	-0.58105	0.0371
CP1	1.44474	1.91054	-0.23681	0.01377
CP2	1.44408	1.86271	-0.2617	0.02338
CP3	1.49049	1.8999	-0.31401	0.02879
CP4	1.43656	1.86875	-0.38625	0.023
CP5	1.4346	1.91124	-0.40478	0.01946
CP6	1.43235	1.99054	-0.37702	0.02212
CP7	1.43738	2.00896	-0.32241	0.00903
CP8	1.41317	2.00573	-0.25035	0.02297

Table 3: Approximate coordinate of object point and common line

In this study, coordinates of CP1 to CP8 (Table 3) are used in circle fitting computation. Coordinate for points CP1, CP4 and CP7 are chosen for computation of centre of the pipe circle and its radius. The single computation of the centre and radius of the circle from three points are illustrated in Figure 9 where the perpendicular bisectors of C1C4 and C4C7 are computed to find the intersection of those two bisectors in order to get centre of the circle. The radius of the circle can be computed by using following mathematic model (Murray, 1968):

$$r_0 = \frac{a'.b'.c'}{\sqrt{s(s-a')(s-b')(s-c')}} \tag{10}$$

where

$$a' = \sqrt{((x_{C4} - y_{C1})^2 + (y_{C4} - y_{C1})^2 + (z_{C4} - z_{C1})^2)}$$
$$b' = \sqrt{((x_{C7} - y_{C1})^2 + (y_{C7} - y_{C1})^2 + (z_{C7} - z_{C1})^2)}$$
$$c' = \sqrt{((x_{C7} - y_{C4})^2 + (y_{C7} - y_{C4})^2 + (z_{C7} - z_{C4})^2)}$$

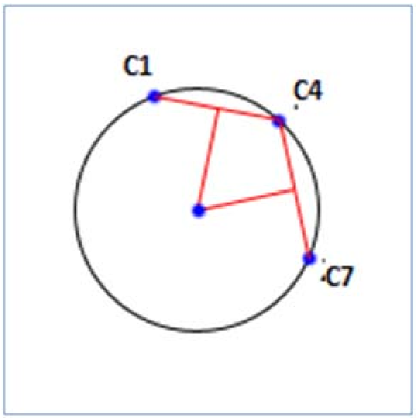

Figure 9: Intersection between two lines (C1-C4 and C4-C7)

Approximate centre of pipe circle & radius			
X(m)	**Y(m)**	**Z(m)**	**radius - mm**
1439.4086	1923.9587	-311.9772	84.9672
Unit Vector			
a(m)	**b(m)**	**c(m)**	**Distance**
-0.003	0.2523	-0.0034	2.3523

Table 4: Approximate Value

Unit vector in Table 4 was is in the LSE processing as an additional condition while the coordinate value of the centre coordinate and its radius is an approximation. The LSE process converged at the seventh iteration. Statistical analysis of the network resulted from 3DCDS components showed that variance of a posterior is 0.0023. According to 3DCDS component in InDA System, the two-tailed 5% significance level global Chi-square test of the network resulted passes (0.0012<1<1.2138). The differential values are shown between (geodetic and photogrammetry) is -2.5mm to 1mm for component of *x, y* and *z*.

Different(mm)			
	x	y	z
C1	-1.0059	0.427	0.3
C2	-0.8591	0.2623	0.089
C3	-0.644	0.237	0.171
C4	-0.347	0.102	0.191
C5	-0.129	0.011	0.469
C6	-2.598	2.704	0.766
C7	-0.455	0.016	0.344
C8	-0.665	0.102	0.469

Table 5: Different between geodetic and laser scanning.

From the radius of the circle in Table 6, the diameter of the circle can be determined directly. In geometry, diameter of the circle is the length of the segment joining a point with one symmetrical respect to the centre. The diameter is equal to twice of the radius. In this study, diameter calculated from geodetic MET intersection is compared to the diameter calculated from photogrammetry technique. The value of the circle diameter resulted from geodetic technique is 169.935mm, while the diameter calculated from photogrammetry technique is 168.721mm. The difference occurred between geodetic and photogrammetry result is 1.214mm. The different maybe caused by the precision of point during selection process between geodetic and photogrammetry. Thus, the intersection of point from geodetic observation and photogrammetry has caused the difference in diameter result.

Estimated Coordinate - Centre of the Circle			
x (mm)	y (mm)	z (mm)	radius (mm)
1443.417	1921.141	-309.571	83.850
Standard Deviation			
x (mm)	y (mm)	z (mm)	
0.2	1	1	

Table 6 Estimated coordinate for centre of circle and estimated radius

6. CONCLUSION

There are several methods to do measurement either contact or non-contact observation. Contact measurement can be grouped as calliper, micrometer, coordinate measuring machine (CMM) and laser tolling. The limitation of the contact measurement is that the instrument component need to be physically in-contact directly and some instruments device cannot be moved. On the other hand, non-contact measurement commonly refers to geodetic instrumentation such as electronic theodolite, robotic total station, photogrammetry and laser scanning system. Electronic theodolite and robotic total station is terrestrial method that has been proven their viability in the laboratory testing result, in this case, Hull object and PVC pipe dimension measurement. The software system is a fully automated in data acquisition. For data processing and analysis, user still able to process and calculated the final result at field or we called it “on-site solution”.

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