PERSPECTIVES OF UNDERWATER OPTICS IN BIOLOGICAL OCEANOGRAPHY AND PLANKTON ECOLOGY STUDIES

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ABSTRACT

The ever expanding fields of UW (underwater) optics cover principal measurements of the optical properties of the sea, development of new methods of monitoring optical properties, techniques for measurements of organisms or structures in the sea and the development and application of optical instrumentation. In this respect, ocean optics is a multidisciplinary (and multinational) endeavour of science and engineering. Ocean optics has applications in the study of upwelling irradiance and chlorophyll concentrations in the ocean, in the penetration of solar radiation in shallow shelf seas and how this influences temperature profiles and ultimately its effect on sound propagation. Recent development in optical holography allow underwater visual inspection and precision measurements, estimation of the biological diversity of ocean plankton and benthos. One requirement is the development of high-resolution tools for the imaging of specimens in the field. We review here current developments of ocean optics as an integrative tool of biological oceanography that holds for surveys in the field as for laboratory studies.

I. INTRODUCTION

Although the world's oceans play a dominant role in the planet's ecosystem, they are possibly the least understood natural habitats. The challenges facing scientists and engineers in the study of the oceanic environment, particularly video optical technology on animal behavior, are immense and

unique [50, 51, 53, 54, 55, 58, 100, 109]. Not only is there a need for the development of new techniques and for advances in classical techniques, but the associated instruments must withstand the forces of the sea. Underwater technology addresses such important technological areas as underwater acoustics, positioning, construction, observation, signal and information processing, undersea robotics, and manned and unmanned (remote sensing) vehicle technology for commercial, scientific and military purposes [22, 102]. Processes monitored by cable or satellite linked underwater observatories can provide real-time data on the processes at work offshore [4, 5]. One of the most prospective methodological fields of biological oceanography is ocean optics – the applications of optical technologies and UW optics for marine research [121, 103]. UW optics is of considerable interest to marine biologists whose primary aim is to understand the marine environment, its properties and the complex interactions of organisms within it (Table 1) [11, 19, 75, 76].

Light in the sea plays a crucial role in energy and carbon dioxide exchange and, therefore, for the global climate [42]. The propagation of light through water is a fundamental characteristic of the oceans themselves [29]. Light is also crucial to the understanding of the marine habitat, and the preservation and utilization of its resources [30]. We need to know what affects transmission and absorption in the water [74]. Hence, optical instrumentation in the field of biological oceanography is increasing, and is replacing more traditional, slower and destructive techniques, such as physically obtaining samples by nets or grabs [24, 25]. Optical techniques provide rapid, precise, non-destructive, *in-situ* sensing and high quality measurements. Turbidity and light propagation measurements are essential in the study of biological productivity and underwater imaging [93]. UW optics covers the measurement of the chemical constituents of natural seawater, the work involved in satellite image analysis, and of the use of optics in the measurement of the flocculation of suspended sediments [106]. Marine radiometric spectrometers allow for simultaneous measurements of upwelling and downwelling irradiance [131]. Underwater CCD cameras enable the flow mapp-ing in particle image velocimetry systems (PIV) to such novel techniques as holography for the measurement of plankton.

UW optical applications range from holography and confocal technologies for the 3D *in-situ* visualization of plankton, and from the measurement of fundamental physical characteristics such as absorption, irradiance and sea-surface reflectance to measurements of the chemical constituents of natural seawater [28], to the measurement of the flocculation of suspended sediments [98]. It has its application in the study of plankton size and plankton concentration in aquatic systems [8, 36, 48]. We review here the current state of our imaging capability with particular focus on photo and video applications in the laboratory and in the field through visual underwater benthic and pelagic surveys.

1. Benthic Surveys

For the management of marine stocks, it is necessary to undertake appropriate resource management strategies based on accurate estimations of population size and structure, and community diversity [117]. Distribution patterns of benthic species can be estimated by *in-situ* observations using towed camera arrays [9], submersibles [7], or diver operated systems [54]. For example Fujikura *et al.* [35] remotely recorded in real time by deep tow TV camera arrays the population density of the crab *Chionoecetes japonicus* from the crewed submersible Shinkai 2000. In order to maintain a constant distance from the sea bottom, a 2 m long chain with a 20 cm sinker was hung below the TV camera.

Field transects are the most widely used survey methods. Point intercept transects (PIT) measure the points of interest at specific intervals either below or adjacent to a belt transect line [123] which may use video recording for documentation and later analysis [17]. PITs provide a relatively high precision in estimating percentage cover of sessile organisms such as corals, since experienced divers can collect data through video taping, whereas experts analyse the video records back in the laboratory. Video transect methods also provide permanent records and greatly reduce field expense and time as compared to visual counting methods. Quality control of consistent substratum or species identification from images is facilitated because images can be archived and viewed again to ensure accurate identifications [88]. Video records of surveys are useful for follow-up studies, such as early detection of diseases in corals and the investigation of species interactions and successions with time (Fig. 1). The statistical power of the transects can be increased in the laboratory by increasing the number of points or frames analyzed that raise the resolution of the PIT method [47]. In addition are images useful for developing outreach products for public information.

2. Surveys in Pelagic Systems

Planktonic animals inhabit an environment of constant water motion [51, 55, 100]. Tracking their motions showed that the animals effectively maintained their depth by swimming against upwellig and downwelling currents, and moving at rates of up to tens of body lengths per second, which also leads to their accumulation at frontal zones. This mechanism
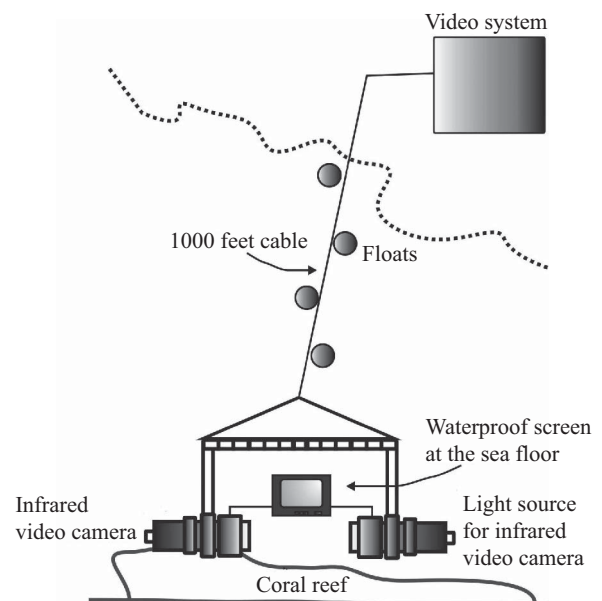

Fig. 1. Photography and video recording at the sea floor, such as coral reef. The analysing system is situated on shore or on a research vessel (modified after Hwang & Strickler [56]).

explains how oceanic fronts become major feeding grounds for predators and targets for fishermen alike.

Oceanographers have traditionally employed nets or pumps to collect plankton. Although nets are useful for quantifying zooplankton distributions and abundances at large horizontal or vertical scales, they are generally inadequate to reveal the structure of patches and layers at finer scales [6, 20, 38, 59]. Pumps have proven useful for exposing vertical structure at smaller scales than nets [24]. Their utility, however, is mainly limited to smaller size fractions of the plankton or less motile organisms since larger zooplankton is able to avoid being collected. Different types of cameras are used to image organisms along the tow path of an instrument [25]. Quantitative instruments in this category are camera-net systems and include towed systems such as the ichthyoplankton recorder, video plankton recorder (VPR) [2, 25]**,** *in situ* video recorder [107], and the shadowed image particle platform and evaluation recorder [98] (Table 1). Additionally, there are profiling systems, such as the underwater video profilers (UVP) [41] and holographic instruments [69]. Optical imaging systems provide a means for estimating the spatial distribution and abundances of mesozooplankton at vertical scales of centimeters or greater. The majority of optical systems utilize video and typically image small volumes of water to achieve acceptable image resolutions. Zooplankton includes a wide range of taxa with very different morphologies that frequently change drastically through ontogeny [31, 104, 122]. Zooplankton also includes transparent and soft-bodied organisms, which confound many automatic recognition systems [33]. This happens because the software relies on shape profile

Table 1. Under water optics technologies that are of particular relevance for biological oceanography including submarines, divers, UW imaging by remote sensing (UW-ROVs, satellites).

- Benthos and plankton
- Biological properties with high-speed applications (swimming, feeding, mating, grooming)
- Productivity (Chla)
- PIVs (particle image, velocimetry systems)
- Pollution
- Survey and analysis of experiments (field/lab)
- Biological sensors that demand light

Table 2. Existing UW optical technologies (L = laboratory, F = field applications).

System	L/F	Technology	Size-spectra	Authors
L-OPC	F	Laser	100-3000 μm	Herman *et al.*, [45]
HOLOMAR	F	Holography	5-250 μm	Katz *et al.*, [62]
VPR	F	Camera	Zooplankton	Davis *et al.*, [26]
ZOOVIS	F	Camera	Euphausiids	Benfield *et al.*, [9]
LAPIS	F	Camera	Gelatinous zoopl.	Widder *et al.*, [120]
UVP	F	Camera	Gelatinous zoopl.	Gorsky *et al.*, [40]
IPR	F	Camera	Ichthyoplankton	Fischer *et al.*, [34]
SIPPER	F/L	Linescan-Camera	Zooplankton	Samson *et al.*, [89]
ZPP	F/L	Camera	Zooplankton	Zhou and Tande, [130]
HAB-Bouy	F/L	Camera	20-2000 μm	GLOBEC, [39]
OPC	F/L	LED-Array	250-2500 μm	Herman *et al.*, [45]
Flow Cam	L	Camera	10-1000 μm	Sieracki *et al.*, [95]
ZOOSCAN	L	Scanner	Macrozoopl.	Gorsky *et al.*, [41]
LaserCam	F	Laser	Plankton	Strickler and Hwang, [100]

characteristics, which may be insufficient for recognition or may not be constant for the species under consideration.

The ecology of planktonic assemblages essentially depends on the behavior of individual zooplankters that can be monitored by ocean optics [124, 128]. The capabilities of a variety of mesozooplankton taxa to form dense, localized patches has been observed for a number of taxa [84, 96, 108, 110, 125]. The importance of enhanced zooplankton biomass at all scales emerged as an important issue in zooplankton ecology [73, 90]. At large scale and some small-scale environments like frontal zones, aggregation into patches is probably a physical process [91]. Active swarming behavior may add at the same time to hydrologically formed passive aggregations. The spatial distribution of plankton is also essential for encounters between predators and prey [111, 115, 116] as well as between grazers and patchily distributed food sources [1, 26, 38, 60, 82, 101], or between conspecifics in search of mates [3, 61, 63].

Constraints for the functional investigation of zooplankton (e.g. its transparency and small size) have been overcome by treating the organisms as phase objects and applying an optical system that functions as an optical signal processor using matched spatial filters [100, 114]. This is derived from the classical Schlieren system and has, instead of a slit as the first spatial filter and a knife-edge as the matching one, a point source (pinhole) as the first filter and a stop as the matching one. Strickler [99] used either a helium-neon laser (632 nm wavelength) or a near-infrared laser diode (890 nm wavelength) as a light-source with energies of less than a milliwatt.

The most long-range instrument currently available for resolution at both time and space scales is the Continuous Plankton Recorder (CPR Survey Team 2004) in the North Atlantic Ocean. However, it only collects enough data of the most abundant 20 species/groups of phytoplankton and zooplankton that are sufficient for statistical analysis. This survey has essentially remained unchanged since the 1930's, retaining the same techniques of sample acquisition and analysis techniques. Regional zooplankton surveys, carried out conventionally by using nets and manual microscopical analysis, can usually be more detailed and often identify more than 300 taxa [86]. An example of this is seen in the CalCOFI study from the Pacific Ocean being conducted for the last 50 years [77].

Practical applications of knowledge of plankton diversity and distribution in the oceans include food web modelling, detection of harmful algal blooms in coastal waters, and ecosystem responses to climate change [83]. Automatic identification of phytoplankton and mesozooplankton species has made advancements. Available techniques are adequate for the identification of higher taxa (e.g. chaetognaths, euphausiids, copepods, and hyperiid amphipods), for biomass estimations and for ecological research on major components of oceanic plankton. For biodiversity aspects, abundance estimates of dominant taxa and the coverage of large areas, information about morphological variation are needed that require high-resolution images that provide specific taxonomic detail [32, 81, 129].

Two-dimensional imaging is not sufficient for reliable taxonomic identification of several taxa. Plankton covers an extremely wide range of individuals including their ontogenetic stages (with different size and structure in the case of larvae) which are represented by many complex 3D and semitransparent objects. Therefore, the normal approach to imaging using multiple 2D views of the organism is not sufficient for *in situ* imaging and recognition. A starting point for the transition to automated 3D systems will be the improvement of 2D imaging techniques in recent years [23].

1) 2D Imaging

About eight different contemporary *in situ* 2D imaging systems have been developed. They all provide sufficient resolution for class/order categorisation and for the estimation of organism size, which may be used to estimate biomass (see [121] for a review of optical systems). These include (Table 2): stand-alone imaging systems such as the Video Plankton Recorder (VPR, [26]), mixed optical-net systems such as the camera-net system [78, 79] and the ichthyoplankton recorder

[67, 119]; and Zooscan [41], *in situ* video profiler [107], Shadowed Image Particle Profiling Evaluation Recorder (SIPPER, [89]), zooplankton visualization and imaging system (ZOOVIS, [9]), and the Flow-Cam [95]. The use of higher resolution, digital formats has permitted an increase in image volume although most systems still record the contents of volumes of several ml to a few liters per image.

Flowcam image volume is less than a μl and suitable for microbiota, such as bacterio- and phytoplankton. In contrast to *in situ* zooplankton systems, a flowcam uses triggered imaging. The quality of images produced by triggered systems is generally adequate for categorisation to the taxonomic level of class or order (e.g. Copepoda, Chaetognatha, Decapoda, Pteropoda) or acoustical sound-scattering model categories (e.g. gas-filled inclusions). When organisms possess distinctive morphological features, categorization to genus or species is possible. However, adequate depth of focus is critical for correct categorization. While 3D imaging is certainly the ideal method, current technology does not allow easily to switch from 2D to 3D imaging.

2) 3D Imaging

Biological studies rely largely on light and electron microscopes, which have always been fundamental tools for analyzing the structure, physiology and function of cells and microscopic organisms. These techniques, however, provide low resolution, which prevent the observation of details and complicated fixation methods or sectioning artifacts, which damage the specimens. Such restrictions were overcome by the confocal microscope, which offers several advantages, including increased resolution, higher contrast, and more suitable depth of field.

3D imaging have been applied to track jellyfish in the deep sea with stereo cameras [87] and holography has been used to estimate volumes of seawater for zooplankton behavioral studies *in situ* [46, 62]. Hwang *et al.* [58] used 3D laser video optical system to compare tethered copepods with free swimming copepods. This system was built with one laser beam and two optical systems. The system was operated by computer manually. Stereo cameras provide sufficiently useful images for a wide range of faunistic and ecological applications. Malkiel *et al.* [69] have used holography for *in situ* behavioral studies of plankton, demonstrating resolutions down to 10 μm. Laboratory experiments by Malkiel *et al.* [70], using digital in-line holography, reveal copepod feeding flow-fields in 3D in the laboratory. In the field all these instruments can be based on ROV's (Remote operated vehicles).

Tomography techniques provide a promising tool for 3D volumetric imaging but are not yet deployed in marine field studies as yet. This technology is now available in several systems: Positron Emission Tomography (PET) [112], and X-ray, and Computerised Axial Tomography (CAT) [65], and Magnetic Resonance Imaging (MRI). Acoustic scanning has been applied in the FishTV system [72], revealing good quality images at millimeter scale. In addition to tomographic techniques, several *in situ* holographic systems have been developed for 3D imaging of plankton [46, 62].

Confocal imaging seems to be a most promising imaging technology. It draws a small spot of laser light across a small volume of space in 3D using the optics of a high quality conventional microscope. Specimens can be optically sectioned in both, horizontal and vertical planes. The reflected or emitted light is reconstructed into a 3D image using a computer. In confocal microscopy, the illumination is scanned as a flying spot through the specimen. The light sensing detector follows the illumination and excess light is removed by placing a pin hole at the detector. The optical sections are detailed and have good contrast [126]. Series of optical sections taken at successive focal planes produce a 3D view of the specimen. The images are processed and stored in a digital format and can therefore be manipulated with image analysis software. All sizes that are necessary for calculating the volume of the specimens can be measured precisely, and the synthesized images can be animated and rotated so that structures can be seen in 3D.

In the laboratory, confocal microscopy offers a useful tool to address biological problems related to cellular structures and processes [21, 71]. Laser scanning confocal microscopy (LSCM) of planktonic organisms provide a means of observing external or internal structures in 3D, such as marine snow [49]. This instrument has further advanced our understanding of the functional morphology of structures belonging to microscopic organisms. The use of LSCM coupled with membrane-specific fluorescent carbocyanine dyes allows rapid identification of sensory structures on copepod antennules and provides insights into the mechanics of signal transduction from the environment to the organism [12]. LSCM was used to study structural details of larval stages of *Temora stylifera* [18], *Calanus helgolandicus* [15], and the decapod *Hippolyte inermis* [132]. The LSCM technique was also applied to rapidly assess embryo viability in *C. helgolandicus* [14] and *Clausocalanus furcatus* [16].

LSCM appears to be particularly valuable for morphological analyses in taxonomy. To identify species and their ontogenetic stages is of basic importance in environmental research aimed at identifying and monitoring biological diversity in plankton ecology. LSCM seems to be the only available optical instrument that shows the morphology of planktonic organisms with high resolution and at the same time allows taking precise measurements of their body for the reconstruction of a 3D image. Current 3D imaging techniques are not fast enough for rapid high quality imaging of large volumes in field studies. For field applications with real-time imaging from a moving ship, 3D systems with confocal optics will not be available for some time according to Culverhouse and coworkers [23].

For the identification of plankton specimens from images, attempts are made to discriminate between supraspecific taxa [10], even at species level [97]. Fourier-based analysis of the profiles assist in creating shape categories. However, these

descriptions are sensitive to the angle from which the camera view the specimen [43]. Partial views and rotations of objects may therefore reduce instrument performance. Enhancements to increase the number of parameters measured from each specimen have resulted in several useful tools for real-time use [68, 105].

Light microscopy images, although essential for identification, have limitations. Manipulation of the specimens and constant refocussing is often necessary to reveal details that are critical for identification. Scanning electron microscopy (SEM) and confocal digital microscopy are preferred as they offer significantly higher resolution. Confocal imaging has become important as images can be viewed from any angle since they are gathered in 3D.

Four 3D sensor technologies are currently available: (1) confocal optics, (2) optical holography, (3) optical tomography, and (4) acoustic tomography [23, 66]. Current confocal scanning rates and depth of field for full 3D large field applications do not approach the speed and resolution required. Holographic images besides suffering from speckle noise, generate large data files, depending on resolution and image field of view. Optical tomography is at present still experimental. Sensors have high background noise levels leading to poor reconstruction of imaging [94]. The conduction velocity of signals in water places a limit on the imaging aperture for underwater-towed operation. Acoustic signals have a relatively slow velocity in seawater, with transit times across a sampling aperture of several microseconds. Acoustic tomography is a promising tool [94] but beyond the scope of this overview.

3. Studies in the Laboratory

Strickler and Hwang [100] outlined the difficulties in observing planktonic organisms in the oceans. For most objectives laboratory approaches are more feasible than *in situ* approaches. The majority of aquatic zooplankton are small and transparent. Pelagic copepods for example live in a three-dimensional environment in which the finding of mates at a sufficiently high rate for population maintenance represents a major challenge to the mainly transparent, millimeter-sized animals [13]. These tiny crustaceans were long regarded as rather passive members of the plankton, carried by water currents and feeding automatically as they swim. In the past two decades, however, our understanding of zooplankton and copepod behaviour has changed profoundly in showing that they are surprisingly active in choosing their diets. This was possible by the application of new techniques, such as high speed video. Progress in the field of direct copepod observations was due to the technological advancements in observing copepods swimming freely in relatively large volumes of water.

With functional capability (including capturing food, locating a mate and avoiding predators – see Table 3), copepods exploit the characteristics of their high viscosity, laminar flow regime habitat. Environmental information in this environ-

Table 3. Functional systems with species-, gender- and ontogenetic differences that can be investigated by Video technologies.

- Locomotion (swimming, walking, motility of body parts)
- Feeding of predators, grazers, parasites (detection, encounter, grasping, partitioning, swallowing)
- Predator avoidance
- Reproduction (detection, encounter, mating)
- Motility patterns
- Signal perception: hydromechanical/ chemical signals/cues
- Grooming

ment is relatively predictable and zooplankter take advantage of this predictablility in finding food particles being highly diluted, and avoiding predators in their three-dimensional environment that lacks physical hiding places, and locating a mate when conspecifics may be separated by several thousand body lengths. The paradigm of copepods as filter feeders was overturned by direct behavioural observations of copepods actively capturing individual algal cells [1, 64, 80, 85]. A better understanding of mechanosensorically mediated copepod escape behaviour was gained experimentally [44, 51, 55, 127].

1) Swimming Behavior

Swimming was digitally recorded by [27] from video-tapes to an IBM compatible computer equipped with a 682 M video-capture card and a 4-Gb hard drive made for video storage. The digital video was controlled from this computer, and individual frames were captured on a second PC and interfaced with video-analysis software (Optimus) on a separate monitor. This software placed captured video frames within a Cartesian coordinate system, and returned the coordinates for specified points. A calibration measure from the video was used to convert the coordinate system from pixels into a metric scale. The vertical axis (i.e. with respect to gravity) was designated as z, and the x- and y-axes formed the horizontal plane. One planar view provided x and z coordinates, the other provided y and z coordinates. The three-dimensional trajectories of copepods were visualized by plotting their sequential coordinate positions.

2) Mating Interactions

Reproduction of biparental planktonic animals requires females and males to encounter each other in a three-dimensional and relatively featureless space. Each must identify the other as a suitable mate, then hook to each other for a period of time that ensures successful sperm transfer. Details of how various planters including copepods, accomplish these tasks were advanced particularly by high-speed cinematography (Fig. 2).

Mating includes mate location and mate recognition systems, in addition to new insights into the functional morphology of the copepod reproductive system and their sexually dimorphic sensory systems. Mating interactions between copepods comprise a sequence of events: encounter, pursuit,
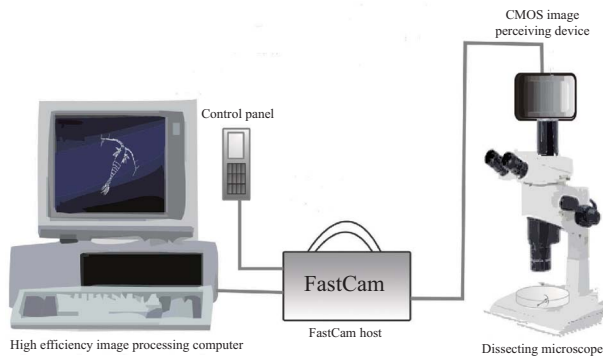
Fig. 2. Micro-enlarged high-speed photography (FastCam) optical system design drawing (modified after Hwang & Dahms, [52]).

Fig. 3. Optical system design drawing of high-speed photography (FastCam)(modified after Hwang & Dahms [52]).

capture and spermatophore transfer. Success of the male at each step permits continuation of the mating sequence, resulting in the deposition of a spermatophore. In some copepods, males are able to detect females at a distance and preliminary experimental evidence suggests that sex pheromones are involved, signalling the males of the presence of females. Doall *et al.* [27], using a 3D video system, demonstrate that males of *Temora longicornis* follow the trails left by swimming females, overtake and mate with them. The males can detect trails up to 10 seconds old and successfully pursue females that are up to 60 body lengths away. According to Weissburg and coworkers [118] does the ability of some copepods like *Temora longicornis* to track a 3D odour trail possibly dependents upon the persistence of water-borne chemical signals created in low Reynolds number regimes. Van Duren and coworkers [113] of swimming patterns in the same species, *T. longicornis*, reveals that females exhibit a different pattern of hops in the presence of chemical signals indicating the presence of males. Using laser sheet particle image velocimetry, Van Duren and coworkers [113] investigated the possibility that these hops serve to create a hydrodynamical signal that increases the encounter probability with potential males.

Yen and coworkers [128] demonstrated that the low Reynolds number regime conserves distinct species-specific cues that can direct mate seeking in copepods. They show that, within small Komolgorov eddies where viscosity limits forces to molecular scales, pheromonal trails of swimming females persist. A new model of mate location in *Temora longicornis* is presented, based on the ability of the male to use its chemosensory and mechanosensory systems to discriminate between biologically formed mating trails and small-scale turbulence, and to recognize the presence of signal molecules left in the trail by conspecific females.

3) Methodical Approaches in Behavioral Studies

Schmitt *et al.* [92] recorded the swimming behavior of *Cosmocalanus darwini* by using an infrared sensitive camera and a video cassette recorder. To avoid a behavioral irritation by any light-indu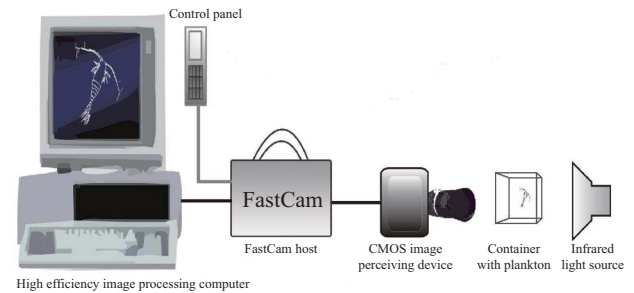ced phototropism, all experiments were carried out in the dark. During the swimming behavior each frame was time marked sequentially by a QSI frame counter. The temporal resolution was 1/30 s as determined by the video frame rate. An editing controller was used for frame-by-frame videotape analysis. The procedure was essentially as provided by Hwang and Turner [57] who filmed several free-swimming copepods in a vessel, using a video camera, videocassette recorder, frame counter, and monitor attached to a dissecting microscope. Similarly, the newly improved video optical system can use FastCam facilities (see Fig. 3)

Behaviour of plankton organisms can also be recorded by video, using a system of laser photography developed by Strickler and Hwang [100]. The authors submerged the filmed vessel in a large water jacket to maintain constant temperature levels during video-recording. Observations were made in relatively large volumes of water (1.5 l), thereby limiting wall effects and constraints on the animals' sensory range and swimming behavior. Behavioral patterns can be dissected into a series of sequential steps, similar to the sequence of events described by Gerritsen and Strickler [37] for predatory interactions in the plankton. Vanderlugt [114] treated the organisms as phase objects and applied an optical system that functions as an optical signal processor using matched spatial filters in order to overcome constraints for the functional investigation of zooplankton (e.g. transparency, small size). This technique is derived from the classical Schlieren system and has, instead of a slit as the first spatial filter and a knife-edge as the matching one, a point source (pinhole) as the first filter and a stop as the matching one. The use of large-format camera lenses allows the TV camera to be dynamically repositioned to follow a swimming animal [100]. The TV camera is mounted on its side to permit recording over the full frame even though this has the disadvantage that the animals appear to sink to the side of the monitor instead of downwards. The focal plane of the objective is also the plane of the 2D Fourier transformation of the collimated light beam and all other incoming optical information [100]. The parallel light (DC signal) is focused at the origin of the transformation and removed by a binary filter, a black dot on the optical axis. When the observational vessel is filled with filtered water, additional binary filters are used to eliminate any impurities in the optical system.

II. CONCLUSIONS

Optical applications in biological oceanography are a promising and exciting area of research, both, in the field and in the laboratory. Applications of UW optics will assist applied sciences, such as environmental monitoring, mariculture, fisheries, conservation management, and fundamental science alike. In the field, ROV and SCUBA survey methods can generally produce higher precision in terms of detecting temporal changes in benthic or planktic communities than physical collections, and more economic as far as time and personal is concerned, and are thus more suitable for scientific research and management purposes. Other advantages of using video transects by SCUBA divers or ROV include provision of permanent records with wider surveys for subsequent studies and public information that require less field time. Still photographs from such recordings for the purpose of analysis, presentation, or publication, however, result in lower resolution pictures as these are restricted by the power of most DVD player's software. In the laboratory OPC laser optics with the possibility of field applications will provide the most promise in the immediate future [45].

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