PAPER

A Focus on Recent Developments and Trends in Underwater Imaging

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ABSTRACT

Advances in the field of underwater optical imaging are reviewed for the years 2005 to present. A synopsis of research and technical innovations is presented, organized in much the same way as the previous report (Kocak and Caimi, 2005). Several recent applications of novel systems are shown as examples, and trends in emerging underwater imaging research and development are briefly summarized.

Introduction

Challenges associated with obtaining visibility of objects at long or short distances have been difficult to overcome due to the absorptive and scattering nature of seawater. Mitigating these effects has been the focus of the underwater imaging community for decades, but recent advances in hardware, software and algorithmic methods has led to improvements in several application areas. For example, advancements such as:

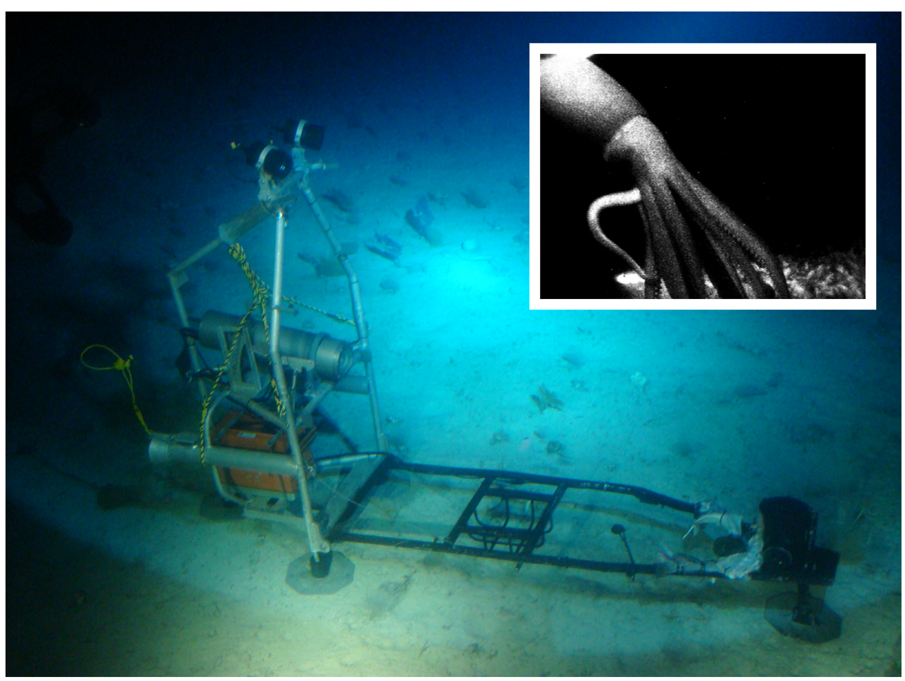
- Affordable, high quality cameras support a suite of fast, inexpensive specialized image processing software and hardware add-ons.
- Digital holographic cameras record interference fringes directly onto solid state sensors (i.e., mega pixel charge coupled devices) to produce time resolved, 3-D movies.
- High repetition rate, moderate power lasers and advanced detector designs enhance performance of two-dimensional (2-D) and three-dimensional (3-D) imaging systems.
- Compact, efficient and easy to program digital signal processors execute algorithms once too computationally expensive for real-time applications.
- Modeling and simulation programs more accurately predict the effects that physical ocean parameters have on the performance of imaging systems under different geometric configurations.
- Image processing algorithms that handle data from multiple synchronous sources and that can extract and match feature points from each such source derive accurate 3-D scene information.
- Digital compression schemes provide high-quality standardizations for increased data transfer rates (i.e. streaming video) and reduced storage requirements.

This paper reports developments over the past three years in the following topics:

- Image formation and image processing methods;
- Extended range imaging techniques;

FIGURE 1

The EITS camera system deployed at Gouldings Cay in the Bahamas at a depth of 488 m. Inset: An unidentified squid recorded by the EITS while the system was deployed in the Gulf of Mexico on the edge of the NR-1 brine pool. This unusual squid, with its short muscular tentacles that lack an obvious club, cannot be assigned to any known scientific family. (Courtesy Edith Widder)



- Imaging using spatial coherency (e.g. holography); and
- Multiple-dimensional image acquisition and image processing.

Along with leading advancements in each of these areas, a few newly applied vision systems are presented. Lastly, trends for future systems are briefly touched upon.

Image Formation and Image Processing Methods

Cameras and Lighting for Underwater Observing

Described in the 2005 State of Technology issue (Kocak and Caimi), the Eye-in-the-Sea (EITS) camera was deployed on the seafloor several times over the past three years and will soon become a part of the Monterey Accelerated Research System (MARS) ocean observatory sensor suite (Widder, 2007). A photograph of the system and a captured image (inset) are shown in Figure 1. The system differs somewhat from the FOVAR (Field of View And Ranging) system developed by HBOI (Tusting and Lee, 1989) for autonomously recording still images of sea life as triggered by far-red wavelength illuminators and photoreceptor. The newer system utilizes a video camera that records footage at scheduled intervals or when bioluminescent light is detected by a photomultiplier tube (PMT). Far-red illumination (680 nm light-emitting diodes with cut-off filters below 625 nm) is used since this wavelength is invisible to most deep-sea inhabitants, and an intensified video camera compensates for the reduced illumination and permits recordings of bioluminescence.

Another recent camera system has been set up to monitor coral reef communities in marine parks (Lam et al., 2007). This system collects 10 minutes of video footage each hour on a year-round basis, during the day and night. Unlike the "stealth" EITS camera system, this system uses two high intensity bulbs that are switched on and off automatically at timed intervals during the night. The benefit of this is being able to capture high resolution color video images that provide sufficient information to identify fish species and invertebrates.

Animal-Borne Imaging

Not all cameras deployed in the sea are stationary or mounted to underwater vehicles. Since mid-1980, animals have become imaging platforms to record *in situ* data *from the animal's point of view*. Today, in addition to video and still images, audio, environmental, and positioning data are logged on systems worn by manatees, sea turtles, sharks, whales, seals, penguins and many others. Animal-borne systems are the focus of the winter 2007/2008 issue of the *Marine Technology Society Journal*. In a previous issue, Marshall et al. (2007) describe how advances in smaller, more ruggedized cameras and solid state recording media have benefited the new generation ("GenV") CRITTERCAM. Where the first Hi-8 CRITTERCAM system was 10.2 cm outside diameter (OD), 31.6 cm in length (L) and weighted 2.4 kg; GenV is 7.6 cm OD, 21.1 cm L and weighs 1.1 kg. This is no doubt a substantial relief for smaller bearers. Whereas Hi-8 videotape recording times allow up to 6 hours, GenV recording times allow up to 10 hours using an 8 GB compact flash and MPEG-2 program streams (PS) at low resolution (352x240 pixels). Even better news is larger compact flash cards (16, 24 and 48 GB) will soon be available and will allow even greater amounts of storage (Murph, 2008). At 75 minutes/GB, a 48 GB card will allow up to 60 hours of video. In addition, solid state memory is non-volatile and contains no moving parts, making it indifferent to loss of power and mechanical shocks.

Image Processing Methods to Simulate Visual Acuity and Perception

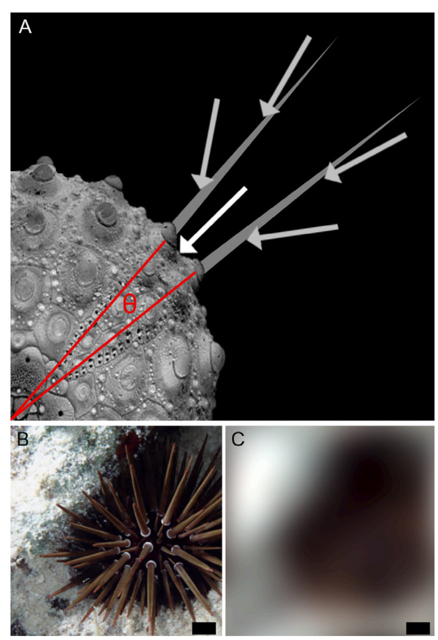
In addition to recording from the animal's perspective, researchers are developing image processing techniques that simulate the visual acuity and perception of the animal (Johnsen et al., 2004). Animals living in the dark depths must trade visual acuity for increased sensitivity by pooling the light from a large number of photoreceptors to increase photon counts to detectable levels, much the same way as in dark-adapted human vision. This is similar to using a bigger F-stop and is referred to as spatial summation. Also of interest is temporal summation, where the integration time of the photoreceptor is increased (i.e. holding a shutter open longer) so that signals are able to integrate over a longer period of time to increase sensitivity. Figure 2 illustrates how the sea urchin (Echinometra luncunter) in (B) would perceive itself (or another sea urchin) in (C). The spatial and temporal resolutions needed to simulate the reduced visual acuity image are dependent on how the animal processes the reflected and absorbed light shown in (A). Techniques to determine the animal's visual acuity and perception are described in Belvins and Johnsen (2004), Frank (2003), and Marshall et al. (2003).

High Definition (HD) Video

High resolution and quality offered by high definition (HD) video can benefit security and surveillance, inspection, mapping and precision photomosaics, photo

FIGURE 2

(A) Test of E. lucunter with two spines. Off-angle light (gray arrows) is absorbed and reflected by the spines. Light within the acceptance angle, (white arrow), reaches the body wall between the spines and is detected. (B) E. lucunter in a typical shelter. (C) Simulated view of B showing how the species would see itself.



excavation and historical documentation, basic work functions, online video for broadcast, education and discovery, cinematography, and many more underwater applications. Current high-end technology is capable of capturing images at 24/25/30 fps progressive or 50/60 fps interlaced at a resolution of 1920 x 1080 pixels. The Sony HDW-F900H CineAlta, for example, utilizes a 2.2 MegaPixel, 1" optical format frame-interline-transfer (FIT) charge coupled device (CCD) and is equipped with various gamma curves for improved image quality. Dual filter wheels (neutral density and color temperature) and comprehensive software adjustment parameters afford user control of the image. The FIT imager is a 2/3", 2,200,000-pixel sensor that provides high resolution images having a 16 (horizontal) by 9 (vertical) aspect ratio. In its standard configuration, the camera can continuously record up to 50 minutes in 24P mode (24 fps with "pulldown" to create 29.97 fps video). Many of the newer cameras utilize the H.264 video-processing LSI codec (Compressor/DECompressor) for the advanced digital signal processor (ADSP), which provides real-time compression/decompression from video stream to display without degradation; smaller size and low power consumption by combining logic and low-power DRAM (FCRAM) on a single-chip; improvement in picture quality and stability using proprietary compression/image-enhancement technology that is optimized for human vision; and improved operational reliability (Fujitsu, 2007).

A recent undertaking involves deploying a HD video camera on VENUS (Victoria Experimental Network Under the Sea) and NEPTUNE (North East Pacific Time-Series Undersea Networked Experiments) (Roston et al., 2007). In a joint effort by McGill University and the University of Victoria, the system is designed to transmit live, full broadcast standard HD video (1280 x 720 pixels in 10-bit color at 60 Hz) over a 1 Gbps network using ultra-videoconferencing software. Rather than decimating the image (e.g., cropping or using 8-bit color), run-length encoding (RLE) is implemented to reduce bandwidth overhead to approximately 830 Mbps—equivalent to about 75% data compression (Lucus, 2008). The system uses a commercial camera having three 2/3" CCDs, a zoom of 44x, and a sensitivity of about 80 lux at F2. The video transmission will be available over the Web and control software will allow a single user to change internal camera settings, lens magnification, the illumination source (arc lamp or light-emitting diode [LED] based), on/off status of three parallel reference lasers, and pan/tilt parameters. The user interface allows scientists to define "change parameters" within a particular region of the image for notification of events of interest. The user interface and system architecture make this system unique.

HD Video Compression Formats

HD obviously provides a larger and much sharper image than standard video but requires much greater bandwidth and storage; something that is not always feasible in underwater applications where electronic "real estate" is limited. Recent image compression formats such as HDV, MPEG-4 AVC/H.264 and VC-1 reduce these demands by allowing reductions of the data rate or memory requirements by up to a factor of nearly 50 (Jones, 2007; Sauer, 2006). This helps make HD a viable option in many underwater applications.

The HDV (High Definition Video) format was introduced in 2004 as the first practical implementation available in low-cost cameras. Where 1 hour of uncompressed 1080i HD video requires 432 GB of storage, 1 hour of 1080i HDV video only requires 12GB. HDV applies anamorphic stretching and compression of the video data to reduce the signal size without overly reducing the quality (Harris, 2007). Anamorphic images were created in the 1950s for cinematography using curved lenses to squeeze a wider image onto a narrow frame of film. In HDV, 1440 rectangular pixels are recorded; where each pixel is 1.333 times wider than it is high, rather than the 1920 square pixels of full HD. This allows the image to appear visually the same as the 1920 width, but with fewer actual pixels and therefore less data. HDV uses MPEG-2 codec for compression and decompression, which is the same as that used in DVDs and digital broadcast signals. MPEG-2 compresses the visual information by organizing frames into groups known as a Group of Pictures (GOP). In this way, HDV records one complete frame and then a group of partial frames that refer back to the first frame, rather than recording all of the individual frames. Though efficient for recording data, this method is very inefficient for editing since it requires a vast amount of computational power and time to unpack the frames and rebuild them on the fly.

MPEG-4 Advanced Video Coding (AVC) is the newest HD format geared towards inexpensive HD video production. AVC is making its way into HD camcorders for everyday home and movie use; whereas HDV is typically found in more expensive cameras for professional use. Like HDV, AVC uses anamorphic stretching but compression is accomplished using the H.264 codec, which is able to compress to half the size of MPEG-2 (using ~3 times fewer bits) without degradation of visual quality. This is up to twice as efficient as conventional MPEG-4. Once again, the disadvantage of AVC is the computational time required to unpack the files for editing.

VC-1 compression is based on Microsoft's Windows Media 9. The codec is part of the MPEG-4 definition but is generally considered to be more efficient, though not necessarily more so than AVC. VC-1 is an acceptable standard for both Blu-ray and HD-DVD formats.

Extended Range Techniques

A primary goal of extended range underwater imaging is to improve image contrast and resolution at greater distances than what is possible with a conventional camera and underwater lighting. In recent years, several advancements have been made in this field. In general, the techniques used can be categorized into six areas:

- Time discrimination/range-gated methods;
- Spatial discrimination/laser line scan (LLS) methods;

- Imaging using structured lighting;
- Scattered light rejection using modulation/demodulation techniques;
- Polarization discrimination; and
- Multiple perspective image construction.

A recent emphasis has been on designing wide swath imagers with the potential to be implemented on the common classes of autonomous underwater vehicles (AUVs). In fact, there are currently only a few design strategies for underwater laser imaging systems that have led to practical field systems. These are: i) synchronously scanned continuous wave (CW) beam and photomultiplier tube (PMT), as implemented in the Raytheon LS4096 and the Northrop Grumman LLS systems; ii) scanned laser beam and high speed linear CCD camera, as implemented in LBath system (Moore et al., 2000); iii) pulsed fan beam with time-resolved signal detection using streak tube, as implemented in the Arete STIL system; and iv) CW fan beam structured lighting system with a CCD camera, as recently implemented in a Bluefin12 AUV by the University of South Florida (USF) and SRI International.

All of the approaches provide intensity reflectance maps of the seafloor and targets, while the latter three also provide 3-D topographic information, either via time-of-flight or triangulation. Each of these systems has limitations or operational challenges that result from the design choices. Such limitations and challenges include: limited depth of field, which leads to difficulty in 'focusing' the system over the variable terrain; large size; high input power requirement; and limited range versatility. The deficiencies vary from system to system, but overall the operational community requires a system that combines reduced operational complexity (size, power, etc.) with enhanced performance.

Recently, Howland (2006) describes the development of a class of imager suitable for medium range imaging in clear water. Utilizing an array of high-power cyan LEDs centered at 500 nm and pulsed via a trigger signal from a high dynamic range, 12-bit high resolution CCD, the system is being designed for the benthic imaging payload of the Woods Hole Oceanographic hybrid remotely operated vehicle (HROV).

Time Discrimination/Range-Gated Methods

Range-gated systems traditionally use low repetition rate (< ~100 Hz) green pulsed laser sources, and have the aim of improving image contrast by rejecting most of the backscattered light between the source and the target. Previous and recent implemented bench top configurations (Fournier et al., 1993; McLean et al., 1995; Seet and He, 2005) use a spatially broadened laser pulse as the illuminating source and a non-scanning gated intensified camera as the detector allowing for the acquisition of a thin temporal slice of the entire (global) scene, over perhaps a 40 degree FOV. Utilizing suitably high sampling rates, these systems can also allow for 3-D image reconstruction from many short time slices (Busck et al., 2005).

More recently, an evolved implementation of this variety of system, the LUCIE2 (Laser Underwater Camera Imaging Enhancer) (Weidemann et al., 2005) has been packaged for use onboard a remotely operated vehicle (ROV) and deployed in very turbid water with encouraging results. The tested configuration allows for propeller blade inspection at 5 attenuation lengths. Ongoing system improvements include optical polarization control to implement polarization difference techniques to further enhance target contrast. A more compact third generation diver-held version of the system is currently under development. Other techniques to extend the performance range and retrieve optical properties of the environment are described in (Hou et al., 2007).

Spatial Discrimination/Laser Line Scan (LLS) Methods

Laser Line Scan (LLS) underwater imaging is a serial imaging technique that involves the optical scanning of a narrow instantaneous field of view (IFOV) receiver in a synchronous fashion with a highly collimated laser source over a wide swath. It has been widely regarded as the optimal technology for extended range underwater optical imaging. Indeed, it can be shown by deriving the optical transfer function of such systems that the achievable image resolution is near the diffraction limit (Jaffe, 2005a).

Although somewhat effective at spatially rejecting scattered light, LLS systems, which traditionally use a CW laser at a blue-green wavelength, are usually limited by receiver shot noise resulting from the temporal overlap between the target return and that of the scattering volume, from both laser and solar illumination. To maximize operational range, CW LLS systems use increased source-receiver separation that reduces the detrimental effect of near field multiple scattered light. However, this can lead to bulky systems which are not compatible with the smaller form factor UUV platforms.

Computer models of such systems have been studied for several years (Gibby et al., 1993; Giddings et al., 2005) and indicate that images can be obtained at up to 6 attenuation lengths in turbid seawater. Indeed, tested configurations, either in the field or lab-based demonstrators, have become contrast limited at around this distance. To reject much of the undesirable scattered light and therefore enhance the performance of the LLS class of imager, it has been suggested to replace the CW laser source with a pulsed laser source and to replace the always 'on' receiver with a gated receiver. The pulsed laser line scan (PLLS) imager has been proven in simulation to be effective at over 7 attenuation lengths, but until recently was determined impossible to implement due to technological constraints, in particular the availability of suitable laser sources. The use of a pulsed laser and gated receiver also offers the capability to reduce the form factor of such systems, which leads to more compact and easier to implement systems.

Due to the availability of suitable benchtop laser sources in the last few years, modelers have been concentrating on synoptic model development to avert the computational burden of Monte-Carlo ray trace methods and to allow system developers to consider the trade-off of system parameters (Shirron and Giddings, 2006). Indeed, recent studies have shown that the use of a pulsed laser makes it possible to temporally separate the volume scatter and target signals and estimate the energy returning from the target alone, thereby offering the potential to improve the image contrast and possibly the successful operational range of the system (Dalgleish et al., 2006b; Caimi et al., 2007).

However, it is well known that in turbid water the backscatter signal at the receiver becomes much larger than the target return signal as the source-receiver separation is reduced. This large backscatter signal can lead to dynamic range limitations, device or amplifier saturation and even component damage, and it has been found that electronic gating is advantageous particularly at a smaller source receiver separation (Dalgleish et. al., 2007).

The use of time-gated pulses within a LLS framework for extended range underwater imaging has been demonstrated by researchers at Harbor Branch Oceanographic Institution (HBOI), who have developed prototype hardware utilizing both custom and off-the-shelf gated-PMT assemblies and a custom high repetition rate (357 kHz), high power green pulsed laser (6-7 ns full width at half maximum Gaussian pulses). The test tank reflectance image comparison in Figure 3 shows a drastic contrast and signal-to-noise ratio (SNR) improvement of the time-gated PLLS over CW LLS in precisely controlled artificial turbidity environment under near-identical system and operational conditions. As the source-receiver separation is reduced, the performance of the time-gated PLLS is expected to be maintained, whereas the CW LLS will become contrast limited at a reduced stand-off distance.

At the limit of detection of the time-gated PLLS, several possibilities exist to extend the performance. The integration of multiple pulses will increase the SNR, albeit with a sacrifice to the achievable image resolution; physically increasing the size of the receiver aperture can also increase the SNR; likewise the use of coded pulses and coherent detection has also been shown to potentially further extend imaging capabilities (Mullen, 1996; Contarino, 1998).

FIGURE 3

Test tank acquired reflectance image portions taken at 6.1 attenuation lengths at 7 meters stand-off distance. Left hand side: CW LLS image using 3W CW laser. Right hand side: Time-gated PLLS image using 2W average power pulsed laser. For both tests, scan speed was 100 lines per second, the source receiver separation used was 23.4cm, the instantaneous FOV of the receiver was 15mrad and the seabed velocity was 1.5ms-1. Laser divergence for both lasers was 2-3 mrad. Note that both images have been histogram equalized and median filtered (3x3).

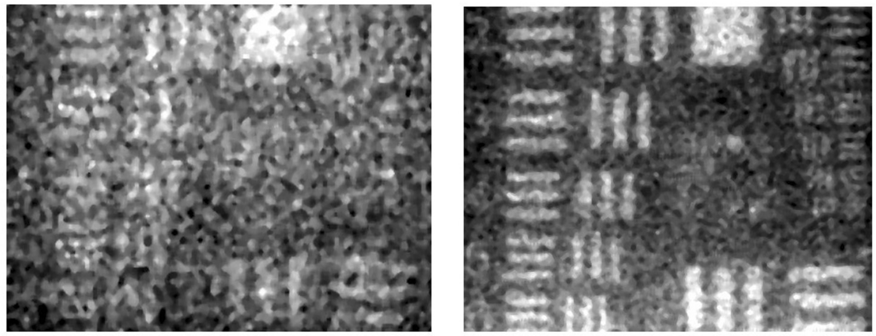
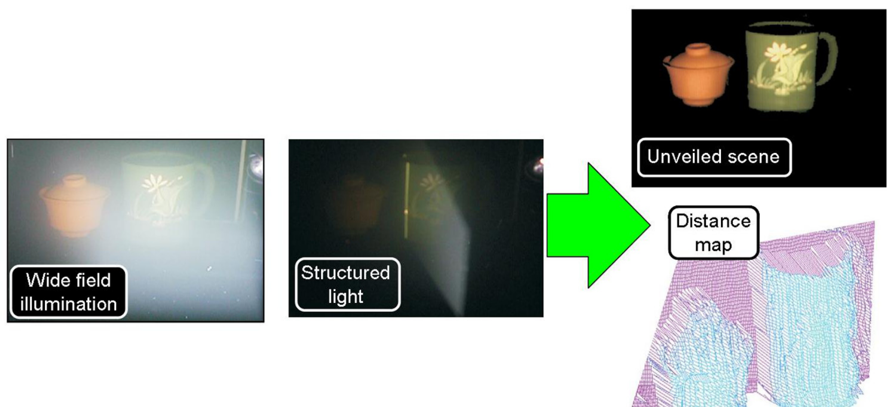


FIGURE 4

The distance-compensated structured light system uses a projector to create structured light patterns, providing contrast better than in wide field illumination. Post-processing compensates for the water attenuation based on recovery of the object distance map. (Courtesy of Srinivas Narasimhan)



Imaging Using Structured Lighting

Distance-compensated Structured Light

When using structured light, a narrow laser beam or plane is typically projected onto the scene, off the center axis of the camera. This configuration significantly reduces backscatter in the raw data and enables recovery of the scene's 3-D structure by means of triangulation (Dalgleish et al., 2005; Carder et al., 2005). Narasimhan et al. (2005) present two innovative additions to this method. First, unlike synchronous scanning systems, scanning is performed without any major moving parts and is instead controlled by a spatial light modulator using a digital light processing (DLP) projector. Second, compensation is made for the attenuation of the water when recovering the object radiance. The attenuation depends on the distance of each object point, where distance is recovered using triangulation. The attenuation is parameterized by the attenuation coefficient of the water, where the parameter is recovered by a method based on the raw frames taken in the scene. This method also recovers a parameter that estimates the phase function of the water. An experimental example of the system output is shown in Figure 4.

Synthetic Aperture Illumination

A method for separating a background object from its foreground backscatter has been developed by Levoy et al. (2004). While most methods of structured light are based on illumination from a single direction, the method proposed here is based on a constellation of illumination sources, each irradiating the scene from a unique position and direction. Moreover, the illumination from each source is structured in the form of multiple bright patches. Figure 5 illustrates an experimental setup in a large water tank and some example images.

In this technique, multiple frames are acquired while different sets of illumination sources are active, where each combination produces a different illumination pattern. The acquired frames contain backscatter similar to that obtained by floodlighting. When the data is post-processed, the backscatter field is estimated based on the set of frames and then the backscatter component is compensated for to enhance the image quality. Two contrast enhanced test target examples are shown, where (b) uses only a floodlight and (c) uses multiple sources as shown in (a). The results in (c) show a dramatic improvement in the SNR. In this example, the attenuation length was about 8 inches and the range to the target was 4 feet or about 6 attenuation lengths.

Scattered Light Rejection using Modulation/Demodulation Techniques

In the underwater imaging community, it is well known that coherent modulation/demodulation methods at optical frequencies fall apart due to the high dispersion in the sea water path (Swanson, 1992). Therefore, intensity modulation of the laser carrier is the only realizable choice in the design of coherent imaging architectures for extended range underwater use.

Earlier underwater coherent detection demonstrations have usually used a CW laser radiating an amplitude modulated beam of light to illuminate a target underwater from an airborne platform or underwater vehicle. A PMT then integrates the backscatter and the target photons together, and by demodulating the AM signal, partially rejects the scattered light signal enabling ranging to the shot noise limit of the receiver.

It has also been recognized that the non-coherent signal detection methods used by earlier LLS systems might also be improved by using sub-carrier coherent detection at the receiver to separate the temporally dispersive scattered light from the target return and to produce target profile or range information. One such system has been developed by NAVAIR to image targets underwater from an airborne platform or underwater vehicle (Mullen et al., 2004, 2007). This system uses a 3W CW laser sinusoid modulated at up to 100 MHz, with complex (IQ) demodulation to recover magnitude and phase information for enhanced contrast and range imaging capabilities. The system has also been demonstrated as having the potential for hybrid imaging/communications capabilities (Cochenour et al., 2007).

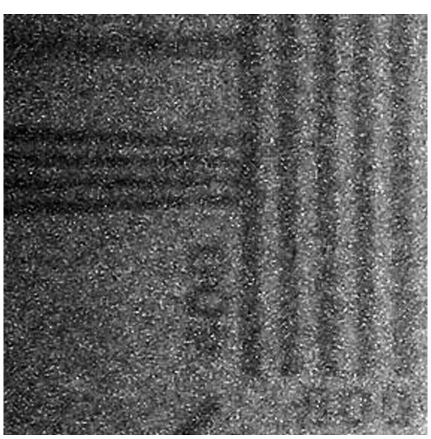
Another recent modulated CW imaging demonstration (Bartolini et al., 2005) utilized a 20 mW single mode laser at 405 nm amplitude modulated at 36.7 MHz via control of the current, and scanned in steps by a miniaturized piezoactuator. In laboratory tests at ENEA Research Center, submillimeter range accuracy was reported at a 1.5 meter stand-off distance in clear water. The diode laser wavelength matches the minimum of the pure water absorption spectrum, and hence this system has been designed for (eventual) long range 3-D imaging in relatively clear water.

The main limitation of these previous efforts were not demonstrating the systems using a full scale test range or with a real-time scanning architecture. However, in

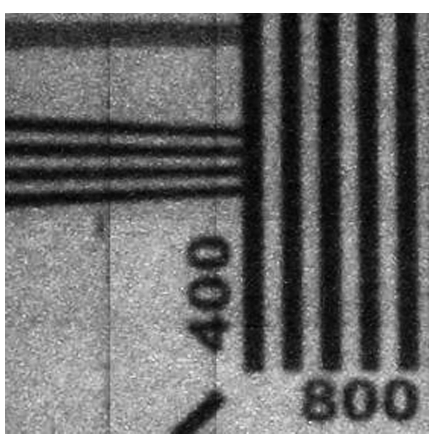
FIGURE 5

(a) Experimental setup and test target examples in very turbid water acquired using (b) single floodlit illumination and (c) multiple illumination sources. (Courtesy Marc Levoy)

(a) Experimental setup of multiple illumination sources in a large water tank.



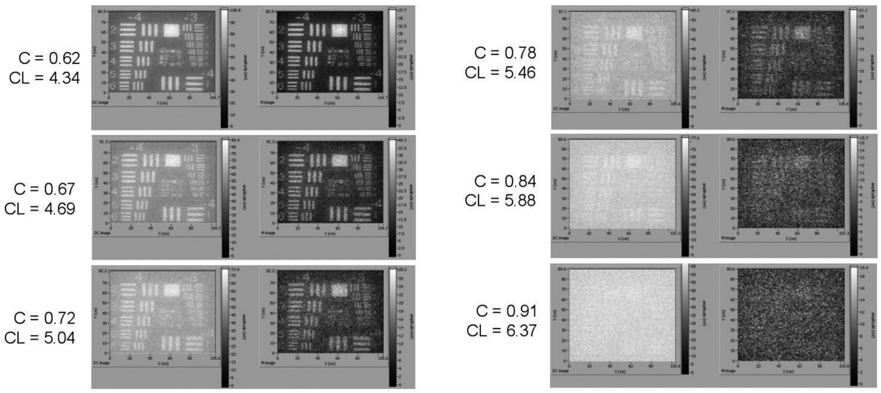
(b) Floodlit



(c) Multiple Sources

FIGURE 6

Raw image comparison from HBOI test tank at 7 meters stand-off distance (contrast stretched between min to max) between CW LLS (Left side images on each column) versus modulated-CW LLS (right side images on each column). Note: C = beam attenuation coefficient in inverse meters. CL = number of attenuation lengths. (Courtesy Linda Mullen)



2007, the NAVAIR system was tested with the HBOI benchtop LLS system (Dalgleish et al., 2006a). The results, which demonstrated a noticeable reduction in backscatter and hence improvement in image contrast when compared to CW LLS in turbid water (shown in Figure 6), were reported in a recent poster (Mullen et al., 2008).

It has been proven in simulation that the use of modulated-pulses, as described by Mullen et al. (1996, 1998), as the hybrid LIDAR-radar technique has the potential to further extend the operational range of LLS systems. The simplest method is to impress a high frequency sinusoidal amplitude modulation on the laser pulse. This in turn makes it possible to reject the lower frequency components of backscatter and ambient light, further increasing the range capability of the system. This type of system has previously been investigated by various research laboratories (Mullen et al., 1996; Pellen et al., 2002) and has been the subject of recent simulations using Metron's radiative transfer solver (Shirron and Giddings, 2006) and other radiative transfer codes developed specifically for pulsed underwater laser imaging systems (Liang et al., 2006).

Within the last few years, the required hardware sub-systems have been under development. In particular, two recent NAVAIR SBIR topics address the development of both high power green modulated-pulsed lasers, and high timing resolution demodulating receivers for this class of advanced underwater imager.

These techniques can offer improvement in the recovered SNR on a pixel-by-pixel basis and consequently can provide better image quality at the range limits of the system. Improved simulation capability and hardware advancements will determine the potential limits of using coherent detection to reject noise and scattered light impairments to the image quality, and this will be investigated over the coming years.

Polarization Discrimination

An image enhancement technique proposed by Treibitz and Schechner (2006) combines an optical step during image acquisition along with digital post-processing. The optical step uses wide-field polarized light to irradiate the scene, while viewing the scene via an additional polarizer. Two wide-field frames are taken in mutually orthogonal polarization states. Backscatter exists in both polarization states (frames) but in different amounts; hence the optical step modulates the backscatter.

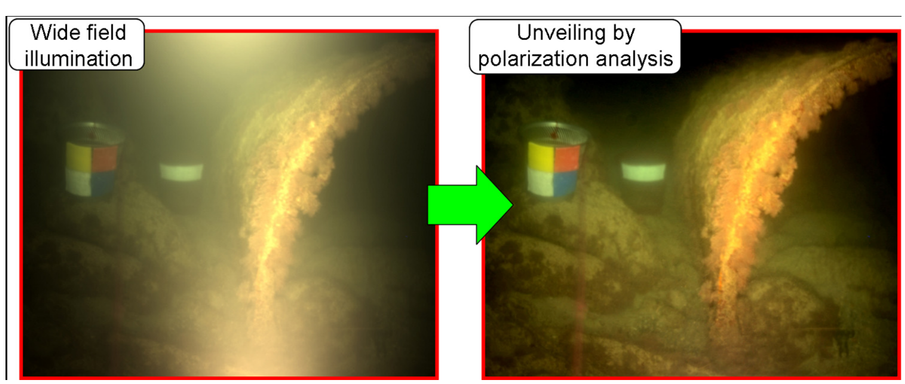
Next, a mathematical process is applied using the two raw frames as input. The process extracts the backscatter field and then estimates the background free of backscatter. This work generalizes the earlier work to scenarios where the illumination is artificial rather than natural (Schechner and Karpel, 2005). Several oceanic experiments were conducted to demonstrate this technique and are described in the 2006 paper. Figure 7 demonstrates the "unveiling" of a turbid Mediterranean underwater scene under artificial illumination using this polarization-based technique.

Multiple Perspective Image Construction

Imagery of a scene collected from different locations is commonly used to derive size and depth measurements, photo-mosaics, and 3-D reconstructions. This can be accomplished by performing high resolution optical reconnaissance sweeps of a desired area using a single imaging system, or using multiple imaging systems that perform the sweeps in a fraction of the time. When a multiple system technique is employed that separates the illumination from the image formation process, images can be captured at greater distances due to a reduction of the backscatter component. Jaffe (2007)

FIGURE 7

Unveiling a turbid Mediterranean underwater scene under artificial illumination by polarization analysis of images acquired during a night scuba dive.

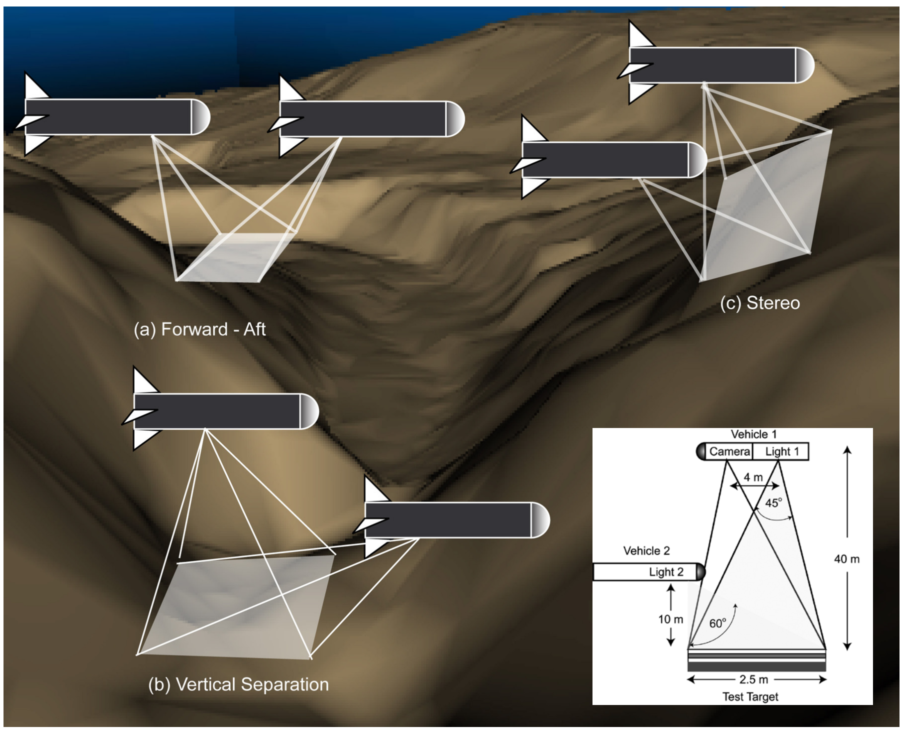


has shown this by simulating different configurations of lights and cameras (Figure 8a), where inputs consist of 3-D locations, pointing angles, characteristics of the lights and cameras, and a reflectance map with an arbitrary reflectance profile. Lighting is modeled as monochromatic or wide band, with its output pattern being a narrow sheet-like beam or a wide beam with theta and phi beam widths and an arbitrary radial dependent intensity pattern. The camera parameters include the f-stop, focal length and number of resolution elements. The inset in Figure 8a illustrates two potential geometries—a single vehicle system (Vehicle 1) equipped with a camera and light (Light 1); and a two-vehicle system where one vehicle (Vehicle 1) is equipped with a camera and a second vehicle (Vehicle 2) is equipped with a light (Light 2). Standoff and separation distances are shown. Simulation results show that the single vehicle configuration provided no useful information from the simulated scene (Figure 8b), whereas the two vehicle configuration provided a clear image (Figure 8c).

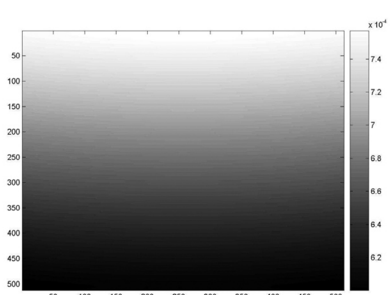
Woods Hole Oceanographic Institution researchers are using two AUVs to cooperatively characterize the Arctic seafloor (Woods Hole, 2007). Unlike the approach described by Jaffe, the two AUVs are launched sequentially with unique tasks in mind. The first AUV, Puma or “plume mapper,” is launched to localize chemical and temperature signals given off by hydrothermal vents; while the second AUV, Jaguar, is sent to those locations to use high-resolution cameras and bottom-mapping sonar to image the seafloor.

FIGURE 8

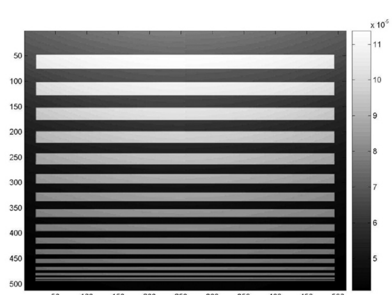
(a) Multiple perspective imaging concepts and (b and c) a comparison of simulated images acquired using the two geometries shown in the insert in (a). (Courtesy Jules Jaffe)



(a) Three concepts for using multiple imaging systems: fore-aft imaging, vertical separation imaging and stereo imaging. Inset: Vertical separation geometry employing a single camera with two light configurations to be illuminated separately.



(b) Predicted image using single vehicle with light source 1.



(c) Predicted image using two vehicles with light source 2.

Spatial Coherency Techniques

Holography is a technique that necessitates post-processing and a tailored optical process. The raw data recorded in holograms is not a projection of the object as in standard photography. Instead, the hologram represents the intensity of an interference between waves propagating from the object and a reference wave—usually at optical frequencies. The physical acquisition resembles a transform: waves evolve from the object according to wave-propagation rules (diffraction); the diffracted waves interfere with a reference wave, creating a combined wave amplitude; and the intensity at the detector plane is a nonlinear version of this amplitude (its squared modulus). In order to recover the object from this transformed data, a hologram reconstruction is necessary. Traditionally, reconstruction is done by optically irradiating a slide encompassing the recorded hologram; i.e., in an analog manner.

Today it is possible for the reconstruction to be done digitally, by mathematically applying the rules of diffraction on the hologram input data. In digital holography, an electronic hologram is recorded directly onto a CCD (charge coupled device) or CMOS (complementary-symmetry metal oxide semiconductor) and then numerically reconstructed. As a result, 3-D information and a fourth dimension, time, form electronic holographic 3-D videos of living organisms and particles in their natural environment, recorded unbeknownst to the subject.

This principle is used by submersible digital holographic systems, as described in Watson et al. (2004), Sun et al. (2007), and Pfitsch et al. (2005 and 2007), to record plankton and other millimeter-sized marine organisms. An example is shown in Figure 9a. (Jaffe [2005] provides a good review of acoustic and optical imaging technologies used for sensing plankton.) The systems mentioned here operate at stand-off distances of about 0.1 mm to several millimeters. When recording over such a small volume there are no significant backscatter or attenuation effects. One might question the benefit of using this approach, rather than conventional underwater microscopy. Microscopy is essentially a projection of the object on the detector plane, and is thus simpler to obtain. However, in standard microscopy, the depth-of-field of each frame is narrow. Hence, for 3-D volumetric information, many frames must be scanned to capture the axial focus settings. In the described holographic systems, a single hologram (a single frame) can provide 3-D information using the aforementioned digital post-processing.

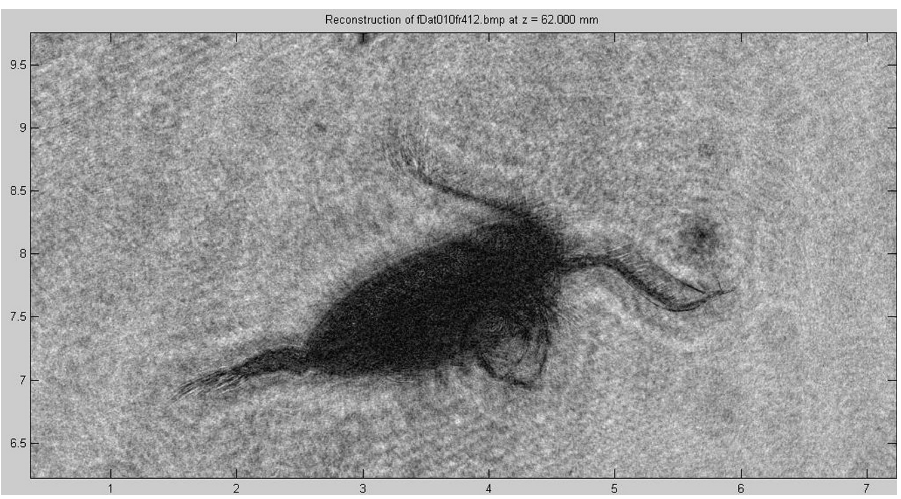
The captured water volume in systems referenced above have a cross section of about 1-squared cm. In the system described by Pfitsch et al., two holograms of the same volume are simultaneously acquired, from orthogonal directions. This improves the axial resolution of the recovered objects. The ocean water freely flows in and around the inspected volume. To view the dynamics of an organism for a relatively long time, the system drifts freely during the holographic acquisition. The system described by Sun et al., eHoloCam shown in Figure 9b, is towed through the water by a boat. Motion blur is avoided by using a pulsed Nd:YAG laser that has the capability of very short exposure times. Recent work pertaining to eHoloCam has focused on reducing the aberrations in the holographic images using an off-axis scheme with normal incidence of the object beam (Dyomin et al., 2007), similar to Pfitsch et al. Such a technique has an advantage at the reconstruction stage since no extra means of compensation is required.

Digital holographic systems offer another advantage as compared to non-digital (analog) systems such as HoloMar (Hobson and Watson, 2001)—the ability to develop and seamlessly integrate custom image processing algorithms like those used to extract 3-D regions of interest (Li et al., 2007) or those used to classify binary plankton images (Tang et al., 2006).

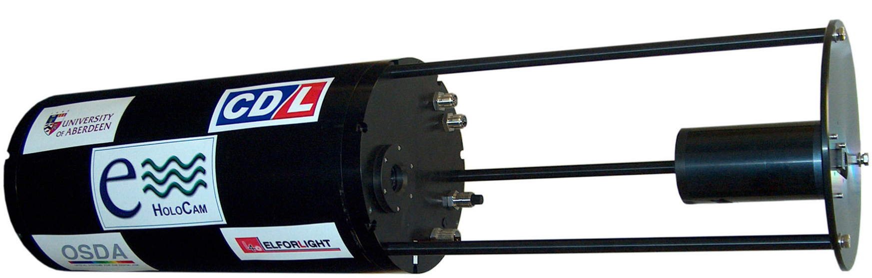
Methods using coherency of spatial gratings formed by structured lighting methods, such as proposed some years ago by Blatt and Caimi have not been investigated due to practical implementation problems (Bailey et al., 2003; Caimi et al., 1998).

FIGURE 9

eHoloCam (a) example holographic image and (b) holographic imaging system hardware. (Courtesy John Watson)



(a) Reconstructed holographic image of a calanoid copepod at a standoff distance of 62 mm



(b) eHoloCam

Multi-dimensional Methods in Image Space

Hyperspectral Images and Perception

The work of Chiao et al. (2000a) sought an explanation for the number of types of color-sensitive visual cones in the eye of marine animals and the response of these cones. For this purpose, they built an underwater multispectral imaging system. In this system a variable interference filter was mounted on a CCD camera. Motion of this filter changed the sensed spectral band per pixel. Across the visible band, the system yielded 40 sub-bands, each having an effective bandwidth of about 15 nm. The wavelength band and its corresponding exposure setting were controlled by a portable computer operated from a surface boat. The collected image data revealed two findings. First, it was found that almost all the variance of underwater object spectra can be expressed using three principal components (Chiao et al. 2000b). This may suggest that a visual system composed of three cone types can capture efficiently almost all the spectral variance. Then, this group proceeded to study a dichromatic model, where only two cone types may exist. Based on the underwater hyperspectral images, they sought a ratio between two cone types, which would optimize underwater scene discrimination. They found that the actual ratio in coral reef fishes appears to yield discrimination which is near optimal.

Optical-Acoustic (Hybrid) Imaging

Methods that combine Dual frequency IDentification SONar (DIDSON) and stereo imagery are being investigated for multiple-view 3-D reconstruction of scenes (Negahdaripour et al., in prep; Negahdaripour, 2007, 2008). The intent is to use the sonar to enhance reconstruction in poor visibility conditions, where visual cues become less informative. DIDSON uses high-frequency sonar (1-2 MHz) to produce range and azimuth 2-D measurements that are acquired in a polar coordinate system. Even in turbid water, near optical-quality 2-D video can be acquired at operational ranges of 10 to 20 meters. Since the geometry of "acoustic cameras" differs drastically from those of pinhole cameras, the greatest challenge in combining sonar and stereo images is calibrating the system to ensure data model consistency (Negahdaripour, 2005; Kim et al., 2005). Not only do the sensors have different areas of coverage, a pixel in polar coordinates maps to a collection of pixels in the Cartesian coordinate system, which further complicates searching and matching of feature points in successive images. Other challenges specific to DIDSON include limited resolution, low SNR, and limited range of sight. Kim et al. (2006) developed an algorithm to enhance sonar video sequences by incorporating knowledge of the target object obtained in previously observed frames. This approach involves inter-frame registration, linearization of image intensity, identification of a target object, and determining the "maximum posteriori fusion of images" in the video sequence.

DIDSON as a stand-alone sensor offers numerous advantages. In high-frequency mode, images from the sound beams can show the outline, shape and features of a target object. A common application is fisheries management and assessment, where fish behaviors such as spawning, feeding and migration can be non-invasively monitored and recorded even in low visibility conditions (Moursund et al., 2003; Baumgartner et al., 2006; NOAA, 2006). In many cases, even fin details of the target fish can be recovered. In Moursund's application, fish were observed in real-time at a 12 m distance in zero-visibility conditions using 1.8 MHz high-frequency mode, where 96 beams covered a 29-degree FOV. DIDSON also provides the ability to count and measure fish (or target objects) automatically, as a software feature. Limitations of DIDSON, however, were apparent in a recent deployment to observe groundfish near the mouth of a trawl (Matteson et al., 2006). DIDSON alone did not provide enough information to reliably identify the fish species and fish above the seafloor were difficult to distinguish when both the sonar and fish were in motion. A better solution in these situations is to combine DIDSON and a video camera, stereo camera system (as in Shortis et al., 2007) or other optical imaging system. Figure 10 shows one such ROV-mounted system that combines DIDSON, a video camera and parallel lasers for fish stock assessments and quantification (Yamanaka et al., 2008; Yamanaka, 2005). Other applications well suited to using DIDSON (and optionally a conventional camera system) include close-range inspection of manmade structures such as dock and bridge pilings (Kloske, 2005) (see Figure 11), ship hulls (Negahdaripour and Firoozfam, 2006; Kloske, 2005) (see Figure 12) and oil pipelines to name a few.

Another system that combines sonar and video, reported in the 2005 technology update, is J-QUEST—Japan Quantitative Echo-sounder and stereo TV-camera system (Takahashi et al., 2004; Sawada et al., 2004). One of J-QUEST's recent applications provided *in situ* measurements of target strength, tilt angle and swimming speed of *Boreopacific gonate* squid at depths approaching 300 m (Sawada et al., 2006). This system uses commercial analysis software to measure the echo levels (TSAN, Kaijo Sonic Corp.).

FIGURE 10

Canadian Fisheries Phantom HD2+2 ROV equipped with DIDSON, video camera and parallel lasers for abundance estimation and fish behavior analysis. (Photo by George Cronkite)

FIGURE 11

Data display at the control and command center (C3) from the USF Mobile Inspection Package (MIP): Topside video from the boat with position, heading and time (upper left); sonar view (lower left); Geographic Information System (GIS) (upper right); 3-D sonar (lower right). (Courtesy John Kloske)

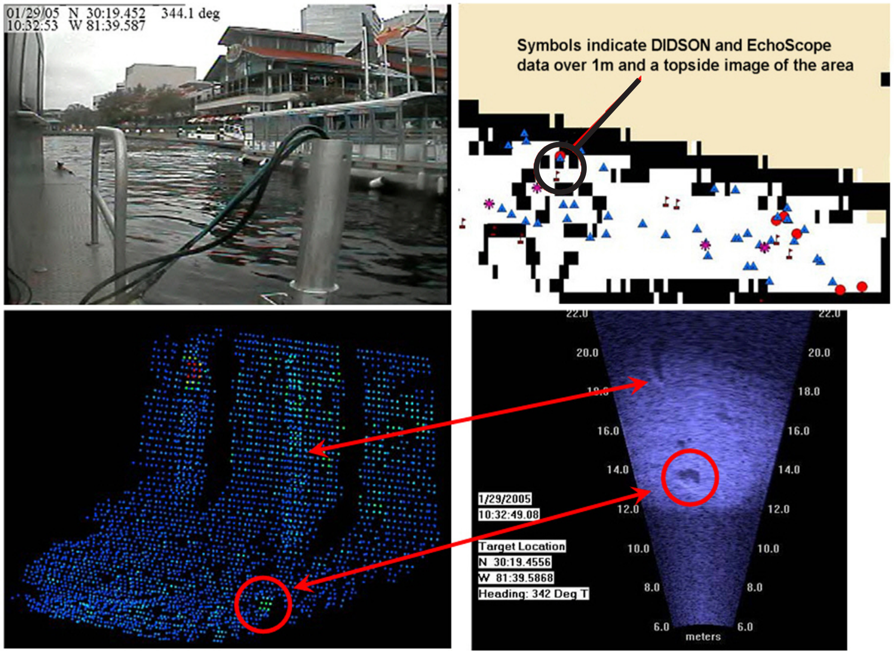
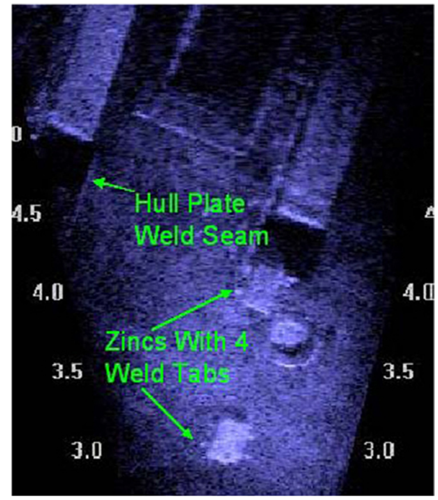


FIGURE 12

Underside of a ship hull taken with USF's ROV-mounted DIDSON. (Courtesy John Kloske)



Recent Applications of Vision System Technology

Fish-Pond Monitor

A new domain in which underwater imaging is employed is agricultural fish ponds. The work of Zion et al. (2007) describes a computer vision system for automatically classifying, sorting and directing live fish in such places. In this work, fish in the pond are trained by feeding habits to voluntarily pass through a narrow channel made of transparent glass. The channel's narrow width effectively allows only a single fish at a time to pass through. As the fish swims through the channel, it is photographed, classified and measured by a computer-vision system.

An underwater camera views the transparent channel perpendicular to the channel's axis; hence, the fish are viewed sideways. One problem is the water in the pond is very murky. To optimize the image, the authors use continuous backlighting. A bright illumination source located on across from the camera, on the opposite side of the channel. When there is no fish in the channel, the image is bright. As a fish passes through the channel, the illumination is blocked and a dark silhouette is cast. The silhouette of the fish provides a very high contrast image that is somewhat preserved even in the presence of a large degree of multiple forward scatter. This enables simple feature extraction (on the outer body) followed by classification of the fish. Consequently, the fate of the fish is automatically determined: once it is out of the channel, the fish is either redirected to its habitat or redirected into a fishnet.

Bed-Sediment Microscope

An additional domain of underwater research is rivers. Geologists are interested in the study of sediments in river beds, particularly those of grain size. According to Rubin et al. (2007), sediments would traditionally be taken out of the water and measured in a lab. To enable fast measurements and tracking of changes over time, the authors developed a method to measure the sediments *in situ*. They describe microscopes whose camera and optics are enclosed in a flat viewport housing. The viewport rests directly over the bed area to be sampled to minimize image degradation caused by water turbidity. The optics are pre-focused on the external port plane. Such a setup was integrated into several systems; particularly a video system lowered from a river boat and a hand-held system based on a digital still camera. In addition, versions for marine use were developed, where the microscope served also as one of the legs in a tripod.

Hand-Held Stereocam

Stereo vision is a major technique in computer vision, and has long been studied underwater. Typically, stereo vision systems are mounted on underwater vehicles. In the work described by Hogue and Jenkin (2006), the track of stereo hardware development is done in parallel to development of the robotic platform. The authors intend to integrate a compact amphibious robot, called AQUA, with a stereo vision system. AQUA is able to maneuver in open water by swimming, as well as on soil by crawling and walking. As its stereo-vision system is gradually developing, hand-held versions are being built. The hand-held stereo rig is designed to be compact, easy to carry and easy to operate by a diver. The prototypes are based on machine-vision cameras using Firewire™ interfaces that connect directly to a computer. VGA-quality data is streamed at video frame rates. Their recent implementation eliminates many cabling and tethering problems. The stereo head is compact and enclosed in a small hand-held compartment, which is easy to operate and control by a single diver. A cable connects this compartment to a separate housing, which includes the computer and associated electronics. Finally, the computer housing can be harnessed directly to the diver, alleviating a need for connection with surface support personnel.

Future Trends

Several areas of technology development are particularly notable when anticipating future advancements in underwater imaging technology. Compact high power light sources, data compression and management, and energy storage, and realistic recreation of the image space continue to be areas where major strides are being made.

LED Technology

White light and single wavelength LEDs have made rapid advancements in the past few years with respect to electrical to optical conversion efficacy and wattage. Single package units are available that can produce output of several hundred lumens—equivalent to 60-watt incandescent sources, but at a fraction of the power. A measure of the output normalized to the wattage is the "luminous efficacy." This can range from 50 lumens per watt to 70 lumens per watt for fluorescent lamps, and as much as 50 and 150 lumens per watt for arc light and HMI sources, respectively. White light LEDs promise efficiencies of 150 lumens per watt (or greater) and can be powered from low voltage sources without expensive or bulky ballasts. This makes them particularly useful for battery powered applications such as dive lights, small AUVs or other vehicles. As the technology advances, higher power units will become available and will ultimately replace lamps that currently are rated at hundreds of watts or more.

Laser Technology Advancement

New developments in laser technology have achieved short pulses at blue-green wavelengths offering stable, high repetition rate (> 300 kHz) and average power (> 2W) laser sources (Q-Peak Inc., Aculight Corp.). In an LLS system, this technology enables temporal separation of the backscatter from the reflected target signal and allows primarily the integration of the target photons during the detection process. This tends to increase the SNR allowing a greater distance for detection/imaging of the target. Further refinements in laser technology will be higher speed modulation capability and greater uniformity of pulse-to-pulse energy stability, as well as increases in power, efficiency, and compactness. This will allow more advanced laser imaging systems to be developed and integrated onto small platforms.

Data Management

Managing data from multiple disparate sensors as well as sensors that produce vast amounts of data is currently a challenge and will continue to be so as technology continues to advance. Data management involves storing, cataloguing, searching, retrieving, interpreting (human in the loop), sharing, editing, reusing, distributing, archiving and thinning. Though specialized systems will need to be developed for custom data types, rich media management and Digital Asset Management (DAM) software for high definition video (for example) and its related data is commercially available (Virage, 2007; Artesia, 2008; Digital News Direct, 2008). These packages include features such as automatically capturing, encoding and indexing TV, video and audio content from any source dynamically; automatically generating a comprehensive range of metadata that is immediately fully searchable and accessible by any user; and full screen streaming of HD video content at reduced costs. There is no doubt that these systems and others will continue to evolve for this challenge. A paper by Leslie et al. (2007) presents considerations for assuring high quality software for large-scale data management.

Manipulation of the data goes hand-in-hand with data management. Viewing and processing high volumes of data are often cumbersome for both the computer and the user, because of memory swapping, slow processing and rendering of the data, and the inability to see all of the data on a typically-sized display. Specialized computers for high-end gaming and video editing are becoming popular, as well as large and multiple widescreen displays. As an example, Alienware presented a "giant 'curved' widescreen" display at the 2008 Consumer Electronics Show in Las Vegas. This display is equivalent to two slightly bent 24-inch liquid crystal display (LCD) screens glued together (Pickstock, 2008).

Fuel Cell Camera

Fuel cell power systems are making their way into the imaging field, led by a wireless system referred to as EnerOptix, shown in Figure 13 (EnerFuel, 2007). EnerOptix captures images using four day/night vision cameras that transmit data over a Code Division Multiple Access (CDMA) cellular network. Real-time control of the camera and retrieval of archived photos can be performed via secured Internet portals. By using a fuel cell, the camera is able to operate for extremely long periods of time without recharging or requiring battery swap (typically > 6 months), making it a promising technology for remote surveillance applications such as port, harbor,

FIGURE 13

EnerOptix fuel cell camera. (Courtesy Drew Wallace)

ship, and buoy security and also for ocean observing applications. Fuel cell technology has several desirable attributes that make it suitable for "top-side" ocean operation (e.g., not corrosive, works well in humid conditions, and environmentally friendly), and designs have also recently been proposed capable of long duration underwater performance (e.g., Dow et al., 2005).

Three-Dimensional Television (3DTV)

A study undertaken by European researchers is exploring the feasibility of 3-D television (3DTV) (Kunter, 2006). Although broadcasting 3-D TV signals is beyond today's capabilities, many recent technological advances (some already in use in underwater imaging systems) may help make this "futuristic idea" a reality. As an example, developers of eHoloCam are lending their expertise in holographic imaging to this cause (Benzie, 2007a; Kovachev, 2007). In another example, deformable meshes and other generic 3-D motion object representation tools found in computer graphics technology provide almost all of the tools necessary for 3-D scene representation. Once 3DTV is developed, its use in underwater filming could be a natural progression.

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