HIGH ACCURACY 3-D MEASUREMENT USING MULTIPLE CAMERA VIEWS

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High accuracy measurement of industrially produced objects is becoming increasingly important. The techniques which can be used for this purpose may be divided into the contact and non-contact. Ideally non-contact methods will give fast measurement as no mechanical movement is required for each measured point. However, these methods are often hampered by other limitations such as that of requiring surface features to act as target points. The limitations will vary according to the technique used, its implementation, and the characteristics of the subject.

A method which has not received high prominence in the Machine Vision community is that of multi-camera measurement. There are advantages to be gained from using multi-camera views: (i) redundancy of measurement; (ii) statistical feedback; (iii) full modelling of all parameters; (iv) mature understanding of the method; (v) wide acceptance of the technique; and (vi) known performance. Against these advantages are: (i) the high level of computation; (ii) the setting up for each measurement case; (iii) a high degree of 'expert knowledge' required; (iv) the lack of techniques for fast or dynamic automated measurement. This paper describes the basic method of photogrammetry and discusses the potential for automated high accuracy measurement in an industrial context.

INTRODUCTION TO MULTI-CAMERA MEASURING SYSTEMS.

The methodology of multi-camera measurement involves identifying and measuring homologous targets or patterns on images of an object which have been obtained from differing viewpoints. These image measurements are then used to compute the three dimensional co-ordinates of the locations of the targets or patterns on the object being measured. Conventionally photo-chemical image systems have been used with time consuming manual processing. However, digital imaging systems promise on-line measurement possibilities. Such advances rely on the use of electronically and mechanically stable high resolution solid state cameras. Current "state of the art" techniques using sophisticated film based imaging systems[1] are able to achieve a maximum precision of 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 error sources are giving rise to very respectable results[2].

Multi-camera algorithms are founded on the theory of a central perspective projection (Figure 1). The associated 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 texts[3,4,5]. Each collinearity equation contains several unknowns: the location and orientation of the camera at exposure time; the **X,Y,Z** co-ordinates of the object point; and its corresponding image co-ordinates in the **x,y** image space. 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 such as those caused by the real lens system, and any geometric distortion of the image due to the camera sensor characteristics. Such corrections, determined *a priori* or simultaneously with object co-ordinate determination, may be simply added to the collinearity equations[6]. Given good network design the result is a homogeneous precision for each target in the object space.

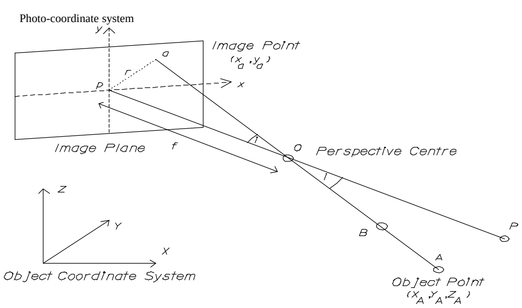

Figure 1. Central Perspective Projection.

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Until recently the use of multi-camera techniques for high precision object measurement has been carried out by an expert performing the following sequence of operations :

- placement of targets on the subject to be measured
- arrangement of cameras to gain the strongest network
- setting the lighting to obtain strongly contrasting targeted features
- collection of images from each view-point
- estimation of camera location by measuring the position of the camera (**X,Y,Z**) relative to the object
- estimation of the camera orientation by measuring the angles of the cameras relative to the object (κ, ω, ϕ)
- identification and labelling of the targets using feature detection techniques
- calculation of the (**x,y**) subpixel location of the targets
- calculation of correspondences between targets from all viewpoints for consistent labelling
- initialisation of focal length, principal point position, lens distortion parameters K_1, K_2, K_3, P_1, P_2, and any other additional parameters using *a priori* knowledge
- least squares adjustment with the initial estimated parameters:
    - if the program converges and the change in the co-ordinates is within some pre-determined limit stop the program
    - if the program does not converge check for errors and repeat with new adjusted values
    - if the program converges, but the change in the co-ordinates is not within pre-determined limits then look for blunders such as incorrectly located or matched targets and assess to see whether they can be omitted

After successful completion of the program, the resulting 3-D co-ordinates are used for visualisation, or analysis. This stage will often require further operations to identify the correct connection between measured points and the surfaces they represent.

The complexity of these tasks has meant that it has not been easy for those who are not familiar with the theory and concepts to pick up the method and use it. However, with the advent of cheap, but geometrically stable, cameras allied to fast computers it is possible for these tasks to be automated or at least simplified.

A CASE STUDY.

A small three bladed marine propeller was chosen for measurement. 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).

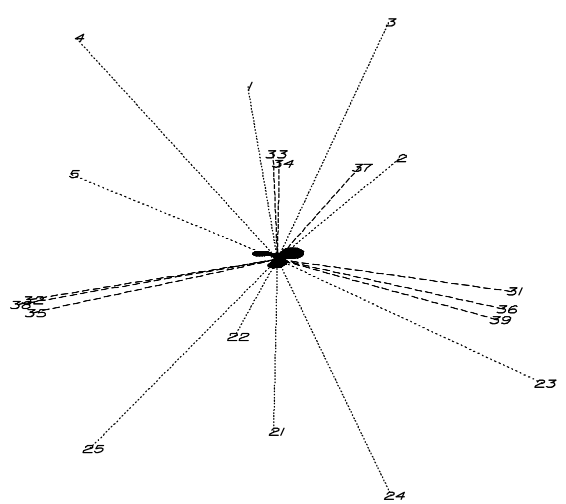

Figure 2. Position of the nineteen camera stations.

The dotted lines show the optical axes of the camera sets which viewed the propeller from the front and the back, whilst, 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, images obtained under diffuse lighting conditions (Figure 3) are 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). 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.

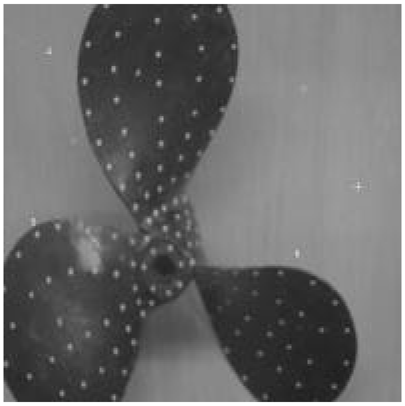

Figure 3. The targeted marine propeller. (diffuse lighting)

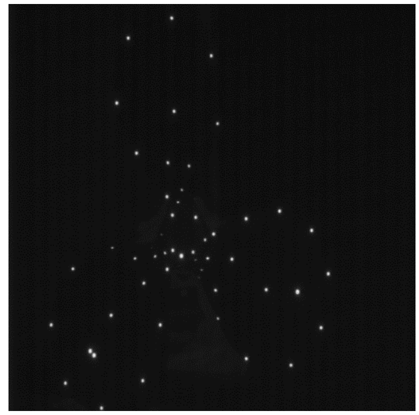

Figure 4. The retro-reflective targets (axial illumination)

All image co-ordinates were used to determine the 3-D object co-ordinates of each target using a bundle adjustment method incorporating self calibration of the camera system used. This least squares method simultaneously estimated all target co-ordinates and camera orientations. Because of measurement redundancy, it could also provide 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 30,000. It is expected that these results can be improved as the imaging 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. Results from the 19 image least squares 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.

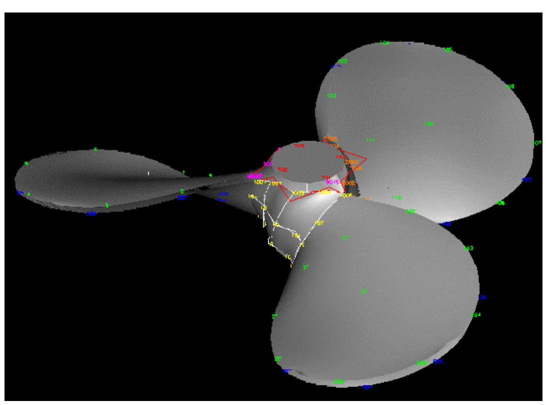

Figure 5. A view of the 3-D model of the marine propeller.

ANALYSIS OF THE METHOD.

Speed. Given a fast mass storage system the initial data acquisition is at camera frame rate, the largest time factors are: setting up, image processing, target labelling, and bundle adjustment processing. The bundle method is computationally expensive as large matrix inversions are required and these rapidly increase in size with the number of parameters to be estimated. The measurement time for these procedures can be improved by faster hardware, improved algorithms, and parallel computers for example.

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 measurement 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 through the bundle adjustment. All relevant information can be combined in the analysis for example: 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.

CONCLUSIONS.

The advantages of multi-camera measurement are :

- The method is statistically based so that each of the co-ordinates has a RMS error associated with it and a global standard deviation for the whole measurement process is available;
- The redundancy of measurement when more than two cameras are used means that the precision of measurement is much higher than would be the case for a system with no redundancy;
- The system is general - there is no limit to how large the measured object can be as long as there are recognisable object features and it is possible to arrange a suitable convergent camera geometry; and
- The method is flexible - the measuring system can move to the object and measurement can take place in situ.

The disadvantages are :

- The current requirement for an expert user;
- The number of processes required; and
- The quantity and depth of knowledge required about the measurement process required if high accuracy is to be achieved.

In this paper the method of multi-camera measurement has been described. The method has been shown to deliver high accuracy measurement at the expense of procedures which restrict the general application of the technique for engineering problems. However, the task of automating the procedures and improving the method of operation is an area that is rapidly developing. The expectation that this technique has a wide range of applications in engineering measurement is not unreasonable, and it is likely that this method will be the optimum solution in a number of cases.

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