# AN UNDERWATER PHOTOGRAMMETRIC MEASUREMENT SYSTEM FOR STRUCTURAL INSPECTION

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## ABSTRACT

The development of an underwater analytical photogrammetry system specifically designed for subsea inspection of oil installations in the North Sea is described. Features of the system include flexibility of cameras, portability and an analytical procedure which dispenses with object space control. Results of some typical applications carried out at depths greater than 140 m are presented.

## INTRODUCTION

Over the past three years, the Department of Surveying, University of Newcastle upon Tyne has worked in collaboration with British Underwater Engineering Subsea Ltd (formerly British Oceanics Ltd) on the development of a system for underwater photogrammetric measurement suitable for routine use in the North Sea inspection industry. BUE Subsea are one of the major North Sea operators of manned submersibles (Figure 1) and remotely operated vehicles (ROV's) for underwater inspection of offshore structures such as production platforms and oil and gas pipelines. Initial proposals and some preliminary results were reported by Baldwin and Newton (1982). Subsequent modifications have been made to the system resulting in increased flexibility and an improvement in accuracy. This paper describes the system which is now offered by BUE Subsea as a commercial service.

## REQUIREMENT FOR UNDERWATER MEASUREMENT

The requirements of underwater inspection for North Sea installations have been discussed by Petrie (1980), Baldwin and Newton (1982) and Leatherdale and Turner (1983). Underwater work systems employing both vehicles and divers that are suitable for operating cameras have been described by Leatherdale and Turner (1983) and Newton (1984). All stress the requirement for in-situ measurement. A recent literature survey (Baldwin, 1984) examined reported cases of inspection and maintenance of offshore structures in the North Sea. The survey showed that in over 60% of the reported cases some form of in-situ structural measurement was required for:-

(i) assessment of the size of a damaged area
(ii) measurement of structural shape and form
(iii) determination of object orientation
(iv) monitoring of the structure over a period of time

The features to be measured are frequently small and isolated and exhibit a complex three dimensional shape which may change with time. They can result from corrosion, cracking, denting or from puncturing of steel members and concrete components. In some cases an accurate determination of the overall shape and orientation is crucial.

Existing Non-Destructive Testing (NDT) techniques can determine material thickness and crack length using methods like ultrasonics and Magnetic Particle Inspection (MPI). However, there is currently some concern over the reliability of such techniques (Moncaster, 1982). New techniques are continually being sought and photogrammetry with its non-contact nature and fast data gathering capability is ideal for underwater measurement provided that it can attain the necessary accuracy.

## SYSTEM DESIGN CRITERIA

The original system design considerations are given in Baldwin and Newton (1982). These may be summarised as:-

(i) The underwater environment is very different from the more usual in-air environment. Pressure, salinity, temperature and the amount and composition of suspended matter in the water all vary with depth and position. These variations and the non-metric character of underwater cameras suggest the use of an analytical procedure with on-site camera calibration and the inclusion of additional distortion parameters.

(ii) The system should be capable of operation offshore so that results can be produced quickly. This restricts the choice of equipment to that which is portable and preferably commercially available.

(iii) The system should be flexible so that photography taken with any camera carried by divers, manned submersibles, or ROV's can be used. In practice, it has been necessary to restrict the cameras to those which can be fitted with reseau plates and the photography to that which can be viewed stereoscopically. Hence a pair of cameras are employed to produce stereopairs of photographs.

(iv) The high operating costs of underwater work systems preclude their employment solely for taking photographs for photogrammetric purposes. The addition of a photogrammetric facility to the inspection system cannot be allowed to significantly increase dive time, particularly as only a small number of photographs are likely to be analysed. The dependence of the system on photo control should be minimal.

(v) The system should be flexible in the presentation of results and should produce a realistic assessment of the accuracy achieved.

## SYSTEM DESCRIPTION

The Underwater Photogrammetric Analysis System (UPAS) operated by BUE Subsea consists of an underwater data acquisition component, a support ship based processing and measurement facility and an analytical method of analysis which is built into a photogrammetric software package. The system can be configured for any underwater work system and the camera arrangements and settings are varied accordingly. The following description applies to the system as configured for a manned submersible and a pair of 70mm cameras Use of an ROV or diver would involve changes only to the underwater data acquisition component. The system can be described in four sections:-

### (a) Underwater data acquisition

The underwater data acquisition component consists of an underwater vehicle, a pair of underwater cameras and a calibration frame.

The UMEL 70 mm camera is essentially a Hasselblad SWC camera fitted with a 38 mm Zeiss lens, a motor drive and a domed front port ( Figure 2). It is housed in a water-tight and pressure resistant housing. The camera has been modified by the insertion of a reseau plate in the focal plane which consists of 2 mm grid crosses with a 10 mm pitch and 20  m line thickness. A pair of these cameras are rigidly mounted together on a pan and tilt unit at the front of the underwater vehicle. The unit also carries electronic flash heads and a video camera which can act as a viewfinder. The cameras

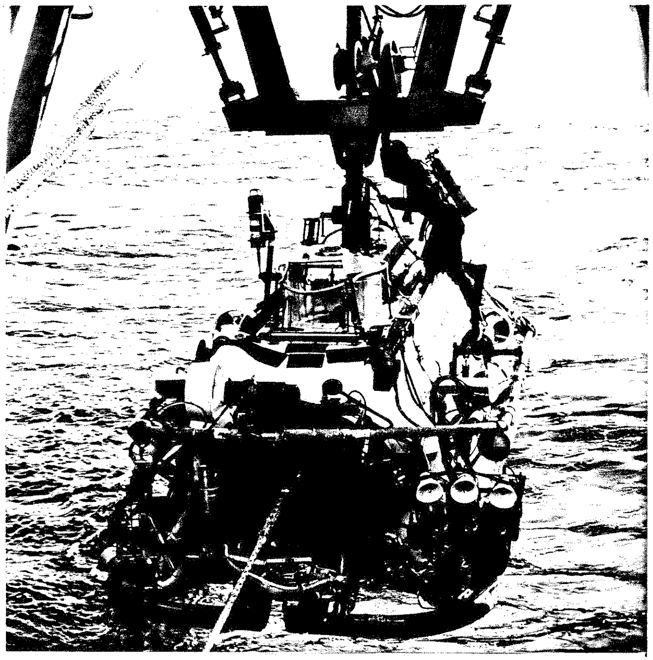

FIG 1. A manned submersible on launch

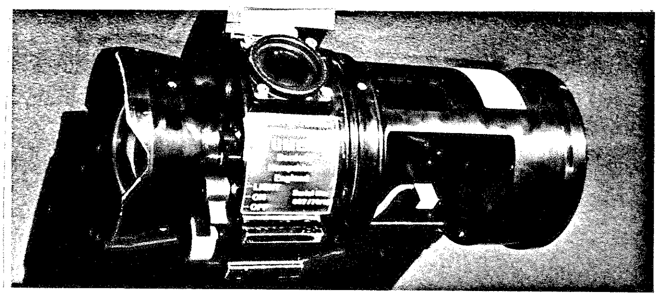

FIG 2. UMEL 70mm underwater camera

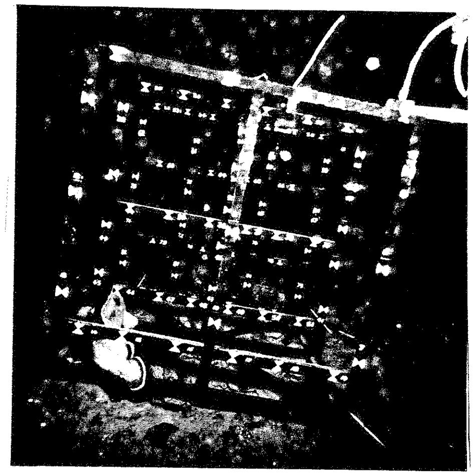

FIG 3. Underwater photograph of the calibration frame

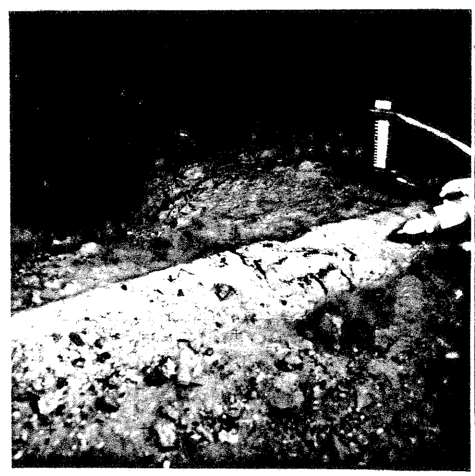

FIG 4. Underwater photograph of damaged pipe

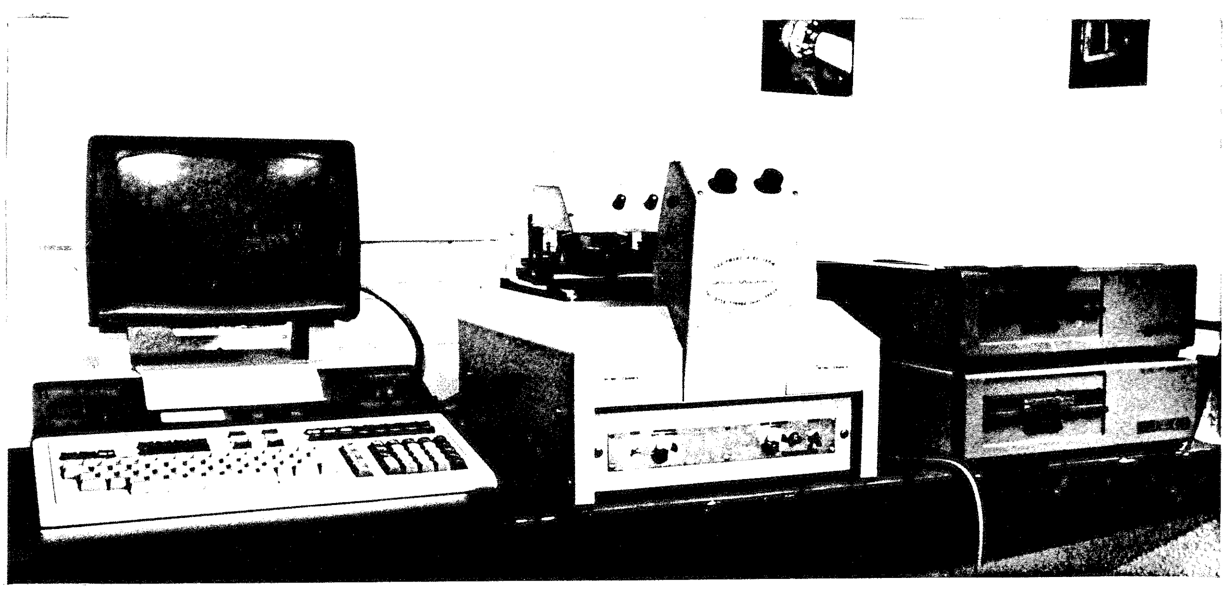

FIG 5. On board measurement and analysis system consisting of Ross SFS-3 stereocomparator, HP9845B computer, dual HP9885 disc drives

are mounted 0.4 m apart with a convergence angle of 15 and a distance setting of 1.6 m. This produces a usable depth of field and area of stereo overlap between 1.1 m and 3.5 m from the cameras. The cameras are wired in parallel and fired by the pilot using a remote contact closure. Flash synchronisation is by the slowest camera shutter actuating the flash. Colour reversal films such as Kodak Ektachrome (ASA 200) are usually used.

The calibration frame consists of a one cubic metre aluminium frame which bears a large number of identifiable control targets whose spatial coordinates have been determined prior to underwater work from photography taken in air with a metric camera. This metric photography is carried out on the support ship on a routine basis every 14 days and, additionally, whenever the frame is thought to have sustained damage.

Operation of the system is relatively simple. Initially the vehicle and the calibration frame are deployed at the work site and the calibration frame is photographed (Figure 3) in such a manner that it fills the camera format (ie at a distance of approximately 1.2 m). The vehicle then moves off to perform its inspection tasks and photographs any items of interest that it encounters (Figure 4). The calibration frame is re-photographed at the end of the work period, if convenient. The calibration frame is only recovered once all the work at the site is complete, which may take several weeks.

(b) Support ship based photographic processing and measurement

The support ship facilities include a photographic darkroom, a portable stereocomparator and computing facilities.

Suitable darkroom facilities are available on most support ships. Once the film is processed, the required transparencies are selected for analysis. The remainder are archived and may be analysed at a later date. Measurement of the photography is carried out using a Ross SFS-3 stereocomparator manufactured in the United Kingdom by Ross Instruments Ltd. This is a lightweight, small format (100 mm x 100 mm) stereocomparator equipped with rotary encoders and a microprocessor based count unit. Resolution is 5 m for x and y, 1 m for px, py. The stereocomparator is linked by a HP 98036 serial interface (RS232) to a HP 9845B computer which is equipped with VDU, thermal printer, tape drives, twin floppy disk drives and drum plotter. The complete system is illustrated in Figure 5.

(c). Photogrammetric analysis

On-site calibration at the underwater site is achieved using a projective transformation with an added polynomial to model distortion (Abdel Aziz and Karara, 1971). The solution includes up to 5 distortion parameters for each camera. The reseau crosses define a photograph system for each camera which can be considered stable during a dive for a constant distance setting (Fraser, 1982). The distortion model is determined from the initial calibration frame photographs and is then applied to all the photographs taken during that dive. An affine transformation is applied to each photograph to correct for film shrinkage and warpage. It is assumed that the reseau plate holds the film flat in the focal plane at the time of exposure.

The analysis method is shown schematically in Figure 6. Initially, the metric camera photographs of the calibration frame are processed using a standard analytical relative orientation procedure which is scaled using precisely known distances to produce a set of 3D coordinates for the control points. The underwater photographs of the calibration frame are then measured and used with the control coordinates to define the projective geometry relationship and distortion model for each camera. The effectiveness of this approach can be assessed by computing photograph residuals and object space coordinates for the control points using the photograph measurements and the derived transformation parameters and distortion model.

The photographs which show objects of interest that are to be coordinated can be termed 'subject' photographs. These are processed in a similar manner, ie, photograph measurement followed by an affine transformation and the application of the projective geometry transformation parameters and distortion models to determine three dimensional coordinates. Variance/covariance matrices are computed for all solutions.

(d) UPAS software package

The UPAS package consists of a suite of programs which are designed to capture information from the stereocomparator; derive the projective transformations; compute three dimensional coordinates and present the results in a convenient manner. The package operates on a HP 9845B computer upgraded to 184 K memory and equipped with I/O and GRAPHICS ROM'S and HP 9885 disc drives. Programs are selected and executed from the menu (Figure 7). Job control is by means of parameter files which enable all data processing to be carried out under direct program control.

The program SFCAP is used to control on -line data capture from the stereocomparator for the metric camera and underwater photographs of the calibration frame. The observations to the control points on the calibration frame are made in three rounds and editing of entries is fully supported. Execution of SFCAP for the underwater calibration frame photographs creates a parameter file which is subsequently used to control the processing of all 'subject' photographs associated with that dive. This ensures that all files are instantly identifiable and that the 'subject' photographs are processed with the correct calibration values.

RELOR is a standard analytical relative orientation procedure which is applied to the metric camera photographs of the calibration frame. Output is a disc file containing spatial coordinates of all observed control points.

The meaned observations taken on the underwater calibration frame photographs are processed by the program PTCON which derives a projective transformation solution for 11, 12, 14 and 16 parameters. These parameters are then used to compute photograph residuals and values of the control points. Control point differences are abstracted and these are used to assess the accuracy of the solution. Generally the solution producing the smallest standard deviation for the control point differences is accepted.

The program PTCAP is used to control on-line data capture from the stereocomparator for the 'subject' photographs. The program accepts observations from the stereocomparator, applies an affine transformation and the chosen projective transformation to compute the object space coordinates by intersection. These spatial coordinates are in an arbitrary system, as defined by the original position of the calibration frame with respect to the camera. By treating the end of dive underwater photographs of the calibration frame as 'subject' photographs, program PTCAP will produce coordinate values for the control points on the calibration frame. These have then been computed in exactly the same way as the coordinates of points

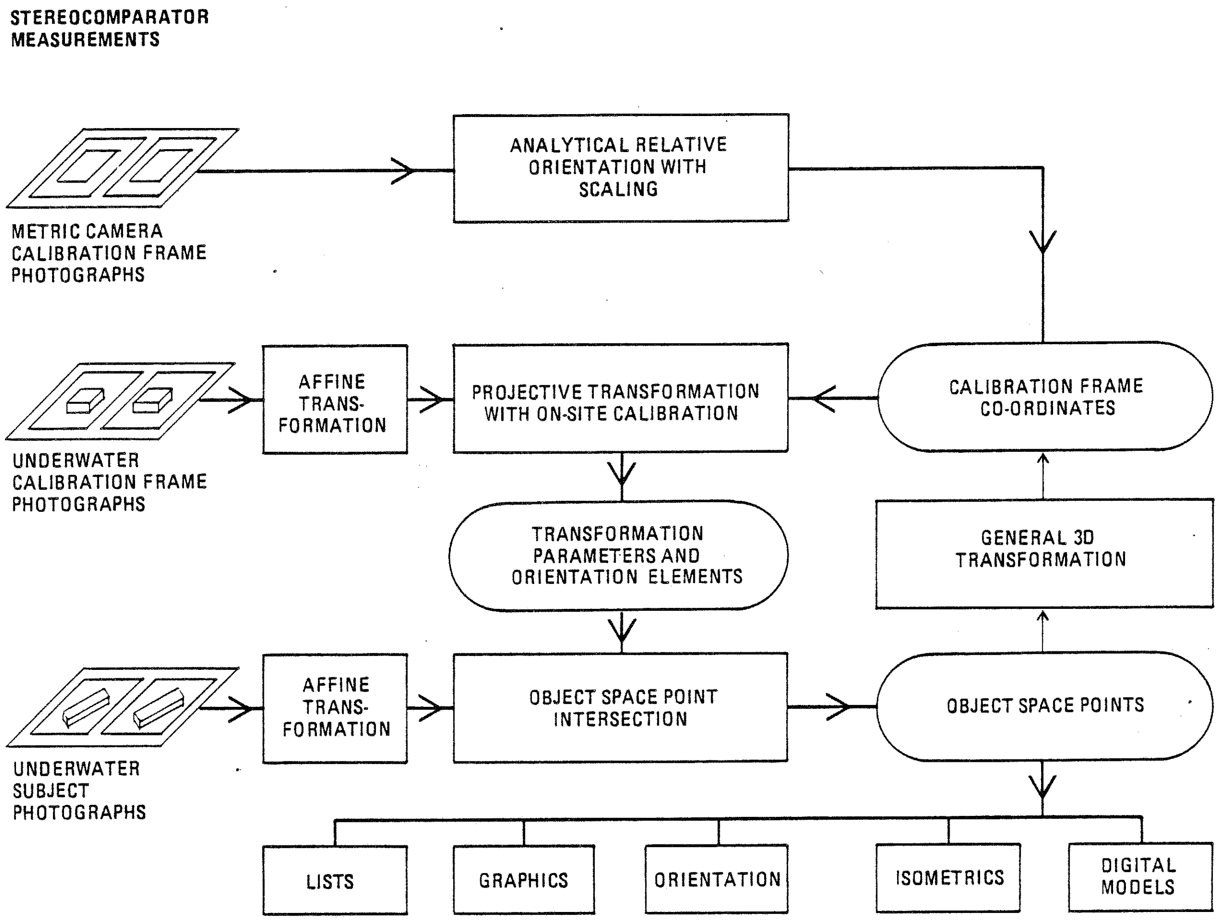


FIGURE 6. Schematic representation of U.P.A.S.

U.P.A.S. Page 2

SFCAP Data capture from stereocomparator (metric photos and underwater calibration frame photos).

RELOR Analytical Relative Orientation (metric photographs).

PTCON Computation of Projective Transformation for underwater photos (calibration frame).

PTCAP Data capture from stereocomparator and computation of 3D co-ordinates on-line (subject photographs).

GEN3D Three dimensional similarity transformation

CALSF Calibration of Ross SFS-3 stereocomparator

EXDOC Documentation and examples

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FIGURE 7. U.P.A.S. menu display (HP9845B).

recorded on the 'subject' photographs. A comparison of the derived and known coordinate values for these points gives a realistic assessment of the accuracy of the system. The three dimensional transformation can be achieved using the program GEN3D. System reliability is closely monitored through checks on the variance/covariance matrix, the photograph residuals of the control points and by independent checks wherever possible.

Program SFCAL is a calibration routine for the stereocomparator which calibrates each of the four measuring axes using a precise glass scale. The program also performs a grid test over the central 60 x 60 mm area and derives an affine transformation in the standard manner.

## APPLICATIONS

Recently the system has been used for two structural measurement tasks in the North Sea. The equipment and method of operation discussed earlier in this paper were employed. Initial coordination of the calibration frame was carried out using a Zeiss UMK 1318 metric camera and a 2 m Wild subtense bar for scale control. The UMK plates were measured using a Zeiss Steko 1818 stereocomparator. The accuracy was assessed by computing distances on a metre rule placed in the foreground and a steel tape stretched behind the frame. A maximum error of 1.7 mm was found over a 2.8 m distance on the steel tape and all other distance errors were less than 1 mm. The control point coordinates were considered accurate to better than $\pm$ 1 mm (vector).

### (a) Underwater structural survey of trial holes

This task was carried out on a North Sea steel platform which experienced problems in the operation of its cement grouting system. Steel platforms are pinned to the seabed by steel piles which may be up to 80 m long, and 2 m or so in diameter. These are driven into the seabed through pile sleeves which are firmly attached to the platform legs and any space between the pile and the sleeve is filled with grouting cement. Parts of the grout system failed when activated and divers were used to drill holes through the pile sleeve to inspect the grout. Unfortunately some of these holes were drilled very close to structural seam welds in the sleeves and hence could cause weakening or tearing of the welds. To assess the possible risk of further damage, it was necessary to define the exact shape and position of all trial holes located within 300 mm. of a seam weld.

As this was the first time that the oil company had used photogrammetry, it was requested that a graduated scale be placed in the field of view of each photograph (if possible) to give a rough visual estimate of size. This scale was positioned by the manipulator arm of the submersible and allowed an independent check on the accuracy of the photogrammetric measurements to be made. Figure 4 shows the scale in one of the photographs of an area of pipe damage for which a 5 mm contour plot was produced. The complete task involved three separate submersible dives to a depth of over 140 m, sometimes in extremely strong currents. A total of 27 pairs of photographs were analysed using no object space control other than the calibration frame.

Figure 8 summarises the precision and accuracy of this work. Figure 8(a) shows the effectiveness of the distortion model in reducing the r.m.s.e. of the photograph residuals for the control points from 15 to 8 m for the 52 control points used as the number of parameters is increased from 11 to 16. The most significant improvement is obtained by the inclusion of a single radial term. Figure 8(b) shows the accuracy achieved in coordinating the

8a). R.m.s.e. of photograph residuals for control points. ( m).

| | 11 parameters | | | 12 parameters | | | 14 parameters | | | 16 parameters | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | x | y | R | x | y | R | x | y | R | x | y | R |
| L | 14 | 15 | 93 | 10 | 8 | 92 | 9 | 7 | 90 | 9 | 7 | 88 |
| R | 14 | 16 | 93 | 8 | 8 | 92 | 8 | 8 | 90 | 7 | 8 | 88 |

8b). Accuracy of Projective Transformation for Dive 1. (all vals mm.)

| No. of param. | CASE A - CONTROL. ACCURACY OF INTERSECTION OF CONTROL POINTS (calib.photos) | | | | | CASE B - NO CONTROL. ACCURACY OF INTERSECTION OF UNKNOWN POINTS (subject photos) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | X | Y | Z | V | R | X | Y | Z | V | Np |
| 11 | 0.6 | 0.6 | 1.6 | 1.8 | 93 | 1.4 | 1.3 | 2.8 | 3.4 | 48 |
| 12 | 0.4 | 0.4 | 0.9 | 1.1 | 92 | 1.0 | 0.7 | 1.9 | 2.3 | 48 |
| 14 | 0.4 | 0.4 | 0.9 | 1.0 | 90 | 0.8 | 0.7 | 1.7 | 2.0 | 48 |
| 16 | 0.3 | 0.4 | 0.9 | 1.0 | 88 | 0.8 | 0.7 | 1.7 | 2.0 | 48 |

8c). Accuracy of distances for 3 Dives for 16 parameter solution.

DIVE 1

| dist | error |
|---|---|
| 200.0 | -0.3 |
| 200.0 | +0.5 |
| 250.0 | +0.4 |
| 150.0 | +1.4 |
| 200.0 | -0.3 |
| 200.0 | -0.5 |

DIVE 2

| dist | error |
|---|---|
| 250.0 | +0.2 |
| 100.0 | -0.4 |

DIVE 3

| dist | error |
|---|---|
| 250.0 | +1.2 |
| 200.0 | -2.0 |

No observations rejected.
No control used.
All values in mm.

R - Redundancy
Np - Number of points.

FIGURE 8. Summary of accuracy achieved for three structural survey dives at depths in excess of 140 m. in the North Sea.

calibration frame from the underwater photography. Case A relates to the start of dive photographs of the frame where control has been used. In Case B the values have been computed by treating the end of dive photographs of the calibration frame as uncontrolled 'subject' photographs and so represent the accuracy achieved for the trial hole photographs. The computed three dimensional coordinates are transformed into the original system using routine GEN3D (with no scale change). Standard deviations (vectors) of $\pm 1.0$ mm for Case A and $\pm 2.0$ mm for Case B are obtained for the 16 parameter solution. Figure 8(c) gives the accuracy of the distances computed on the graduated scale included in certain photographs on each of the three dives and this represents a totally independent check on the system accuracy. The maximum error is 2.0 mm (Fig 8(c), Dive 3) if the graduated scale is considered to be error free. The results were presented to the client as a series of plots showing the position, shape and, in some cases, depths of the trial holes. Distances to the nearest seam weld were also computed.

(b) Underwater measurement of protective anodes

Protective anodes are used to reduce the corrosion of steel structures which are in contact with sea water. When steel is placed in sea water a weak electrolytic effect is established which attacks and destroys the exposed surface. If the steel is connected to a more active metal, such as zinc, the electrolytic effect will preferentially waste the exposed zinc until it is all used up. Hence it is very important to monitor the rate of wastage of the anodes attached to steel structures.

The examination of routine inspection photography taken of a particular North Sea structure showed an unexpectedly high rate of wastage of the protective anodes. The photography had been taken as stereopairs and included photography of the calibration frame at the work site. The oil company requested determination of anode wastage some weeks after the photography had been taken. A total of 14 pairs of photographs taken at a depth of 140 m were measured and analysed. Generally the photo coverage was poor and many anodes were partially covered by anode waste product and layers of silt. The photographs were measured and the trapezoidal shape and longitudinal section along each anode was determined. The digital models were levelled to produce a data set which describes the shape of the anode relative to the front face of the structure. The results were presented as plan and side elevations of the anode superimposed onto the original (as built) anode dimensions (Figure 9). The anode wastage was estimated by comparison of the original and measured volume. The accuracy achieved was similar to that given in Figures 8(a) and 8(b).

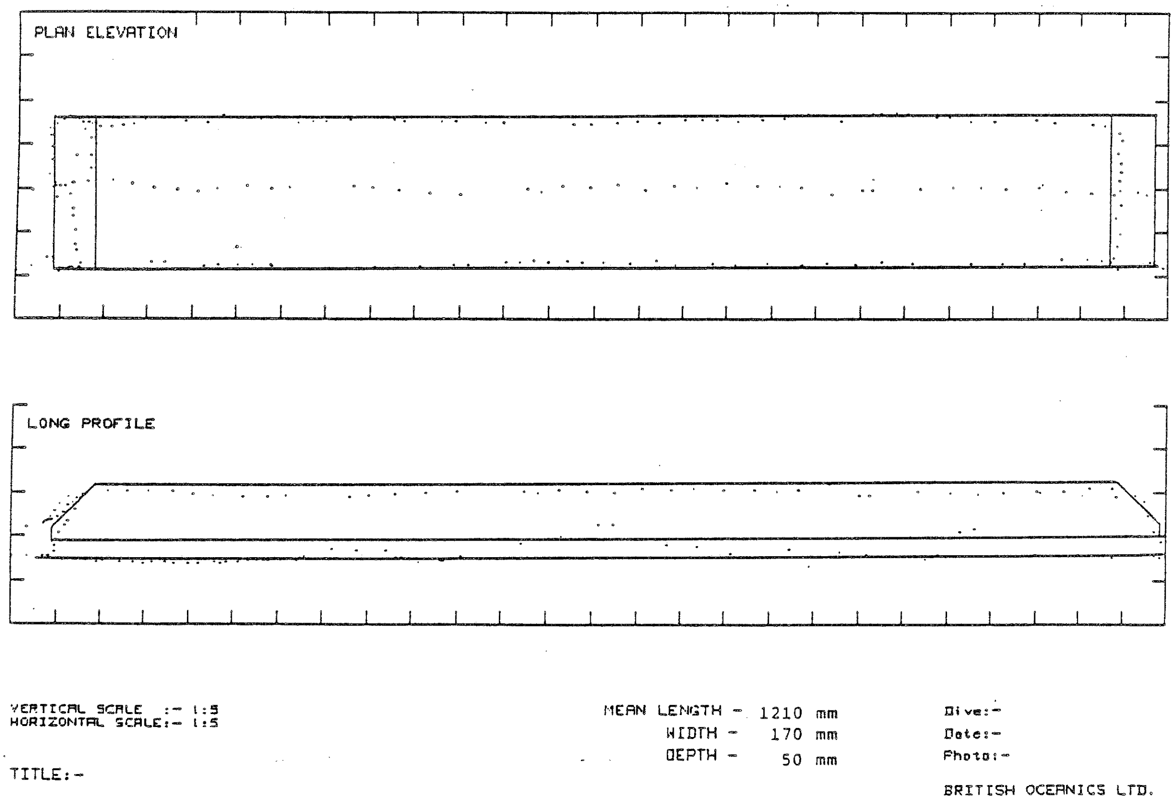


FIGURE 9. Determination of Anode Size.

## DISCUSSION

The major advantages of the system are seen as its portability, freedom from control and use of an intersection method for space point calculation. This is particularly useful in the case of incomplete models where relative orientation methods are never very satisfactory. A test carried out using both methods on the same set of data (Baldwin, 1984) gave results which were of the order of 2-3 times better for the intersection method.

The main disadvantage of the system is the necessity of deploying and photographing the calibration frame at the start of each dive to allow on-site calibration. This adds to total dive time. Methods of reducing the frequency of calibration with no loss of accuracy are being sought. Another problem, is the need to measure a high number of points to adequately define the shape of the object. In the case of the anodes mentioned above, some 200-250 points per model were measured.

A Hasselblad MK 70 metric camera will soon be added to the system which will photograph the calibration frame on-board the support ship. The resulting photography will be suitable for measurement using the Ross SFS-3 stereo-comparator. A HP 9000 CAD/CAM package will soon be used for manipulation and presentation of the digital models of the 'subject' photographs.

Sometimes, an object will be photographed that cannot be covered with a single stereopair. In this case models are joined together and some form of external control is required to control the independent model adjustment. This is a new area of development but should follow standard methods.

## CONCLUSIONS

The UPAS system is capable of rapid measurement of structures using any cameras which can be operated as a pair and are fitted with reseau plates. The system can be used with any underwater work system; is portable, independent of photo control and uses on-site calibration. Work carried out under operational conditions in the North Sea at depths in excess of 140 m have yielded consistent accuracies of $\pm$ 2 mm (vector s.d.) for objects up to one cubic metre in size and located between 1 m and 3 m from the cameras. This system is one of several currently under development which it is hoped will demonstrate to the offshore industry that photogrammetry can be of value in underwater measurement tasks.

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