A comparison of three methods for the 3-D measurement of turbine blades.

T.A. Clarke, S. Robson, & J. Chen.

School of Engineering, City University, Northampton Square,
LONDON, EC1V OHB, U.K.

ABSTRACT.

The accurate measurement of objects such as turbine blades is of great importance in determining 'as built' dimensions. From these data further information can be derived which allows assessment of: balance, damage, and adherence to design plans. In this paper three techniques for the reconstruction of 3-D shape are compared and contrasted. Examples of data collected from: Photogrammetry, Optical Triangulation, and Moiré, are presented. The method chosen for a particular task will depend on the qualities of each technique, sufficient information is given to assist in an appropriate selection.

1. INTRODUCTION.

For a variety of reasons many structures occupying $0.5m^3$-$5m^3$ require rapid measurement to mm or sub mm accuracy. The three methods considered in this paper are all able to acquire spatial data with speed and accuracy. However, each method has strengths and weaknesses and a knowledge of these is necessary to choose the best method for a given measurement project. While only three techniques are discussed here, there is sufficient variety to be of value in choosing an appropriate non-contact optical system for an industrial application. The three methods which have been chosen for review have been used extensively by the authors[1,2,3,4,5,6] and practical case studies are discussed in each case.

2. PHOTOGRAMMETRY.

2.1. Introduction to Digital Photogrammetric Systems.

Photogrammetry is an established discipline, having gradually matured over the last 100 years. The methodology involves identifying and measuring targets or patterns on photographs or images of an object which have been taken from disparate viewpoints. These image measurements are then used to compute three dimensional co-ordinates of the locations of the targets or patterns on the object being measured. Conventionally Photogrammetry has used film based image systems, however, rapid advances are being made in the photogrammetric use of digital imaging systems. Such advances rely on the development of electronically and mechanically stable high resolution solid state cameras. Current "state of the art" techniques using sophisticated film based imaging systems[7], are able to achieve about 1 part in 1,000,000 of the object space. These levels of precision are as yet unrealised with solid state imagery, 1:30,000 being currently attainable, however, rapid advances in sensor technology and a better understanding of sub-pixel measurement techniques are giving rise to very respectable results[8].

Photogrammetric algorithms are founded on the theory of a central perspective projection (Figure 1). This theory enables sets of equations to be written which relate each point on the object to a set of measurements made in the image space. These equations are known as collinearity equations, many examples of their derivation exist in standard photogrammetric texts[9,10]. Each collinearity equation contains several unknowns, the location and orientation of the camera at exposure time, and the X,Y,Z co-ordinates of the object point. A solution to these unknowns can be performed using a simultaneous least squares adjustment of all collinearity equations, known as a bundle adjustment. Since real imaging systems only approximate to the central perspective projection, functions must also be included to model departures caused by the real lens system, unflatness of the imaging surface, and any electronic distortion of the image. Such corrections, determined *a priori* or simultaneously with object co-ordinate determination, may be simply added to the collinearity equations[11].

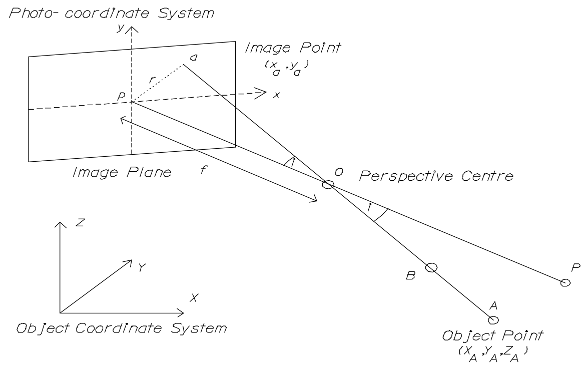


Figure 1. The Central Perspective Projection.

2.2. Case Study.

The subject measured was a small three bladed marine propeller. The complete propeller was targeted with small circular retro-reflective targets. The target diameter was chosen to be contained by a window of 20x20 pixels in the image. Nineteen images were taken to obtain complete multi-photo coverage of the propeller (Figure 2).

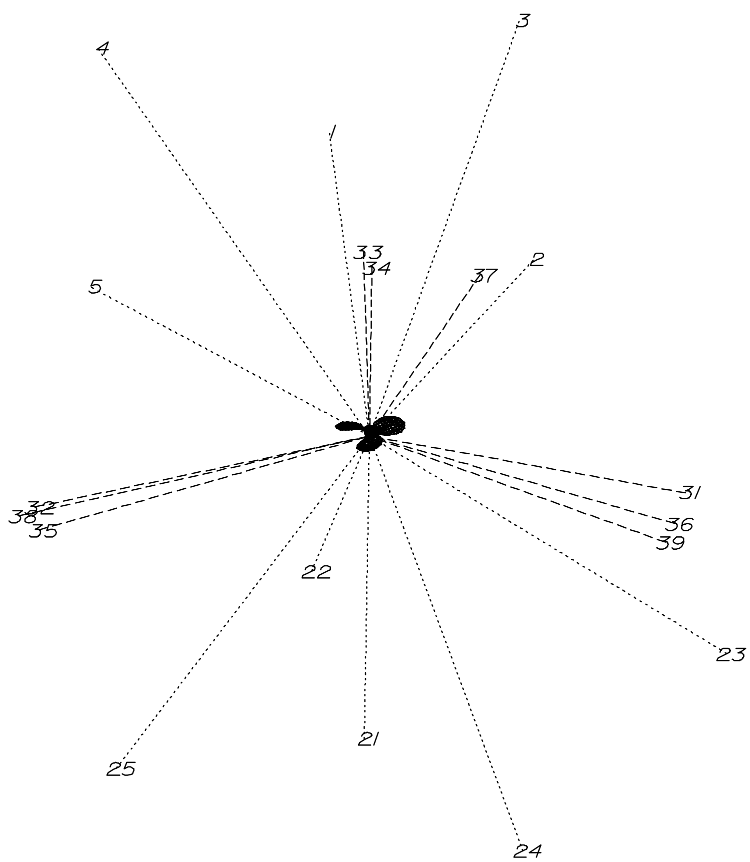
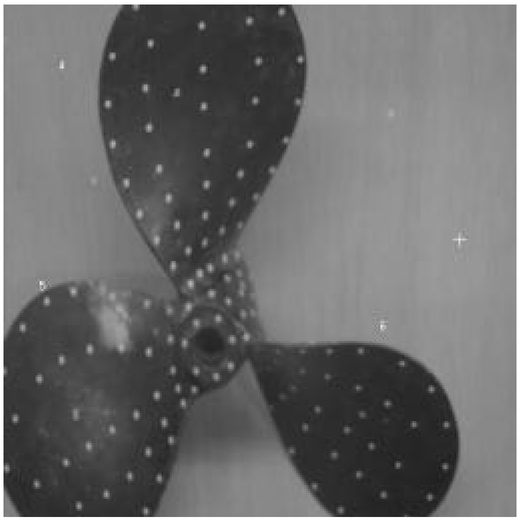


Figure 2. Position of the nineteen camera stations.

The dotted lines show the main positions of the cameras which viewed the propeller from the front and the back, while the dashed lines show the positions of some additional viewpoints which were used to link together the upper and lower surfaces of the propeller. The targets had to be distinguished from the background illumination and precisely located. Poor target image signal to noise ratios and uneven background illumination are known to cause poor target location, hence, the image obtained under diffuse lighting conditions (Figure 3) is not suitable for accurate measurement. By using retro-reflective targets and illumination which was axial to the camera the quality of the image was improved (Figure 4). The targets were identified using binary thresholding and shape detection based on three parameters: area, perimeter and degree of ellipsymmetry. Each target, in each image, was given a label and an approximate position. The centroid of each target was then computed using the grey scale image to provide a subpixel estimation of each target location. The final image processing task gave consistent labels for each object target point in all images. Labelling was carried out manually since the available matching algorithms were not sufficiently robust to enable a proximity sensor to label each target according to designated master images.



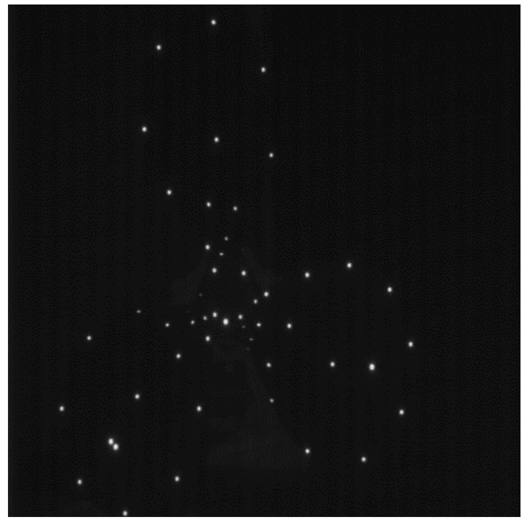


Figure 3. The targeted marine propeller (diffuse lighting). **Figure 4. The retro-reflective targets (axial illumination)**

All image co-ordinates were used to determine the 3-D object co-ordinates of each target using the bundle adjustment method incorporating self calibration of the camera system used. This least squares method simultaneously estimates all target co-ordinates and camera orientations. Because of measurement redundancy, it also provided statistics concerning the precision and accuracy of all the estimated parameters. Some of the parameters and their standard deviations are shown in Table 1. These statistics indicated that, in this case, a subpixel image measurement accuracy of around a tenth of a pixel was attained. Given the network geometry, this resulted in a precision of approximately 1 part in 5,000 of the object space. Subsequent work has shown an improvement to 1 part in approximately 15,000. It is expected that these results can be improved as the techniques and adjustment procedures currently used are refined.

Degrees of	Variance factor	RMS Image Co-ordinates.		RMS Object Space Standard Deviation, and object precision		
Freedom	σ_o^2	x	y	X	Y	Z
998	0.338	1.74µm	1.16µm	63.2µm	60.3µm	61.1µm
	Subpixel	0.1	0.1	1:4747	1:4972	1:4911

Table 1. of Results from the 19 image photogrammetric adjustment.

The resultant X,Y,Z co-ordinates of the target points were downloaded into a CAD package and used to derive three dimensional B-Spline surfaces representing each of the propeller surfaces. A view of this CAD model is shown in Figure 5.

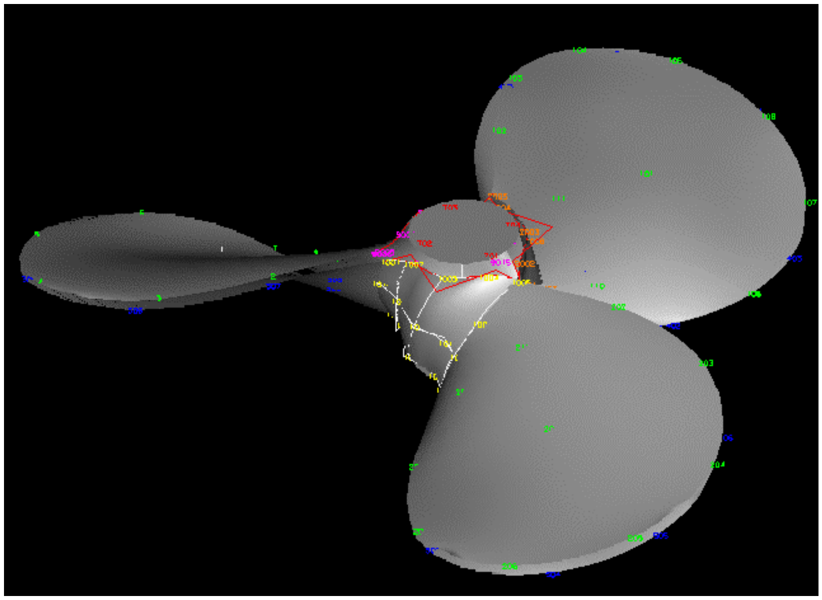


Figure 5. A view of the 3-D model of the marine propeller.

2.3. Characteristics.

Speed. Given a fast mass storage system the initial data acquisition is at camera frame rate, the largest time factors are: the setting up time which can be reduced for multiple measurements, the image processing, target labelling, and bundle adjustment processing time. The bundle method is computationally expensive as large matrix inversions are required, these rapidly increase in size with the number of parameters to be estimated.

Accuracy. The accuracy of the method is dependent on several factors: the number of observations, the type of target or surface feature, the strength of the measurement network, camera stability, and operator experience. The case study was carried out with an old 512x512 camera, improvements in hardware and software combined with increased redundancy of measurements means that object space precision's of 1:30,000, or better, may routinely be obtained.

Reliability. During the bundle adjustment procedure statistics are obtained concerning the estimated object space co-ordinates. It is also possible to detect image target location errors as they propagate though the bundle adjustment. All relevant information can be combined in the analysis i.e. distances and angles between targets; camera positions; lens distortion; and physical camera properties. The method can be adapted for the detection of natural features for example edges or patterns, as well as specifically placed targets.

3. OPTICAL TRIANGULATION.

3.1 Introduction to Optical Triangulation Systems.

There are many configurations and active components that may be used in an optical triangulation system. Some of the more successful systems use such components as: a rotating mirror with a single detector and an angle to time measurement[12], a rotating polygonal mirror and a PSD detector[13], a light stripe projection and CCD camera[14], and a single laser and CCD linear array camera[15]. This latter system is perhaps the most robust and simple to construct, the laser points to a single spot on a surface which is observed by a CCD linear array or Position Sensitive Device (PSD) linear sensor camera (Figure 6). Because in this configuration the base length 'B' is known, and the laser pointer and connecting bar form a right angle triangle, the distance 'D' can be computed by knowledge of the angle 'θ'.

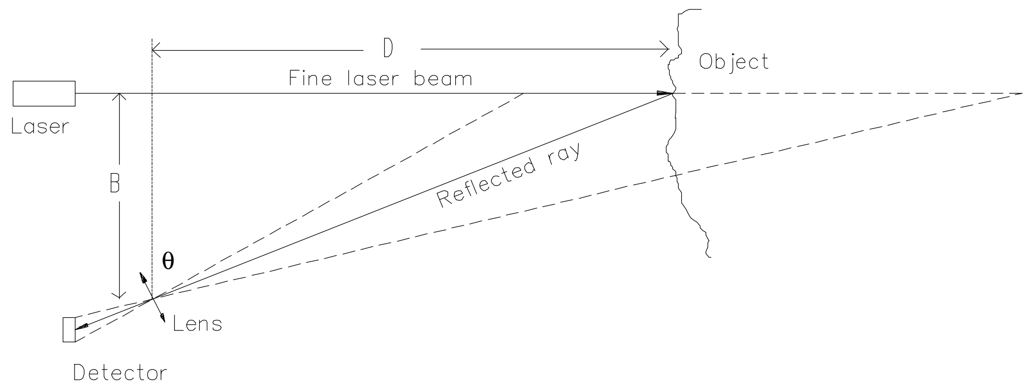


Figure 6. Simple Optical Triangulation configuration.

The simple optical triangulation system is a reasonable choice for high speed and high accuracy measurement if the following methods and equipment are used:

(i) a CCD linear sensor. The high geometric stability, high resolution, and fast repeat speed of CCD linear sensors gives better performance than the similar PSD linear sensor which is not so good in this context. This is because the PSD provides an analogue voltage which is proportional to the position of the image which is formed on the sensor. It is not a simple task to provide long term stability when calibrating such sensors,

(ii) a semi-conductor laser collimator, rigid bar, camera configuration. The advantage of this configuration is that it is stable and provides low inertia with respect to rotation about the rigid bar axis, and

(iii) calibration is used instead of calculation. It is possible to calculate the distance of the object from the measuring instrument if the camera and lens are properly calibrated, and all other parameters are known. In practise there is no need as calibration points mapping image position to distance from the measuring system provides, by interpolation, a unique distance for each image calculated image position. Figure 7 shows a typical system calibration curve.

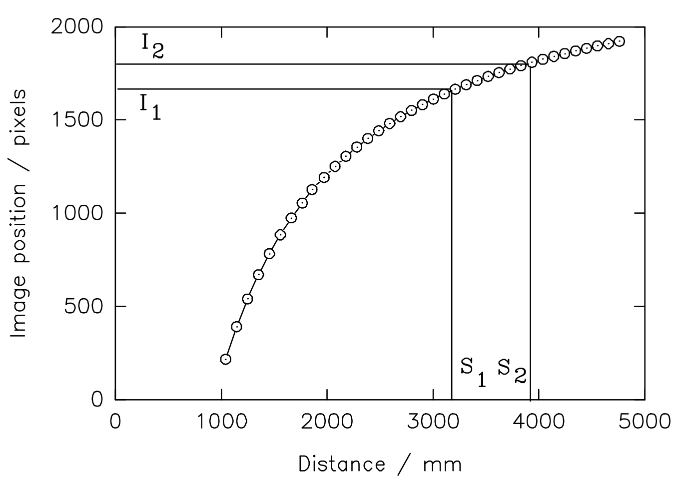


Figure 7. Typical system calibration curve.

There are many sources of error in optical triangulation devices which can adversely affect measurement integrity. Some of these errors can be shown to be of little consequence, such as atmospheric effects, while others are of major importance if the intrinsic accuracy of the system is not to be diminished dramatically. The major error sources are: (i) camera focal length changes, (ii) base length changes, and (iii) laser pointing instability. Of these errors the latter is random and has the greatest effect in degrading the overall performance, while the first two errors are systematic and temperature related. Laser pointing errors can now be minimised by appropriate selection of a solid state laser and collimator. For example, the Lasers manufactured by ILEE[16] range from a typical pointing stability of 0.1 mrad/^{o}C to 0.005 mrad/^{o}C. If the latter laser collimator were used then this would reduce this problem dramatically. A prototype triangulation measuring system developed at City University is shown in Figure 8.

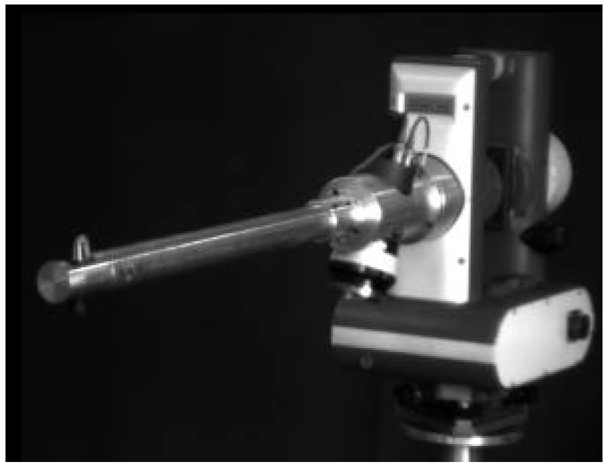


Figure 8. Prototype optical triangulation system.

Laboratory tests have shown that it was possible to obtain measurement accuracy with a standard deviation in the region of 0.33 mm at approximately 3 metres distance when a 2048 pixel sensor and range of 4 metres was used. This equates to a precision of one part in 12,000, or a subpixel resolution of 0.2 pixels. As these tests were conducted with a laser that exhibited poor pointing stability, this resolution appears reasonable to obtain in practise, although further tests would be necessary to verify this. One of the main advantages of the optical triangulation system when applied to a specific problem is that the range of the device can be tailored specifically for the application. Hence, the maximum use can be made of the available resolution. An additional two parameters are required for 3-D measurement; if the measuring head is rotated and the angle recorded then the other parameter can take the form of a linear translation stage, or rotation table. These rotation and translation mechanisms can usually be obtained to a much higher accuracy than the triangulation distance measuring system.

3.2. Case study.

To collect data concerning a section of wind vane the measuring instrument and object were set up as shown in Figure 9.

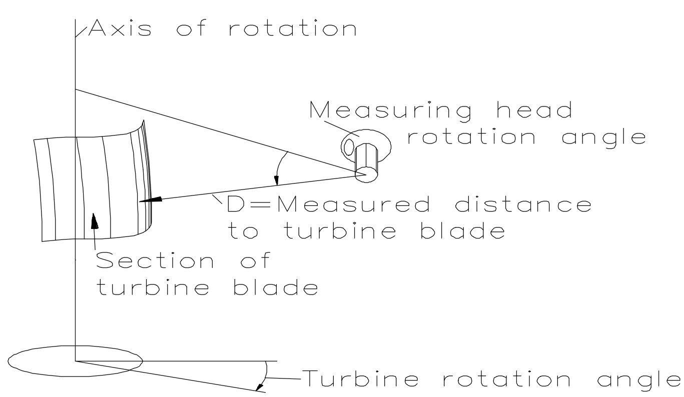


Figure 9. Physical set up for measuring section of turbine blade.

The wind vane section was mounted so that its axis of rotation was vertical as measured by a plumb line. The rotation table was marked at 11.5 degree intervals. The measuring instrument was set up so that the line of measurement was vertical and in the same plane as the axis of the table. The distance between the table axis and the instrument was measured indirectly by placing an object at a known distance from the axis and measuring this distance with the instrument. The approximate size of the wind vane section was 2.0m x 0.5m x 0.1m. It was decided to measure a section which subtended an angle of 50 degrees to the measuring system at approximately 1.4 metres from the blade. Distances were recorded at 0.5 degree intervals so that 100 points were measured for each rotation of the wind-vane. These distance data were converted to 2-D Cartesian co-ordinates using the known horizontal measurement at the mid-point and the table axis as the origin. These data were then converted to 3-D Cartesian co-ordinates using the known rotation of the wind vane. Conversion to a format suitable for input into a CAD software package took place so that the results could be visualised (Figure 10).

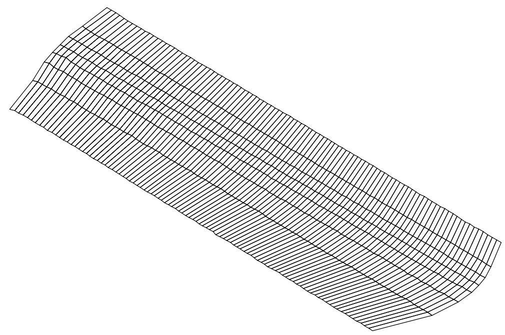


Figure 10. Display of wind vane data.

One of the problems encountered in these trials was that of backlash. These data were collected in the space of approximately half an hour with a prototype instrument and manual rotation of the artefact. It is evident that this is quite a reasonable time for the collection of 3,200 data points, however, scope exists for dramatic increases in the speed of data collection.

3.3 Characteristics.

Speed. The speed of measurement of the prototype device depends on three factors: the exposure time of the camera, the time to move to a new location, and the time taken to compute the distance measurement. A measurement rate of between 100 and 10,000 points per second is attainable if mechanical movement of the sensor or the object can be made quick enough.

Accuracy. The simple optical triangulation scheme described here uses a CCD sensor with 2048 pixels, while sensors with up to 7926 pixels are currently routinely produced. A subpixel algorithm was used which has a theoretical resolution in excess of 0.01 of a pixel. However, in the real world, factors such as: electronic noise, surface edges, variable reflectivity of surfaces, laser pointing instability, and surface roughness, means that an precision that relates to one fifth of a pixel spacing is to be expected. Hence, using the latest CCD sensor a conservative estimate of precision would be one part in 5x7926 of the instrument range. If high accuracy measurements of a surface such as that of a propeller blade were required then the instrument could be optimised for this purpose, and achieve much better results.

Reliability. Because of the simplicity of the measuring system, reliability of measurement is usually very good. However, problems can be experienced at edges and with surfaces which have surface roughness of the same or smaller magnitude compared to the size of the illuminating spot. Most systems are non-linear over any reasonable range, while this does not pose a problem to the reliability, it may affect the way in which the system can be used.

4. THE MOIRÉ CONTOUR METHOD.

4.1 Introduction to Moiré measuring systems.

The Moiré method was proposed by Foucalt in 1859 as a possible method of testing optical systems. The technique is based on the interference fringes which are produced when two amplitude gratings of similar frequency are oriented approximately parallel to each other. Three methods of applying the technique to the measurement of surfaces are generally used[17].

(i) The intrinsic method, whereby a master grating engraved onto the object is viewed through the reference grid. This can provide displacements of the surface with respect to their initial position.

(ii) Projection Moiré. The master grating is projected onto the object before viewing through the reference grid. This method provides displacements of the object surface with respect to a reference surface.

(iii) Reflection Moiré, which uses a half-silvered mirror set in such a position that the image of the projected master grating is reflected onto the object and also directly at the observing system. This method provides the slope of the surface with respect to the reference grating.

Whilst all methods are capable of precise 3-D surface determination, the case study examined in this paper utilised the projection technique. Consequently only the principle behind the projection Moiré method will be described in detail.

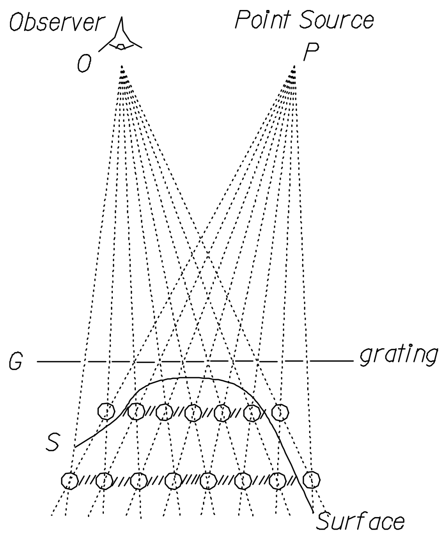


Figure 11. The Moiré principle.

Figure 11 demonstrates how a set of fringes pertinent to the shape of object 'S' are produced at the observer 'O'. The point light source 'P' casts the shadow of grating 'G' onto the surface of the object 'S'. Since the grating 'G' is viewed by the observer 'O' in addition to the partially obscured shadow image, Moiré fringes are produced. A fringe will be produced each time the rays projected from 'P' and those received at 'O' intersect. These fringes sets describe cylindrical surfaces based on generators parallel to the grating lines. Each fringe set will intersect the object surface giving rise to a fringe map or set of contour lines.

In order to determine displacements and strains on the surface under study from the generated fringe map, it is necessary to know the geometric relationship between: the reference grating, the master grating, the observation system, and the surface being studied. Such formulae may be found in[18,19,20]. Applications have included biostereometrics, particularly in the study of back deformities[21], high precision measurements of the mechanical properties of materials[22,23] and Aircraft Panel Testing [24].

With the refinement of digital image sensors, it has become possible to study not only static fringe maps to determine the shape of a surface under test, but also to measure the dynamic response of the surface under applied external forces. Examples include crack propagation in metals and real time back posture monitoring [25,26].

4.2. Case study.

The subject measured was a hydro-electric power plant turbine blade which was produced by a large Chinese factory. The company produces various types of turbine blade each of which were in the range 1-7 metres long per blade. Three blades are required for each complete fan. The weight of the largest is approximately thirty Tonnes. Hydro-electric power generation is important in China because of the natural water resources and the energy requirements of a large population. The blade has to be balanced before use otherwise problems of mechanical vibration may result. The traditional process of checking blades is by comparison with large heavy templates. The measuring process may take several days to check a single fan with relatively low accuracy.

The turbine blade was measured using the configuration shown in Figure 12. A light projection system and CCD camera camera were used The image of the grating was projected onto the surface of the object and deformed by the surface. When viewed through the reference grating (of the same number of lines per mm) situated in the plane of the sensor, a series of fringes was produced. These fringes represent contours of equal object surface height, the magnitude of which was calculated by the use of a reference plane.

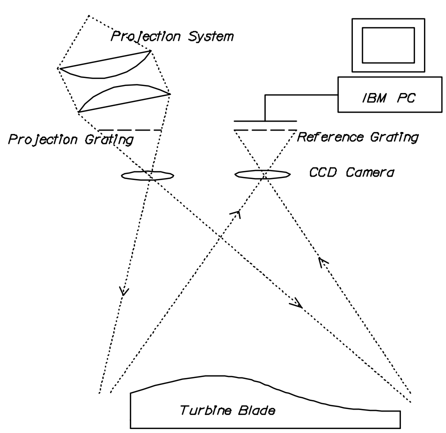


Figure 12. The turbine blade measuring configuration.

The choice of the Moiré method was determined by the adverse environment of the factory which was not suitable for a precision instrument. The required accuracy was +/-2mm over a metre long blade which equates to 0.2% of the object space. It was thought that Moiré would be able to achieve this. The data collection instrument was ruggedly constructed while image processing was performed in a clean environment. The reference grating was fixed parallel to the projection grating. To overcome the problems of strong background ambient lighting a cooled Quartz halogen bulb (3000 Watts) was used. The camera used filters to stop the wide band illumination from saturating the silicon sensor.

The system was specifically developed to measure two types of hydraulic turbine blade with dimensions of approximately 1.5m x 1.5m x 0.5m. This blade is a crucial part of a hydro-electric power generator. In operation the projection grating was projected onto the surface of the object. When viewed through the reference grating an image (512x512x8 bits) of the Moiré fringes was produced. Further processing was required to remove high frequency components and background noise. The resulting image was segmented into a binary image so that the Moiré fringes could be extracted for a subsequent thinning and tracing process. Finally, the 3-D co-ordinates of all pixels on the fringes were calculated and transformed to the reference co-ordinate system. These data could be displayed from any viewpoint on a computer screen as individual points or as a triangulated grid. Figure 13 and Figure 14 show the 3-D data collected from two types of turbine blade.

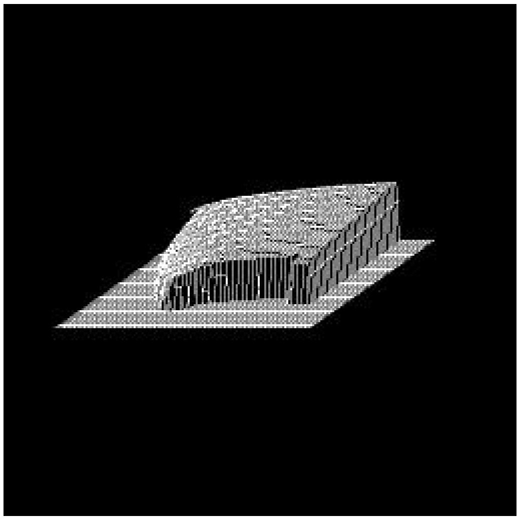


Figure 13. Graph of turbine fan No. 1.

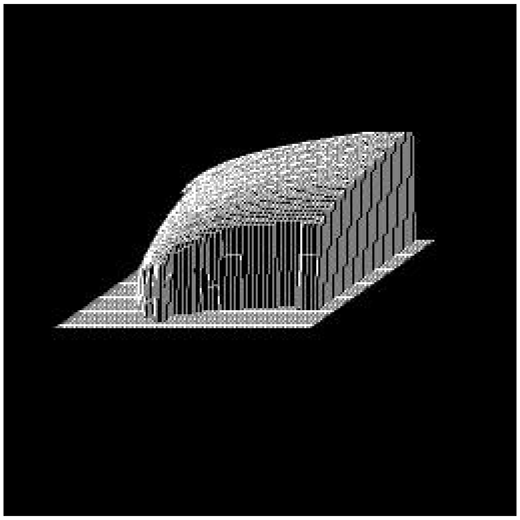


Figure 14. Graph of turbine fan No. 2.

This method was found to be satisfactory, and replaced the manual methods for use on medium or small turbine blades, but was not satisfactory for the larger blades. Since this work was completed in 1990 improvements in techniques and the availability of better equipment means that it should be possible to improve upon the results obtained.

4.3 Characteristics.

Accuracy. The accuracy of Moiré is dependent on the number of fringes that can be resolved in one CCD camera image. Each fringe represents an equal depth contour of the object surface, hence, Moiré may achieve high accuracy if small relative displacements require measurement. For absolute measurement a calibration procedure is required to define contour height and eliminate non-linearity in the equipment.

Speed. Speed of measurement is high. The initial data is collected quickly and the computations, although intensive (10 minutes in 1989 for a 8 MHz 286 PC), can be speeded up with improved hardware and software.

Reliability. The equipment required is very simple and robust. Data reliability is high provided the subject does not change shape rapidly and stray illumination is minimised. Where a large subject covering more than a single image frame is to be measured, problems of location and matching are encountered that are difficult to solve. Problems can also be encountered with missing fringes due to surface discontinuities which may give false results.

5. COMPARISON OF TECHNIQUES AND CONCLUSIONS.

5.1 Discussion.

The relative merits of each of these techniques are not easy to quantify in the absence of specific hardware or software. Any assumptions about the design or operating conditions, which may difficult to produce outside of the laboratory, make comparisons difficult. However, an attempt has been made in Table 2 to give a broad comparison of the relative merits of the techniques.

Characteristic	Moiré	Optical triangulation	Photogrammetry
Data acquisition speed	fast	fast	fast
Data processing speed	medium	fast	slow
Object precision	1:4,000	1:20,000	1:30,000
Reliability	good	good	excellent
Error checking	no	no	yes
Cost	high	high	medium
Availability	special equipment	special equipment	off the shelf
Expertise	med/low	low	high
Computation level	med	low	high
Subject restrictions	smooth subject	occluded subject	targeted subject or surface detail
Problem subjects	transparent	transparent	transparent

Table 2. Relative merits of the three techniques.

5.2. Conclusion.

Three techniques for acquiring spatial data have been considered, all are capable of accurate measurement. Examples of 3-D data collected from each method have been shown. The choice of method for a particular task will depend on many of the features discussed in this paper, these are summarised here:

Photogrammetry is the most flexible of all the methods reviewed accepting a wide range of measurement information to compile results. However, at the present time, a large knowledge base is required to obtain the best results for a given set of conditions. A time consuming problem is encountered since the object must be targeted, and each object target must be uniquely labelled, however, software methods are available to assist in this process. In its favour is the statistical analysis of measurement quality and high accuracy attainable for many applications. Self calibration is carried out in the measurement process.

Optical Triangulation is the simplest of all the methods and provides immediate measurement of distances. However, to reconstruct 3-D shape additional information must be obtained by either moving the sensor or the object. At the present time the potential accuracy and speed of measurement are offset by the requirement for purpose made instrumentation. Calibration or regular instrument checks are required to ensure correct operation as no feedback exists concerning measurement reliability.

Moiré is useful for measuring small surface displacements very precisely, but has limitations when large objects need to be measured and precision is sacrificed for range. The technique is useful for repeated measurement as no targets or surface features are necessary, it also gives information about the complete surface rather than selected points. A calibration must be carried out prior to, or after, measurement.

Other methods such as Electronic Speckle Interferometry, Holography, or contact methods have not been discussed, but may provide a better method of measurement in some circumstances. A review of the characteristics of all these techniques should allow an appropriate choice for a given application.

6. ACKNOWLEDGEMENTS.

The assistance of SERC in funding the Research Fellowship of Dr. T.A. Clarke is acknowledged. The continued support of the Engineering Surveying Research Centre, and the Measurement and Instrumentation Centre of City University has been fundamental to the research work carried out for this paper. The support of Prof. S.L. Huang is acknowledged in supporting J.Chen in his work using the Moiré technique in China.

7. REFERENCES.

1. S. Robson., "The contribution of the photographic process to the determination of photogrammetric co-ordinates". PhD Thesis, City University, London, 1991, 321 pages.
2. S. Robson., "Film deformation in non-metric cameras under weak geometric conditions - an uncorrected disaster?" International Archives of Photogrammetry and Remote Sensing, Vol. 29, V/1, Washington, 1992, 7 pages.
3. T.A. Clarke, "The application of optical techniques to surveying", PhD Thesis, City University, London, 1991, 309 pages.
4. T.A. Clarke., "The use of optical triangulation for high speed acquisition of cross sections or profiles of structures", Photogrammetric Record, 13(76)) October, 1990, pp 523-532.
5. J. Chen, & T.A. Clarke, "The automatic recognition, location, and labelling of targets in digital photogrammetric engineering measurement", ISPRS Conf, Vol. XXiX, Part B5, Commission V, pp 686-693, 1992.
6. T.A. Clarke, & S. Robson, "Building a digital close range 3-D measuring system for under 5000 pounds", Photogrammetric Record, October, 1993.
7. C.S. Fraser., "Photogrammetric measurement to one part in a million", Photogrammetric Engineering & Remote Sensing, vol. 58, No. 3, March 1992, pp. 305-310.
8. H.A. Beyer, "Geometric and Radiometric Analysis of a CCD camera based Photogrammetric Close Range System", PhD thesis, Institut für Geodäsie und Photogrammmetrie, Zurich, Switzerland, May ,1992, 186 pages.
9. P. Wolf, "Elements of Photogrammetry", 2nd Edition, Pub. Mc Graw Hill Book Co, U.S.A., 1993
10. C.C. Slama, "The manual of Photogrammetry", 4th Edition, Falls Church, American Society of Photogrammetry, 1056 pages, 1980.
11. M.A.R. Cooper, "An introduction to Photogrammetry - Functional and Stochastic Modelling, 80, 7(8), 16pp.
12. N. Nimrod, A. Margalith, H.W. Mergeler, "A laser-based scanning range finder for robotic applications.", Robot sensors, Vol. 1, Ed A. Pugh, IFS Publications Ltd, U.K., pp. 159-173.
13. M. Rioux, "Laser range finder based on synchronised scanners.", Robot sensors, Vol. 1, Ed A. Pugh, IFS Publications Ltd, U.K., pp.175-190.
14. "LARIS", 3-D Scanners Ltd, South Bank Technopark, 90 London Road, London, SE1 6LN, U.K. Product information.
15. T.A. Clarke, K.T.V. Grattan, N. E. Lindsey, "The use of laser based triangulation techniques in optical inspection of industrial structures", Int. Symposium on Optical and Opto-electronic Applied Science and Engineering, 1990, Proc SPIE Vol. 1332.50.
16. I.L.E.E. AG, Gewerbe 2000, CH8902, Urdorf, Switzerland, Product Information.
17. C.A. Sciammarella, "The Moiré method - A review", Experimental Mechanics, November, 1992, pp.418-433.
18. P.S. Theocaris., "Moiré fringes in strain analysis", Pergamon Press, New York, 1969.
19. H.Takasaki, Opt. Acta. 26(8), 1009, 1979.
20. C.A. Sciammarella, et al, "A computer based Moiré technique to measure very small displacements.", SPIE Vol. 814, Photomechanics and Speckle Metrology, 1987, pp. 262-268.
21. H.Takasaki, "Moiré topography", Applied Optics, 12, 1467, 1970.

22. J.M. Burch, C. Forno, "High resolution Moiré photography", Optical Engineering, 21(4) August, 1982, pp 602-614
23. A. Kearney, & C. Forno, "The mechanical properties of card measured by photographic Moiré, May 1987, National Physical Laboratory, Internal report.
24. B.C. Dykes, Proc. Fourth Int. Conf. Stress Anal. , Cambridge, 125, April, 1970.
25. Yatagai T, Idesawa M Ohshima, H. and Suzuki M 1981. "Automatic Measurement of 3D shapes using scanning Moiré method". Moiré Fringe Topography and Spinal Deformity, Proceedings of an International Symposium. 249-257. Pergamon Press Inc., New York.
26. D. Zawieska, & A. Spik., "Topography Moiré using phase stepping method with CCD camera", SPIE Vol. 1395, Close range photogrammetry meets machine vision, 1990, p. 1215.

PAPER REFERENCE

Clarke, T.A. Robson, S. & Chen, J. 1993 A comparison of three techniques for the 3-D measurement of turbine blades. ISMTII , Wuhan, China, SPIE Vol 2101, pp. 1-12.