A COMPARISON OF THE UTILITY AND EFFICIENCY OF DIGITAL PHOTOGRAMMETRY AND INDUSTRIAL THEODOLITE SYSTEMS

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ABSTRACT

This paper reports on the suitability of digital photogrammetry as a viable and effective alternative to theodolite triangulation. Particular attention is drawn to a case study where both methods were initially considered as appropriate measurement techniques. Emphasis has been placed on some of the practical aspect involved in determining which method could be ideally applied to the case outlined. Based on this evaluation the project was completed using the digital photogrammetric technique which emerged as the clear choice. Sufficient detail is given to provide the reader with some useful insight into the logistics of this type of project. The discussion also provides the reader with a feeling for the different features and factors inherent in each system.

INTRODUCTION

Theodolite triangulation has been successfully applied in a variety of metrology applications for a significant period of time. The use of theodolites for angular intersection can be traced back to as early as 1944 (Shortis and Fraser 1991). The principles of such systems is well known (Allan, 1988) and they have gained widespread acceptance for industrial measurement applications (Roberts and Moffitt, 1987; Woodward, 1987). The underlying concepts of triangulation are fairly simplistic and a number of similarities can be drawn with the field of close range photogrammetry. These similarities relate to both the computational and logistic requirements of the method.

Until recently digital photogrammetric equipment and techniques were not sophisticated enough to match the accuracy attainable through the use of first-order theodolite systems. Fortunately developments in large area CCD sensors and target image location algorithms have pushed the accuracy attainable using digital photogrammetry to a level where it can comfortably challenge theodolite triangulation systems. (Fraser and Shortis 1995). In a modern vision metrology system for industrial measurement, object space positional accuracies surpassing 1:100,000 of the principal dimension of the object are now routinely attainable with large-area CCD cameras and photogrammetric data processing (Fraser et al, 1995) High resolution still video cameras such as the Kodak DCS460 have CCD arrays of up to 2000 by 3000 pixels are readily available, thus representing a significant improvement on earlier examples of still video cameras. Target image location algorithms such as the weighted centroid have theoretical accuracies of approximately 1-2% of the image pixel size and have been utilised in many videometric applications.

This paper reports on the suitability of digital photogrammetry as an alternative measurement technique for applications that have traditionally been completed using theodolite triangulation. The discussion is carried out with reference to the particular features of both triangulation methods as well as factors governing their application. The features and factors examined are shown in Figure 1a and Figure 1b respectively

The paper examines a case study where digital photogrammetry was successfully used as an alternative to theodolite triangulation. Digital metrology techniques were utilised to determine three dimensional coordinates of key points necessary to model the spatial relationship between three critical openings of a large furnace hopper assembly (Ganci and Shortis, 1995a). Determination of the flange thickness of one of these openings was the primary objective of the project. Both measurement techniques discussed in this paper were considered for the project with the digital photogrammetric approach emerging as the favoured choice. The factors influencing the metrology method selected are discussed, along with the measurement results obtained and other project logistics.

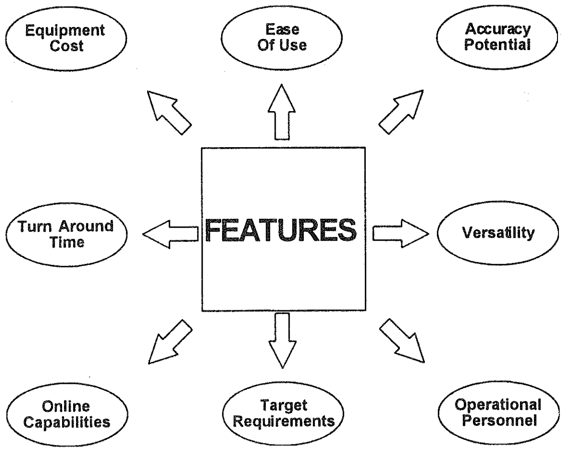

Figure 1a: Features defining the measurement methodology

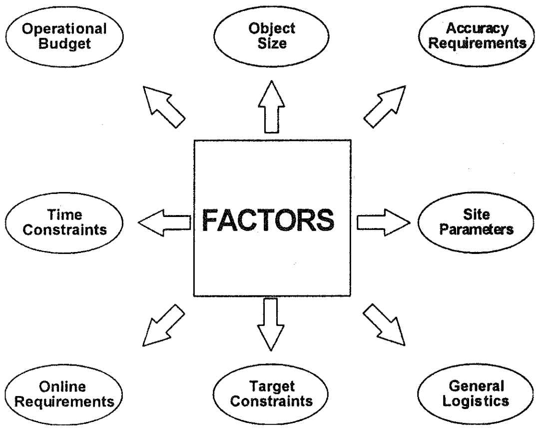

Figure 1b: Factors governing the measurement methodology

BACKGROUND

The Department of Geomatics at The University of Melbourne was approached to assist in the measurement of the top section of a furnace material hopper shown in Figure 2.

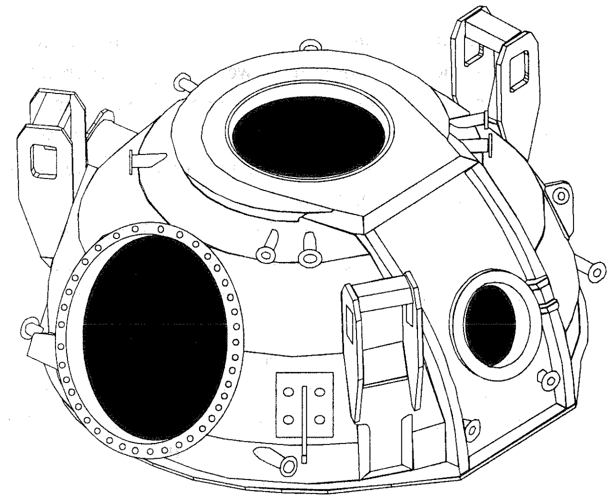

Figure 2. Diagram of the material hopper furnace top.

The measurement was required to determine the amount of milling required to ensure that design specifications for a critical flange were met. The flange is initially over dimensioned so that it can be milled to the correct dimension once the component is completed. Milling of this flange is carried out just prior to installation by the manufacturer. It is critical that the furnace hopper meet the prescribed design specifications, as ultimately the flange must couple with existing components. Figure 3 shows an image of the furnace flange prior to milling

OPERATIONAL CONSIDERATIONS

A strict schedule was enforced to ensure that the component could be transported and placed into position according to the prescribed completion timetable. Restrictions for the project dictated that milling data be supplied within a day of the component measurement. Once the initial milling was completed it was envisaged that the measurement would be repeated to recompute the flange thickness. The primary requirements in the project was the provision of coordinates to an accuracy of ±0.5mm, the computation of spatial coordinates based on best-fit surfaces and of course rapid turn around time.

A routine inspection of the site revealed very little of concern in terms of measurement obstructions. Despite the object size, relocation to a larger working area was possible through the use of an overhead gantry crane. However this was unnecessary as the object was located in a relatively uncluttered section of the workshop. The only obstructions were located on one side of the object where it was within one metre of an adjoining wall. A reasonable setback distance was available even with the appropriate consideration being given for workshop machinery and other components under construction.

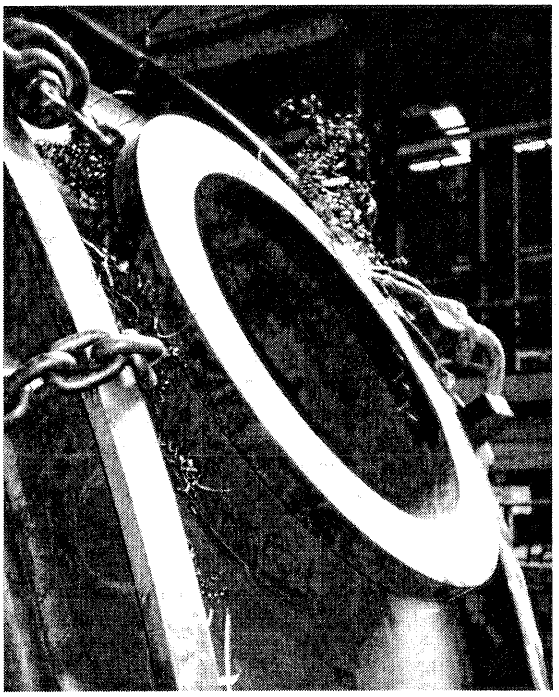

Figure 3. Image of the flange requiring milling

Having inspected the site it was necessary to establish a measurement methodology capable of satisfying the accuracy and organisational requirements of the task. In order to compute the milling required it was necessary to first establish the as built state of the furnace hopper. From this data and the appropriate design dimensions it would be possible to relate the cutting data back to the surface of the flange. The project could be clearly segmented into two distinct components, namely coordinate determination and coordinate manipulation.

To define the design coordinate system and the location of the flange, as well as provide checks on design dimensions, coordinate determinations was required for each of three key areas shown in Figure 4.

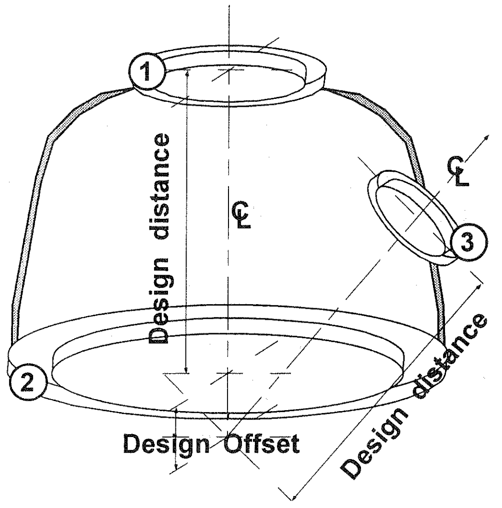

Figure 4. Diagram showing key areas and dimensions

As can be seen from Figure 4, each of the areas concerned is circular in nature and the centre point and radius of each was of prime concern. The vertical axis of the hopper is defined by the upper and lower circles designated 1 and 2 in Figure 4, whilst the origin of the design system is defined as an offset below the centre of circle 2. The flange, designated as circle 3 in Figure 4, defines the horizontal orientation of the design system and is specified to be at a design distance and angle from the origin.

Clearly, each circle would have to be targeted appropriately to allow the computation of the plane of best fit and circle of best fit, then the centre and radius. The measurement task here was the coordinate determination of approximately 50 target points. The location of these targets is shown in Figure 5. Additional targets shown on the sides of the hopper are necessary for photogrammetric measurement only, in order to strengthen the self-calibrating network.

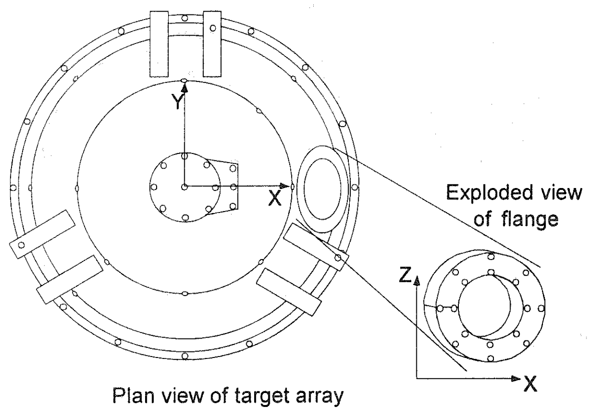

Figure 5. Target locations in principle planes

THEODOLITE TRIANGULATION

Initially the use of an on-line triangulation system, comprising of three total stations and PC based software was considered. The advantage of the online system is that it provides coordinates with a quality measure for every intersection measurement as it is taken, and measurements can be repeated immediately as required. The online capability of theodolite triangulation initially proved to be very enticing.

Based on an object diameter of 6 metres and a minimum instrument set back of 5 metres, it was calculated that approximately ten instrument stations would be required to adequately cover the object. This ideal configuration and a configuration which accounts for the proximity of the wall and other obstructions along one side of the object are shown in Figure 6.

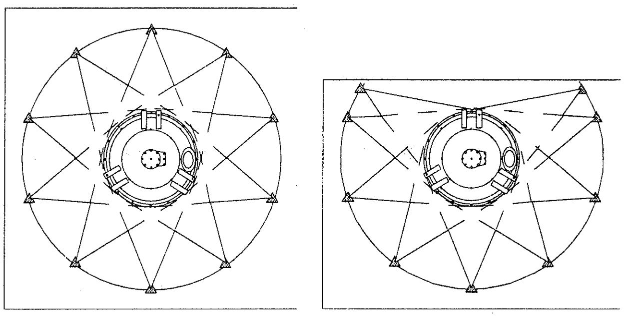

Figure 6. Ten station coverage with and without obstructions

Points adjacent to the obstructions will no doubt suffer a degradation of accuracy due to fewer, sharper intersection angles. The number of instrument stations can be reduced by increasing the minimum set back to effectively improve the angular coverage. This improvement will of course be at the expense of target coordinate precision due to the increase in target range. The level of coordinate precision degradation can of course be estimated through network simulations. Naturally enough, even a six or seven station network would be complicated by the need to "leap-frog" instruments around the object. The establishment of a three head triangulation system requires 1-2 hours depending on the determination of control. Once established, approximately 30 minutes is required to shift and reintegrate a new instrument station into the system. Based on the following parameters it is possible to estimate the time taken to complete the measurement phase using theodolite triangulation :

Three instrument initial establishment	1.5 hr
Seven station re-establishments (30 minutes each)	3 hr
Target measurement (50 targets @ approx. 2min. each)	1.5 hr
Total measurement time	**6 hr**

These figures do not take into account object targeting which is a requirement regardless of the measurement method selected.

The height of the object poses other issues which must be addressed. The hopper stands to a height of 2.5 metres and for easy work access was supported on a tooling jig, giving an additional 1 metre of height. Sighting to points on the top of the hopper would therefore require the purchase or manufacture of an offset rod which could be placed flush against the edge of the top circle surface. The number of measurements for offsets is doubled or tripled, as offset rods have multiple targets which provide the information necessary to locate the point of interest, based on the known geometry of the rod. The additional measurements will obviously influence the overall measurement time. In addition to these concerns, the use of such an offset rod would make it difficult to exactly revisit the same points in subsequent surveys. This would reduce the ability of the surveys for self-checking and to detect changes within the network between the two measurement epochs.

With regard to target intersection there are other issues which bear consideration. Many of the targets along the base will be difficult to intersect purely because of their orientation relative to that of the instrument. Figure 7 demonstrates the effects of viewing angle on target visibility. It is clearly evident that certain viewing angles make accurate pointing to targets quite difficult.

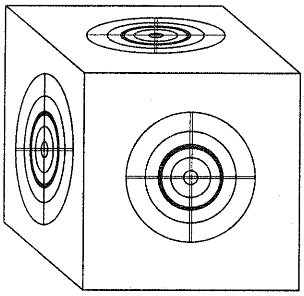

Figure 7. Effect of viewing angle on circular targets

The personnel required to operate the system was also a concern, as a three instrument system requires at least four people for efficient operation. An operator is needed for each instrument, plus a fourth person to operate the PC and act as a task coordinator. A fifth person would be required in this case to manipulate the offset rod.

Finally, the ability of the system to produce "real time" or online coordinates is somewhat negated by the fact that all coordinates are needed before the best fit planes and circles can be computed. Hence coordinate information can not be used until all targets for the particular surface have been triangulated.

DIGITAL PHOTOGRAMMETRIC TRIANGULATION

The alternative optical triangulation technique assessed was digital photogrammetry. The development of "still video" CCD cameras with onboard storage capabilities has simplified the digital photogrammetric process. Image capture, transmission, analog to digital conversion and the digital image storage is carried out internally in a convenient and portable package. The CCD camera can be operated via a direct link to a notebook PC if required, or alternatively images can be stored on the internal disk for subsequent image processing and mensuration. The ability of these cameras to collect multiple, high resolution digital images without a cumbersome computer interface makes them a very useful digital photogrammetric tool (Fraser and Shortis, 1995).

The Kodak DCS 420 is such a still video cameras. The CCD chip present in the camera has a resolution of 1524 by 1012 pixels and is capable of producing maximum accuracies of at least 1:80,000 (Beyer, 1995; Fraser and Shortis, 1995). The DCS 420 uses a removable, credit-card sized PCMCIA (Personal Computer Memory Card International Association) type hard disk for convenience, portability and interchangeability with other computers. Transfer of the image data can be completed through a SCSI interface included with the camera back, or by physically transferring the PCMCIA hard disk card to a computer with an appropriate interface (Ganci and Shortis, 1995b).

By far the most appealing features of photogrammetry for this project were the speed of data acquisition and the ability to optimise accuracy through the use of multi-station, convergent imaging geometries. The time of observation needed to be only as long as the time it would take to capture the necessary images as defined by the simulation. This means that deformation measurements can be made with minimal disturbance to the production process. Photogrammetric networks are also advantageous it that they can be readily designed to optimise the accuracy and economy of the project at hand. They can afford considerable flexibility in camera positioning and the number of images involved. This flexibility is particularly advantageous for adapting the network design to the prevailing environment and conditions at the work site. With a single, roving still video camera, the addition of new camera stations or extra images at pre-designed camera stations is straightforward, whereas the inclusion of extra theodolite stations is a major exercise.

In addition, photogrammetry is advantageous as it permits non-contact measurement even in the absence of a stable camera platform. The gantry crane walkway used in this project is a prime example of how a relatively unstable platform can still be utilised for data collection. Theodolite triangulation from a such a platform would of course be highly inaccurate if not impossible. Finally, only one person is required to operate the still video camera, whereas four or perhaps five people are needed to operate and manage the theodolite system. This represents a considerable saving in the cost of manpower.

METHODOLOGY EVALUATION

In almost all the criteria areas examined, the digital photogrammetric measurement option was better suited to the measurement task than the theodolite, or indeed any other, approach. In this instance the online triangulation system was deemed unsuitable as it could not satisfy many of the requirements of the project. The lack of flexibility coupled with the significant personnel requirements made it highly unlikely that the project could be completed without the resolution of significant concerns. This is especially evident in the face of the alternative method. The flexibility of the digital approach is clearly evident when comparing the relative size and complexity of the equipment required for data collection. The theodolite system requires three total stations, stands, cabling and an on site computer. The photogrammetric approach requires but one camera and a flash. In terms of the time required to collect the data the photogrammetric approach required but 20 minutes. This represents an 18 fold saving on the estimated theodolite triangulation case.

In this project it was fortunate that there was no requirement for online coordinate determination. Had this been the case then the digital photogrammetric method would have undoubtedly proven to be unsuitable. Projects which require "real time" coordinates will remain the domain of theodolite triangulation systems until digital photogrammetry can match the theodolite systems. The likelihood of this "real time" aspect developing is remote given that by their very nature these systems are based on single sensors and multiple exposures. What is perhaps more plausible is the likelihood that these systems will become streamlined to a point where the time lag between collection and coordinate determination will be acceptable for the majority of applications

IMPLEMENTATION

Having established a methodology it was necessary to verify that the accuracy requirements could be met. This was accomplished through the use of a network simulation (Fraser, 1984) to design and analyse the photogrammetric network. Utilising approximate camera station positions and likely target locations, plus the expected measurements and their respective precision, it is possible to estimate the likely precision of all coordinates. No actual measurements are required at this stage, the results of the simulation are purely based on the geometry of the networks and the types and precision of measurements.

The coordinate precisions obtained from the simulation are a very useful diagnostic tool for the design, and re-design, of the photogrammetric network. The specified tolerance for the design dimension determinations was set at ±0.5mm. To be confident of meeting such a tolerance, the precision of coordinate measurements should be of the order of ±0.15mm at the one sigma level.

Based on a network of 9 camera stations with 2 exposures at each station the simulation yielded an object space accuracy of the order of ±0.1mm. Using the results of the simulation it was possible to compute the minimum target diameter necessary to satisfy the requirements for centroid determination. The size of these targets is computed using the lens focal length, the average object distance and the minimum desirable image diameter. Based on a minimum target image diameter of four pixels it was determined that 22mm diameter targets would be required.

Once the object was available for data collection the targets were applied to the pre-defined locations (see Figure 5). These target locations were determined interactively during the simulation process. The target placement is a mix of pre-selected primary locations to define surfaces and circles, and secondary locations selected on-site to strengthen the photogrammetric network and fill the format of the still video camera.

An unforseen complication was the location of the drive components of the gantry crane. The location of these components prevented an unobstructed view of the factory floor on one side. This tended to bias the network of camera stations, as the crane had to be driven further to one side than expected to obtain adequate coverage of the hopper. For the first epoch of photography this forced some rapid changes to the initial network design. Additional camera stations were included to compensate for what would otherwise be a weaker network, leading to 11 stations with an average of 2 exposures per station.

For the second epoch a new design was adapted to overcome the physical limitations of the environment. The original number of 9 camera stations was employed, but in this case biased to compensate for the weakness detected in the first network. In essence, more camera stations were used on the more distant side of the network.

A small selection of frames were measured manually on site to facilitate the computation of initial target and station coordinates. These coordinates formed the basis of the resection process utilised to measure the remaining frames semi-automatically. The resection is almost entirely automatic except for the initial target identification needed to orientate the frame. All image locations were computed using an intensity weighted centroid algorithm. Thresholds were computed in a 16 by 16 pixel window for each target using the pixel intensity values (Shortis et al, 1994).

Following image mensuration, restitution via bundle triangulation takes place. This least-squares estimation operation essentially reconstructs 3D XYZ data from 2D image measurements, while at the same time providing a self-calibration of the camera and the precisions of the target coordinate data.

MEASUREMENT ANALYSIS

Due to changes in the design of the networks, changes in the flash exposure intensity and changes in the quality of some target images, the two networks gave markedly different results. As can be seen from Table 1, the image space precision for the second epoch is significantly improved.

Result	Epoch 1	Epoch 2
Image space RMS error (pixels)	0.044	0.032
Number of digital images	22	18
Number of targets	63	62
Mean object space precision (mm)	0.16	0.17
Relative accuracy	1:58,000	1:50,000
Min. object space precision (mm)	0.07	0.07
Max. object space precision (mm)	0.56	1.01

Table 1. Results of photogrammetric network computations

In an apparent contradiction, the average object space precision for the second epoch is slightly degraded, caused by an unforseen loss of target images. Due to the few days between the two epochs, many of the targets were smeared with rust and oil, reducing the retro-reflective response despite attempts at cleaning, changing exposures and the outright replacement of some targets.

The precisions of the derived centres and radii of the circles ranged from 0.1mm for the flange to 0.3mm for the bottom plate, which are also in broad agreement with the predicted object space precisions. The top plate and flange certainly met the accuracy specification of ±0.5mm with a large degree of confidence, whilst the bottom plate met the accuracy specification only at a 1.7 sigma level.

The results of the first epoch of measurement indicated that the design dimensions were out of tolerance. The height of the hopper, using the separation of the top and bottom plates, was some 6.3 mm in excess of the design. To verify that this was not an error in the overall scale of the photogrammetric network, spirit levelling was used to independently determine the separation of the plates. The result of the levelling was a excess separation of 5.5mm with a precision of 1mm, which agreed with the videometric determination.

The design dimensions for the critical flange were also in out of tolerance, although this was expected as the surface had been deliberately left "green" with some excess material. The amount of surface material to be removed at each target location was computed. The average thickness to be removed was 4.4mm.

The flange was to be reduced in thickness using a "bolt on" milling machine. The milling machine incorporates a calliper-like measuring system to determine cutting depth. The measurements made with the calliper disagreed with the photogrammetric determination of the planarity of the surface, in the worst case by 1mm. The face was therefore milled to within 1mm of the design dimension.

After the second epoch of measurement, constant dimensions were verified and the excess in the design dimensions for the flange had reduced as expected. The over dimension of the height of the hopper was verified at 6mm and the centre of the critical flange was 1mm in excess of design. Again the photogrammetric and calliper measurements could not be reconciled, so the flange face was milled at a compromise depth which resulted in an average of 0.4mm of under-cut. Although this problem was never resolved, the flange was nevertheless within the ±0.5mm design tolerance according to both systems.

CONCLUDING REMARKS

Developments in digital photogrammetric equipment and techniques will no doubt have a significant effect on a variety of metrology applications. The development of large area CCD sensors and corresponding improvements in target location algorithms have placed the modern digital photogrammetric system at a point where it can offer traditional users of triangulation systems a very attractive alternative. The case study examined is but one example of how the digital photogrammetric alternative is finding increased acceptance. What is perhaps even more significant is the obvious savings available both in terms of time and money. Given that the accuracy achievable is commensurate with that of a theodolite triangulation system it is clear that in due course the digital photogrammetric system will find its appropriate niche in the metrology market.

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