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3-D reconstruction of biological objects using underwater video technique and image processing

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Abstract

This paper describes a 3-D reconstruction method which allows accurate measurements of volume, surface area and other morphometric measurements of three-dimensional biological objects, without removing them from the sea. It represents a novel approach based on multiple views (eight resulted to be sufficient) from underwater video images and a new image processing procedure (MOD3D), whose application has met the basic requirements (i.e. to work on images recorded in turbid waters, with nonuniform lighting, to investigate large areas and in reasonable time, etc.) imposed when operating in the marine environment with simple, easy-to-use and nonprofessional equipment. It is a noninvasive, nondestructive and in the field fast method, thus suitable for sampling also at relevant depth, whose applicability has specifically been set up for a range of growth forms from massive to submassive and irregularly shaped. The accuracy of the method was assessed using models with three levels of 3-D complexity: simple, moderate and complex morphology. A high accuracy of volume measurements made through MOD3D image analysis software was achieved when compared with the laboratory water displacement method, which represents the most accurate method for volume measurement, with an overall mean percent error of about 1.7% (S.D. 2.2%). For all three levels of morphologic complexity, no significant differences ($p>0.05$) were found. Volume measurements obtained in field based on geometric approximation resulted rough, with significant differences from the MOD3D values ($p<0.05$). The geometric approximation was lower than MOD3D for simple and moderate morphology, and variable for complex morphology. For all three models, MOD3D values for surface area computation were consistently lower (mean error 13%) than the foil-wrapping values ($p<0.05$), due to overlap error when foil wrapping. Two applications were made with the bryozoan *Pentapora fascialis* and the coral *Cladocora caespitosa* to quantify carbonate standing stock and biomass of these two carbonate framework builders, whose importance has been recently recognised among the temperate sublittoral benthic species. Time required for the 3-D reconstruction method (about 3 h) makes it suitable for routine application particularly for

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relatively large area investigations, with irregularly shaped objects on rough substrate and several biological objects within the area.

Keywords: Bioconstructors; 3-D modelling; Morphology; Surface area; Underwater video; Volume

1. Introduction

Since the work of Petersen (1918), quantitative estimate of the total mass of an organism measured as volume or mass (live, dead, dry or ash-free weight) has been considered of fundamental and practical importance in benthic ecology, in particular for understanding energy flow, cycling of organic matter, carbonate production, and exploitation of demersal fish stocks in aquatic ecosystems (Golikov and Scarlato, 1973; Pomeroy, 2001).

However, measurement of organism mass and other morphologic characteristics is often a time-consuming process, needs repeated sampling and requires complicated laboratory procedures. For example, one of the most accurate methods to measure biomass is by 'ash-free dry weight', which involves drying and incineration (Edgar, 1990). Other techniques for accurately calculating volume, and indirectly biomass, imply measurement of water displaced after placing the specimen in a cylinder filled with water (Schiller, 1993) or recording water displacement after inclusion of the whole specimen in ice (Cocito and Ferdeghini, 2000).

Another fundamental determinant of physical and biological processes of which organisms are concerned is the surface area. As well as volume or biomass, most of its measurements involve destructive sampling: sampling may be followed by specimen wrapping with aluminium foil (Marsh, 1970) or latex rubber (Meyers and Shultz, 1985) or molten wax (Stimson and Kinzie, 1991) and then by calculating weight or extension or amount respectively of the substance used. However, these methods are complicated, time-consuming and not always repeatable, particularly with morphologically complex specimens.

All these methods can only be applied once the specimen is removed from the sea, and are only used on relatively small specimens. The routine measurement of only small or juvenile organisms, for example, of corals, is extremely restrictive in a group of organisms that may reach several meters across and in which both size and age are important characteristics of ecological functions (Hughes and Connell, 1987; Soong et al., 1999; Stocker, 1991).

A clear need for noninvasive, nondestructive, non-size-limited and faster methods has been advocated by many authors, who have thus preferred easily obtained in situ rough morphometric measurements of organisms such as length, height, diameter (Tanner, 1995; Cocito and Ferdeghini, 2001; Peirano et al., 2001) or biovolume (Castric-Fey and Chassé, 1991) to estimate surface area, volume, carbonate standing stock and biomass. However, these methods appeared to be less accurate.

In order to obtain accurate measurements, particularly for three-dimensional objects, not only the size of an organism but also the morphology can complicate applicability of a

method (Pichon, 1978; Bythell et al., 2001). Complex morphology of an object, as for erect and branching organisms, requires a method which minimises inaccuracy and imprecision. Moreover, large areas under investigation and sampling at relevant depth, where bottom time is reduced for divers, need a fast-application method.

In the past 20 years, considerable advances have been made in developing underwater imagery techniques and equipment, which involve photography, photomosaic, stereophotography and photogrammetry (Done, 1981; Fryer, 1983; Warren and Underwood, 1986; van Rooij and Videler, 1996; Beck, 1998). In order to gather accurate quantitative data on growth rates or spatial relationship between organisms, in particular small, hidden colonies, photography has been substituted with stereophotography and photogrammetry in the study of change in coral communities. Photogrammetry was applied to corals to correct planar (2-D) measurements of surface-area cover but not to produce 3-D surface measurements (Done, 1981). A recent application of photogrammetry techniques for surface area and morphometric measurements of irregular objects has been proposed by Bythell et al. (2001), but many routine application are precluded by time requirements.

To obtain 3-D measurements of volume and surface area of objects through visual methods based on image analysis efforts have mainly been addressed for application in architecture (Baillard et al., 1999), computer graphics (Zisserman et al., 1999), microscopy (Cookson, 1994) and biomedicine (Weninger et al., 1998). Applications in terrestrial and marine sciences are scarce, especially in the marine environment, where constraints and logistic difficulties make accuracy and repeatability of measurements often problematic.

As a matter of fact, 3-D reconstruction of marine, biological targets has to meet some basic requirements:

- to be able to work on images recorded in turbid waters, with nonuniform lighting, and with foreign objects that could interfere in the scene, for example, projecting shadows or obscuring the target;
- to investigate a relatively large area with a certain number of biological targets within the area;
- image acquisition has to be easily performed in situ, to be done with commercial, simple equipment and the whole process, including object reconstruction, has to be done in reasonable time.

We describe a novel technical approach to accurately measure volume, surface area and other morphometric measurements of three-dimensional biological objects from underwater multiple views taken with an underwater video camera. It is a noninvasive, nondestructive and relatively fast method whose applicability has specifically been set up for a range of growth forms from massive to submassive (Jackson, 1979; Pichon, 1978), with subcircular to elliptic perimeters, often bearing expansions resulting from fusion of neighbouring objects (i.e. individuals, colonies, etc). The accuracy of the method was assessed using models of known dimensions with varying levels of 3-D complexity. Volume and surface area measurements were compared to those obtained with standard laboratory and in the field techniques.

For some benthic species, namely the bryozoan *Pentapora fascialis* (Pallas) and the coral *Cladocora caespitosa* (Linnaeus), the 3-D reconstruction method was applied in the

field in order to compare different environmental conditions and, analysing advantages and disadvantages of the method, to evaluate if routine application can substitute standard techniques in studying aspects of the biology and ecology of some benthic species. Moreover, the application of the method was used to quantify carbonate standing stock and biomass of these two carbonate framework builders, whose importance has been recently recognised among the temperate sublittoral benthic species (Cocito and Ferdeghini, 2001; Peirano et al., 2001).

2. Materials and methods

2.1. Image acquisition

Image recording was carried out using a diver-deployed digital video camera Sony DV1000 equipped with a 112° extra-wide-angle aspheric lens Thalaspheric Pro DV®, twin Isolux 100 W lights and a 5-in. LCD colour monitor. The lens allowed filming 1 m^2 at 0.75 m camera-to-object distance. Utilisation of a digital video camera provides a huge number of images if compared with photography and allows to simultaneously control viewpoint through an underwater colour monitor and to control lighting by adjusting the light orientation during recording. Notwithstanding the relatively lower image definition provided by the digital video camera compared with that obtained from colour slide digitalisation, the large library of image captures of the same scene gives an unexcelled advantage.

The extra-wide-angle aspheric lens reduces spherical distortion thus reducing the need for lens distortion calibration and reduces camera-to-subject distance thus allowing recording in turbid waters, as found commonly in some shallow coastal northwestern Mediterranean seawaters, where visibility can be reduced to 1–2 m.

In order to compute viewing angles and distances (camera calibration), a reference object represented by a cube of known dimensions was positioned within the scene, laying on the substratum. The size of the cube used ranged from 10 to 25 cm, depending on the dimension of objects to be reconstructed. The cube faces were alternatively painted with bright colours, in this case yellow and red, displaying the face's number. The cube was supported by a tripod. Images were taken by a SCUBA diver operator rotating around the scene while recording multiple perspective views from different viewpoints, always including the scaling cube required for all images.

2.2. Image processing and generating 3-D models

Images and model processing were carried out on a Pentium III 600 MHz personal computer with 256 MB RAM, running DVCapture® software and DV Master® images acquisition card provided by FAST Multimedia. Suitable frames, i.e. recording both the reference object (the cube) and biological objects to be reconstructed, were selected from the film and stored in bmp format (720 × 576 pixels; 16 M colours). A new software, called MOD3D, was purposely developed jointly by ENEA and AVS (Advanced Visual Systems, Milan) for 3-D reconstruction and visualisation. The software is flexible to

accept rapid algorithm changes and supporting continuous functionality upgrades. Algorithms work in sequence on camera calibration using 'vanishing points' computed from the reference object imaged vertices (Cipolla and Boyer, 1998). After silhouette outlining of biological objects, volume reconstruction is obtained by applying the method of 'volume intersection' (Niem, 1997).

Image processing included the following steps: filtering was applied to each image in order to sharpen and contrast edges of cube and objects (Fig. 1a). Manual outlining of cube vertices and objects was performed (Fig. 1b). The accuracy in outlining the cube is fundamental to define vertex coordinates in order to compute camera position. Manual outlining accuracy computed on replicated measurements on the same set of images of different objects ranged from 0.12% to 0.3% for surface area measurement and from 0.07% to 0.5% for volume measurement. The aim of the image functionalities embedded in MOD3D is to help manual corner marking of the reference object, object silhouette extraction and ground mark point extraction. The available filters are: weighted sum of RGB values, various convolutions, edge extraction (Nevaita Babu, Sobel, Prewitt) and

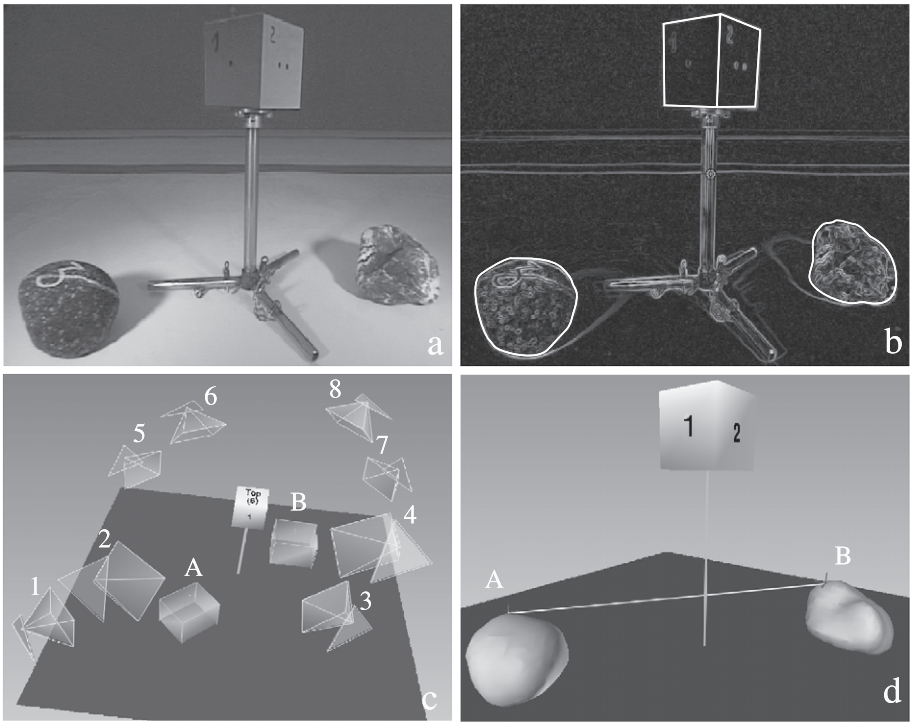

Fig. 1. Image processing and 3-D reconstruction of two objects in controlled condition (aquarium) after selection and filtering of each view (a). Manual outlining of cube vertices and objects (b). Computation of coordinates defining camera position (numbered in the figure) for each of the 8 views used for this application. 'Bounding boxes' (A and B) represent position and a rough estimate of volume of the two objects (c). 3-D reconstructed objects and measurements of linear dimensions (d). Cube dimensions are 10 cm on a side.

local contrast enhancement. An automatic silhouette extractor based on 'snake' function is also present, but after evaluation on real field images we found more effective the manual marking process.

After manual outlining, MOD3D generated 'bounding boxes' that represent the position and a rough estimate of volume of the objects (Fig. 1c). When images do not allow good reconstruction of the substrate (i.e. for irregularly rough substrate), MOD3D generates 'tail' volume underneath objects. In fact, the volume intersection reconstruction method obtains the 3D object model intersecting generalised cones whose vertex lies at the camera position and pass through the object silhouette on the image plan. The number of such cones in a real setup is limited and does not cover all the possible positions around the object. This leaves unintended 'tails' behind the object. In our setup they are mostly below the ground. To alleviate the problem, the ground plane starting from recognised conspicuous marks ('landmarks') positioned on the ground (i.e. pebbles, crusts, etc) (for example, see Fig. 4c) was reconstructed and then all the model parts lying below were removed. Generating a 3-D model yielded volume estimation of objects and measurements of their linear dimensions and distances (Fig. 1d).

In order to allow MOD3D application to all commercial, nonprofessional wide-angle lenses, a software for correction of optical distortion has been developed. Off-line camera calibration extracts and saves camera internal parameters and lens radial and transversal distortion data. The information is used to improve the model reconstruction accuracy. The calibration routine starts from several views of a planar model object containing a regular grid of point. A 5×4 black and white checkerboard printed on a rigid waterproof panel was used. To achieve accurate calibration, the views covered a board range of positions and orientations in the camera field of view. 20 images resulted to be sufficient to compute correction parameters.

2.3. Assessing 3-D reconstruction accuracy

Various stages at which errors can be avoided and image processing optimised are to be considered. In order to process the 3-D reconstruction correctly, the images used should be spatially distributed and show the objects entirely from every orientation. This is needed in order to exactly map the relative position among objects. 3-D reconstruction is guaranteed and facilitated by providing a conspicuous set of images.

Errors generated by low resolution images can be minimised by using the reference object (the cube) with dimensions comparable to the size of objects to be reconstructed.

Levels of natural 3-D complexity of biological objects are variable. With reference to this, the accuracy of 3-D reconstruction was assessed using modelling objects with varying levels of 3-D complexity in controlled conditions such as in aquarium. A gradient of morphologic complexity, from simple to moderate to complex morphology, was analysed using models ranging from dressed objects approaching an ellipsoid to irregularly shaped objects (Fig. 2).

'Real' (V), modelled (mV) and geometric (gV) volume were calculated on three objects for each model (simple, moderate, complex). 'Real' volume was measured using the laboratory standard technique of water displacement, which represents the most accurate method for volume measurement. MOD3D was applied on the same set of images for each

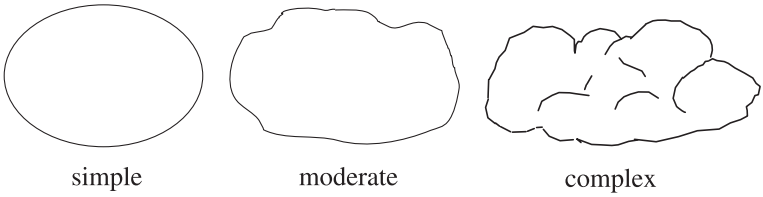

Fig. 2. Varying levels of 3-D complexity from dressed objects approaching an ellipsoid to irregularly shaped objects used to assess accuracy of 3-D reconstruction. Three objects for each model of simple, moderate and complex morphology were used to calculate real, modelled and geometric volume, and foil-wrapping and modelled surface area.

object to obtain the modelled volume. Geometric volume was estimated by measuring linear dimensions such as length, width and height, approaching the models to standard geometric solids (in this case, to an ellipsoid).

Accuracy of surface area computed with MOD3D (mS) was assessed by comparing measurements obtained with the laboratory standard foil-wrapping technique described by Marsh (1970): models were wrapped with aluminium foil, the excess clipped, and the surface area computed (S) using a surface area-to-weight calibration. For each object, computing surface area with MOD3D was based on the same set of images.

MOD3D volume (mV) was compared with V and gV and differences among methods were assessed through paired t-test. The same test was used to compare differences between surface area measurement methods.

3-D reconstruction technique was applied in the field to calculate volume and surface area of two benthic species displaying massive and submassive morphology. The first species was the bryozoan *P. fascialis*, which forms carbonate, mounds-like colonies approaching an ellipsoid in isolated and undisturbed colonies. Colonies may change shape over time when crowding prevents free concentric growth, resulting in directionality and irregular shape of larger colonies (Cocito et al., 1998). The site investigated was Dante Shoal (44°02′N; 9°51′E—Ligurian Sea, northwestern Mediterranean), where *P. fascialis* forms a stable population mainly on flat rocky substrate at about 15 m. Conversion factors and regression analysis computed by Cocito and Ferdeghini (2001) allowed the estimation of carbonate standing stock and biomass of *P. fascialis*.

The second experiment was conducted at Bonassola, 10 miles from the first site, at 27 m depth. Images were recorded on a bank of the coral *C. caespitosa*, developed on a rough rocky substrate. Estimation of carbonate standing stock was based on the conversion factor suggested by Peirano et al. (2001).

3. Results

There was a consistent asymptotic relationship between the volume computed by MOD3D and the number of views utilised for models reconstruction (Fig. 3a–c). For all three levels of complexity modelled, at least 8 and sometimes 10 images were required to produce an adequate 3-D reconstruction and thus volume computation. Repeated model-

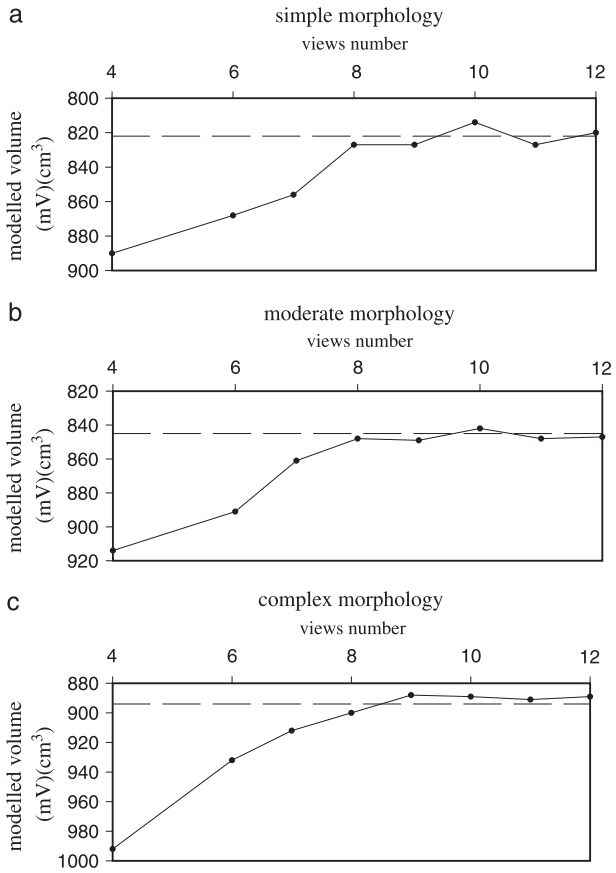

Fig. 3. Relationship between volume computed by MOD3D and the number of views utilised in the models for the three level of morphologic complexity (a = simple, b = moderate, c = complex).

ling suggested that better results were obtained when the 8–10 images were spatially distributed, thus with an inter-image angle of about 35–40°, and showing objects entirely.

For all three levels of 3-D complexity, no significant differences ($p>0.05$) were found comparing MOD3D volume (mV) with 'real' volume (V), computed with the standard water displacement method (Fig. 4a), with an overall mean percent error of about 1.7% (Table 1). When mV was compared to gV, i.e. approaching the models to standard geometric solids, significant differences were found ($p<0.05$). The geometric approximation (gV) was lower than MOD3D for simple and moderate morphology, and variable for complex morphology.

MOD3D volume measurements of the different models were computed by using the same set of 8 views (i.e. images), since additional views did not improve accuracy of measurements.

For all three models, computation of surface area with MOD3D gave values consistently lower than the foil-wrapping values, with a mean percent error of about 11% for

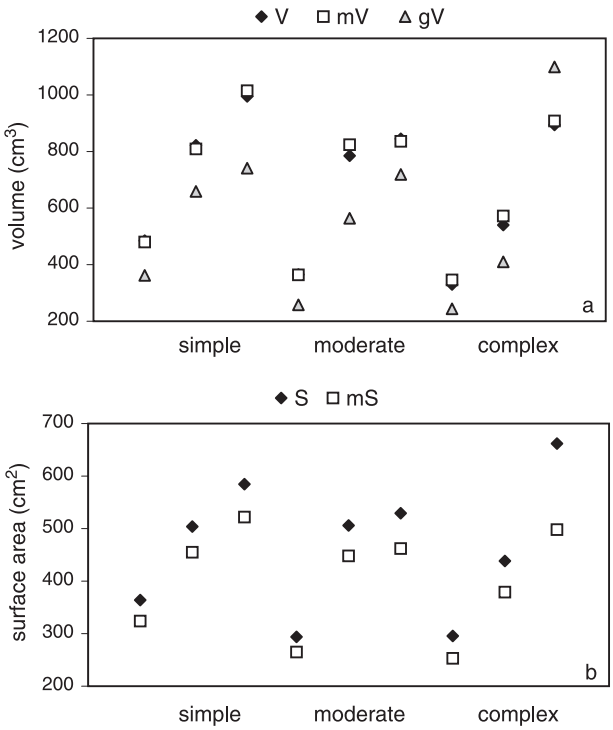

Fig. 4. Volume (cm^3) and surface area (cm^2) computed on three objects for each model of simple, moderate and complex morphology. No significant differences were found with paired *t*-test ($p>0.05$) comparing real volume (*V*), computed with the standard water displacement method, with MOD3D volume (mV), whereas *V* and mV were significantly different ($p<0.05$) when compared with gV, i.e. approaching the models to geometric solids (a). Surface area computed with foil-wrapping method was significantly different from MOD3D measurements ($p<0.05$) (b).

simple and moderate morphology, and 18% for complex morphology (Table 1). Paired *t*-test gave significant differences when comparing the two methods ($p<0.05$)(Fig. 4b). Overlap error when foil wrapping, as experienced particularly on complex morphology during laboratory work, can represent a methodological bias responsible for such differences between the two methods.

The whole procedure for 3-D reconstruction was applied in the field on the bryozoan *P. fascialis* and the coral *C. caespitosa* (Fig. 5). Fig. 5a shows one view of massive, elliptic

Table 1
Mean percent error (± S.D.) of MOD3D volume (mV), water displacement volume (*V*), geometric volume (gV), MOD3D surface area (mS), foil-wrapping surface area (*S*) for each model of simple, moderate and complex morphology (*n* = number of objects)

Morphology	*n*	mV/*V*	mV/gV	gV/*V*	mS/*S*
Simple	3	− 0.2 (± 1.9)	30.8 (± 7.3)	− 23.6 (± 3.2)	− 10.5 (± 0.7)
Moderate	3	1.2 (± 3.3)	34.5 (± 16.0)	− 24.1 (± 8.0)	− 11.3 (± 1.5)
Complex	3	4.1 (± 2.3)	21.3 (± 33.5)	− 9.1 (± 27.7)	− 17.6 (± 6.2)

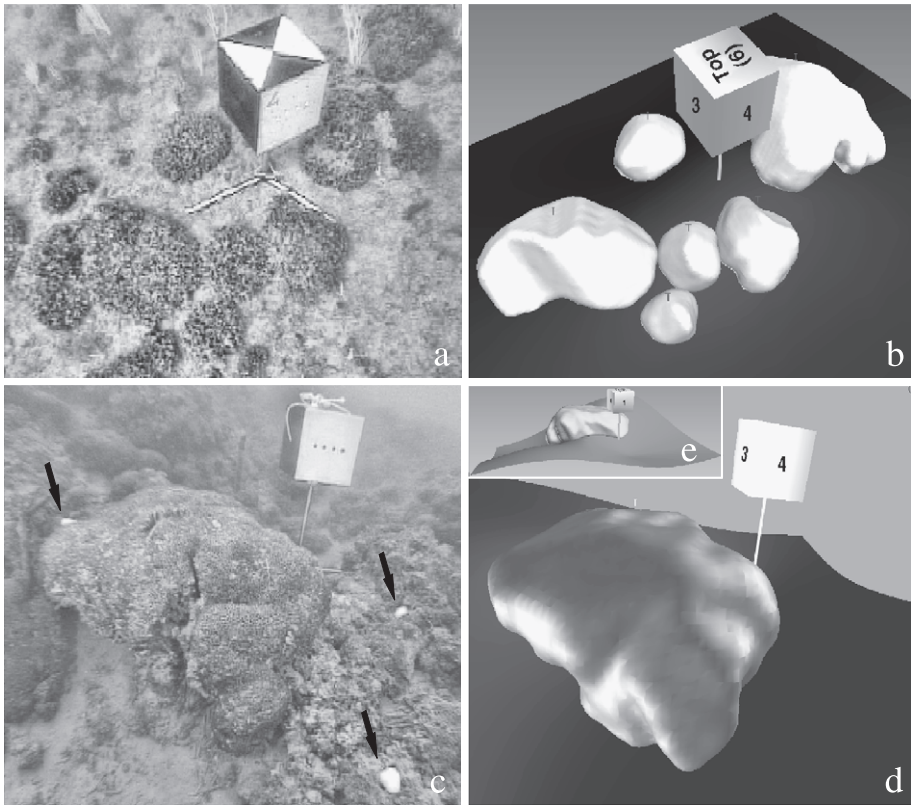

Fig. 5. Application of MOD3D to two temperate, sublittoral benthic species. Six massive, elliptic colonies of the bryozoan *P. fascialis*, growing on an almost flat substrate (a) and their MOD3D reconstruction (b). One submassive, large block of the coral *C. caespitosa*, laying on an irregularly rough substrate (c). Note the white pebbles on the bottom (black arrows) used for the substrate reconstruction, particularly perceptible from some viewpoints (e). MOD3D reconstruction of the *C. caespitosa* block (d). For image calibration, cube dimensions were 20 cm in the first application (a, b) and 25 cm in the second application (c, d).

colonies of *P. fascialis*, with occurrence of fusion among neighbouring colonies, growing on an almost flat substrate. For images calibration, a cube of 20 cm side was used. MOD3D allowed the complete reconstruction for the six colonies completely visible in all the eight images used and the computation of their volume and surface area (Fig. 5b).

A large, submassive colony of *C. caespitosa*, laying on an irregularly rough substrate, was chosen for the second field application (Fig. 5c). A cube of 25 cm side was used. Particularly in this case, substrate reconstruction function resulted to be essential for volume and surface area computation by MOD3D (Fig. 5d and e).

The time required to produce the whole 3-D reconstruction process for *P. fascialis* and *C. caespitosa* colonies, including the field work, was about 3 h in both cases (Table 2). In the case of the coral, twice the time was needed to identify landmarks on the substrate (the white pebbles indicated in Fig. 5c) recognisable in all the eight images used by MOD3D to

Table 2
Time recorded to produce the whole procedure of 3-D modelling, included the field work, of the colonies of the bryozoan *P. fascialis* and the coral *C. caespitosa* in the field applications illustrated in Fig. 5

Operation	*P. fascialis*	*C. caespitosa*
Cube positioning and images recording	10 min	10 min
Frames selection and storage	15 min	15 min
Images processing and calibration	30 min	30 min
Substrate reconstruction	30 min	60 min
Manual outlining of biological objects	90 min	45 min
3-D reconstruction	10 min	10 min
Total	3 h 5 min	2 h 50 min

reconstruct the irregular sea bottom, whereas for the flat substrate on which *P. fascialis* grew, 30 min were sufficient (Fig. 5a).

Manual outlining seemed to be largely influenced by the number of colonies to be modelled: about 90 min were recorded for outlining 6 colonies (i.e. 6 colonies per 8 images = 48 outlinings) even if their shape and borders were easily identifiable. The same phase required about 45 min (i.e. 1 colony per 8 images = 8 outlinings) for the complex, irregularly rimmed formation of *C. caespitosa* (Table 2).

Depending on image quality, the time employed for substrate reconstruction along with manual outlining of biological objects was up to a maximum of 2 h 30 min, particularly when identification or lack of reference points on the substrate and border identification were hindered by water turbidity.

The application of the procedure allowed the morphometric measurements and the estimation of carbonate standing stock and biomass of *P. fascialis* at Dante Shoal (Ligurian Sea) in four sites of which one is illustrated in Fig. 4a. *P. fascialis* population was formed by colonies with diameter ranging from 15 to 45.8 cm (mean 35.9 cm, S.D. = 13.8) and 3-D modelled volume varied from 1036 to 26,667 cm^3. Carbonate standing stock resulted 887.6 ± 186 g m^{-2} and colony biomass was 29.74 ± 5.03 g m^{-2}.

MOD3D applied to the colony of *C. caespitosa* at Bonassola (Fig. 5d) computed 195,153 cm^3 volume, 21,145 cm^2 surface area and carbonate standing stock was 122.95 kg $CaCO_3$.

4. Discussion

The 3-D reconstruction method developed allows us to accurately measure in the field volume, surface area and other morphometric measurements of three-dimensional biological objects. It represents a novel technical approach based on multiple views (eight resulted to be sufficient) from underwater video images and a new image processing procedure, whose application has met the basic requirements imposed when operating in the marine environment with simple, easy-to-use and nonprofessional, commercial underwater equipment.

Its applicability has been specifically set up for massive and submassive and irregularly shaped colonies, which are common growth form among benthic, carbonate bioconstruct-

ing species. Modelling of complex morphologies, such as branching corals, still remains problematic and largely inaccurate when visual methods, based on photographic images, are used (Bythell et al., 2001).

The method is noninvasive, not requiring tags or labels to be fixed on the object to be modelled, thus avoiding possible damage, no framer or other devices are to be fixed to the video, but only one reference object of known dimension to be laid on the substrate and required for all images in order to calibrate the position of the camera.

Using models with different morphologic complexity, high accuracy of volume measurements was achieved when compared with the laboratory water displacement method, which represents the most accurate method for volume measurement. In fact, for all three levels of complexity, no significant differences ($p>0.05$) were found. Volume measurements obtained in the field through the geometric approximation resulted rough, with significant differences from the MOD3D values ($p<0.05$). Geometric volume values were less than MOD3D values for simple and moderate forms, and variable for complex form.

When computing surface area, significant differences were found comparing MOD3D and the standard foil-wrapping method ($p<0.05$). The laboratory foil-wrapping method consistently produced a 13% larger surface area than MOD3D. The difference is consistent with results found by other authors (Hoegh-Guldberg, 1988; Bythell et al., 2001), who suggested that some of the error can be due to overlap error when foil wrapping. During laboratory work, painting of aluminium foil was tried in order to use a laser scanner to measure the surface area, thus avoiding error when wrapping, but the experiment failed both because of fragility of the foil and difficulty in outlining the highly indented rims of the scanned area.

Time has not to be considered a limitation of the whole procedure. Several applications of 3-D modelling on different sites, displaying different colonies morphologies and environmental conditions (visibility, roughness of substrate, etc), confirmed that average time recorded for the whole procedure, including the field work, was about 3 h. Time requirements make it suitable for routine applications particularly for relatively large area investigations, with several biological objects within the area. Due to scarcity of similar applications found in the literature comparisons are not possible. Bythell et al. (2001) reported 3–4 h as time requirement for a single photogrammetry technique application to one small coral colony for measuring surface area.

Moreover, a valuable advantage is represented by the short time involved for field work, thus making the method particularly suitable for sampling at depths where time limits become crucial for divers. Future field experiments at prohibitive depths should consider the use of remotely operated vehicle (ROV) in order to substitute diver intervention in cube positioning and image recording.

Concerning image processing, large advantages in outlining accuracy will be achieved when higher resolution images (about 1280×1024 pixels) are available from underwater digital video and camera.

Using for camera calibration a reference object (i.e. a cube) of size comparable to those of biological objects to be modelled, a vast range of size, and thus age, can be adequately monitored. For example, the coral *C. caespitosa* often displayed in the studied area large blocks up to 1 m of diameter, resulting from accretion of several colonies (Peirano et al.,

1998). As camera calibration was specifically designed for differently sized cubes, the method has the advantage to be, theoretically, non-size-limited. The only limitation could be due, in case of a large area to be recorded, to water turbidity thus preventing good quality image recording.

When roughness of substrate or density of colonies was particularly high, the hard, carbonate structure of *C. caespitosa* allowed the cube to be positioned directly on the top of colony, without using the tripod as support.

Many potential applications in the field are possible with the 3-D reconstruction method proposed: these, related to surface area, include ecophysiological studies by measuring tissue biomass, long-term monitoring of partial mortality due to predation, bleaching and other disease episodes, symbiont density, filtering surface and other ecologically important processes. The procedure is also applicable to morphometric measurements such as height, branch length and spacing, cavity width, distance among satellite colonies, and to volume measurements, useful to estimate biomass, growth rate, carbonate standing stock and carbonate production.

Studies of growth and carbonate production rate in temperate waters are rare. We applied the procedure to two of the major carbonate bioconstructors among the sublittoral benthic species, the bryozoan *P. fascialis* and the coral *C. caespitosa*, thus giving a contribution to the quantification of global carbonate budget of the Mediterranean Sea (Cebrian et al., 2000).

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