# A Comparison and Full Error Budget Analysis for Close Range Photogrammetry and 3D Terrestrial Laser Scanning with Rigorous Ground Control in an Industrial Setting

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**Key words**: Error Budget Assessment, Laser Scanning, Photogrammetry, CAD Modelling

## SUMMARY

Commercially available scanners offer a high degree of automation in data collection and processing, and the technology is accessible to users with little knowledge or background in electronic distance and angle measurement, CAD, or three dimensional object modeling. A drawback to this is that it is difficult to gauge beyond manufacturer specifications actual errors in the scanning and modeling process, and automatic measurement can make it difficult to develop robust tests for accuracy and precision. This paper describes a comparison between close-range photogrammetry (CRP) and laser-scanning with a Cyra 2400 in process facilities. All of the data collected is compared against a rigorous ground-control network established using high-precision survey techniques. The objective of the research was to determine what significant errors exist between these systems through data collection, processing, and object modeling.

# A Comparison and Full Error Budget Analysis for Close Range Photogrammetry and 3D Terrestrial Laser Scanning with Rigorous Ground Control in an Industrial Setting

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## 1. INTRODUCTION

Previous work on the characterisation of the precision of laser scanners deals mainly with the hardware errors, in terms of accuracy and precision of the scanner component observations, and environmental effects on the scanner accuracy, for instance Gordon *et al* (2001). Whilst this is important, studies of such calibration errors and their corrections form only one part of the analysis of geodetic networks. Since the 1970s the process of network analysis and design has been determined to have the three fundamental parts of observation quality, network configuration, and datum (Graferend, 1974). Each of these affects the quality of the estimated parameters from the network, but is reliant on differing criteria. This has long been recognised in close-range photogrammetry, a method closely analogous, in network terms, to that of laser scanning, for instance in the treatment of 'generic' networks (Mason, 1994). Ideally, a rigorous error propagation would be modelled, similar to that employed in 'self-calibrating bundle adjustment' in photogrammetry. Establishing such a full error propagation method for scanner surveys is difficult due to the segmented nature of the scanner survey process, particularly:

- Calibration of the internal parameters of a scanner requires knowledge of internal geometry. Unlike photogrammetry, there is no simple projective relationship between the recording medium and the light directing equipment. Thus, a parametric equation to be included in the error analysis for calibration (pre-, post-, or 'on-the-job') for a scanner is difficult to develop and would vary between scanner types. Due to this difficulty the scanner internal calibration has yet to be included mathematically in any treatment of the overall accuracy of scanner surveys.

- Scanners are oriented in the chosen co-ordinate system using targets established by total station measurement. This usually employs radials from a single traverse station; it is rare that any form of triangulation is undertaken since this is costly. This has two consequences:
  - The subsequent precision estimates of the scanner resection do not include error propagation from the establishing traverse
  - Biases in the radials may not be found during resection of the scanner orientation

- The datum for the scans is commonly achieved using a six-parameter transformation (3 translations, and 3 rotations), with scale established in the scanner co-ordinate system by the laser measurements. Yet this may not agree with the scale established for the 'World Co-ordinate System' (WCS) by the establishing traverse. This may cause problems when a number of clouds are registered together then transformed without scale being considered.

- The observation of surfaces from scanner data is accomplished after the registration of laser point clouds; therefore these observations do not aid the overall orientation of the laser or of the overall network in the WCS.

The same propagation of error problems can, of course, be seen in the method of 'pair-wise' photogrammetry (PWCRP) that uses a single pair of images with 80-90° convergence around one axis. With the exception of internal calibration methods, the points made above apply equally to the PWCRP approach. The measurement of facilities such as chemical process plant was one of the primary focuses of laser scanner development, and promised a more efficient method of 3D model generation than PWCRP. However, objective comparisons between the two have been difficult to make since neither method has been analysed for accuracy in terms of their abilities in modeling within the chosen WCS which is of great importance, for instance, in revamp work where large distances can separate the individual surveys.

This paper reports on experiments designed to test the precision of terrestrial laser scanning (TLS) in the measurement and modelling of process facilities by comparison to the equally non-rigorous PWCRP and to a rigorously analysed terrestrial network established using a total station. Practical problems encountered are addressed, such as occlusions or geometric weaknesses in the networks.

## 2. METHOD

Two scenarios were studied in this project, with two different network styles applied in the laser scanning of process areas. The first was a 'link' traverse along a pipe-rack; the second a 'polygon' traverse around a piece of process equipment.

### 2.1 Pipe Rack Survey

#### 2.1.1 <u>The Survey</u>

Figure 1 shows the pipe-rack section of approximately 70m in length. This section was chosen since the pipe-rack made two turns that would require the laser scanner to be oriented in different geometries. The underside of the pipe-rack was scanned using a Cyra 2400 scanner in nine consecutive scans in the direction shown by the arrows, with four Cyra targets appearing in the overlap between the scans. The Cyra 2400 had been analysed for its accuracy in the lab prior to the survey (Habib *et al*, 2003).

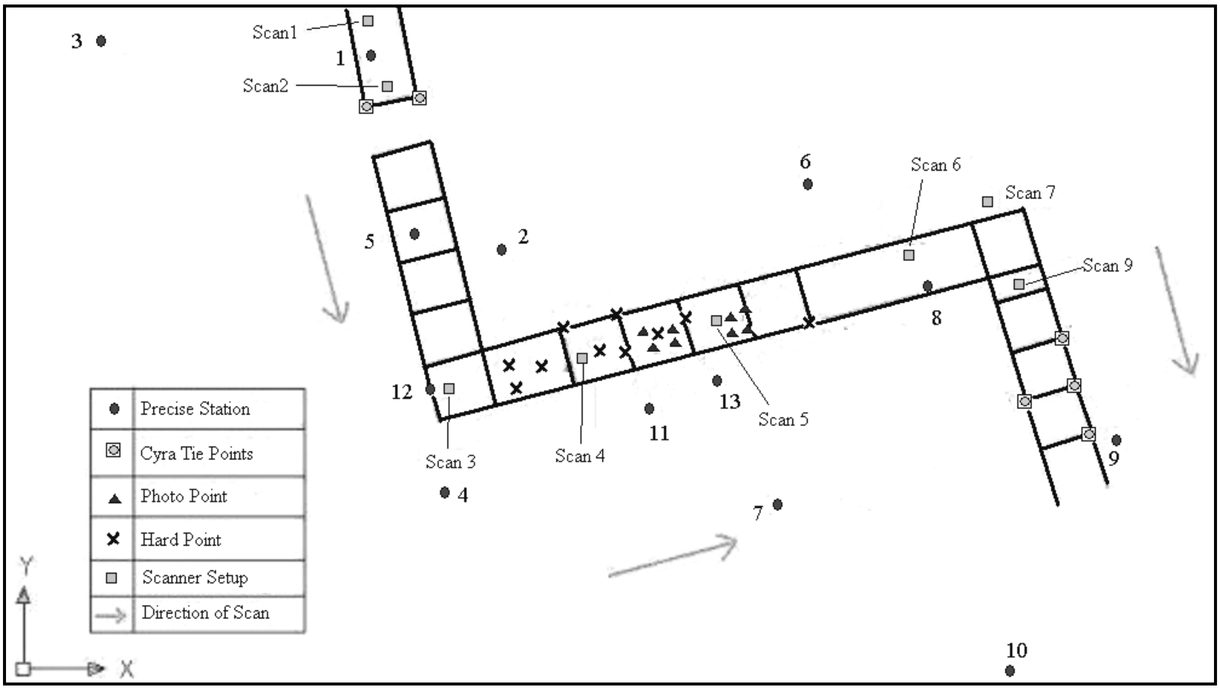


**Figure 1**: Overhead view of pipe rack section

A network of 13 stations was installed for the high precision survey using a Leica TC2003 total station (0.5” angular, 1mm EDM). Figure 2 shows the network geometry and the 2D confidence ellipses (95%). The stations used to measure the ’Hard Points’ for comparative purposes (middle of the network, Figure 1) had an estimated precision of between 0.1 and 0.6 mm at this confidence level, with at least three reciprocal observation sets to each station. The geometry of the network was constrained by buildings in the area (not shown), a common problem in the measurement of process areas.

Convergent pairs of images (Figure 3) of the ‘Hard Points’ were taken using a Sony DSC F707 digital camera, pre-calibrated in the lab using a self-calibrating bundle adjustment and the Vision Measurement System (VMS). The images were resected in VMS using four control targets, manually measured. No tie points were introduced to the solution.

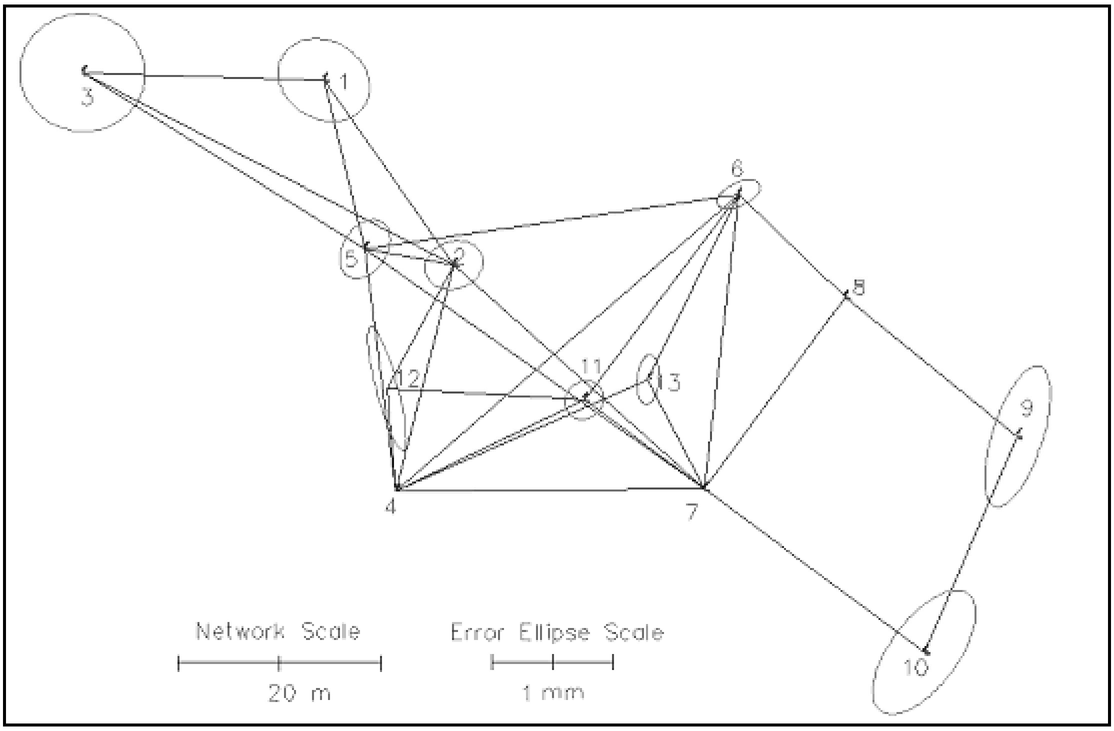


**Figure 2**: Network Geometry and Error Ellipses

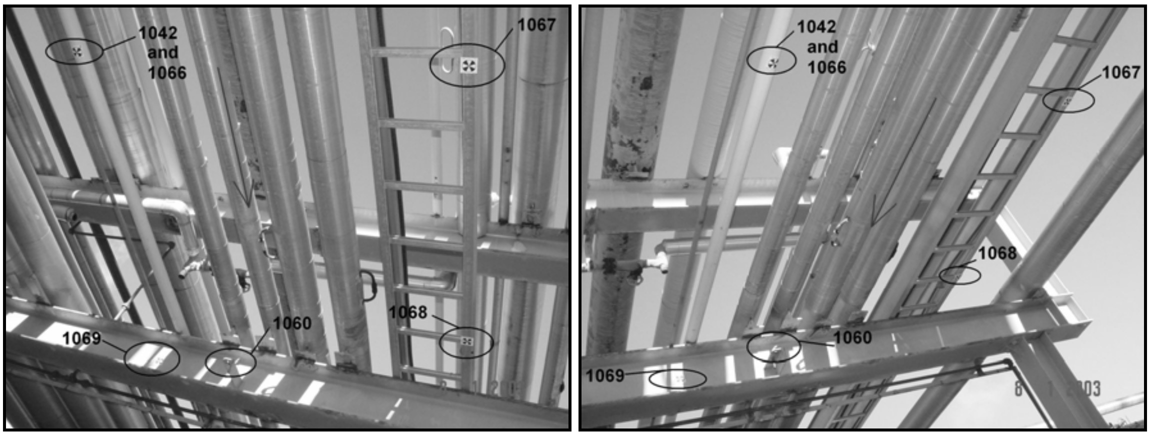


**Figure 3:** 'Hard Points' Used for Photogrammetry

### 2.1.2 Results of the survey

The laser scans of the pipe rack were registered together using Cyra Cyclone 4.0 utilising the overlapped Cyra target points except for scans 5 and 6, between which scaffolding had been erected in the line of sight of the scanner. This is another common occurrence when scanning in process areas. In this case, some of the targets placed behind the scaffolding were occluded. The image from the on-board camera on this Cyra 2400 being very poor, areas that were not occluded could not be identified in the volume and targets placed appropriately. For this reason, the post-survey registration of this pair relied on a visible target, a modelled centreline from an I-beam, and the centreline from a (presumed) horizontal pipe, all of which features appeared in the two scans. This process is fully supported for registration in Cyclone, but it would not be expected to give the same registration accuracy as the proprietary targets. The resulting registered point cloud was transformed into the survey co-ordinate system using the dialogue box shown in Figure 4. It is desirable to calculate transformation parameters using data from a wide extent of the volume surveyed, as in the choice of a minimum constraint datum. The choices are shown in Table 1; Points 1002 and 1003 are Cyra targets appearing in Scan 1, Points 1076 and 1079 are the final Cyra targets in Scan 9. Cyra provide a proprietary staff with two targets on a levelled rod for the vertical alignment but this was not available for this project; two points were therefore manually picked on a vertical stanchion

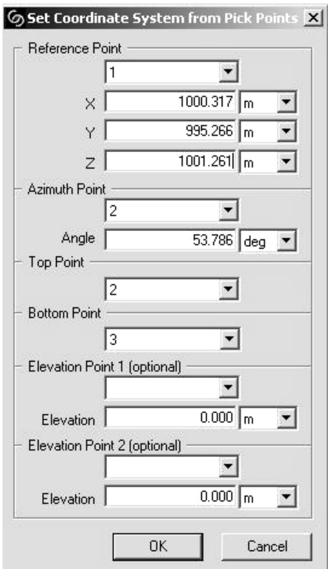


**Figure 4**: Transformation dialogue Box

| | ASSOCIATED CYRA TARGET(S) | |
|---|---|---|
| **Reference Point** | 1002 | |
| **Azimuth** | **At Point** | **To Point** |
| | 1002 | 1079 |
| **Vertical Alignment** | manually picked in Scan World 9 | |
| **Elevations** | 1003 | |
| | 1076 | |

**Table 1.** Minimum Constraints Datum Choice

The 'Hard Points' were identified in the transformed laser cloud, measured in the photogrammetry, and compared to the precise survey co-ordinates for these points. The results are shown in Table 2. The exceptional result in height for the scanned data is suspect considering the poor network geometry for determination of this parameter. The fact that the standard deviation is relatively high and the same as the RMS figure would normally indicate a low significance to the mean value of 1mm.

**Table 2:** Coordinate Comparison to Precise Survey

| **Statistic** | LASER SCANNING | | | PHOTOGRAMMETRY | | |
|---|---|---|---|---|---|---|
| | **Northing (m)** | **Easting (m)** | **Height (m)** | **Northing (m)** | **Easting (m)** | **Height (m)** |
| *Mean* | 0.007 | 0.007 | -0.001 | 0.002 | 0.000 | 0.002 |
| *Std. Dev.* | 0.004 | 0.001 | 0.012 | 0.002 | 0.004 | 0.002 |
| *RMS* | 0.011 | 0.009 | 0.012 | 0.003 | 0.004 | 0.004 |

The discrete PWCRP has a significantly higher accuracy than the laser scans in the link traverse. This does not mean that a discrete laser scan similarly oriented using control targets in each scan would not perform equally well, only that the common method of registering multiple scans before transformation into a world co-ordinate system is generally less accurate. Figure 5 shows the 3D accuracy of estimation of points with distance from the first scan. A linear trend of decreasing accuracy with distance from the initial scan is evident. The relatively high scatter in scans 4 and 5, compared to the end scans, is attributed to the fact that the end scan points were included in the estimation of transformation parameters, especially in the height component. The Scan 9 points are found to be precise but not accurate, assumed to be the effect of the difference in scale between the laser and terrestrial networks.

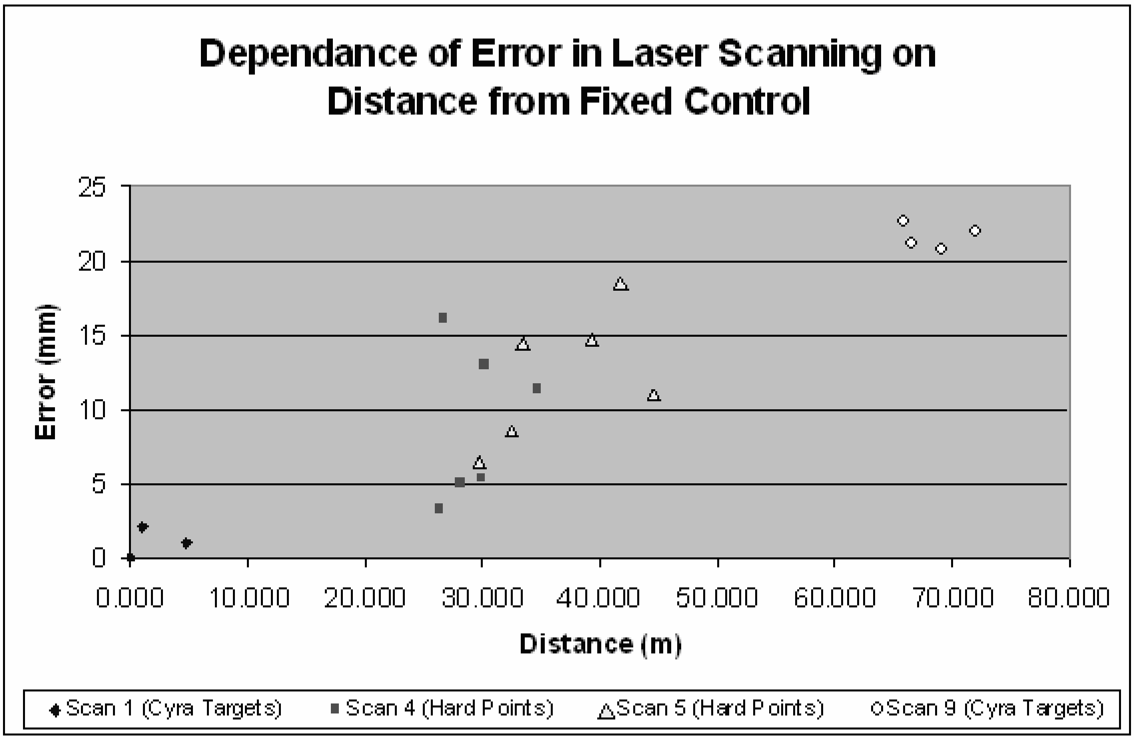


**Figure 5:** 3D Error vs. Distance

Overall, the scanner network performs very well compared to the expectation of this system, particularly since the unit was operated at -20°C. Anecdotally, the network accuracy of a scanner has been suggested as around ±30mm, and this is definitely given credence by these results.

## 2.2 Equipment Survey

Another survey was undertaken to assess the accuracy of a ‘closed’ registration and of the effects of the errors of CAD modelling. Figure 6 shows the piece of equipment used for the measurement campaign, a typical feature in process areas. Five scans were taken around the unit, and a pair of images taken from each side. 4 ground-station points were set up around the unit, with multiple observations between the different stations made with the TC2003. Estimated qualities of the parameters from this control network were in the order of 0.5 mm at 95% confidence in both horizontal and vertical components

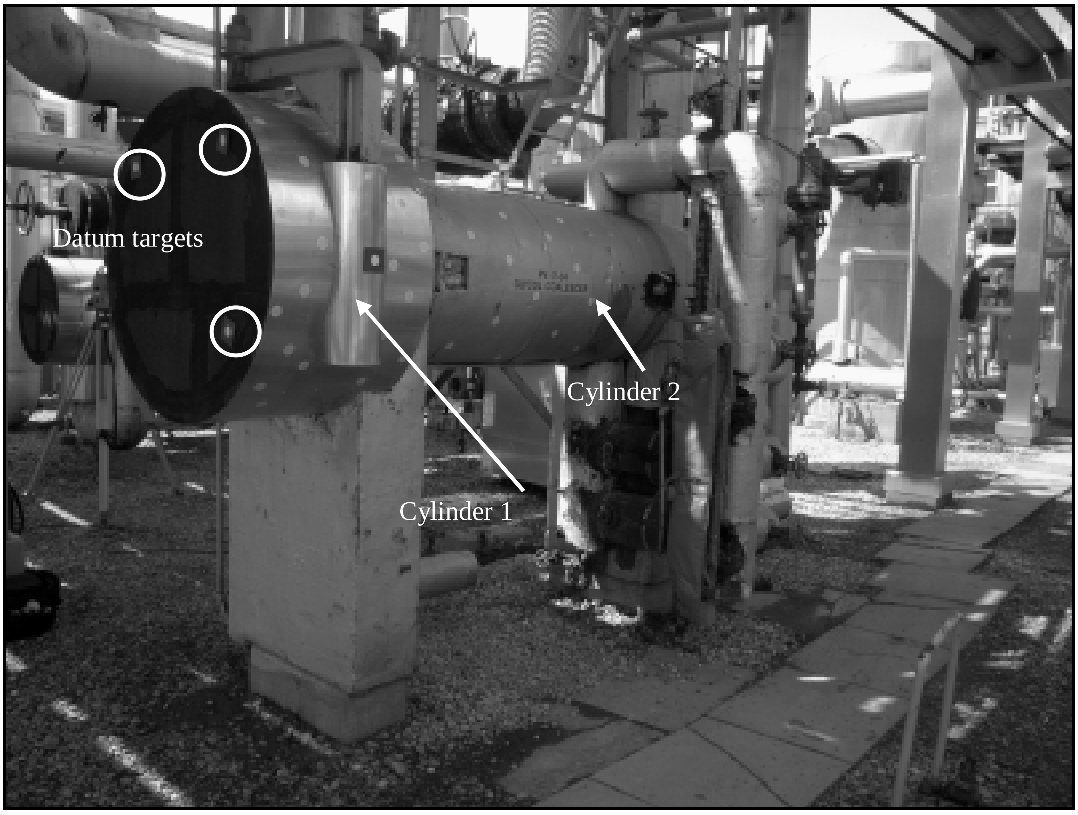


**Figure 6:** Unit for Equipment Survey

Three control targets on the equipment (detail, Figure 6) were surveyed from the control stations with high redundancy (3 distance and 6 angle measurements to each target) to form the datum for the laser scanning campaign. Similar results were achieved for these targets, with sub-millimetre errors at 95% confidence.

#### 2.2.1 The Scanner Network

Scans were taken all the way around the structure in 5 setups with a stand-off distance of around 2-3m, with 4 Cyra targets appearing in the overlap between pairs of scans, and closing the last scan onto the first. The locations of the scanner positions were, once again, restricted by the topography of the surrounding structures. Tie points between setups were placed as close to the edges of the scanner views and with as much variation in depth as possible while still being viewable from the next setup location. The scans were registered using Cyra Cyclone 4.0. Closing the scan loop greatly affected the registration results. Without closing the scan network, the coordinates of the control targets measured in the last scan were 12-15 mm from their ground truth values. Once registered, the error level dropped to 2-3 mm. This agrees with the error results found in the hanging leg survey shown in section 2.1.2 and confirms the propagation of error as scans progress from control points.

### 2.2.2 Targeted Measurements

A series of targets suitable for both surveying and photogrammetry were placed on the two cylinders shown in Figure 6 (30 targets on Cylinder#2, 28 on Cylinder#1). The Leica TC2003 was used to measure these targets using single radial observations for each (estimated 95% 2D error-ellipse parameters of 2.5mm, 1.0mm). The same set of targets was then photographed in convergent pairs using a pre-calibrated Rollei d7Metric5 camera. The image pairs were resected as before using 4 homologous control points, and the remaining points intersected. The accuracies of the results compared to the control survey are shown in section 3.1.

## 3. RESULTS

### 3.1 Point Measurement

Table 3 shows the accuracy results of the point measurement using PWCRP compared to the control survey for 58 intersected points in the two pairs of images.

**Table 3:** Error in Point Measurement between pair-wise photogrammetry and the control survey

| | Error X (mm) | Error Y (mm) | Error Z (mm) |
|---|---|---|---|
| **Average** | -0.45 | 0.28 | -0.03 |
| **Standard Deviation** | 2.32 | 1.40 | 0.98 |

The average error is significantly smaller than the standard deviation of the results on all three axes, indicating that the PWCRP results agree with the control survey within the precision of the survey. The worse results in the X-axis compared to the Y-axis are explained by the geometry of the convergent pairs, which converge around local gravity in the direction of the X-axis. It would be expected that the Z-axis component would be worse than shown, considering the poor photogrammetric geometry in this direction. However, in previous experiments the authors have noted that this component is always suppressed in this configuration by the overconstraint of the four control targets. Addition of further images followed by inner constraints has allowed this component to respond correctly in the past. These results are not as good as those obtained in the link traverse, mainly due to environmental conditions; whereas the link traverse images were observed in well-lit conditions with the camera flash active, there was poor ambient light on the equipment survey and for safety reasons the flash was not permitted. The result was lower quality photographs adding to the pointing error in the measurement.

### 3.2 Modelling

The difficulty in comparing laser scanners to other geodetic instruments is that the scanner is unable to measure specific object points without using specialized scanner targets. In addition, when using the scanner in practice, it is typically the accuracy of the CAD model of the object that is important. The objects considered for this experiment were the two large cylinders on the main body of the processor. These were modelled using scan, photo and survey data, all within Cyclone 4.0 so that the same modelling routine would be used for all the modelling, eliminating implementation errors. Several model comparisons were then made. Firstly, the reported quality of fit of the modelled cylinder, from the Cyclone software, is shown in Table 4.

**Table 4:** Cylinder Modelling Quality

| | **Fit from Survey Control network** | **Fit from Photogrammetry** | **Fit from registered scans** |
|---|---|---|---|
| **Cylinder #1** | | | |
| Abs. Mean Error | 1 mm | 2 mm | 2 mm |
| Standard Deviation | 2 mm | 2 mm | 3 mm |
| **Cylinder #2** | | | |
| Abs. Mean Error | 1 mm | 1 mm | 2 mm |
| Standard Deviation | 1 mm | 2 mm | 4 mm |

The other important modelling comparisons are the parameters of the cylinders themselves. In this case, estimated length is not an applicable comparison due to varying ranges of data along the cylinders for each method. This is usually catered for in CAD modelling by the intersection of two modelled objects. However, radius and centreline are also important factors in this comparison. Table 5 shows the radius of both cylinders as modelled from the three data sets.

**Table 5:** Cylinder Radii Comparison

| | **Cylinder #1** | **Cylinder #2** |
|---|---|---|
| **Fit from survey** | 0.5480 m | 0.3810 m |
| **Fit from photo** | 0.5475 m | 0.3805 m |
| **Fit from scan** | 0.5500 m | 0.3840 m |

While the survey and PWCRP agree very closely, the TLS result varies by 2-3 mm. The CAD model derived from the control survey is considered as the basis of comparison in this work since it has a statistically significant number of points in the cloud (60 points – 7 parameters for the cylinder definition) and higher observation accuracy than the other two methods. The scanner fits many more points but at a lower accuracy, and the photogrammetry fits the same number of points as the control survey at a lower accuracy. The scans were made with the mean direction of the scanner roughly perpendicular to the cylinder axes. The distance measurement standard deviation for the scanner (± 4mm) should, of course, even-out the errors in the point cloud to give the mean zero position of the cylinder surface. Yet the angular error, at a standoff of 2m, would have to be in the order of 5 arc minutes for the error to be in the range experienced (quoted standard deviation is 12 arc seconds). Since no biases in the scanner measurement were detected in the lab calibration (Habib, *et al*, 2003), the differences between radii calculated using control survey and scanner data are difficult to isolate.

The other major component of the cylindrical parameters, the centreline, can be given by two endpoints, or a unit vector. In this case, since the length varies, the unit vectors were compared for alignment, and the angular error propagated into a positional error at an equal distance along the centreline for each method of data collection. For Cylinder #1 this was set at 0.6m long, and for cylinder #2 at 2m long, resulting in the larger misalignments for cylinder #2. Table 6 shows the alignment results for each pairing of data collection methods. It is to be expected that estimation of the direction of a cylinder will improve with the length over which observations are made, and this proves to be the case when comparing the higher angular errors in Cylinder 1 (shorter axial length) with Cylinder 2. It is also not surprising that the high redundancy of observation offered by the scanner gives a better result in this case than the photogrammetry. The shortest distance between centrelines is indicative of the translational accuracy of the cylinders. All the results are quite small except for cylinder #2 derived from the scanner data, especially compared to the survey model. However, the lower accuracy of fit of Cylinder 2 from the scan cloud (Table 4) could have caused the translation of the centreline from its surveyed location.

**Table 6:** Comparison of the alignment of cylinder centrelines

| | **Survey – Photo** | | **Survey – Scanned** | | **Photo – Scanned** | |
|---|---|---|---|---|---|---|
| | Cylinder #1 | Cylinder #2 | Cylinder #1 | Cylinder #2 | Cylinder #1 | Cylinder #2 |
| **Angular misalignment (°)** | 0.24976 | 0.18981 | 0.17944 | 0.07861 | 0.20167 | 0.1575 |
| **Endpoint positional difference (mm)** | 2.6 | 6.6 | 1.9 | 2.7 | 2.1 | 5.0 |
| **Shortest distance between centrelines (mm)** | 1.5 | 0.7 | 1.3 | 6.3 | 0.3 | 3.4 |

## 4. CONCLUSIONS

The experiments reported here were designed to compare a rigorous survey using a high-accuracy total station against that achievable using commercially available laser scanning techniques and the method of pair-wise close-range photogrammetry. Two scenarios were studied in the field of process facility measurement, a common application for both methods. The first examined the use of a ‘link’ traverse of scans along a pipe bridge; the second involved the use of a ‘closed’ series of scans on a piece of process plant. The results show the roughly linear increase in error as scans proceed away from the control in the link traverse, and the errors smoothed out when closed back on the control in the equipment survey.

The final models show that the centreline alignments for the photogrammetry are significantly worse than the scanner. This is due to the low redundancy of data in photogrammetry relative to the scanner. However, the centreline translation is worse with the scanner. This may be due to the scanner having the lowest accuracy in distance measurement (perpendicular to the cylinder axis). It can be seen with both, as compared to the control surveys, that the level of error in the model is significant for higher precision industrial work. The data was collected over a relatively short distance, and when taken in the scope of an entire processing area, the misalignments and translations would be quite significant. This type of engineering measurement often calls for CAD model accuracies of between 2-30mm, often on the same contract. It is clear that the CRP gives limited coverage (CCD sensors) but can achieve a higher accuracy, whilst laser scanners capture large amounts of data but have lower accuracy if used in a line of scans. Both methods are directly reliant on the quality of the control survey for their relative accuracy across a facility, and it is stressed that the network utilised here was, for comparative purposes, much more rigorously implemented than is usual for this type of work. It is recommended from these findings that great care be taken in the implementation of any survey network that requires relative accuracies of 1cm or less using either laser scanning or pair-wise photogrammetry. If higher accuracies are required, or very reliable measurements needed (for instance of weld lines), CRP can be used in a bundle method. Further planned work will involve the simulation of laser scanning full error budget in a CAD environment for network planning purposes.

This research has utilised the Cyra 2400 scanner and associated software, both of which outperformed their manufacturer’s specifications. It is recognised that not all scanners are alike or that their processing strategies are the same. However, it is believed that this method of analysis of the absolute accuracy for the chosen instrument in a facilities environment has potential to assess other systems regardless of these parameters.

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