THE DEVELOPMENT OF AN UNDERWATER MEASURING CAPABILITY USING PHOTOGRAMMETRIC TECHNIQUES

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ABSTRACT

Obtaining direct measurements underwater is a complicated and difficult task. In this hostile environment, photogrammetry is a viable measuring tool, provided that the cost of equipment and the level of expertise are kept to a minimum. An underwater measuring capability using non-metric cameras, the theory of projective transformations and a desk top computer has been developed at the University of Cape Town. This paper describes the techniques used to obtain stereopairs, the manner in which stereo-coverage is increased and the process used to reduce the measurements. The method developed is suitable for engineers, scientists and researchers to use. It is also capable of fulfilling the requirements of precision photogrammetry as defined by Schwidefsky.

INTRODUCTION

The objective of this research was to determine the feasibility of using a new photogrammetric technique underwater. Scientists, engineers and researchers engaged in measuring activities underwater are not photogrammetrists. An essential requirement of the technique is that it be usable by them to satisfy their own applications.

Photogrammetry has been used on a number of occasions, to measure underwater. Generally speaking the methods developed were dependant on the use of very expensive and sophisticated equipment operated by highly trained specialists. They were therefore relatively inaccessible to the underwater researcher. Requirements for making the science of photogrammetry more available to other disciplines had to be formulated.

These requirements were used as a guideline to formulate and design a photogrammetric capability for a small research organisation. An analytic approach was adopted, the essential elements of which depended on the use of a non-metric camera, a small computer and the theory of projective transformations.

A NEW APPROACH

As a measuring tool photogrammetry has several advantages over contact techniques, in the water environment:-

(i) Minimal time is required to make measurements. This reduction in water time can be considerable when a subject is complex or difficult to measure by conventional techniques.
(ii) The uncertainties in measurement and observation due to diver error are done away with.
(iii) A subject can be measured without it being disturbed.
(iv) Evaluation of the photographs can be done at any time, in the comfort of an office. Repetition and amendments are always possible.
(v) The photographs store both sematic and metric data with a very high density.

(vi) The photographs are related to time - preserving a perfect record of observations which can always be refered to.
(vii) Very high accuracies and resolutions are obtainable.

Although the science of photogrammetry has become highly sophisticated for measuring and recording objects in air, progress underwater has been less rapid. This is due mainly to the following factors:

(i) Man is operating in an alien environment.
(ii) The conditions of photography underwater are very different from those in air.
(iii) The development of photographic equipment for use underwater has been slow.

By 1950 these factors had largely been eliminated:-

(i) Modern diving equipment and training allowed man to work relatively safely underwater.
(ii) Techniques and artificial light sources were sufficiently advanced to handle most underwater lighting problems.
(iii) Photographic equipment has been developed to cope with the conditions underwater.

It was possible to use photography as a measuring tool underwater. However up until recently the method has not received wide acceptance. In four of the case studies examined by the writer use was made of very expensive specialist photogrammetric equipment and complicated analysis techniques. This equipment and knowledge is not generally available to the underwater metrologist. It is the writers opinion that this factor is one of the prime reasons why photogrammetry has not been used more extensively underwater.

It would appear that if photogrammetry is to be used as a measuring tool underwater, to any great extent, then a change in approach is required:-

(i) The user must make his own observations and reduce his computations himself.
(ii) He must be able to work in his own laboratory.
(iii) Minimal expert photogrammetric knowledge and skill must be required of the user.
(iv) The method must be simple fast economical and accurate.

To satisfy (i) and (iii) above implies that expensive photogrammetric equipment must not be used, as the user neither has these instruments nor is he trained to use them. Secondly, it means that some other type of equipment, that the user has in his laboratory or is readily available to him, must be used.

Instrument manufacturers have not catered for underwater photogrammetry. No suitable underwater metric (Adams 1981) camera exists. Using a suitably housed metric camera is not a solution. The metric qualities of the lens would be lost unless a suitable corrector lens for the air/water interface is found. The camera system would then have to be recalibrated. The only viable alternative is to use non-metric cameras which are readily available.

Most research and engineering organisations have, or have access to, small desk top computers or micro-processors. An X, Y digitiser attached to a desk top computer becomes a convenient photogrammetric comparator. By adding an XY plotter to the system a limited stereoplotter capability is developed. This idea has been successfully tried by Adams (1979) in a study using X-ray photogrammetry. It is therefore sensible to build a measuring technique around a small computer and its peripherals. No photogrammetric expertise other than an ability to see steroscopically, and an aptitude to operate a small computer is required of the user. The necessary photogrammetric mathematics will have been developed and programmed by the photogrammetrist.

Conventional photogrammetric procedure dictates that the elements of inner orientation be known. Having to 'metricate' a camera represents an inconvenience and expense to the user. It would be far more practical if he could use a camera 'off the shelf' and dispense with camera metrication. The problem is to eliminate all direct reference to principal distances, fiducial marks, principal points, etc, and proceed directly from image co-ordinates to space co-ordinates. This is achieved using the theory of projective transformation.

Adams (1982) describes the suitability of non-metric cameras, projective transformations and small computers for satifying the requirements of the wider adoption of photogrammetry underwater. The developed technique is the subject of this paper.

THE TECHNIQUE

The underwater photogrammetrist has to overcome the problem of obtaining accurate control in the object space. This task is extremely difficult, because of the handicaps imposed on the diver. The exercise also has to be repeated at each site. The problem was resolved by introducing a portable frame of well defined targets. The framework is positioned over the area of interest introducing an arbitrary control system.

The portable frame is co-ordinated in air. To give the scientist or engineer versatality in the selection of the size and shape of a control frame it is envisaged that he do his own frame co-ordination. The co-ordinates of the portable frame are obtained from a stereopair of the latter inside a masterfield. Being of a more permanent nature, it is calibrated accurately by traditional survey methods.

A stereopair needs to be taken of the frame underwater. Any two images (of the same object), taken from any two positions, even with different cameras, constitutes a stereopair. The theory of projective transformations does not place constraints on camera configurations. Four methods of obtaining stereo coverage were tested. The various trials are discussed later in this paper.

Once stereopairs have been taken, paper enlargements are made using an ordinary photographic enlarger. The prints are mounted for stereoscopic viewing on the digitiser tablet. Stereoscopic viewing is achieved by viewing through a modified mirror steroscope. Image co-ordinates are measured with a double digitiser cursor, in the same manner that a parallax bar is used. The modified stereoscope and digitiser are the only 'specialist' pieces of photogrammetric equipment required.

The measured image co-ordinates feed directly to the computer and the projective tranformation parameters are used to transform the former into object space co-ordinates. The user is required to view the images stereoscopically and follow a series of computer instructions in order to reduce his measurements.

The technique is analytical. The resultant point by point restitution can be outputed in the form of co-ordinates, measurements or plots. This is the only real disadvantage, making the technique tedious and time consuming in comparison to analogue techniques.

PROJECTIVE TRANSFORMATIONS

Although the user is not required to understand the theory of projective transformations a knowledge of the relevant formula will be of assistance. The following model can be set up for each photograph:-

$$x_i = \frac{b_{11} X_i + b_{12} Y_i + b_{13} Z_i + b_{14}}{b_{31} X_i + b_{32} Y_i + b_{33} Z_i + 1}$$

$$y_i = \frac{b_{21} X_i + b_{22} Y_i + b_{23} Z_i + b_{24}}{b_{31} X_i + b_{32} Y_i + b_{33} Z_i + 1}$$

$X_i Y_i Z_i$ are space co-ordinates of point P_i
$x_i y_i$ are digitised image co-ordinates of point P_i refered to an arbitrary origin
b_{ij} are transformation parameters.

A minimum of 6 control points is needed to provide a unique solution to the 11 transformation parameters. Of the six points no more than four may be coplanar and no more than three points may be colinear. The remaining two points must not be colinear with the vertex or perspective centre.

The calculation of space co-ordinates using a stereopair is performed using any three of the following:-

$$(x_i b_{31} - b_{11})X_i + (x_i b_{32} - b_{12})Y_i + (x_i b_{33} - b_{13})Z_i + x_i - b_{14} = 0$$

$$(y_i b_{31} - b_{21})X_i + (y_i b_{32} - b_{22})Y_i + (y_i b_{33} - b_{23})Z_i + y_i - b_{24} = 0$$

$$(\bar{x}_i \bar{b}_{31} - \bar{b}_{11})X_i + (\bar{x}_i \bar{b}_{32} - \bar{b}_{12})Y_i + (\bar{x}_i \bar{b}_{33} - \bar{b}_{13})Z_i + \bar{x}_i - \bar{b}_{14} = 0$$

$$(\bar{y}_i \bar{b}_{31} - \bar{b}_{21})X_i + (\bar{y}_i \bar{b}_{32} - \bar{b}_{22})Y_i + (\bar{y}_i \bar{b}_{33} - \bar{b}_{23})Z_i + \bar{y}_i - \bar{b}_{24} = 0$$

Where the unbarred and barred elements refer to the left and right hand pictures respectively.

In practice more than the minimum 6 control points are used. Many solutions to the unknowns are possible because of the inconsistency of the redundant data. It is expedient to adopt a 'least squares' adjustment method of finding a solution with redundant information.

A number of least squares solutions have been developed. Abdel-Aziz and Karara (1971), Bopp and Krauss (1978), Adams (1979). The writer has adopted Adams' approach in his research. The reader is refered to Welham (1982) for an in depth study of the method. It is possible to improve the measuring accuracy of the above transformation by introducing correction terms for lens distortion and film deformations. However these solutions tend to become complicated. The user will have to decide whether the additional effort is warranted.

ACCURACY STATISTICS

In photogrammetry the problem of estimating the accuracy of results is very complex. There is a multiplicity of factors to be considered when accuracy is evaluated. Complex criteria can be developed to estimate accuracy, but they would not be suitable for daily use by engineers and scientists. The argument for using least squares accuracy criteria was rejected for this reason. A more convenient criteria was desired which had the following properties:-

(i) Simplicity
(ii) Reliability for the whole volume
(iii) If possible, be independent of the space configuration (stations, orientation of the optical axis, object volume) in order to be able to compare results obtained from different working scales and from all available focal lengths.

The following statistics were developed using Hottier's (1976) arguments. Consider n check points in the object space, ie points whose true co-ordinates are known, but which have not been used in the photogrammetric computation. Then if X_{iT}, Y_{iT}, Z_{iT} are the true co-ordinates of a check point (i = 1 to n) and X_{ip}, Y_{ip}, Z_{ip} its photogrammetric co-ordinates an estimation of the RMS spatial residuals is:-

$$RXYZ = \frac{1}{n} \sqrt{[(X_{ip} - X_{iT})^2 + (Y_{ip} - Y_{iT})^2 + (Z_{ip} - Z_{iT})^2]}$$

The maximum spatial residual among the n check points is determined:-

$$RMXYZ = \max \sqrt{(X_{ip} - X_{iT})^2 + (Y_{ip} - Y_{iT})^2 + (Z_{ip} - Z_{iT})^2}$$

(the true RMS residual RXYZ, is in fact the limit of RXYZ for n infinite, with points in every part of the object space).

The analogous quantities for the three axis can also be estimated. For example in the X direction:-

$$RX = \frac{1}{n} \sqrt{(X_{ip} - X_{iT})^2}$$

$$RMX = \max | X_{ip} - X_{iT} |$$

These above criteria are simple and good estimates of the accuracy provided that:-

(i) The number of check points is sufficient. "It is seen that even for a small number of check points, the RMS residual is not so bad ie, it is satisfactory when n = 15" Hottier (1976).
This was confirmed experimentally using a UMK camera and up to 80 check points. No significant improvement in accuracy was obtained when more than 20 points were used.
(ii) The distribution of the n check points inside the object space is regular.

(iii) The object space is not too deep. If the volume is too deep then evaluation accuracy has to be estimated for successive slices.

In the practical working situation it is inconvenient to provide enough control points and check points. We may however use the RMS residuals computed with control points say R'XYZ, R'X etc. Unfortunately if the number n of control points is below 25 to 30 there is (statistically) an over estimation of accuracy. That is:-

$$R'_{XYZ} < R_{XYZ}$$

It is possible and reliable to compute a correction coefficient k so as to have $kR'_{XYZ} = R_{XYZ}$
K depends on the number n of control points, the computational method and the number r of unknowns estimated in the least squares adjustment. If for each control point we obtain p observation equations we compute k from:-

$$k = \sqrt{\frac{p\,n}{pn - r}}$$

In the projective transformation used r = 11 and p = 2.

Schwidefsky's (1970) definition of precise photogrammetry has been interpreted as meaning:-

$$\frac{1}{1000} < \frac{R_{XYZ}}{D} < \frac{1}{10000}$$

where D is the mean object distance or range.

CONTROL AND CALIBRATION

We have assumed when calculating the transformation parameters and the accuracy statistics that the co-ordinates of the control points are error free. In practice we only have an estimate for the true value. We assume that the residual errors in the control co-ordinates were so small that they do not affect the accuracy of the measuring techniques.

Experiments conducted showed that between 16 and 20 control points should be used to determine the transformation parameters. The configuration of the control was not significant provided that they were reasonably well distributed in the object space.

UNDERWATER PHOTOGRAPHY TECHNIQUES

Photographic conditions underwater differ considerably from those experienced in air. Interested readers are refered to Schulke (1978). It was the writers problem to obtain stereoscopic coverage underwater. Four techniques were attempted:-

(i) Single camera

The results of this experiment were poor. The fact that the diver is not motionless, combined with a slow shutter speed, resulted in image movement during exposure. The cameraman was not able to retain his position or use the viewfinder properly resulting in poor picture framing. There is a large scale variation between successive photographs, many of them oblique. Again this is because the diver is not motionless. These problems can no doubt be overcome by practice and experience, however, a more controlled situation was desired.

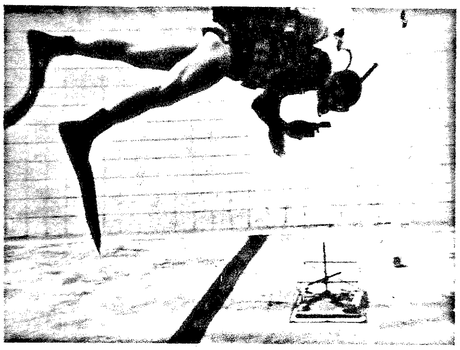

Fig 1 swimming diver

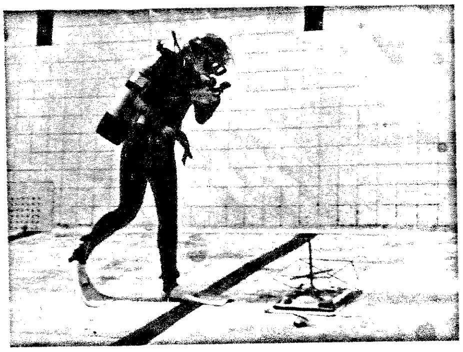

Fig 2 standing diver

(ii) a pair of cameras mounted on a basebar

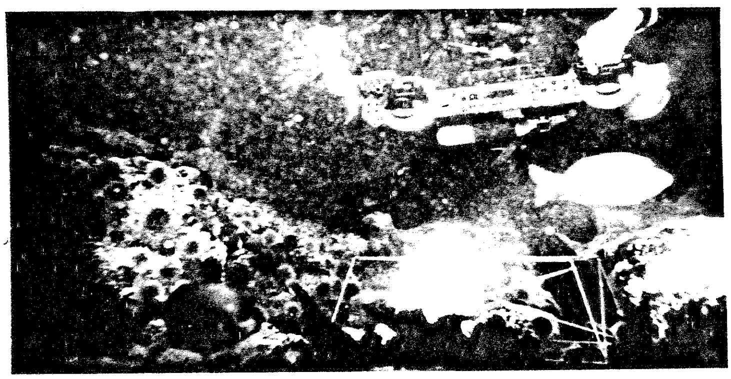

Fig 3 Diver swimming over frame with the basebar

The cameraman 'floats' over the frame, aiming through a central gunsight, before triggering the cameras simultaneously. The results were very good, however, a few practical difficulties still existed. It was hard to obtain the desired camera positions as the basebar obstructed the divers mobility to a greater extent. It was also difficult to control the range.

(iii) A single camera and image splitter.

This technique has advantages as well as disadvantages. Slower shutter speeds can be used as the camera was stationary. Rapid exposures were possible since the diver did not have to swim into position. The divers safety was improved since he was not attached to the equipment. Stereoscopic coverage was halved since the image area was divided. The size of the frame made it extremely difficult to move with underwater, particularly while ascending to the surface.

(iv) A single camera and doubleport basebar

This apparatus was constructed on the same principle as the image splitter but with the advantage that stereoscopic coverage was increased. The same advantages and disadvantages existed.

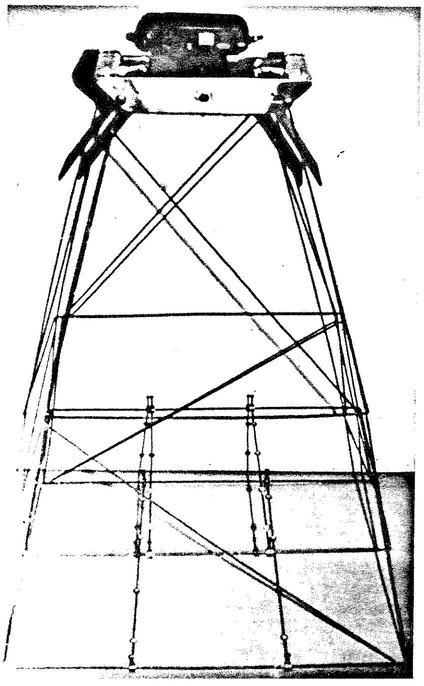

Fig 4 Image splitter

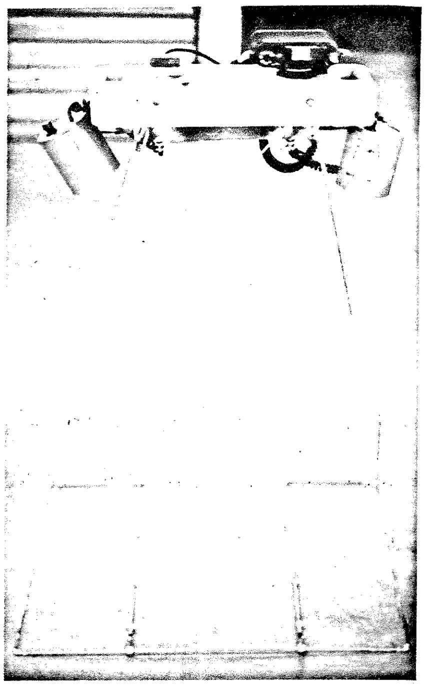

Fig 5 doubleport basebar

It is possible to use all four of these techniques. The diving team would need to be competent and have aquired the necessary skill in working with the respective apparatus. The writer has not been able to overcome many of the problems related to the art and skill of underwater photography. It is obvious to him that it is an aquired skill. Practice makes perfect, and there is no substitute for experience.

The backup support required by diving operations is imense. It is imperative that such operations are successful. The sea is a hard task master sure to expose inefficiency, bad planning, poor technique and equipment inadequacies. Time is also of the essence, since occasions when the sea is calm enough for working in are limited.

Any photogrammetric method should therefore be quick, operational in low light conditions and cover as large an area as possible.

Perhaps the most important consideration is to check all equipment well in advance. Nothing is more counter-productive than to reach the underwater working place to find that the equipment is malfuntioning.

RESULTS

The writer has come to the following conclusions from his research:-

(i) Measuring accuracy is affected significantly by the base/range ratio. For accurate results strong configurations (base/range ratio 0.8) should be used.

(ii) The measuring accuracy using a digitiser is not inferior to that of a comparator. It is, however, necessary to use suitable enlargements.

(iii) It is perfectly feasible to fix the co-ordinates of the control frames using a master field, a non-metric camera and a digitiser. Accuracy is improved by:-
- using strong geometry
- maximum enlargement factors
- high resolution films
- at least 20 control points in the masterfield
- multiple exposures Hottier (1976).

(iv) It is possible to use predictors developed by Hottier (1976), Abdel Aziz and Karara (1971) to estimate accuracy.

(v) There is a fall off in the measuring accuracy when extrapolating. It is however not possible to avoid doing so in certain instances. A researcher must therefore be aware of the consequent errors.

The following table reflects the available measuring accuracies of 3 of the above photographing techniques Adams (1982):-

Sets of typical results of tests carried out

Lens	Control	No of Control Points	Measuring Apparatus	Mode	Enlargement	Distance (m)	Base (m)	Rms (mm)				B/H Ratio	Accuracy	Schwidefsky Definition
								X	Y	Z	Vector			
35 mm	Testfield	80	Comparator	Air	1	6	2	0,7	1,3	2,1	2,6	1/3	1:2 300	Precise
35 mm	Testfield	80	Digitizer	Air	7	6	2	1,8	2,8	4,6	5,7	1/3	1:1 100	Precise
28 mm	Beamsplitter Combined	14	Comparator	Water	1	1	0,2	0,3	0,3	1,1	1,2	1/5	1:850	Marginal
28 mm	Beamsplitter Combined	14	Digitizer	Water	7	1	0,2	0,4	0,4	1,3	1,4	1/5	1:700	Marginal
28 mm	Basebar Portable	14	Comparator	Water	1	1,3	0,5	0,1	0,1	0,8	0,8	1/2,6	1:1 600	Precise
28 mm	Basebar Portable	14	Digitizer	Water	10	1,3	0,5	0,2	0,4	1,2	1,3	1/2,6	1:1 000	Precise
15 mm	Short Base Portable	14	Comparator	Water	1	0,8	0,35	0,1	0,1	0,4	0,4	1/2,3	1:2 000	Precise
15 mm	Short Base Portable	14	Digitizer	Water	10	0,8	0,35	0,4	0,2	0,9	1,0	1/2,3	1:800	Marginal

The above results show that it is possible to meet the requirements of precise photogrammetry underwater.
The question of whether accuracy is improved using convergent photography was not resolved. A number of prominent researchers are not in agreement on this issue.

CONCLUSION

The research conducted has been confined to single stereopairs. Due to the complications of visibility and available light, the area covered by a stereopair is very small. In a sense therefore the application of the technique is restricted to measuring small objects. It might be possible to extend the size of the area by taking multiple stereopairs. Research is presently being done in this direction.

The underwater techniques discussed were developed for diver use. This restriction was imposed by practical considerations. There is no reason why the technique cannot be utilized by submersibles or unmanned experiment platforms.

The results show that using suitable camera configurations, it is possible to achieve a measuring accuracy that satisfies Schwidefsky's definition of precision. The writer is of the opinion that this accuracy cannot be equalled by direct measuring techniques, without considerable effort.

The conclusion drawn is that the requirements for the wider adoption of photogrammetry underwater have been satisfied. It is the writers hope that engineers and scientists will make greater use of the technique developed.

ACKNOWLEDGEMENTS

The writer is indebted to the staff of the Department of Surveying at the University of Cape Town for their help and encouragement. He is particularly grateful to Professor L.P. Adams and Dr H. Rüther for their unfailing assistance; The Institute for Maritime Technology and Mr W.G.A. Russell-Cargill for the financial assistance and help that made this research possible.

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