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NOTE

The CaveCam—an endoscopic underwater videosystem for the exploration of cryptic habitats

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ABSTRACT: We designed a self-contained, diver-operated endoscopic underwater video system, the CaveCam. It consists of a high resolution finger camera connected by a 3.8 m cable to a viewing and recording unit. Different housings accomodate lenses, from superwide-angle to telephoto. The smallest camera head measures only 25 mm in diameter and 109 mm in length and allows access to narrow crevices. Accessories are available for perpendicular viewing, underwater focussing, near- and far-field scaling and lighting. We successfully employed the CaveCam for mapping cryptofauna communities, measuring small-scale currents and observing animal behaviour.

KEY WORDS: Cryptofauna · Underwater video · Caves · Crevices · Coral reef · Coelobites · Image analysis · Endoscope

Reef caves and crevices have been recognized as potentially important habitats by many authors (Garrett 1969, Bonem 1977, Ginsburg 1983). Especially smaller cavities, ranging between 0.01 and 1.0 m in diameter, are ubiquitious features of coral reefs. They are often interconnected and can extend several meters into the reef body (Zankl & Schroeder 1972). Estimates of cumulative cavity volume range between 30 and 90% of total reef volume (Garrett et al. 1971, Ginsburg 1983), providing an internal surface area which far exceeds that of the outer reef surface (Jackson et al. 1971). Cavities thus provide the substrate for a wide range of sessile filter-feeders and algae, whose biomass is believed to approach or even exceed that on the surface of reefs (Hutchings 1983, Logan et al. 1984). In addition, cavities represent important retreats and offer living space for fishes and other vagile organisms like crustaceans and crinoids. Cryptic suspension feeders have been shown to efficiently filter picoplankton from the water percolating through the reef cavities, accounting in large part for the depletions of bacteria and phytoplankton over coral reefs (Gast et al. 1998, Richter & Wunsch unpubl.). Due to their filtering capacity they are considered potential indicators of reef health (R. P. M. Bak pers. comm.).

While large submersed marine caves and tunnel systems are well studied (Riedl 1966, Vasseur 1974, Logan 1981, Logan et al. 1984), the smaller coral reef cavities which are too small for divers to enter have been almost entirely neglected, mainly due to the lack of appropriate tools for their exploration. In fact, the available cryptofauna studies concentrated on easily accessible environments such as the underside of coral rubble (Meesters et al. 1991, Gischler & Ginsburg 1996, Gischler 1997), the underside of foliaceous corals and fragments of corals and reef rock (Brock & Brock 1977, Hutchings & Weate 1977, Jackson & Winston 1982). Destructive methods are out of the question for large-scale or routine inspection of reef framework cavities, especially in view of the progressive degradation of reefs worldwide and enforcement of conservation laws in many countries. Non-destructive survey methods, however, have to cope with the physical dimensions of the framework crevices and the particuliarities of the cryptobionts they harbour.

The long and narrow crevices called for the design of an endoscopic underwater camera: the CaveCam. In contrast to commerically available systems used e.g. for under-ice studies, our system needed to be independent from the surface, self-contained and watertight, portable, and operable under water by a single SCUBA diver. In contrast to glass-fibre optics used in conventional endoscopic systems, we relied on miniature video optics for best possible resolution. Customized off-the-shelf components kept our system at an affordable cost.

System description. The CaveCam consists of 3 main parts (Fig. 1): (1) a small camera head which is intro-

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Fig. 1 The CaveCam, featuring the 25 mm diameter camera head, a 3.8 m cable and the recording/control unit in a transparent housing (center left); camera housing for the superwide-angle lens and the bracket with an attached mirror (lower left); and camera light and power cable (right; battery tank not shown)

duced into the cavities, (2) a recording and control unit, and (3) a light system.

(1) The heart of the system is a Panasonic GP-KS162 CCD finger camera featuring digital signal processing for excellent colour reproduction. Its ½" colour chip produces a high resolution of 752 × 582 pixels and 480 horizontal lines. The camera head (measuring 17 mm in diameter and 56 mm in length) can be equipped with a range of lenses. We chose a 3.5 mm superwide-angle lens for overviews inside the caves and a 7.5 mm wide-angle lens as the standard survey lens, which is also useful for close-up studies. A 15 mm telephoto lens allows higher magnification at a greater working distance. Other suitable lenses include photographic microscope lenses such as the Leica Photare or Canon 3.5/35 mm, which we employ for close-ups.

Camera housings were engineered from polyamide to accommodate the different lenses: one for the 7.5 mm and the 15 mm lenses with 25 mm diameter, a second for the superwide-angle lens with 35 mm diameter. In order to avoid optical refraction under water, spherical glass lenses were employed for the wide-angle lenses and sealed with silicon sealant to the front of the housings.

Focussing was based on the magnetic induction principle: we inserted 2 sections of a ring magnet into a PVC ring of 20 mm wall thickness, fitting snugly on the respective housing. Two thin iron plates were attached to either side of the lens focus ring. The 2 plates respond to rotation of the magnetic field when the outer PVC ring is turned, inducing a corresponding change of focus in the lens.

A critical part of the CaveCam is the connection between the camera head and the control/recording unit. We coated the delicate 3.8 m connecting cable (Ø 5 mm) with a 2 mm layer of silicon sealant to protect it against seawater and physical damage. Pieces of PVC tubing protect each end of the cable. The PVC tubing is filled with 2-component cable resin and has silicon on the rim. Waterproof cable-glands seal the cable ends to the housings.

(2) The cable connects the camera head to its control unit (Panasonic GP-KS162 CU, 120 × 36 × 157 mm) and a Hi-8 camcorder (Sony TRV 91 E). The camcorder records the signal from the control unit and displays it on a built-in 4" LCD monitor—a feature which is essential for manoeuvering the camera head. The finger camera system is powered by 10 rechargeable AA-size NiMH or, alternatively, by 8 alkaline batteries.

The camera control unit plus power supply and Hi-8 camcorder are contained in a transparent polycarbonate housing (20 × 14 × 16 cm, manufactured by Ikelite, Indianapolis, IN, USA). Its original lid was replaced by a customized and anodized aluminium plate equipped with a handle and all essential controls: on/off for the camcorder/monitor; record/stop; on/off for the control unit; and manual white balance control. The latter assures control over constant colour reproduction—an important feature for any subsequent colour-based image analyses. A rubber tube shades the LCD monitor and protects the housing against damage.

(3) Underwater videography in dark places requires proper lighting for reproducible colour temperature. This is especially important when image analysis software is used. Commercially available lighting systems were either too large or not bright enough to meet this demand. We designed lamps from the end section of a test tube, 18 mm in diameter and 50 mm in length, ground from the inside and the outside for more even

lighting and containing a 12 V/20 W halogen bulb in a socket with a small aluminium reflector. The set-up was held in place with 2-component glue and sealed with silicon sealant. The lamp is powered by a commercially available, switchable NiCd tank. A 4.5 m cable connects the lamp to the battery.

Accessories. Accessories which may be used with the CaveCam to expand its functionality include the following:

- A polyamide bracket (H 37 × W 30 × L 110 mm) (Fig. 2) allows the camera to be mounted on a rod or tripod. We use tripods of different sizes for fixed-point time-series observations, and fixed-length flexible rods (e.g. plastic coated copper wire) as well as telescopic rigid aluminium tubing for spatial surveys. Depending on the application, the camera head either can be pre-positioned and then inserted into a crevice or can be mounted loosely onto a rod and steered by pulling 2 strings on either side of the camera housing. However, there is a limit to handling in winding crevices, since the head has to be controlled manually from the entrance.
- A mirror (45 × 60 mm) can be attached at a 45° angle to the bracket (Fig. 2). It is supported by a solid triangular piece of polyamide and produces a view perpendicular to the direction of the camera itself, thus allowing the inspection of very narrow cave walls.
- We built several framers from aluminium and carbon-fibre tubes (∅ 4 mm) to fit either the bracket or the mirror. These keep the camera at a defined distance from the substratum, giving a constant image area.
- We fabricated a twin laser-pointer which can be mounted on the bracket or used independently. It allows the projection of a 50 mm reference distance into the recorded picture for later image analysis. Two small parallel laser-pointers (∅ 13 × L 60 mm) are inserted into a PVC frame. They are powered by 2 AAA-size alkaline batteries and controlled by a magnetic switch.

Fig. 2. Close-up of bracket with the mirror attached at a 45° angle for perpendicular viewing, and aluminium spacers

Applications. ***Mapping cryptic communities:*** We used the CaveCam for inspecting coral reef crevices of 0.1 to 1.0 m opening diameter and 0.25 to 4.0 m length providing, to the best of our knowledge, the first video images of narrow coral reef framework cavities. Fig. 3 reveals the high cryptobiont cover and complex morphology of a typical Red Sea coral reef cavity, as seen with the superwide-angle lens. Fig. 4 gives an example of the wide-angle close-ups we recorded for the quantitative assessment of the cryptic community, To this effect, the CaveCam was mounted on a flexible 50 cm rod made of a special aluminium alloy. This was then attached to a standard aluminium profile of the required length. For narrow caves the mirror set-up was employed to obtain plane shots of the walls (e.g. Fig. 4). The frame size was adjusted to 6 × 4.5 cm and, at the beginning of each work session, a cm scale was recorded for reference.

Sampling with the CaveCam is quick: our routine for an average 1.50 m transect takes about 20 to 25 min. Every 25 cm, we record a set of 24 frames in a 4 × 6 frame configuration, yielding a total 168 frames (approximately 4500 cm^2) for the entire cavity, covering roof, bottom, left and right side. Thus, we usually cover 3 to 4 crevices per dive.

Image analysis routinely takes 1 to 5 min per frame when assessing the areal cover of the dominant taxa. We use a Macintosh platform with a high quality frame grabber card and the public domain software NIH-Image developed at the U.S. National Institutes of Health, available on the Internet (http://rsb.info.nih.gov/nih-image/). This obviously requires good familiarity with the cryptic fauna and flora, which for the layman are sometimes difficult to distinguish even at the phylum level. Groundtruthing of the video data is a must where this is possible, both physically and legally. Small samples of selected cryptic organisms are sufficient for microscopic analysis by taxonomic experts.

Flow measurements: Water exchange rates in cavities are of particular interest for cryptofauna ecology but difficult to assess directly. We used the CaveCam to trace suspended particles in the moving water in order to determine small-scale flow patterns and current speeds in narrow crevices (Richter & Wunsch unpubl.). We oriented the CaveCam perpendicularly

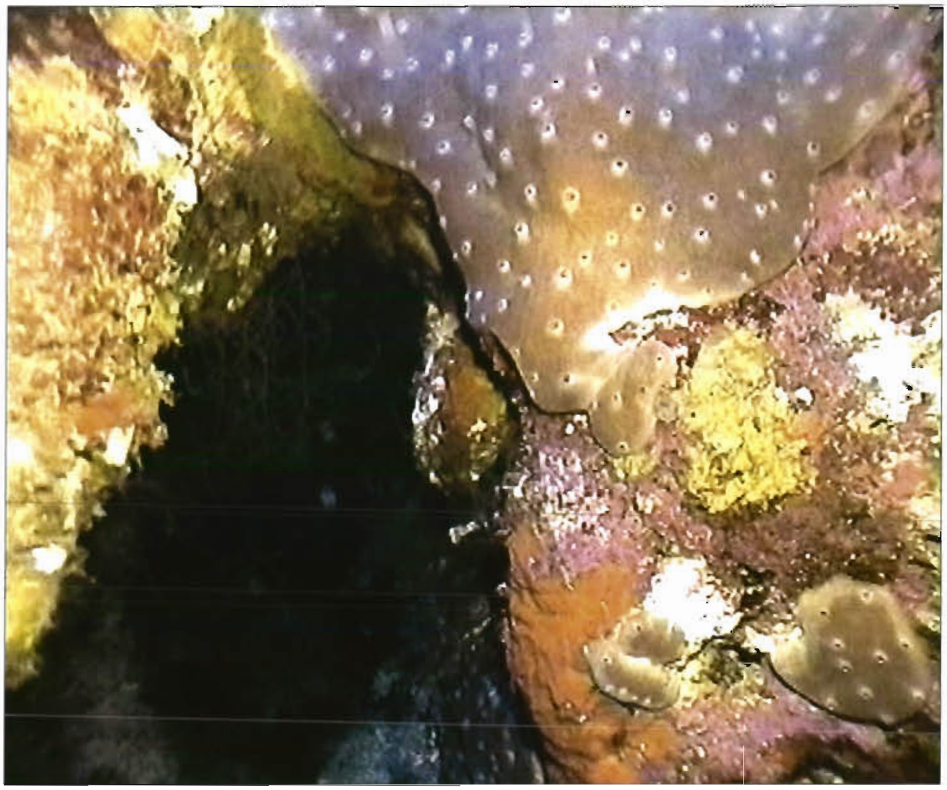

Fig. 3. CaveCam 3.5 mm superwide-angle overview of a 2 m long, 0.4 to 0.7 m wide cavity at 12 m depth at Ras Mohammed, Egypt. Note the dominance of coralline algae and encrusting sponges

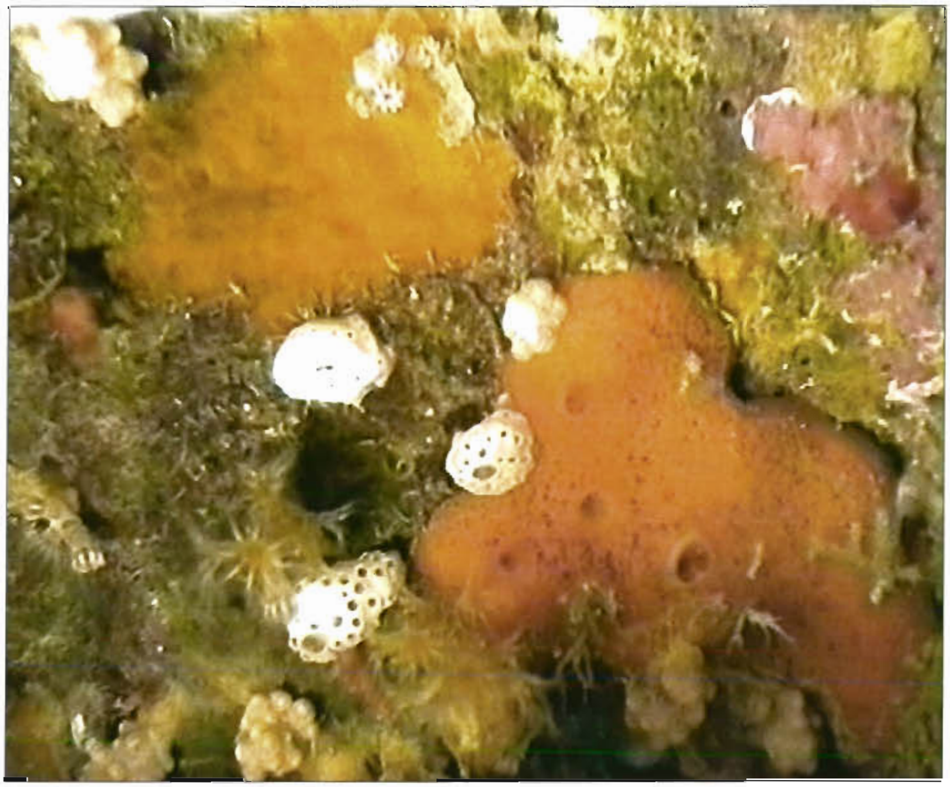

Fig. 4. Wide-angle (7.5 mm) close-up of the cryptic community in the same cavity as shown in Fig. 3 (6.0 × 4.5 cm), filmed with the 45° mirror set-up 1.10 m from the cavity entrance. Suspension-feeding sponges, ascidians and octocorals are prominent components of the cryptofauna

to the prevailing water stream, or used the 45° mirror looking sideways at the current plane. We recorded with the lens focus adjusted to a typical frame size of 4 × 3 cm and with the aperture opened completely, giving us a minimal depth of field of about half a millimeter. The sequences, recorded at a rate of 24 frames s^{-1}, were played back frame by frame on a video monitor. We counted the number of frames it took a particle to cross the known distance from one side of the monitor to the other, or measured the net displacement after a certain number of frames. Only particles in focus were monitored. The CaveCam surpasses conventional techniques (e.g. thermistors) by also providing information on the flow pattern, e.g. it was possible to visualize oscillations due to wave action, small-scale turbulence, etc.

Behavioural studies of cryptic and non-cryptic organisms: Due to its small size and the set of different lenses available, the CaveCam is very helpful for close-up studies of individual organisms and for monitoring cavity sections for extended periods of time, with minimal disturbance. For example, we observed the feeding activity of small sponges and single coral and hydroid polyps. A time-lapse circuit built by W. Metzler, Dept of Geology, Bremen University, enabled us to record sequences over several hours.

Conclusions. Video cameras have been employed in a number of studies to collect data for reef mapping and monitoring (Carleton & Done 1995, Vogt 1995). The process of sampling is relatively quick and the amount of data that can be stored on a 90 min video tape is immense. Video documentation saves expensive working time underwater and the analysis can be done any place at any time. For the mapping of framework cavities there is no alternative to the CaveCam. Photocameras, such as the Nikonos V or Motomarine with close-up attachments, are too large for many of the crevices studied and data storage is limited to 36 frames per dive and camera.

Other set-ups have been used for monitoring the flow around particle-feeding crinoids (Leonard et al. 1988) and prey-capturing scleractinian corals (Sebens & Johnson 1991), but again the systems employed are far too bulky for reef crevices.

The use of a high resolution finger camera instead of an endoscopic optical fibre and of spherical lenses for the housing provided the best image quality we could obtain at an affordable cost. The advent of digital video technology holds promise for considerable improvement of the CaveCam in the near future. Yet, while this technology has revolutionized the video market in both the hobby and professional sectors, miniature cameras and recorders in a portable 12 V version appear to be lagging behind. Digital versions were not available at the time this manuscript was written.

The CaveCam is a powerful, cost-efficient, non-destructive tool for *in situ* observation and documentation of the small-scale structure and dynamics of cryptic communities. Other potential applications include the study of any other spatially confined habitat, e.g. sediment burrows, the understorey of kelp or mangrove canopies, seagrass meadows, creeks and ponds, the sculptured underside of ice, etc.

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