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A COMPARATIVE STUDY OF MEASUREMENT PERFORMANCE BETWEEN TWO PHOTOGRAMMETRIC SYSTEMS AND A REFERENCE LASER TRACKER NETWORK FOR LARGE VOLUME INDUSTRIAL MEASUREMENT

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Abstract

This paper determines the capability of two photogrammetry systems in terms of their measurement uncertainty in an industrial context. The first system - the V-STARS INCA3 from Geodetic Systems Inc. (GSI) - is a commercially available measurement solution; the second system comprises of off-the-shelf photographic hardware, a Nikon D700 digital SLR fitted with a 28mm Nikkor lens and the research based: Vision Measurement Software (VMS). The uncertainty estimate of these two systems is determined with reference to a calibrated constellation of points. The calibrated points have an average associated standard uncertainty of 12.5µm, spanning a maximum distance of approximately 14.5m; subsequently, the two systems'

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uncertainty was determined. The V-STARS INCA3 had an estimated standard uncertainty of 43.1μm - out performing its manufacturer's specification – and the Nikon D700 digital SLR and Vision Measurement Software (VMS) achieved a measurement with a standard uncertainty of 187μm.

KEYWORDS: photogrammetry, co-ordinate comparison, uncertainty, laser tracker.

INTRODUCTION

Laser trackers are used extensively for large-scale industrial and scientific metrology (Peggs et al., 2009) . The aerospace sector utilises laser tracker systems for the setting and conformance tasks required for wing-level manufacture, in particular jigs and fixtures. In part, this is due to the dynamic measurement capability of laser trackers. However, many static point measurements are required in these applications and photogrammetry systems are often overlooked. Photogrammetric systems hold many advantages over the laser tracker. These include:

- simultaneous multiple target measurement,
- quick measurement time,
- lower operator skill level,
- inexpensive measurement targets.

These benefits are offset by the systems' accuracy and cost. The cost is comparable to the laser tracker, however, the accuracy is invariably considered to be not as good as the laser tracker, even though in certain operating environments comparable accuracy levels are attained. As computational costs reduce, and readily available digital cameras rise in standard - in terms of mechanical construction, sensors and lenses - photogrammetry could provide a far more cost effective alternative to laser tracker measurement systems. This work compares the capability of two imaging systems: 1) the V-STARS INCA3 from Geodetic Systems Inc. (GSI) and, 2) an Nikon D700 digital SLR fitted with a *28mm* Nikkor mm lens and Vision Measurement Software (VMS). The V-STARS system is representative of a commercial photogrammetric system built around a custom designed imaging system and software, whereas the second system utilises an off-the-shelf 12MP digital camera and lens in combination with research based photogrammetric software; costing an order of magnitude less than the commercial system. Manufacturers state an instrument's performance in terms of measurement uncertainty, however this is often assessed and determined in a controlled environment and in accordance with VDI/VDE 2634, and not in the intended industrial setting. Consequently, an independent verification of a measurement system's capability in an environment similar to that of the intended application environment is required to achieve confidence in an instrument's performance; especially for tolerance critical operations, such as those found aerospace. The uncertainty of measurement for each system in our industrial environment – typical of aerospace manufacture - is an output of the study. The measurement uncertainty is determined by using a method of co-ordinate comparison. The reference network provides a co-ordinate definition with a known measurement uncertainty, improving on the use of a single laser tracker as a reference standard (Summan et al., 2015).

The uncertainty estimates for the two photogrammetric systems are compared to a single station laser tracker measurement, utilised in manufacturing applications, as a performance benchmark.

METHODOLOGY

The evaluation will determine the measurement uncertainty of static measurements in an environment and volume similar to the intended industrial application, that is, the conformance measurement of wing-level tooling structures within aircraft manufacture.

The estimated measurement uncertainty is determined by using a method of co-ordinate comparison; comparing the measured co-ordinates with a *reference network* with a quantified associated uncertainty (Muelaner et al., 2009; Hughes et al., 2010). A reference network of discrete points will be established with an accurately determined co-ordinate definition. In turn, the photogrammetry systems will re-measure the reference network. Subsequently the total uncertainty of measurement will be determined by constructing an uncertainty estimate in accordance with the ISO/IEC Guide 98-3:2008: GUIDE TO THE EXPRESSION OF UNCERTAINTY IN MEASUREMENT.

UNCERTAINTY TERMINOLOGY

The following terms are used throughout this uncertainty evaluation and are defined by ISO/IEC Guide 98-3:2008 and 99:2007:

Uncertainty: parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand (*Y*). Where: $Y = f(X_1, X_2, \dots, X_N)$.

Standard uncertainty: $u(x)$, uncertainty of a measurement expressed as a standard deviation.

Combined standard uncertainty $u_c(y)$, standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariance of these other quantities weighted according to how the measurement result varies with changes in these quantities. In the case for independent input quantities the combined standard uncertainty is given as:

$$u_c^2(y) = \sum_{i=1}^{n} \left(\frac{\delta f}{\delta x_i}\right)^2 u^2(x_i)$$

Sensitivity coefficient: c_i, describes how the output estimate y varies with changes in the values of the input estimates $x_1, x_2, ..., x_N$, such that:

$$c_i = \frac{\partial f}{\partial x_i}$$

Expanded standard $U = ku_c(y)$ quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.

Coverage factor k numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty ($k > 1$).

REFERENCE NETWORK

The reference network is a constellation of 11 points within an approximate volume of 13.5m x 8m x 3m (with a maximum point-to-point distance of 14.5m), accurately measured using a *Leica AT401* laser tracker. Each of the 11 points within the reference network was measured 9 times from different laser tracker positions (Fig. 1). The co-ordinate definitions from each measurement location are combined using a weighted least squares regression, with the intent to minimising the associated point uncertainty based on the instruments' uncertainty characteristics (Muelaner et al., 2010). The weighted network adjustment is in turn based on the three main components of the laser tracker uncertainty model, that is, the two angular encoders and radial distance measurement. Subsequently, an optimized co-ordinate for each point is defined and the uncertainty associated with each point computed via a Monte Carlo simulation. The constellation of points, n_m, was computed with an average magnitude uncertainty, $u(n_m)$, of 11.8µm at k = 1 (a confidence interval of 68.26%). This analysis was carried out with SpatialAnalyzer software.

Measurement errors attributable to variations in the refractive index and temperature during the data acquisition has not been explicitly compensated in the network adjustment. As a result any errors arising from this will be seen in the network residuals and internal correlations between measurements and parameters. The computed uncertainty includes a number of uncertainty contributions, including the instrument parameters in ranging and angular uncertainty, but also the uncertainty associated to the Spherically Mounted Retro-reflector (SMR) target, n_t, and magnetic nests, n_n. These variations are implicit within network adjustment and subsequent Monte Carlo simulation (MCS) based uncertainty evaluation. However the number of measurement samples is limited, and therefore cannot be thought of as a robust characterisation of these components of uncertainty. As a consequence the SMR and magnetic nests have been explicitly included within the uncertainty budget (Table I).

Repeatable magnetic target nests are used to hold 1.5” diameter spherical targets such as SMRs, tooling balls or split bearings; this allows the same point in space to be measured by each instrument. The repeatability of magnetic target holding nests was experimentally evaluated. The magnetic nest repeatability was determined by placing a tooling ball in the nest and measuring the runout in each of the three axes with a digital dial indicator ten times for five different nests, this totaled 150 runout measurements. The combined standard uncertainty for the magnetic nest, $u(n_n)$, was demined as 1.48µm.

The SMR uncertainty, $u(n_t)$, can be attributed to a mechanical centering tolerance of 6µm, with an equal probability applied to the tolerance band. Hence we can assume a rectangular distribution, and obtain the standard deviation as:

$$u(\mathrm{n}_t) = \sqrt{6} = 3.46\ \mu\mathrm{m}$$

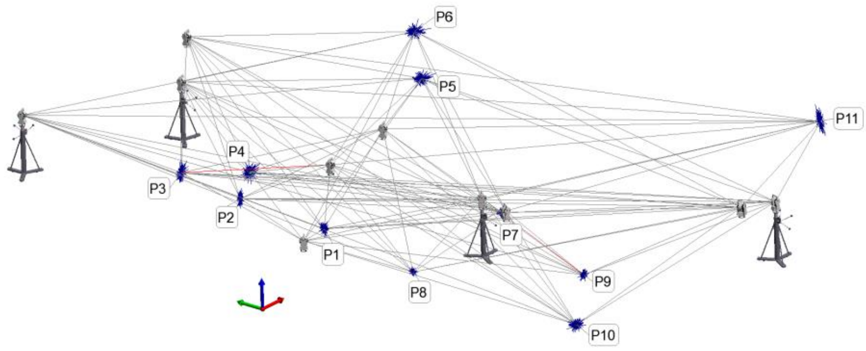


FIG. 1: Reference measurement analysis for the uncertainty evaluation (with point uncertainty fields and co-ordinate system).

The co-ordinate definition of the points in the reference network (n) can be expressed as function of the following sources of variation:

$$n = f(n_m, n_t, n_n)$$

The estimated uncertainty associated to the co-ordinates, $u(n)$, can subsequently be determined (Table I).

TABLE I: Uncertainty estimate for the reference network measurement.

Standard Uncertainty component $u(x_i)$	Source (X_i)	Value of standard uncertainty $u(x_i)$	*Sensitivity coefficient* $c_i = \frac{\partial f}{\partial x_i}$	$u_i(n) = \lvert c_i \rvert u(x_i)$
$u(n_m)$	*Network measurement*	*11.80*	*1*	*11.80*
$u(n_t)$	*Target manufacturing tolerance*	*3.46*	*1*	*3.46*
$u(n_n)$	*Nest manufacturing tolerance*	*1.48*	*1*	*2.41*

$$u_c^2(n) = \sum u_i^2(n) = 153.44\ \mu m$$

$$u_c(n) = 12.53\ \mu m$$

ANALYSIS

V-STARS INCA3 Photogrammetric System

The V-STARS INCA3 is a purpose built metric camera with a 8MP CCD sensor, with a 21mm focal length, and a 77° × 56° field of view (GSI, 2005).

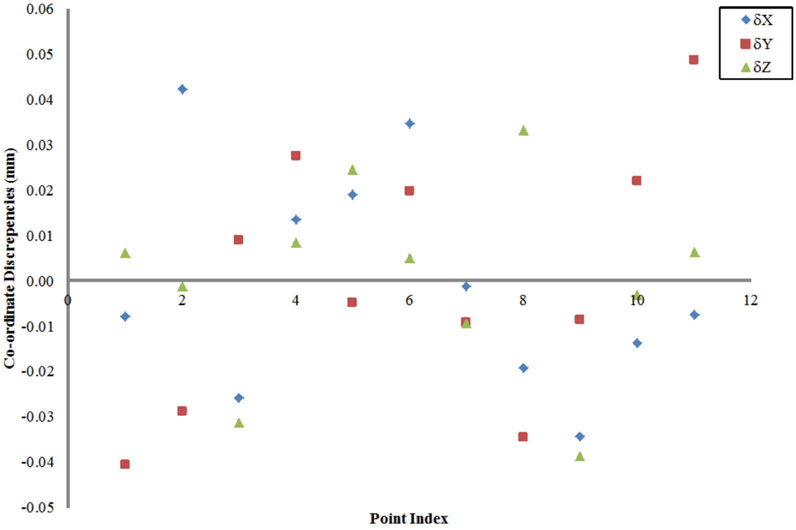
The reference network was re-measured using the V-STARS INCA3 camera using additional scale bars for the bundle adjustment, without any knowledge of the reference network's co-ordinate definition. The photogrammetric network comprised 359 images and 853 object points, including the 11 reference points. The uncertainty evaluation is based on a six degrees of freedom (6DOF) un-weighted least-squares regression; using the network of points from the laser tracker network as a reference and 'best-fitting' the constellation of points measured using the INCA3; Table II summarises the best-fit result. Fig. 2(a) shows the individual co-ordinate discrepancies in each axis, for each reference point. Fig. 2(b) shows the magnitudes of the co-ordinate discrepancies and an indication of the levels of the overall 3D measurement uncertainty present. The standard deviation from the least-squares fit residuals is 43.0µm; the standard deviation is similar in each of the three axes and shows a good 3D agreement.

Comparing the inter-point distances of the two data sets - the maximum point to point distance is approximately 14.5m - compares the *shapes* of the two data sets. Here the standard deviation is 40.6µm, with a maximum deviation of *101µm*; which is close to the standard deviation of the least-squares fit, and is therefore consistent. The standard deviation of the coordinate transformation residuals is the main component of uncertainty included in the uncertainty estimate for the network measurement (Table III) The INCA3's instrument specification is 5µm + 5µm/m (at k = 1), the reference network spanned approximately 14.5m; at this distance the system's specified uncertainty is 77.5µm (at k = 1); our uncertainty estimate shows that the system performed well within its specification with an uncertainty of 43.1µm (at k = 1).

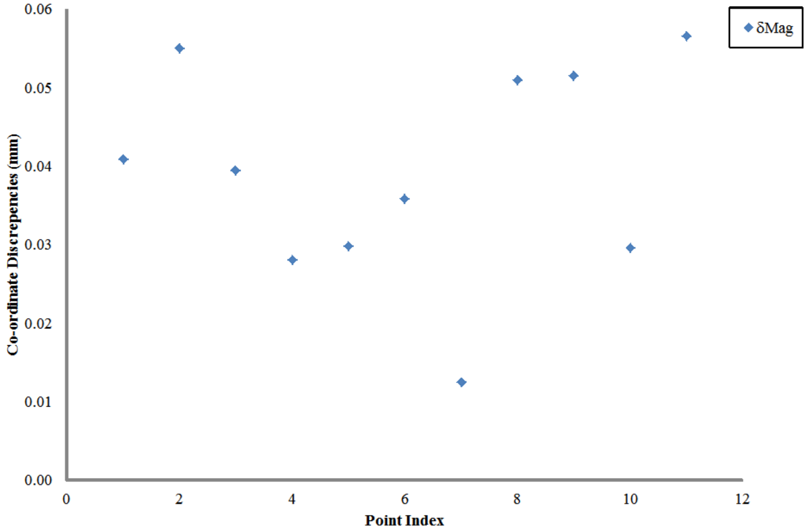
TABLE II: Summary of the V-STARS INCA3 best-fit with the reference network points.

	Best-Fit (6DOF) Transformation Residuals (mm)			
Results	*X*	*Y*	*Z*	*Mag*

Max Error	*0.042*	*0.049*	*0.039*	*0.052*
Std. Dev. Error	*0.025*	*0.028*	*0.021*	*0.043*



(a) Target Coordinate Discrepancies from reference network in each co-ordinate axis.



(b) Magnitude of Target Coordinate Discrepancies from reference network.

FIG. 2: Comparison of V-STARS INCA3 co-ordinates after un-weighted least-squares regression with reference co-ordinates.

The co-ordinate definition of the photogrammetric measurement (p) can be expressed as a function of the of reference network, n (from above), and the best-fit residuals , p_f, such that:

$$p = f(p_f, n)$$

An uncertainty estimate can subsequently be determined (Table III).

TABLE III: Uncertainty estimate for V-STARS INCA3 measurement.

Standard Uncertainty component $u(x_i)$	Source (X_i)	Value of standard uncertainty $u(x_i)$	*Sensitivity coefficient* $c_i = \frac{\partial f}{\partial x_i}$	$u_i(n) = \lvert c_i \rvert u(x_i)$
$u(p_f)$	*6DOF fit residuals*	*41.23*	*1*	*41.23*
$u(n)$	*Reference standard*	*12.39*	*1*	*12.53*

	network uncertainty			

$$u_c^2(n) = \sum u_i^2(n) = 1856.92\mu m$$

$$u_c(n) = 43.09\ \mu m$$

Off-the-shelf Photogrammetric System

The off-the-shelf photogrammetric system comprised of a Nikon D700 digital SLR fitted with a *28mm* Nikkor lens and Vision Measurement Software (VMS). The measurement was processed using a self-calibrating photogrammetric adjustment. Following the same processing chain, the standard deviations of the 6DOF least-squares fit residuals to the reference network coordinates gives a standard deviation of 186µm (Table IV) and the inter-point distances give an standard deviation and maximum deviation of: 155µm and 364µm, respectively. From Table IV the *y*-axis (reference Fig.1) exhibits a larger degree of variation than the *x* and *z* axes, which agreed with one another. The *y*-axis is aligned to the length of the reference network, this longer distance could be more sensitive to scaling errors which manifest as *y*-axis errors. More generally, the high best-fit residuals dominate the uncertainty estimate (Table V) and the total measurement uncertainty for the off the shelf camera is 186.6µm (at $k = 1$). This is likely to be a consequence of several limitations in comparison to commercial system, the combination of which will increase the uncertainty of the target coordination within the self-calibrating bundle adjustment process. Factors are listed as follows:

(a) The camera had an unstable interior orientation. The focus of the Nikon lens was fixed during image capture however instabilities in the physical fixture of the lens to the camera body and of the CMOS imaging sensor to the camera body will contribute to small image to image geometry variations.

(b) Fundamental to a high quality result is the geometry of the imaging network with multiple convergent lines of sight to each target. Unlike the state of the art commercial photogrammetric system, the low cost system does not have provision to connect to a host computer and carry out on-line bundle adjustment as images are captured. This limitation means that the operator does not receive guidance as to where the photogrammetric imaging geometry should be improved during the capture process.

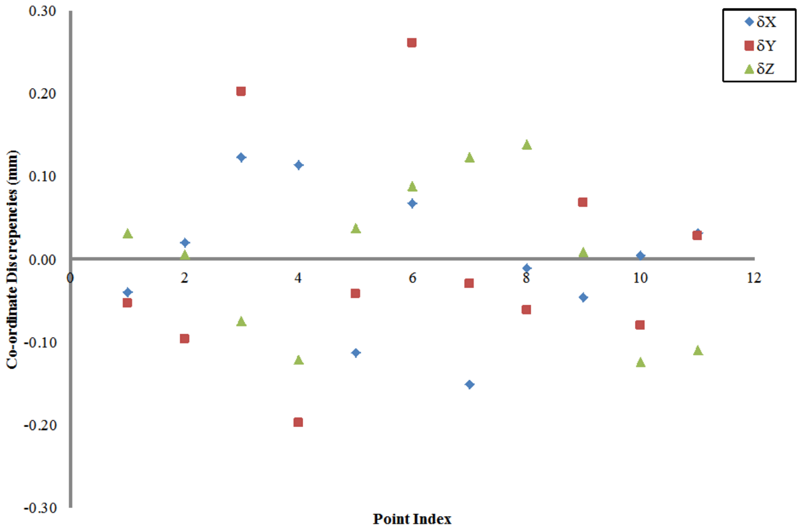
(c) Retro target image quality is critical for a high quality result. Whilst images were captured using retro-reflective targets and an electronic flash with the low cost system, there were no optimisations, such as multiple exposures and changes in exposure, to ensure optimal target image quality. This limitation is compounded with a reduction in retro-target image quality following the camera

Beyer colour correction that is integral to the design of the DSLR sensor (Luhmann, 2010).

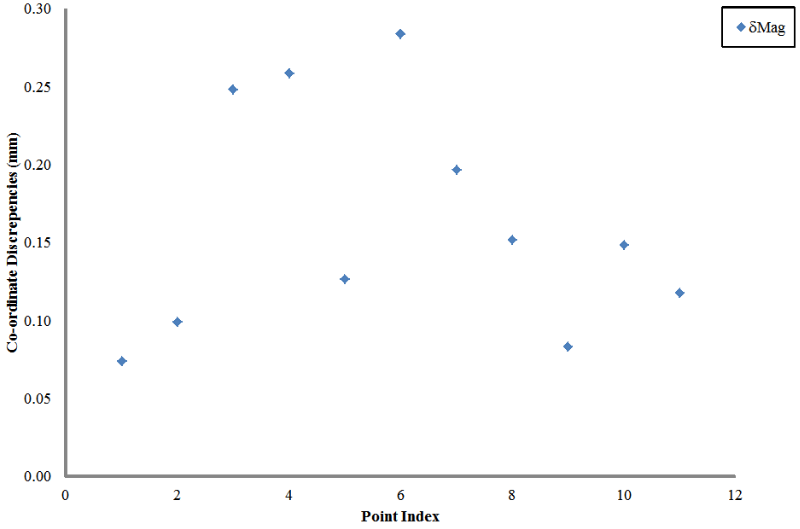
(d) Target eccentricity corrections (Luhmann 2014) were not included in VMS in November 2010 when these data were captured.

TABLE IV: Summary of the Digital SLR/VMS best-Fit with the reference network points.

	Best-Fit Transformation (6 DOF) Residuals (mm)			
Results	*X*	*Y*	*Z*	*Mag*
Estimated uncertainty – mean (worst case)	*0.085 (0.097)*	*0.121 (0.366)*	*0.064 (0.090)*	*0.161 (0.389)*
Max Error	*0.151*	*0.261*	*0.138*	*0.284*
Std. Dev. Error	*0.086*	*0.134*	*0.096*	*0.186*



(a) Target Coordinate Discrepancies from reference network in each co-ordinate axis.



(b) Magnitude of Target Coordinate Discrepancies from reference network.

FIG. 3: Comparison of Digital SLR and VMS bundle adjustment co-ordinates after un-weighted least-squares regression with reference network co-ordinates,

TABLE V: Uncertainty contributions for digital SLR measurement

Standard Uncertainty component $u(x_i)$	Source (X_i)	Value of standard uncertainty $u(x_i)$	*Sensitivity coefficient* $c_i = \frac{\partial f}{\partial x_i}$	$u_i(n) = \lvert c_i \rvert u(x_i)$
$u(p_f)$	*6DOF fit residuals*	*186.16*	*1*	*186.16*
$u(n)$	*Reference standard network uncertainty*	*12.53*	*1*	*12.53*

$$u_c^2(n) = \sum u_i^2(n) = 34813.92\mu m$$

$$u_c(n) = 186.58\ \mu m$$

Comparison to laser tracker

In order to assess the photogrammetry systems' suitability for large volume measurement, the current industrial practice must be taken into consideration in order to make meaningful comparisons. At present a laser tracker can be used in a single station configuration or networked together to minimise point uncertainty; however, the former is more common. A single station laser tracker's uncertainty was calculated using the reference network points; Table VI shows the summary. This summary is the result of ten data sets from individual tracker stations, as some tracker positions are better placed than others, this should provide a balanced residual. To ensure the experimental results are not unreasonable, Table VII has been constructed to compare the experimental results with those of the manufacturers' specified performance. The laser tracker shows consistent agreement with the manufacturer's expectation, whereas the V-STARS *INCA3* is performing significantly better than the manufacturer's specification. However, the laser tracker network has a much lower measurement uncertainty than that of the other systems.

TABLE VI: Laser Tracker single station average best-Fit with reference network points (metrics calculated from 10 individual stations' best-fit residuals)

	Best-Fit Transformation			
Results	*X*	*Y*	*Z*	*Mag*
Max Error	*-0.1148*	*-0.1373*	*0.0669*	*0.1840*
Std. Dev. Error	*0.0339*	*0.0314*	*0.0198*	*0.0503*

TABLE VII: Manufacturers specifications compared to experimentally derived standard measurement uncertainty.

	Laser Tracker		*Photogrammetry*	
	Single Station	*Network*	*V-STARS INCA3*	*Nikon & VMS*
Manufacturers specification	*7.5µm + 3µm/m*	*n/a*	*5µm + 5 µm/m*	*n/a*
System expectation at a maximum dimension of 14.5m	*51.0µm*	*n/a*	*77.5µm*	*184.5 µm*[6]

[6] Value based on the network adjustment error propagation for the worst-case target in the network.

Experimentally determined specification at 14.5m	*51.8μm*	*12.5μm*	*43.1μm*	*186.6μm*

CONCLUSIONS

This paper highlights the capabilities of three optical metrology systems suited to large volume industrial measurement. A laser tracker, a state of the art commercial photogrammetric system (V-STARS INCA3) and a photogrammetric system based on an off-the-shelf camera of considerably lower cost (Nikon and VMS). Results have been characterised within the context of measurement uncertainty since this is a key factor in relation to meeting and verifying tolerances for critical measurements. Typically, a 95.45% (k = 2) measurement confidence is required – at least – for large scale manufacturing measurements.

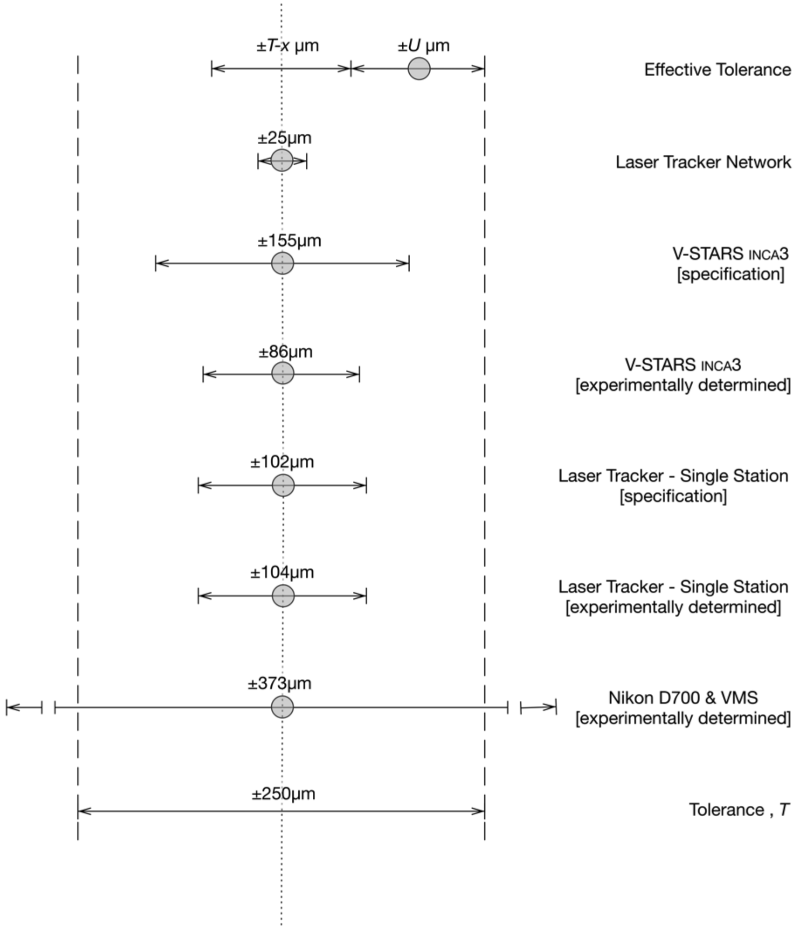


FIG. 4: A typical tolerance band for jigs and fixture setting with the instruments' associated measurement uncertainty at a *k=2.*

The impact of measurement confidence with reference to a design tolerance of ±250µm for the measurement task undertaken for this analysis is summarised in Fig. 4. This data demonstrates the impact of using a laser tracker in isolation when compared to a networked arrangement, although it should be noted that an industrial tracker network is unlikely to be quite as strong, as not *all* stations have line of sight to *all* targets. Nevertheless, networking instruments still yields significant improvements with respect to the associated uncertainty.

Fig. 4 also contextualises the *INCA3's* performance and its suitability for these measurement tasks. The *INCA3's* is comparable to - and less than - the laser tracker's uncertainty as single station measurement instrument. However for this application the V-STARS *INCA3* meets the uncertainty requirement and is a suitable substitute for the single station laser tracker measurements. It should also be noted that the V-STARS system *could* be discounted as an instrument using the manufacturer's specification alone. Further improvements could be made to the performance of the photogrammetric system if a global scale was accessible. This global scale could be generated via laser tracker network measurements.

The non-commercial photogrammetric system is working within its expected uncertainty estimation from the bundle adjustment, but this far exceeds the desired uncertainty level, and tolerance band for this application: this makes confidence in achieving the tolerance impossible. In its current configuration, the system could provide low-cost measurement for less critical tolerances, e.g. ±*1mm* across the 13.5m x 8m x 3m volume used for this series of experiments. Improvements to the system could be carried out, for example stabilising the lens to camera mounting, including elliptical eccentricity correction and using the simulation tool within VMS along with next best view estimation (Hosseininaveh et al 2014) to improve on the improvised network image geometry.

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REFERENCES

1.

GEODETIC SYSTEMS INC., 2005. Picture Perfect Measurements, http://www.geodetic.com/products/systems/v-stars-s.aspx (Accessed: 6th March 2015)

HOSSEININAVEH, A., SARGEANT, B., ERFANI, T., ROBSON, S., SHORTIS, M., HESS, M., & BOEHM, J. (2014). Toward fully automatic reliable 3D acquisition: from designing imaging network to a complete and accurate point cloud. Robotics and Autonomous Systems, -. doi:10.1016/j.robot.2014.04.001

HUGHES, E. B., FORBES, A. B., SUN, W., MAROPOULOS, P., MUELANER, J., JAMSHIDI, J. AND WANG, Z., 2010. iGPS Capability study, NPL Report ENG 23, National Physical Laboratory, Teddington, UK. ISSN: 1754-2987

ISO/IEC Guide 98-3:2008, *Uncertainty of measurement: Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*, 2008.

ISO/IEC Guide 99:2007, International vocabulary of metrology - Basic and general concepts and associated terms (VIM), 2007

LUHMANN, T., 2010. Close range photogrammetry for industrial applications. *ISPRS Journal of Photogrammetry and Remote Sensing*, 65(6): 558–569.

LUHMANN, T., 2014, "Eccentricity in images of circular and spherical targets and its impact on spatial intersection," The Photogrammetric Record, vol. 29(148), pp. 417-433.

MUELANER, J. E., WANG, Z., JAMSHIDI, J., MAROPOULOS, P. G., MILEHAM, A. M., HUGHES, E. B. AND FORBES, A. B., 2009. Study of the uncertainty of angle measurement for a rotary-laser automatic theodolite (R-LAT). *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 223(B3): 217– 229.

MUELANER, J. E., WANG, Z., MARTIN, O., JAMSHIDI, J. AND MAROPOULOS, P. G., 2010. Estimation of uncertainty in three-dimensional coordinate measurement by comparison with calibrated points. *Measurement Science and Technology*, 21(2): 25106.

PEGGS, G. N., MAROPOULOS, P. G., HUGHES, E. B., FORBES, A. B., ROBSON, S., ZIEBART, M. AND MURALIKRISHNAN, B., 2009. Recent developments in large-scale dimensional metrology. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 223(6): 571–595.

SUMMAN, R., PIERCE, S.G., MACLEOD, C.N., DOBIE, G., GEARS, T., LESTER, W., PRITCHETT, P., SMYTH, P., 2015. Spatial calibration of large volume photogrammetry based metrology systems. *Measurement*. 68: 189-200.

VDI/VDE 2634 - 1,2,3 2002 Optical 3D measuring systems - Imaging systems with point-by- point probing (Berlin: VDI, Beuth Verlag).