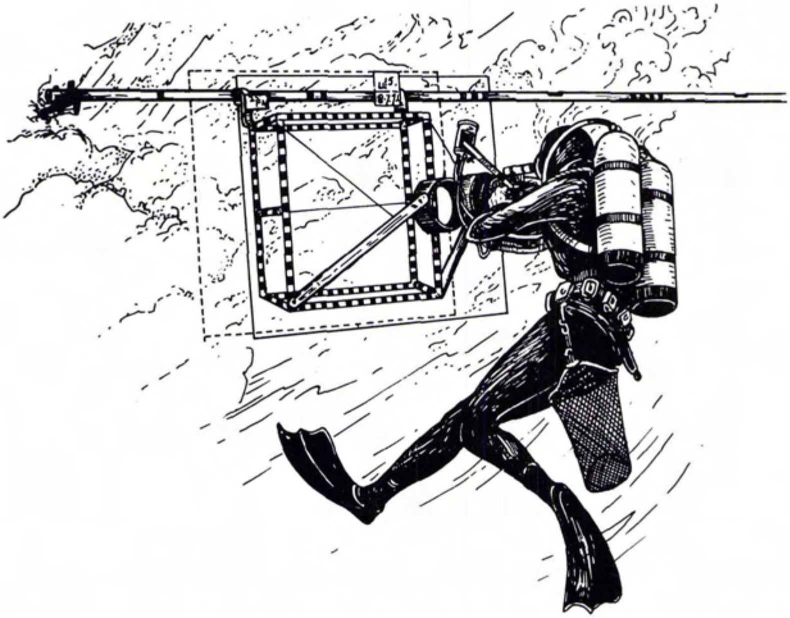

FIG. 1. A diver at work with stereophotographic recording of permanently marked test areas. The areas covered by the photographs are indicated in the figure. (From Lundälv, 1971).

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Under-Water Analytical System

Photogrammetry offers a simple, rapid, economical and accurate system for obtaining quantitative measurements for marine research.

(Abstract on page 288)

INTRODUCTION

UNDERWATER photography provides the marine biologist with a rapid method for collecting data on biological bottom communities. Along with the development of autonomous diving techniques, the underwater camera has become a standard tool in marine research. By photography the diving biologist can cover large areas in a short time and then study the pictures to attain information. This documentation is most commonly of qualitative nature. However, quantitative data is usually required in research work. Data on frequency and distribution can be obtained from photographs by simple methods. To acquire data on size, shape, area or volume more sophisticated methods are required (Figure 1). In this instance photogrammetry provides the adequate solution on the problem of measurement. So far, underwater photogrammetry has been used primarily for detailed surveys of deep-sea bottoms. Studies employing this technique and its applications are given in References 1 and 2. Most of the applications use small-scale photographs.

In the following a technique is described which has been designed to be simple for the diver, rapid in evaluation, accurate, economical and without need of a specialized photogrammetrist for evaluation. The photogrammetric determination of geometric data is not the only reason for stereoscopic photographs; it is also more accurate than single pictures in species identification and density determinations. The biological applications of the method are discussed in Reference 4.

Both authors have collaborated in the development of the basic ideas and in the execution of the practical work for the preparation of this paper. The senior author (K. Torlegård) is primarily responsible for the mathematical derivations used.

ABSTRACT: *The system is based on stereoscopic underwater photography by scuba diving using a single camera and a reference frame for calibration of the stereopair of pictures. The measurements are made in a microstereocomparator. For computation a programmable desk calculator is used. The analytics yield size-determinations of high accuracy. The system was developed for quantitative studies on dynamic processes (including long-term effects of pollution) within biological rocky-bottom communities along the Swedish west coast. Well defined and permanently-marked test areas on rocky bottoms are photographed at intervals and changes within the biocoenoses are studied in detail. The stereophotos are analyzed with respect to species composition, density, cover, size distribution, biomass (determined indirectly) and pattern. Population dynamics, growth rate and productivity can be studied by comparison of photographs from the same test area obtained on different occasions.*

EQUIPMENT

CAMERA

The camera is a Hasselblad SWC (superwide camera) with a Zeiss Biogon 38-mm lens and a 70-mm frame magazine in a standard underwater casing fitted with a Zeiss corrective glass port. The camera is fitted with an electronic flash unit which is always applied. As a result of the use of the corrective glass port, a comparatively high photogrammetric accuracy can be obtained by simple mathematics. Moreover, due to the wide picture angle (90°), the camera can be brought close to the object, thus reducing the negative influence of particles in the water. Furthermore, a favorable relationship can be obtained between stereobase and photography distance (approximately 1:3).

FILM

Positive 70-mm color film (Ektachrome MS) is used. The picture size and the color are of great value in analysis. Up to now practically all photographs have been technically acceptable. Black-and-white prints of two stereopairs are shown in Figure 2.

REFERENCE FRAME

The frame serves two purposes. To begin, the test areas are accurately defined from time to time by a system of dowels and rods, on which the frame is positioned and, secondly, the stereoscopic pair of pictures are calibrated on the frame.

The reference frame is made of stainless steel tubes which form the edges of a parallelepiped and is 0.50 × 0.50 × 0.10 m in size. The sides are marked at 2-cm intervals in black and yellow colors. The midpoints of the 0.5-m bars have small black dots which are measured in every stereopair for calibration in the evaluation procedure. The frame is fitted with a camera support in order to permit the camera to be placed consecutively in two well-defined positions with a horizontal spacing of 0.20 m (the stereobase) and at a distance of approximately 0.60 m from the bottom to be photographed (Figure 1). The image scale is approximately 1:16. The camera is oriented quite accurately with the aid of a special view-finder comprised of two crosses aimed at two points on the frame. This procedure provides stereoscopic pictures according to the so-called *normal case of photogrammetry*, with very small approximations.

MICROSTEREOCOMPARATOR

The stereo photographs are measured in a Wild microstereocomparator, MSTK. This is a small precision instrument suitable for 70-mm transparencies. The picture holders have common movements in x and y which are measured with micrometer screws. The

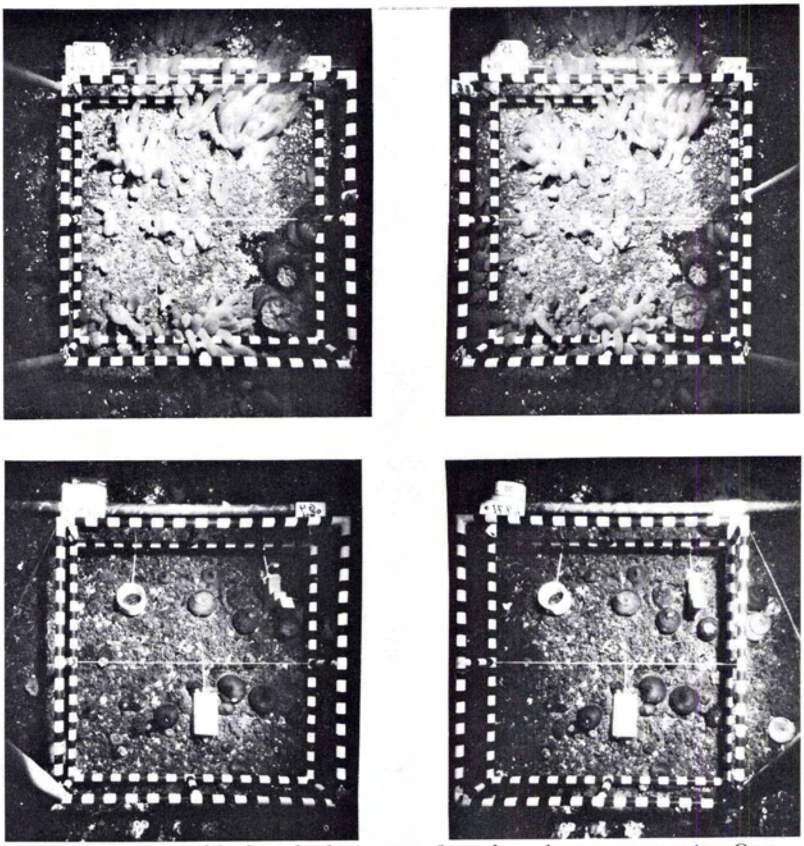

FIG. 2. Stereoscopic black-and-white prints from the color transparencies. One of the pairs contain the accuracy test objects.

right picture can be rotated to eliminate differential κ and the left one has a separate translation to remove vertical parallaxes *(py)*. As the measuring marks are introduced in the ray path within the eyepieces, the horizontal parallaxes *(px)* are measured with a micrometer in the right eyepiece.

DESK CALCULATOR

The last instrument necessary is a programmable medium-size desk calculator. There are many makes on the market and most will do as the formulas given below are very simple to program. The memory requirements depend on the make of the calculator, a capacity for a few hundred program steps and eight registers will suffice. The total investment for equipment amounts to approximately \$6,000 to \$7,000.

FORMULAS

The normal-case of stereophotogrammetry, with notations as shown in Figure 3, gives the following relations between image and object coordinates:

$$X = (B/p')\,x'$$
$$Y = (B/p')\,y'$$
$$Z = (B/p')\,c$$

where $p' = x' - x''$.

In the microstereocomparator are measured x, y and p-values on scales. The following relations exist:

$$x' = x - x_0$$
$$y' = y - y_0$$
$$p' = p - p_0.$$

Procedures for the determination of $x_0\, y_0$ and p_0 are given in the following.

The *normal case* formulas also contain the constants B and c, which are the stereobase and the principal distance of the pictures. Variations can occur in the base B as the camera is moved between the two exposure positions on the reference frame. The principal distance c can vary due to film shrinkage and differences in temperature and salinity of the water. Thus B and c are computed for every pair of pictures from image coordinate measurements on the reference frame. Formulas for B and c are given next.

The origin of x' and y' is assumed here to be

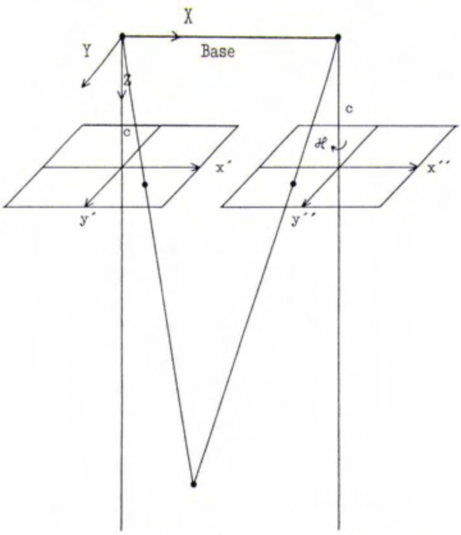

FIG. 3. Normal case of photogrammetry.

located in the picture center and thus determined from the measurements on the picture edge. All of the pictures to be measured are oriented in a standardized manner (the procedure is described in the following paragraph). Thus the origin x_0, y_0 of the x', y' - system is determined once and for all. In the event that an error should occur, it is always eliminated in the calculating procedure.

TABLE 1. COORDINATES OF FOUR POINTS ON THE REFERENCE FRAME.

No.	*X*	*Y*	*Z*
1	B/2	D/2	$Z_1 = Z_0$
2	B/2	D/2	$Z_1 = Z_0$
3	B/2	−D/2	$Z_3 = Z_0 + dZ$
4	B/2	−D/2	$Z_3 = Z_0 + dZ$

The origin of p' is computed from the measurements on the reference frame which has known dimensions. Four points are measured on the reference frame. They have the coordinates as shown in Table 1 where $D = 0.5$ m and $dZ = 0.1$ m. See also Figure 4. The distances 1-2 and 3-4 are in the image $d_{1\text{-}2}$ and $d_{3\text{-}4}$ Thus, the camera constant is:

$$c = \frac{dZ}{D_{3\text{-}4}/d_{3\text{-}4} - D_{1\text{-}2}/d_{1\text{-}2}} = \frac{dZ}{S_3 - S_1}.$$

From the scale factors S_1, S_3 and the camera constant c the Z-values are computed for the points 1-2 and 3-4.

The p'-origin p_0 is now calculated from parallax-readings on the four points:

$$p_{12} = \tfrac{1}{2}(p_1 + p_2)$$
$$p_{34} = \tfrac{1}{2}(p_3 + p_4).$$

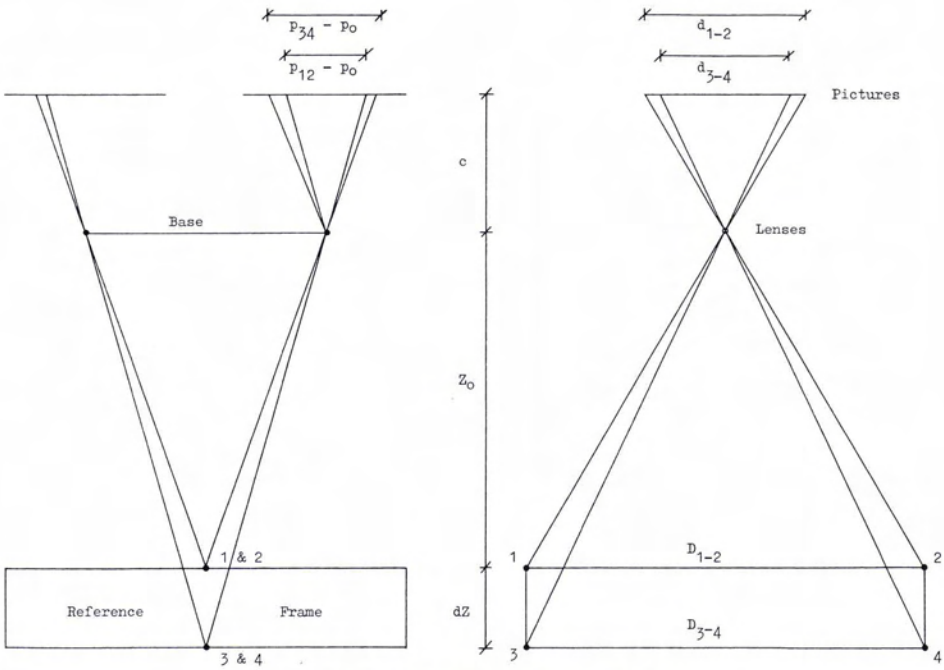

FIG. 4. Calibration on reference frame. See text.

From the normal case formula for Z we obtain:

$$c \cdot S_1 = \frac{B \cdot c}{p_{12} - p_0}$$
$$c \cdot S_3 = \frac{B \cdot c}{p_{34} - p_0}.$$

Solving these for B and p_0 we attain:

$$p_0 = \frac{S_1 \, p_{12} - S_3 \, p_{34}}{S_1 \, S_3}$$
$$B = \frac{S_1 \, S_3}{S_1 - S_3} \, (p_{34} - p_{12}).$$

Introducing the computer constants we arrive at the following formulas:

$$X = \frac{x - x_0}{p - p_0} \, B$$
$$Y = \frac{y - y_0}{p - p_0} \, B$$
$$Z = \frac{B \cdot c}{p - p_0} \quad .$$

Measuring Procedure

The left picture is placed along the left side of its frame-holder in the microstereocomparator, and the right picture is placed along the lower side of its frame-holder. The vertical parallaxes of the stereo-pair are eliminated with the py-movement of the left picture. Then the right picture is rotated, so as to coincide with the same horizontal parallax (p') of points 1 and 2. The following procedure is performed:

a. Read p of point 1.
b. Read p of point 2.
c. Set p to the mean of the readings on point 1 and 2.
d. Place the floating mark on point 2 by the differential rotation κ.
e. Repeat procedure from *a* to *d* until the same p is read on both points.

As the py-movement of the microstereocomparator is on the left picture, the values of x_0 and y_0 are almost the same for all stereopairs, as long as this orientation procedure is applied. In practice the same x_0, y_0 are used for all stereopairs, in order to speed up the orientation. The actual deviations do not introduce any errors in the results because the results always are based on coordinate differences.

The reference frame points 1, 2, 3 and 4 are measured with y' and p' observations. The x' values are approximately the same and do not influence the following computation. From the y' and p' observations the calibration values of c, p_0 and B are computed on the desk calculator. The values are stored in the calculator memory.

Then x', y' and p' of all points of interest are measured. The values are fed into the calculator which is programmed to give X, Y and Z-object coordinates. From these coordinates, the values for distances, angles, areas, volumes, etc., can be derived.

After some training an operator can measure and compute approximately 100 points per hour.

Accuracy of Distances

One of the purposes of the photogrammetric determinations is to study the growth rate of living matter. Primarily, distances are needed to determine dimensions such as diameters, height, etc. of the organisms at different times. Therefore, all distances are computed in three dimensions:

$$D = \sqrt{[(X_A - X_B)^2 + (Y_A - Y_B)^2 + (Z_A - Z_B)^2]}$$

A complete study of the photogrammetric accuracy of the system would have included determination of principal point, camera constant, radial distortion and perhaps even more parameters of interior orientation according to methods described by Torlegård[3] in 1967. The same technique also gives values for the exterior orientation elements of the stereo pictures. The final precision of computed object coordinates can be deduced by applying the general law of error propagation. This is the proper way of handling the problem if the system is used for a general analytical evaluation of image coordinates.

However, in this particular application we almost surely can say that all determinations concern distances shorter than, let us assume, 0.1 m. Thus, we take a series of underwater photographs of test objects of approximately this size. They differ in size and shape; there are boxes and cylinders as indicated in Figure 2.

Given values of the test objects are acquired by caliper rule measurements. These readings are made to 0.1 mm and repeated to give a good average. From the test photographs, three-dimensional coordinates are determined for the endpoints of the corresponding distances on the test objects. The distances are computed from the sets of three-dimensional coordinates. The values obtained are given in Table 2.

After applying χ^2-distribution test, Bartlett's test, variance analyses and Student's T-test, it can be concluded that:

TABLE 2. MEASUREMENTS OF TEST OJECTS. VALUES IN MM.

	Given distance	*Photogrammetric* determination	*Error*	*Linear* Mean	*Root mean* square	*Standard* error
Stereopair 1	101.9	100.8	−1.1			
	91.0	90.7	−0.3			
	63.1	63.0	−0.1	−0.28	0.53	0.51
	71.2	71.5	+0.3			
	83.0	82.8	−0.2			
Stereopair 2	101.9	102.2	+0.3			
	48.0	48.3	+0.3			
	95.7	95.5	−0.2			
	73.3	73.4	+0.1	+0.13	0.21	0.18
	34.3	34.5	+0.2			
	63.1	63.1	0.0			
	96.3	96.5	+0.2			
Stereopair 3	101.9	101.2	−0.7			
	48.0	47.4	−0.6			
	98.0	98.2	+0.2	−0.28	0.44	0.38
	99.0	98.7	−0.3			
	92.8	92.8	0.0			
Stereopair 4	101.9	102.4	+0.5			
	50.5	50.3	−0.2			
	87.0	87.3	+0.3	+0.24	0.38	0.34
	82.0	82.0	0.0			
	63.2	63.8	+0.6			
Stereopair 5	101.9	102.0	+0.1			
	48.0	48.4	+0.4			
	62.9	62.8	−0.1	−0.02	0.28	0.31
	34.4	34.0	−0.4			
	98.0	98.2	+0.2			
	43.8	43.5	−0.3			
Stereopair 6	101.9	101.5	−0.4			
	48.0	48.1	+0.1			
	91.0	90.8	−0.2	−0.03	0.29	0.31
	101.0	101.5	+0.5			
	96.9	96.9	0.0			
	82.0	81.8	−0.2			
			Totally	−0.03	0.36	0.37

The term *standard error* is used as an expression for photogrammetric accuracy, i.e., the closeness of observations to the given or true values, or to mathematical conditions.[5] Statisticians commonly denote this as standard deviation.

The error distribution is normal.
The accuracy is homogeneous.
The mean of this distribution is zero.
The standard error (accuracy) of measured distances is 0.37 mm.
The standard error is 0.023 mm in the image scale.

DISCUSSION

The method described provides a rapid means of acquiring quantitative biological data from large sea bottom-areas. This is important in marine studies where the duration of underwater work is limited due to environment, especially in deep or cold waters. Furthermore, comparative studies can be performed over long periods of time without interfering with the organisms studied.

The simplicity of measurement and evaluation is of great value for the biologist. He can make his observations and computations by himself, in his own laboratory and at the precise moment the geometric data are needed.

It must be remembered that photogrammetry is only one of the numerous observations made in marine research. It is therefore, essential that photogrammetry be simple, fast, economical and accurate. It seems that the above described system meets these requirements.

ACKNOWLEDGEMENTS

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