PAPER

The Current Art of Underwater Imaging –

With a Glimpse of the Past and Vision of the Future

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This State of Technology Report on Underwater Imaging provides a historical synopsis of underwater imaging, discusses current state of the art, and suggests future possibilities for continued advancement of the field. The history presented herein provides information assembled in a manner not found in previous reviews. Present work is grouped according to imaging methodology wherein foremost research and technical innovations of the field are highlighted, with a focus on the past five years. Trends in research and development are also discussed as they relate to emerging underwater imaging techniques and technologies.

INTRODUCTION

Observation and exploration of the underwater realm has been of interest since ancient times and has forged the development of many technological advances. Advancements in diving apparatus, submersibles, underwater cameras and optics, underwater lighting, sonar, remotely operated vehicles (ROV),

- Electromagnetic (EM) methods that utilize transparent regions of the spectrum (near infrared, ultraviolet, visible, and very low frequency [VLF]);
- Acoustic imaging techniques that include 3-D reconstruction and mosaicking; and

vances are often associated with imaging hardware and methodology, credit must also be given to developments in computer vision and pattern recognition that allow extraction or interpretation of useful information from raw imagery or data. This focus and autonomous underwater vehicles (AUV) are the most notable. Although the quest to travel to ocean depths has been pursued for centuries, emphasis on recording and obtaining or interpreting information beyond that available from the human visual system is an important recent endeavor. Various hardware, software, and algorithmic advancements, as well as better understanding of ocean physical parameters make this possible. For example:

- Conventional imaging methods that utilize standard cameras;
- Extended range imaging techniques that utilize time-gating or angular field restriction to reduce unwanted image noise resulting from optical scatter in the transmissive medium;
- Laser line scan methods that produce 2-D or 3-D imagery;
- Holographic or other techniques that exploit spatial coherency;
- Optical methods using frequency conversion (fluorescence, Raman, etc.) to develop higher-dimensional image data;
- Multiple-perspective methods that achieve range depth or 3-dimensional (3-D) image formation and display (including mosaics);
- Image intensity algorithms based on image processing techniques that exploit effects such as shading, filtering, or motion;
- Temporally discriminant or signal-coded methods that support multidimensional image representations.

Detailed descriptions of many of these preceding methods have been published elsewhere (Potter, 1999; Kocak and Caimi, 2001), and in Jaffe et al., 2001, where an emphasis is placed on extended range imaging.

Historically, imaging developments have been slow to evolve and have taken decades to reach the present state of the art. This has been due, in part, to limitations stemming from incomplete understanding of radiative transfer in optical media such as air and seawater, limitations in image sensor electronic and optical hardware, and restrictions in data transfer, recording, and signal processing throughput. Continued advancements in these areas have effectively countered contrast and range reduction resulting from severe physical effects of light propagation in seawater. Similar observations hold for sound propagation and acoustic imaging. In 1999, a review of the field revealed dramatic advances in video technology, electronic ballasting of HMI lighting, laser technology, mechanically and electronically scanned sonar, and sonar processing algorithms (Olsson, 1999). Although these advances has been noted in a recent publication that underscores the difficulties and challenges of underwater imaging, which is written for the computer vision community (Murino and Trucco, 2000a).

A Glimpse of the Past

"We can chart our future clearly and wisely only when we know the path which has led to the present."

Adlai E. Stevenson (1900-1965)

"The farther back you can look, the farther forward you are likely to see."

Winston Churchill (1874-1965)

Many advancements have enabled the evolution of underwater imaging, including: direct methods for observation such as scuba, underwater housing technology and vessels; development of the electronic camera, photography, video recording and light sources; invention of the laser and fluorometric analysis; as well as the fields of information processing, artificial intelligence and computer vision. Some key milestones in these topics are illustrated in the timeline shown in Figure 1 and are summarized on the following pages.

FIGURE 1

Historical timeline of events leading to present day underwater imaging.

Direct Observation Techniques

As early as 4500 B.C., diving provided a

they could pick up bottom sediment to determine the topography (Hohler, 2002).

derwater visualization techniques. Dive apparatus inventions included the first practical means for food gathering, commerce or warfare for coastal cultures such as those found in Greece, Mesopotamia, and China. In 360 B.C., Aristotle wrote of sponge fishers using an air-supply diving bell; and in 332 B.C. Alexander the Great was reported to have made several dives in a crude glass diving bell for observation (Bachrach, 1998). In the 1500's, Leonardo da Vinci envisioned the first known self-contained underwater breathing apparatus (SCUBA) that combined an air supply and buoyancy control in a single system. In the 1850's, mariners recorded depth measurements, called *soundings*, by lowering a hemp rope marked in equal distances with a lead ball on the end until the tension in the rope changed to indicate that the ball had reached bottom. By covering the ball with grease,

Increasingly, direct observations were sought by traveling into the depths of the sea. The first successful submersible vessel was built around 1620 by Cornelius Van Drebbel. The watertight vessel was wood-framed and sheathed in leather, capable of carrying a total of 20 people to a depth of 20 m. In 1667, Robert Boyle observed a gaseous bubble in the cornea of a snake during his experiments with compression and decompression; however,many years passed before Boyle'sdiscoverywas put to practical use in humans (Borrillo, 2001). John Scott Haldane created a procedure for staged decompression to avoid "the bends" in 1908, which culminated in the publication of the first U.S. Navy dive tables in 1912.

Developments enabling man to remain submerged for longer periods led to early un- SCUBA in 1825 by William James, a diving helmet converted from a patented "smoke helmet" for firefighters in 1828 by Charles Anthony Deane, and, that same year, the first known buoyancy compensator by Lemaire d'Augerville. However,it was not until 1869 when Jules Vern'snovel entitled *20,000 Leagues Under the Sea* was published that the inventions of SCUBA were introduced to the world.

Camera, Photography and Video

Along with advancements allowing travel into the ocean depths, other inventions provided a means of documenting what was being seen both above and below the ocean's surface. The Chinese philosopher MoTiprovides perhaps the earliest written mention of imaging in his description, dating from the 5th

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century B.C., of images formed by a small opening. In 4 B.C., Aristotle made similar observations. Ibn al-Haitham (Alhazen) reported this concept in 10 A.D. and was credited with inventing the pinhole camera. In the 1500's, many artists used a dark box or room with a hole in one end, known as a *camera obscura*(Latin for dark room), to project

ber of plates. Three years later Eastman announced the invention of photographic film in rolls and, in 1888, provides the first Kodak camera designed to use roll film. With these inventions, Eastman established the Eastman Kodak Company (Bellis, 2005a).

The world's first underwater exposure was recorded at a depth of 6 m in 1856,

Technologies, 2005). In 1979, National Geographic was the first to use a CCD television (TV) camera in the deep ocean. The story behind this expedition is provided here, paraphrased from Emory Kristof (2005):

> *In early 1977, the hot water vents are discovered about 100 miles north of the Galapagos Islands at 8,500 feet*

inverted images onto the opposite wall where they could be traced. Giovanni Battista della Porta's writings in 1591 document the first use of a camera obscura with lens, to increase brightness and clarity (Hammond, 1981). In the early 1800's, William Hyde Wollaston introduced a *camera lucida*(Latin for light room), which was merely a prism mounted above a drawing board that allowed an artist to trace the superimposed image in ambient light.

All of these discoveries led up to the invention of *photography*, a term coined bySir John F.W. Herschel in 1839, meaning *writing with light*.Toaccomplish this, a special ink would be required that responded to light. More than 2000 years before the invention of the camera obscura, it was known that a particular snail, the *purpura,*would leave a yellow substance in its wake that turned purple in sunlight (Grundberg, 2005). Experiments in photographic chemistry were recorded in 1727 when Johann Heinrich Schulze observed that silver salts darkened when exposed to light. By 1800, chemist Thomas Wedgwood succeeded in producing images using silver salts, but the images eventually faded. In 1826, Joseph Nicephore Niepce used a bitumen-coated plate in camera obscura to capture the earliest photograph still in existence. Following this, in 1837, Louis-Jacques-Mande Daguerre solved Wedgwood's problem of stopping the exposure process by washing away remaining silver iodide using a solution of warm water and table salt. Just after the announcement of Daguerre's process, called *daguerreotype*, in 1839 William Henry when William Thompson published his experiment in the Journal of the Society of Arts (Baker, 1997). Thompson took the photograph from the surface using a camera attached to a pole (a precursor to the ROV) with an exposure time of 10 minutes. Not surprisingly, the camera flooded but the image survived. In 1872, Ernest Bazin allegedly took photos at an underwater observatory using an electric lighting system; however, none of the photographs have been found (Gilbert and Alary, 1996). In 1893, Louis Boutan was credited for taking the first photographs with diving gear, equipped with a (not so portable) purpose-built camera and housing weighing 400 pounds.

In the 1900's many underwater inventions followed: in 1915 John Ernest Williamson produced the first underwater movie; in 1923 William H. Longly and Charles Martin took the first underwater color photos using magnesium lighting (Gilbert and Alary, 1996); in 1939 Hans Hass, considered the father of modern underwater photography, produced the first underwater film entitled *Stalking Under Water*; in 1957 Jacques Yves Cousteau and Jean DeWouters invented the first waterproof 35-mm camera named *Calypso Phot*, later known as *Nikonos*; and in 1960, EG&G developed an extreme depth underwater camera for the U.S. Navy (Bellis, 2005b).

The decade of the 1950's brought about color television'slarge-scale commercial introduction, with several notable events including development of the first two-inch format video tape in 1956 by Ampex Corporation.

(2,590.8 m). National Geographic publishes the first story on the vents in 1977. A decision is made by the National Science Foundation (NSF) to fund a second Galapagos Rift Expedition with biologists. National Geographic decides to produce a second story and a one-hour PBS TV show. My investigations into TV camera technology reveal that 3 tube cameras are too large to package for exterior use on ALVIN, and that the quality of 1 tube cameras are insufficient. All known TV cameras use tubes. Shortly thereafter, a group from National Geographic meet with diver/film maker Smokey Roberts from Lancaster, Pennsylvania in a bar in Woods Hole where Smokey tells us about a diving student of his, Harold Krall. Harold is Vice President of RCA in Lancaster and is in charge of building a revolutionary new TV camera based on a radical new solid-state device called a CCD. The potential for reducing the size of a TV camera is amazing. Four days later, I head a group from National Geographic to meet with Harold. At the time, RCA is leading the world in this technology (about 18 months ahead of Sony) and has experimental cameras in its lab. This is all new to National Geographic. RCA agrees to build a camera for the expedition and Benthos agrees to build the deep-sea housing. The camera is used on 7 dives in early 1979 and the video results are wonderful. The RCA engineer who built the camera, Fred Engle, makes the

FoxTalbot revealed a similar invention called *photogenic drawing*. Talbot'sprocess, later refined and renamed the *calotype*, formed the basis for most modern film technology, which relies on negatives to produce multiple positive prints. By 1880, George Eastman had invented a dry plate formula for film and had patented a machine for preparing a large num-

Mass-market Betamax and VHS videocassette recorders became available much later, in 1975 and 1976 respectively (Fenton, 2004).

The origin of the charge-coupled device (CCD) digital camera stemmed from the need to storedata in a computer memory.In1969 Bell Lab scientists Willard Boyle and George Smith proposed the idea of the CCD (Lucent

trip and a dive to fine-tune the camera. Al Giddings and I operate the camera, with Al shooting most of the footage as chief TV photographer. The National Geographic Magazine article is published in 1979 alongside of the PBS show "Dive to the Edge of Creation." This Emmy-winning production on the vents is the

first show ever filmed with a solid-state device (in this case a CCD). It is also the first show ever filmed in the deep ocean with an externally mounted color TV camera. The National Geographic magazine ran one color still photo making it the first use of digital photography in the magazine.

Soon after, camera technology was launched into the digital age with the first commercial solid-state camera (Sony'sMavica) introduced in 1982 and the first digital camera system (DCS) targeted at professionals and journalists introduced in 1991 by Kodak (Bellis, 2005c). In1994 Apple'sdigital camera launched home-use of the technology.

For nearly 30 years, the CCD was the prevailing digital image sensor. However, at the beginning of the 1990s, small packaging

cial lighting underwater. In1899, Boutan used a magnesium-filled flash bulb, designed by Chauffour, at a depth of 50 m (Marshall, 2005a). Dr. Paul Vierkotter (1925) and Johannes Ostermeier (1930) made improvements to this bulb design, which resulted in the first commercially available flash bulbs. In 1931, Harold Edgerton developed the first high-speed electronic flash called the *stroboscope*(Marshall, 2005b).

Inrecent history,lasers play an important role in underwater imaging. In 1917, Albert Einstein first theorized about "stimulated emission," the process that makes lasers possible. Forty-one years later, Arthur L. Schawlow and Charles H. Townes received a patent for theory extending their "maser" (microwave) technology to infrared and visible spectrum light (Bertolotti, 1983 and Bellis, 2005d).

sonar listening device to detect icebergs (Bellis, 2005e). Soon after, in 1915, Paul Langevin invented the first sonar device for listening to submarines. A more comprehensive history of sonar can be found in Theberge (1989).

Artificial Intelligence (AI) and Computer Vision

Computer vision developed from signal processing research, whereas image understanding is the branch of artificial intelligence (AI) that seeks to provide computers an ability to derive semantic formalisms that accurately describe the meaning of a scene or features of an image. Goals include what are thought to be high-level visual functions in animals and humans, such as registration, segmentation, localization, recognition, classification, tracking, motion of the complementary metal oxide semiconductor (CMOS) transistor allowed an alternative imaging technology to develop.Throughout the 1990s, CMOS imager circuitry evolved from passive to active pixel systems to provide performance nearly matching that of the CCD process. The active pixel system (APS) provides random pixel access, on-board amplification and gating, as well as low power consumption. Unlike CCDs, CMOS sensors suffer reduced sensitivity; however, CMOS technology continues to be used predominantly for high-speed imaging and offers the following advantages: freedom from blooming when over-exposed, less power resulting in smaller and less complex drive electronics, flexible read-out allowing frame rates to be increased, spectral sensitivity matching that of the human eye, and low cost due to high-volume of manufactured semiconductors.

Ongoing developments in digital imaging technology are expected to support on-board pixel specific processing, such as sensitivity normalization, anti-jitter,thresholding, filtering, image compression and other functions that now require separate processing in software or digital signal processing (DSP) hardware.

Lighting and Laser (Light Amplification by the Stimulated Emission of Radiation)

Louis Boutan is one of the first photographers (often credited *as the first*) to use artifi-

Fluorometry

Although earlier observations of fluorescent organisms were reported, C.E.S. Phillips published the first observation of fluorescence in a marine organism in 1927 (NightSea, 2005a). In 1964, the same year WHOI's*Alvin*submersible recorded its first dive, Rene Catala was the first researcher to systematically examine and photograph fluorescence in corals. Morerecently, diver-held fluorescence imaging cameras have been developed with built-in ultraviolet (UV) lighting such as light emitting diodes (LED), and a variety of laser-excited fluorescence imagers for discrimination of manmade, versus naturally occurring, objects for biological investigation. Digital extraction of fluorescence from regular photographic or videographic images is also possible. Typically an excitation filter for stimulating a fluorescence response is placed over an intense, focused light source such as a high intensity discharge (HID) bulb, and a barrier filter is placed over the still or video camera lens to block unwanted reflections (NightSea, 2005b).

Sonar (SOund Navigation And Ranging)

Although early sounding methods advanced to a depth of 1 mile, it was not until 1906 that an electric echo sounder was developed when Lewis Nixon invented the first

estimation, shape estimation, and depth estimation, as well as methods for enhancement of images not possible by natural vision systems, such as mosaicking, 3-D reconstruction, and filtering (e.g., deblurring and noise reduction) (Picardi and Jan, 2003). These functions are achievable using numerous imaging modalities (e.g., conventional 2-D, 3-D methods, sonar, EM, fluorescent, Raman, etc.).

The birth of "modern" AI may have been motivated by Alan Turing's publication (in 1950) of *Computing Machinery and Intelligence*, wherein he posed the question "Can machines think?" Others assert that AI began in 1955, when Allen Newell and Herb Simon developed a computer program called *The Logic Theorist*. Subsequent noteworthy events include a 1956 Darmouth computer conference that described the future of AI research and the development in 1958 of LISP (LISt Processing) language for AI—both led by John McCarthy. The first attempt at solving problems in computer vision may have occurred in 1967, when Marvin Minsky so assigned an MIT graduate student, believing that the problem could be largely solved within one summer (Olson, 2003). In 1982, David Marr's book *Vision: A Computational Investigation into the Human Representation and Processing of Visual Information* further motivated the study of human and machine vision as well as the application of machine vision to quality control on manufacturing assembly lines.

A Look at the Present

"Yesterday's the past and tomorrow's the future. Today is a gift – which is why they call it the present."

Bil Keane (1922-present)

"Seize the day."(Carpe Diem)

Horace (BC 65-8)

Today's technology supports a wide assortment of fast, inexpensive specialized image processing software and hardware, and high-quality affordable consumer cameras. Lasers continue to be used for 2-D and 3-D quantitative measurements, along with sonar processing utilizing fast microprocessors, field-programmable gate arrays (FPGAs) and DSPs. Algorithms once too computationally expensive are now feasible and as hardware continues to advance, new applications are becoming possible.

Conventional Imaging Methods

Twenty-first century developments include advanced cameras with resolution ex- et al., 1997). Morerecently, streaming video compression standards having better compression ratios are being developed for next generation commercial video applications. The Advanced Video Standard (AVS) codec (compression-decompression hardware/software) being developed in China is a subset of the popular H.264 standard that offers a bit rate 61% of that required for MPEG-4. AVS uses an 8x8 pixel macro block, while H.264 uses a 4x4 block thereby taking advantage of granularity in the processing scheme. Standard definition decoders are currently available for the H.264 standard and high definition decoders are expected later this year (Mu, 2005; HD Issues, 2005). Development of the JPEG2000 real-time video codec utilizing wavelet compression enables rich content, high resolution, and scalability features at 30 fps, and is rapidly making its way into the consumer, medical, defense and aerospace markets (Johnson, 2005; Pearson and Gill, 2005). A feature of JPEG200 over other streaming compression schemes is complete independence of encoding/decoding for the subject frame from other frames in the sequence. Video compression advancement will no doubt continue to provide benefits for real-time undersea video transmission over bandwidth limited channels, as well as archival data storage. perpendicular strike angle (Cardinal, 2001; Taylor, 1980).

Changes in broadcast formats planned for the past decade, such as the high definition television (HDTV) 1080i standard, are finally reaching the consumer market, which has motivated development of HDTV cameras and display devices. The packaging of these devices for underwater operation has been a recent design activity: several underwater HDTV cameras are now available. Transmission of HDTV signals over long distances can be accomplished with fiber optic converters and single mode fiber optic cable, although multiplexing of multiple HDTV signals has not been well addressed by the industry.Specialty cameras, such as HDTV, IMAX 3-D, Reality Camera System (Anthony, 2001), low light silicon intensifier target (SIT), intensified SIT (ISIT), and intensified CCD (ICCD), have contributed to deep-sea applications and cinematography.

Low light HDTV cameras such as the HARP-type employ image pickup tubes that use the avalanche multiplication effect within photoconductive film. Sensitivity and lag characteristics are remarkably improved in the Super-HARP tube as a result of using a thick 25 µm photoconductive film, providing ultra-high sensitivity (11 lux at F8 which is 640 ceeding 20 million pixels. High-speed CMOS imaging systems are now available offering frame rates of up to 3,000 frames per second (fps) with $1{,}024^2$ pixel image resolution and frame rates in excess of 150,000 fps with reduced image resolution. The replacement of film media with digital CCD or CMOS sensors is providing numerous options for underwater operation. These cameras can prove useful for high-speed inspection applications where image blur would normally be a problem and promise high-quality images even under adverse illumination (e.g., < 1 lumen per square meter [lux]).

In addition, video sequences can be encoded with discrete cosine transform (DCT) based schemes (H.261, H.263, MPEG1 and MPEG2), wavelet and sub-band filtering technology, fractal-based algorithms, or image segmentation/region based compression schemes (MPEG4) to minimize the data transmission rate or on-board storage requirements (Hunter

Video clip recording capability for devices utilizing these new techniques will progress from minutes to hours over the next few years.

Output interfaces from digital still cameras have evolved from serial RS-232, PCI or enhanced PCI bus, to universal serial bus (USB), to IEEE 1394 (FireWire), while video uses NTSC or PAL formats with Ethernet interfaces. Soon, wireless interfaces will be available using ultra wideband (UWB), 802.15.3, 802.11n and other protocols.

Additional trends in the development of high-density CMOS image sensor arrays include enhancing the image format to allow compatibility with standard 35mm format lenses. Wide angle imaging from CCD arrays is a more difficult problem since the sensitivity drops rapidly away from normal light incidence on the array. This effect mandates the use of telecentric lens designs that map an angular input field into a proportional displacement at the lens focal plane with near

times that of conventional tube camera), negligible lag and a high resolution of over 700 TV lines (NHK, 1998).

Several new processing techniques being developed for conventional imaging systems will be directly applicable to underwater cameras. For image enhancement, noise reduction software will be embedded in cameras to produce apparent improvement in sensitivity (DxO Labs, 2005). Lens distortion, vignetting, and lateral chromatic aberration will be corrected automatically, even if the amount or type of correction differs significantly from one image to the next. Software will take into account the sensor characteristics and will reduce noise to produce images characteristic of several f-stops less. Motion stabilization software is being integrated into cameras, to reduce image blur at longer exposure times thereby increasing sensitivity while reducing blur. These techniques are particularly appropriate for on-the-fly inspection application of pipelines or any appli-

cation requiring rapid survey and high resolution. Spectral filtering algorithms designed specifically for underwater cameras have been added to digital cameras and camcorders to correct for the increased red attenuation of seawa-

confined spaces. A significant advancement in CMOS chip technology allows construction of underwater micro-video cameras. Carrillo Underwater Systems has reduced video camera circuit boards to single chips.

transparent particles visible to a camera (Strickler and Hwang, 2000). Backlighting and lighting of known water volumes to quantify the particles and animals (Caimi and Tusting, 1988; Carder and Costello, 1994) ter. Range dependent correction is also possible using algorithmic approaches.

Other methods of enhancement, such as brightening and sharpening, will be integrated directly into image sensor chips. Minolta's Vectis Weathermatic Zoom Camera is the first camera to combine zoom, autofocus (AF) and Advanced Photo System features. With a depth rating of 33 feet (10 m), the camera's passive AF system determines its focus based on the contrast of subjects, as opposed to less sophisticated active range finding systems that often use a light beam that scatters or attenuates in the water. This makes clear, sharp pictures possible below water without the complexity of added hardware. Range measurement systems, however,will be incorporated into cameras at the pixel level to allow entire 3-D range maps to be produced by a single CMOS sensor (Bamji and Charbon, 2003). The idea of recording the zoom setting and focal length adjustment to obtain a better idea of image size is a possibility that would obviate the need for auxiliary range finding hardware.

Innovative commercial off-the-shelf (COTS) underwater cameras include diver controllable models that accommodate both wide-angle lenses and macro lenses, and weigh less than three pounds in air. SeaView Video Technology offers a "Twin-Cam" system with simultaneous full-color video for bright sunlight and clear water, and infrared (IR) illumination used with black and white video for deep water, murky bottoms and night viewVideoRay has developed a swimming miniROV camera system, VideoRay Pro, having a minimum sensitivity of four lux. Optionally, an infrared camera having 0.03 lux sensitivity is available and has been used at NASA/Kennedy Space Center to inspect tanks, culverts, and hazardous submerged areas, and by Discovery Channel to capture footage of sharks for the documentary Sharks of the Great White North.

In addition to camera advancements, new glass housings have been created to withstand hadal pressures below 10 km allowing advancements in deep-sea photography. One system named GlassCAM, developed at Scripps Institution of Oceanography, currently utilizes a Nikon CoolPix digital camera (Hardy et al., 2002). The system has been successfully deployed 18 times in locations from the Sea of Cortez to the Aleutian Trench, reaching a maximum depth of 4.2 km.

Illumination Methods

Specialized illumination systems have been developed utilizing forward scattered light to view small aquatic organisms and bubbles. The most recent illumination schemes provide information regarding trajectories of zooplankton and utilize Schlieren optics to make nearly

FIGURE 2

Atolla jellyfish: (a) full view, (b) bioluminescent pattern and (c) LED simulated bioluminescent pattern.

(Photos by Edie Widder.)

have recently manifested in the Video Plankton Recorder (VPR) (Wiebe et al., 2002). This system utilizes a CCD video camera with a high magnification lens and short pulse duration, collimated 80-W xenon strobe with a parabolic reflector to image fixed volumes of water at a rate of 60 Hz.

What wavelengths of illumination do ocean dwellers see? Recent scientific research is devoted to learning how animals perceive their environment (Marshall et al., 2003; Milius, 2004; Hart et al., 2004). Studies suggest that many of the fish living near the surface or in coral reef habitats are able to see ultraviolet-A (UVA) wavelengths (Losey et al., 2003). One advantage of this may be that many planktonic species transparent at visible wavelengths appear opaque at UVA wavelengths due to increased light scattering and presence of UV-protective pigments (Johnsen and Widder, 2001). Improvements in cameras (e.g., UV-sensitivity) and equipment for analyzing light and color are making this research possible.

A recent development, referred to as "Eye in the Sea," uses red light outside of the animals' normal vision range to illuminate a video camera's field of view unobtrusively (HBOI, 2005). The system is designed to operate on the seafloor ing – an excellent fit for underwater inspection applications. A Bowtech/ROS camera features a solid-state CCD that has low light level performance nearly matching that of a conventionally tubed SIT camera without the concerns of mechanical impact survivability.

Undersea cameras are also becoming miniaturized. Inuktun Services provides a small amphibian camera equipped with a pan assembly. At only four inches in diameter, the remote camera can fit through small openings for inspection inside of tanks, pipes and other

automatically and, most importantly, unnoticed by animals. The video camera is triggered to record footage at scheduled intervals or when bioluminescent light is detected nearby. In a recent deployment in the Gulf of Mexico (just prior to and during Hurricane Katrina's arrival) the system was equipped with a "jellyfish lure" consisting of blue LEDs programmed to simulate bioluminescent patterns of the Atolla jellyfish (Figure 2).

Extended Range Techniques

LIDAR (LIght Detection And Ranging)

Oceanographic LIDAR systems have pri- can be formed with conventional camera lighting at 1-2 attenuation lengths and at 2-3 attenuation lengths with some control of the camera and light separation. Extended range image techniques provide the possibility of imaging at 3-7 attenuation lengths.

A variety of range-gated imaging systems have been developed in the past two decades. The first systems used lower powered pulsed lasers and time gated image microchannel plate (MCP) intensifiers to enable the image capture as the laser photon packet arrived after a round trip from source to target, thereby screening photons traveling longer or shorter round-trip distances due to scatter in the near optional digital camera assembly for collecting passive light, a position and orientation system, and processing hardware. The systems produce real-time geo-rectified 3-D images and topography from an airborne platform and collect time-synchronous LIDAR range and image data from an optical receiver. The resulting image frames can be mosaicked and orthorectified in real-time. The LIDAR range data and passive image data may be referenced to a position and orientation system to transform the 3-D range images to a single geographically referenced multispectral 3-D image (Pack and Frederick, 2003). Deployment of an airborne system consisting of bathymetmarily been developed for aerial hydrographic mapping and surveillance. These systems have been in use for several decades and have evolved as the result of improvements in high power laser technology. High repetition rates, high energy, and multispectral capability are important factors in modern LIDAR systems capable of 3-D rapid environmental assessment (REA).

The state of the art in commercially available hydrographic LIDAR allows depth measurements from just under the surface to 50 m with an accuracy of 0.25 m over a swath width of about 250 m or 0.6 times the flight altitude at a 1000 pulse-per-second data rate (Optech, 2003). Typical system power is 2 kilowatts supplied by the 28-volt aircraft power system. Imaging of objects suspended within this depth range is a byproduct of the hydrographic mapping capability and the horizontal accuracy of 2.5 m or 1 part in 100. The speed of objects moving in the water column can also be estimated from LIDAR measurements (Wilkerson et al., 2003). Software for geo-referencing, as well as data management and analysis has also reached maturity.

Range binning of LIDAR return imagery has the effect of removing scattered light effects from water volumes outside the range bin and is therefore useful for imaging through highly turbid media. Using amplitude returns from a single range bin (range gating) removes scattered light from much of the illuminated volume within the camera's field-of-view (FOV), thereby improving contrast at a fixed range distance and more importantly, increasing the distance over which images can be field. Over the years, progress in MCP design has reduced noise contributions from random noise (speckle)—newer third generation devices exhibit much improved signal-to-noise ratios (SNRs) compared to first or second generation intensifiers. These improvements, in addition to advancements in pulsed laser technology, make possible today's range-gated imaging systems. One particular system, Laser Underwater Camera Image Enhancer (LUCIE) is able to use high repetition rates of 2000 pulses per second with subsequent averaging to reduce image noise (Jaffe et al., 2001). Various forms of this system have been developed—both diver held and ROV/AUV deployable. The most recent systems exhibit reduced size (25 cm diameter and 70 cm length), operating with a 22 KHz repetition rate and 5 ns pulse length (Weidemann et al., 2002). Image performance is 3-5 times that of conventional image systems under artificial lighting and approximately twice that of divers' visual discrimination under natural illumination. Future improvements to the system will include automated control, improved image filtering, and sonar assisted range estimation via automated gate setting.

More recent developments in LIDAR stem from the multispectral capabilities of pulsed lasers, allowing multispectral and hyperspectral data sets to be obtained. Water quality, object recognition, and biological and geological assessment are potential byproducts of analysis of multispectral LIDAR images. Systems typically consist of a laser transmitter light source, a laser detection assembly, optics that couple ric LIDAR, topographic LIDAR and a digital camera is scheduled to include a passive spectral imager (Francis and Tuell, 2005). This upgraded system will be able to measure LIDAR, camera and hyperspectral data simultaneously to extend missions beyond conventional hydrographic surveying—targeted for REA in the littoral zone.

Time Resolved Imaging LIDAR

One approach to obtaining a simultaneous image and temporal history of the returned photon packet is to use a streak tube to simultaneously record one dimensional (1-D) image data from a pulsed laser fan beam. The Streak Tube Imaging Lidar or STIL (Bowker and Lubard, 1995) is a classic example illustrating performance achievable with this method. The system comprises a scannerless design that uses only a cylindrical lens to form a fan beam from the pulsed laser source. Since the entire time history is available for each channel across the fan beam at the detector, the system can generate a full 3-D range map by successively combining azimuth-range images along the track. The STIL has evolved into a tow body deployed surveillance imaging system, and has been tested extensively in turbid waters (Jaffe et al., 2001).

Laser Line Scan (LLS) Systems

Synchronous Scanning

Synchronous Scan imaging systems tend to outperform other system types due to reduction of shared volume between the illumination and the detection systems, but at the expense of complexity. Bylimiting the FOV,both formed at a given contrast. Typically images the outgoing and incoming laser signals, an forward scatter and backscatter effects are mini-

mized. These systems were originally developed by Raytheon (Leathem and Coles, 1993 and Coles, 1997). Current systems employ multi-spectral line rather than single line laser illumination, and use simultaneously scanned multiple Photomultiplier tube (PMT) receivers with separate color filtering to render output imagery in 12-bit color (Nevis and Strand, 2000). The 12-bit dynamic range produces highly detailed images at optical ranges of up to 7 attenuation lengths.

3-D Optical Image Formation

Methods based on triangulation have been demonstrated for obtaining 3-D range and intensity maps (Caimi et al., 1993; Caimi et al. 1996; Kocak and Caimi, 1999). Those systems relied upon a 2-D laser scan of a volume of water (nominally 1 cubic meter) and a high sensitivity, image intensified 2-axis photodetector that is position sensitive. Images from such systems can be formed over larger volumes but tend to suffer from backscatter effects that adversely impact accuracy in turbid media. Other developments include a system originally patented by Moran that uses phase mapping assessments (Carey et al., 2003; Amend et al., 2004). Although storage and bandwidth limitations were revealed, the surveys demonstrated feasibility of the technology for conducting benthic assessments. Second generation LLS have since improved data capture and storage methods, and currently offer three-color imaging (Mazel et al., 2003) and 3-D imaging (Moore et al., 2000). For example, *3D Sea Scan*uses a triangulation method implemented in terms of a 1-D point-by-point laser scan and 1-D CCD detector. The system produces a full 3-D range map by using vehicle motion (*y*-axis) perpendicular to the scan (*x*-axis) to accumulate sequential azimuth-range (*x*-zplane) data slices. This system has been used to produce bathymetric data sets as well as surface maps of mine like objects (Moore, 2001).

Temporally Coded/Coherent Methods

Holographic Imaging

Holographic imaging of particulates was demonstrated decades ago (Thompson, 1990; Carder, 1979). Recent developments include Katz et al., 1999, where an in-line hologram is

The scanner uses mechanically coupled mirrors to scan an Argon laser at 488nm, as well as four narrow FOV PMT receivers fitted with interference filters—typically at 488nm, 520 nm, 580 nm and 685nm. The imaging system therefore produces outputs for red, green and yellow fluorescence, as well as at the excitation wavelength. The cross track resolution is typically 10 milliradians or less, while the in track resolution is determined by the sensing configuration speed, beam divergence and scan mirror rotational speeds. The system produces images useful for discrimination of different substrates and biota (Strand, 2002).

More recent studies have improved the FILLS images byDiscrete Fourier Transform (DFT) filtering and logarithmic scaling. Identification studies have been performed using rule based processing with ENVIcommercial software (Mazel, 2002).

Systems have also been developed commercially. NightSea offers two products for “seeing, videotaping, and photographing” fluorescence underwater, which enable a diver to visualize fluorescence, while accessory filencoding of a waveform and simultaneous modulation of the gain of an image intensified array to achieve an intensity-encoded 2-D range image (Moran et al., 1993). Range can easily be displayed in pseudocolor encoding of the observed scene. More complex schemes are possible, which perform better in turbid conditions (Mullen et al., 1999; Mullen et al., 2004).

A multi-dimensional laser line scanning imaging system has been developed to serve as a platform for new concepts in underwater imaging (Fuchs, 2004). The system has expanded on its patented 3-D range data predecessor (Caimi and Smith, 1995), adding relative reflectance of each pixel and five channels of fluorescence emission in the scene. Applications for such data range from Homeland Security issues such as mine detection and ship husbandry,to environmental studies offering an understanding of the nature and significance of fluorescence and reflectance characteristics of benthic marine organisms, particularly in coral reef areas.

Northrop-Grumman's first-generation laser line scan (LLS) imaging system, SM2000, was used on several occasions for benthic habitat formed, recorded, and subsequently converted into a 3-D image capable of 10 ìm-particle resolution. Further refinement of holographic imaging systems (Watson et al., 2001) supports recording of both in-line and off-axis reference beam holograms. Off-axis holograms require a higher spatial frequency carrier and high resolution recording media, but have the advantage of being able to record higher particle densities compared to in-line methods.

Optical Methods using Frequency Conversion

Fluorescence Imaging

Fluorescence imaging, as well as other imaging methods that exploit inelastic optical processes, is useful for detection and identification when other methods fail or give ambiguous results. The Fluorescence Imaging Laser Line Scanner (FILLS) is a variant on the RGB color scanner that uses synchronously scanned laser with a reduced FOV and multiple, optically-filtered PMT receivers to reduce forward and backscatter (Strand et al., 1996). This method is able to produce images at up to 6 optical attenuation lengths. ters for photo and video equipment make it possible to record the effect. One model uses high-intensity UV for stimulating fluorescence of hydrocarbons, tracer dyes for leak detection, and other fluorescent materials used in non-destructive testing, while the other system uses lower intensity blue illumination for observing biological fluorescence and some fluorescent dyes.

For still photography with film or digital cameras, custom filters are available that fit over existing electronic flash units to stimulate fluorescence, with a complementary filter in front of the camera. Either ultraviolet or blue light can be used for photography or videography. NightSea has also developed a compact unit that incorporates a Nikonos camera and two small strobes for taking pictures in the daytime. One of the camera models was used to locate a leak in an intake pipe in a reservoir using drinking-water-safe fluorescent dye (Jones, 2001).

Raman Imaging

Raman imaging allows probing of molecular vibrational states via inelastic scattering

(Hu and Voss, 1997) and has been used for moving objects, significant illumination 2004; Zhang and Negahdaripour, 2005) foremote sea surface temperature measurement, which is useful for detection of various objects and substances. Recent developments of Raman imaging systems at close range are the Deep Ocean Raman *in situ* Spectrometer or DORISS—a Raman probe designed for geochemical analysis. It requires precise focusing and location-finding ability that is obtained from Monterey Bay Aquarium Research Institute's (MBARI) precise underwater positioner (PUP) work platform (Kirkwood et al., 2003). PUP uses laser photogrammetric methods (Caimi and Tusting, 1988) to position the probe at or near required focal distance. The probe uses a cooled CCD array and holographic spectral grating for detection and Nd:YAG laser for excitation of mineral or other species. Gas and mineral analysis have been achieved in geological samples (White et al., 2004).

Multiple Perspective Methods

A number of recent activities combine video imagery taken from multiple views of a scene to derive size and depth measurements (Liu, 2001; Baglio et al., 2001; Boynton and Voss, 2004; Takahashi et al., 2004), photo-mosaics (Fleischer et al., 1996; Xu and Negahdaripour, 1997; Negahdaripour et al., 1998a; Negahdaripour and Xu, 2002; Garcia et al., 2001; Roman and Singh, 2001; Espiau and Rives, 2001; Rzhanov et al., 2001; Gracias and Santos-Victor, 2001; Gracias et al., 2002; Gracias et al., 2003; Gracias and Negahdaripour, 2005) and 3-D reconstructions (Plakas et al., 1998; Khamene and Negadaripour, 2003; Negahdaripour and

changes, transect superposition, and positioning drift. Figure 3 demonstrates Gracias and Negahdaripour'sconstruction of mosaics using data captured at multiple altitudes, where the two color shades are used to distinguish images coming from each of two altitudes (2005). In this mosaic, 5,000 image frames were rendered and 496 key frames were used in the global registration to cover an approximate area of 400 m^2. The resulting mosaic image provides a resolution of 2.5 mm/pixel useful for ongoing monitoring and health assessment of coral reef mapping funded byDoD's Strategic Environmental Research and Development Program (SERDP).

Recent stereovision techniques (Lacey et al., 2000; Adams et al., 2002; Pizarro et al., 2003; Pessel et al., 2003; Zhang and Negahdaripour,

cus on methods designed to decrease time, improve accuracy and enhance robustness of locating point correspondences in image pairs using RANSAC-based algorithms (Fischler and Bolles, 1981). In one application, for example, quadranocular (2-pair) stereo video images are used for 3-D reconstruction to automate the trajectory of the camera'sposition onboard an ROV (Zhang and Negahdaripour, 2003). Unlike most reconstruction techniques that rely on knowing the camera's geometric position relative to the target, this method accounts for the 6 DOF platform motion and recovers position and pose automatically from the video data. Another stereovision application uses a simpler feature-matching scheme (not using RANSAC) to perform closed-loop tracking of gelatinous animals in open water for visual

FIGURE 3

Complete video mosaic taken in Key Biscayne, Florida covering an area of approximately 400 m^2.

Madjidi, 2003; Pizarro et al., 2004). These activities support (semi-) autonomous or operator-supervised missions pertaining to automatic vision-guided station keeping, location-finding and navigation, survey and mapping, trajectory following and online construction of a composite image, as well as search and inspection of seabed structures and ship hulls (Leabourne et al., 1997; Negahdaripour et al., 1999; Lots et al., 2001; Negahdaripour and Firoozfam, 2005). These tasks require an accurate estimation of camera position, together with fast, accurate correspondence determination, particularly for real-time registration. Common sources of error include non-planar seafloor,

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servoing for ROV navigation control (Rife and Rock, 2001). In instances when these nearly transparent subjects become invisible in one camera image, a feature-based scaling method, rather than stereo triangulation, is used to compute range. More recently, Rife and Rock (2003) introduce a predictive assessment method for analyzing segmentation methods required for tracking an object of interest—in this case jellyfish.

Single camera stereo systems with mirror

Image Intensity Algorithms Based on Image Processing Techniques

Optical imaging provides high-resolution imagery at fast sampling rates, permitting operations requiring high-precision and online performance. Nearly all subsea vehicles are equipped with at least one standard video camera. Cameras are passive, providing a natural choice for covert and reconnaissance operations, and optical imagery contains rich visual cues (e.g., color, shading, texture, and

for transmission (Negahdaripour et al., 1998b; Yu et al., 2003; Schmalz, 2005), image enhancement and object recognition using multidimensional spectral analysis (Soriano et al., 2001; Madjidi and Negahdaripour, 2004), polarization (Schechner and Karpel, 2004), pose (Crovato et al., 2000), or other methods and data (Bailey et al., 2003). Some recent developments are described below.

reflectors, called *planar catadioptric stereo systems*, have been used in terrestrial applications but have not yet migrated to subsea applications (Gluckman and Nayar, 1999; Tan et al., 2004). Instead, specialized, multi-camera configurations have been used to effectively expand the FOV in ocean applications. One system, comprised of 6 standard CCD cameras having overlapping fields of view,combines images from each camera to form a single, high-resolution image for high-volume data capture (Negahdaripour et al., 2001; Firoozfam and Negahdaripour, 2002). Results show that the extended field of view enhanced robustness and accuracy for selected computer vision algorithms, including 3-D motion estimation. A conical panoramic stereo imaging system has also been tested, comprised of 12 standard CCD cameras (Firoozfam et al., 2003). This system targets 3-D visualization and improved scene reconstruction by utilizing correspondences in more than 2 views of the scene at modest distances.

Other hybrid systems combine multiple views with secondary sensor data. For example, a laser line imaged by a stereovision system is used to measure bedform geometry such as wave ripples (Baglio et al., 2001). Another system uses a Kalman filter-based framework to integrate the shading flow with image motion and stereo disparity to recover 3-D motion and structure of a seafloor environment (Khamene and Negahdaripour, 2003). Lastly, J-QUEST (Japan QUantitative Echo-sounder and Stereo Tv-camera system) combines an echo sounder for esti-

surface markings) for numerous recognition applications. New techniques are being adapted from traditional image processing and computer vision research that allow improved image formation, data analysis and visualization. These often rely on complex mathematical operations to obtain apparently hidden or underlying information or to reduce noise or extraneous information. Examples are image stabilization algorithms (Barufaldi et al., 2003; Plakas and Trucco, 2000), reduction of redundant image information to reduce bandwidth requirements

FIGURE 4

Image enhancement by removing degradations caused by polarization of light: the left side shows the best raw image; the right side shows the recovered image.

Polarization-based Image Enhancement and Extended Range Viewing

A new physics-based approach to computer vision extends visibility in naturally illuminated underwater images by removing degradations caused by polarization of light (Schechner and Karpel, 2004). The algorithm makes use of at least two images taken through a polarizer at different orientations (e.g., horizontal and vertical). Significant improvements in scene contrast and color correction can be obtained, as illustrated in Figure 4, which features white balancing based mating fish density per unit volume and a stereo, low light TV camera system to identify fish species and estimate length and tilt angle of the observed fish for fish stock assessments (Takahashi et al., 2004).

on a nearby white sand patch. In terms of the raw image, this process quickly loses its effectiveness as objects become more distant, but with appropriate processing, colors are recovered over longer distances. In addition to enhancing visibility, an estimate of the scene's relative range map can be obtained. Thus, if the distance to a single point is known, then the absolute distance to any point in the scene can be derived.

Interestingly, as noted by Johnsen (2005), "the simplicity of this [visibility enhancement] algorithm suggests that it may be used by polarization-sensitive species for the same purpose." For instance, one species of squid is known to use polarization sensitivity to enhance contrast of possible prey (Shashar et al., 1998). Other sea creatures, such as cuttlefishes and mantis shrimps, possess polarization vision and use polarization patterns for signaling (Cronin et al., 2003).

For example, researchers at CSIRO Marine Research (CMR) in Australia use a dual-video camera system with 4 reference lasers each, equipped to a small ROV to study benthic habitats and community dynamics. In this application, an Optimas™ image processing add-on tool developed at MBARI, called Laser Measure©, is used to extract quantitative measurements from the laser-referenced imagery (Barker et al., 2001). New algorithms are currently being added to the toolbox, such as determining the focal length of a zoom lens using the position of a single laser (Davis, 2005).

Similar to this system is a three-reference laser system, "3-Beam", developed for Washington State Department of Fish and Wildlife researchers to assess population density of ground fish (Kocak et al., 2004). This system offers automated processing of the sequential images based on time, distance traveled or random sampling. Im-

Electromagnetic Methods

Electromagnetic signatures can be obtained for ships and other seagoing vessels. Many different sensor types are used for detection and rely generally on low frequency or static field measurement. Mapping of the earth'smagnetic field anomalies can provide a background against which other anomalies can be detected. Visualization of the sensor data over 2-D and 3-D regions is therefore of interest for salvage, geological monitoring, and for military applications. Sensor types include high and low temperature superconducting magnetic gradiometers useful for seafloor mapping. The Proton precession magnetometer and the more sensitive alkali vapor magnetometer are commonly used for detection of magnetic field anomalies at a close distance to the seafloor from a towbody. High sensitivity is also possible from optical magnetometers (Deeter et al., 1993; Dandridge, 1994; Zyra et al., 1995).

Photogrammetric Methods

Ongoing research uses undersea video and still photogrammetric systems to extract quantitative measurements such as object size, area, volume, shape, density, and movement; distance between objects; as well as range to a point, object plane or surface. Automated methods require recognition and segmentation of multiple laser spots and laser stripes or alternately might use camera and lens information in conjunction with algorithms that discard out of focus (or fuzzy) regions. Since these systems offer a low-cost, low-impact addition to standard video, a growing application for this technology can be found in marine resource management—particularly the documentation, long-term monitoring and estimation of the geographic extent of critical habitats. Many of these applications require unique customization (i.e. automated sequential image processing based on distance traveled, image correction for vehicle roll and pitch motions, inclusion of metadata from system sensors, etc.) not found in commercially available systems such as C-Map Systems Video Ruler, Tritech ISS-Soft, and Eos Systems PhotoModeler Pro (Bythell et al., 2001).

ages are collected at a measured slant angle taking into account the vehicle roll and pitch motions, and vehicle position data is stored for each image for geo-referencing. In a May 2005 cruise with Canadian Department of Fisheries (DOF) researchers, video and observed data were collected onboard Nuytco's Aquarius submersible to compare quillback rockfish density estimates over a survey area using strip vs. line transect methods. In addition to the video, forward-looking sonar data was collected to monitor observed fish for attraction or repulsion behavior. A fourth laser, parallel but off-axis, was added to the 3-Beam system to derive local rugosity (roughness) measures of the benthic surface to assist in habitat classification. Other techniques to obtain roughness or relief measurements have recently been published using laser stripe patterns (Chotiros et al., 2001; Wang et al., 2001).

Two systems utilizing 5 reference lasers mounted to DOE Phantom XTL ROVs that are also used for seabed surveys are University of Plymouth'sAutonomous Benthic Image Scaling System (ABISS) (Pilgrim et al., 2001; Parry et al., 2003) and NOAA Southwest Fisheries Science Center's "5-Beam" system (Pinkard et al., 2005).

Other magnetic sensing approaches use field generation with subsequent detection of field perturbation from conductive material on the seafloor. Images are produced by platform motion since magnetometers are inherently omnidirectional.

Algorithmic methods for inversion of the sensor data to form 3-D image maps of the subsurface region are an active subject (Lesselier and Habashy, 2000). The future is expected to bring advancements such as those now sought by the Navy's Distributed Undersea Warfare Pyramid Electromagnetic Sensor development program. Arrays of sensors will cooperate to produce 2 and 3-dimensional image representations that will require data processing to determine variations or shifts in magnetic field intensity in real-time.

Acoustic Imaging Techniques

Advances in DSP technology have paved the way for reduced cost and higher capability acoustic systems. Both long-range and shallow water short-range systems have received recent attention. Since the end of the Cold War,a shift in emphasis for military acoustic detection systems has gone from passive to active types due to changes in the military threat profile.

Active Acoustic Systems

New developments in active acoustic systems include: long range Low Frequency Active Sonar (LFAS), Parametric Sonar, and very high frequency acoustic (VHFA) active imaging systems. LFAS uses 100-500 Hz for detection at long distances using the deep-water channel. Range and speed estimates can be made for detection and identification of small targets at distances beyond torpedo range. Parametric sonar systems rely on beat frequency interaction from two relatively narrow high frequency beams. The apertures required are relatively small so that the side lobe emission can be controlled sufficiently to avoid backscatter from surface and bottom. Recent advances have improved the efficiency for producing the beat frequency above the previous 2-4% levels (Potter, 1999). Itis expected that 2-D parametric sonar arrays will evolve with subsequent requirements for multidimensional data display for interpretation. One 2-D sonar system has been successfully employed by the German Navy. Acoustic imaging systems using VHF sparse arrays have recently been produced and trends will be to improve resolution and image quality.The advantage of these systems over advanced optical imagers is the ability to operate in very turbid waters in shallow water regions.

A VHF acoustic camera that began development in the mid 1990's for Navy divers to use in underwater surveillance has recently Imaging systems designed for these applications require situational awareness for visual search, contact detection, recognition, identification under most weather conditions, navigation support, real-time imagery analysis and imagery enhancement. Often this implies a multi-sensor approach. With funding from ONR and the U.S. Coast Guard, University of South Florida's (USF) Center for Ocean Technology has recently developed a Mobile Inspection Package (MIP) designed for port security that is easily deployable on numerous platforms. The MIP consists of a navigation module (ring laser gyro and Doppler Velocity Log), complimentary sonars (DIDSON and ES MK II), optical systems (USF 3-D laser line scanner and video), a laser/video photogrammetric system (3-Beam or ISS), and high-speed Ethernet communications link. An example data set is shown in Figure 5 (a-d). Data and images collected by these sensors, including rotation of the 3-D sonar for viewing at varying angles and perspectives, can be closely evaluated at a Command and Control Center in real-time. In low visibility and turbid water conditions, sonar images are used to pilot the vehicle. All data is geo-referenced and stored in a Geographic Information Stytem (GIS).The first real-world application was at the 2005 Super Bowl in Jacksonville, Florida, where the system inspected the piers that housed the cruise liners. During this inspection, one target was found warranting further assessment. The team marked the target location with a buoy and in less than two minutes the diver determined its threat potential.

Other VHFA high-resolution imagers include the Norwegian Echoscope operating at 150, 300, and 500 KHz (Anderson and Hansen, 1996). This ROV mountable system produces images at a 5-10 Hz frame rate at a range of up to 100 m with a resolution of 0.6 - 2.5 degrees. A second system produced byThomas Marconi operates at 5-10 MHz for very high-resolution imaging (1 mm at close range of 5 m) (Jones, 1999) and another low cost shallow water system by BlueView Technologies operates at 450KHz with resolution of 2 inches at ranges to 450 ft. and 10 Hz update rate.

FIGURE 5

Mine-like object on a seawall recorded from the MIP: (a) target in air; (b) camera image with scaling lasers (191.7 mm measured, 196.0 mm actual); (c) DIDSON image (0.47 m measured, 0.46 m actual); and (d) ES-1600 image (0.5 m measured, 0.46 m actual).

(a)

defined a new class of identification sonar that produces near video quality images (Belcher et al., 2002). This "Dual-frequency IDentification SONar", known as DIDSON, has advantages over optical systems that are limited by low light, turbid water and short-range capability. Two models are available: a 1 to 30 m version that operates at 1.8 MHz and 1.1 MHz, and a longer-range, 1 to 80 m version that operates at 0.70 MHz and 1.2 MHz. A recent publication addresses software methods for uniquely calibrating the camera (Negahdaripour et al., 2005).

One application well suited for this identification sonar is security and safety-of-ship systems. Since September 2001, new regulations have been adopted to enhance ship and port security and to avert shipping from becoming a target of international terrorism.

(d)

Multibeam high frequency sonar has also been useful for large volume midwater biological surveys where detection, tracking and characterization are required. Accurate calibration may be accomplished in small volume tanks using coherent subtraction of surface or other reverberation to obtain best results when multiple objects are to be observed. (Chu et

enced. Co-located pixels are added incoherently to generate a multiple aspect image from which target shape can be estimated using tomographic reconstruction, allowing subsequent classification. The receiver array size is 1.5 m but can be reconfigured into a linear array for AUV "wing" mounting. This tomographic reconstruction method has been

FIGURE 6

ROMANIS array in transit to deployment site.

al., 2001). A least squares method for calibration of multibeam sonar for target azimuth localization to within 0.1 degrees has also been demonstrated where accurate Direction-of-Arrival is required (Chu et al., 2001).

Sidescan sonar configurations have also advanced and are particularly suited to synthetic aperture combining to increase resolution along the track. One recently developed synthetic aperture sonar (SAS), the 4400-SAS side scan sonar, was introduced at the Undersea Defense Technology conference in 2004 (EdgeTech, 2004). This sonar is designed for installation on a towed body,AUV or ROV and obtains high-resolution images at medium ranges (120 kHz) with range independent along track resolution of 10 cm. It is expected to be highly effective in mine countermeasure applications.

A novel combined-mode subsea acoustic system developed at Simon Fraser University is now commercially licensed to Benthos, Inc. (Fluxgold, 2003; Tidd, 2005). The C3D system combines bathymetry and sidescan sonar for towed or fixed-mount operation, producing both depth and imagery information. The C3D system uses Small Aperture Range Angle Computed Angle of Arrival Transient Imaging (SARA CAATI) for estimating the backscatter arrival spectrum. Though similar to interferometry in that an angle-of-arrival estimation is used, this system solves the problem of concurrent arrivals from multiple images.

A 3-D acoustic imaging system has also been developed using a 252-element receiver shown to provide more information than available with Maximum Intensity Projection (MIP) derived imagery.

GOATS (Generic Oceanographic Array Technology Systems) Joint Research Program has continued the development of environmentally adaptive autonomous underwater vehicle technology directed toward Rapid Environmental Assessment and Mine Counter Measures in coastal environments (Edwards and Schmidt, 2002). By combining theory and modeling of the 3-D environmental acoustics with experiments involving AUVs and new sensor technology, the program has the potential of relaxing navigation accuracy required by the competing SAS method in complex topological environments and for reducing the need for significant aperture overlap between consecutive receptions. One element of the program involves the development of a multi-static sonar concept, which uses a low frequency source on a single AUV to sub-critically insonify the seabed, and in addition a team of multiple AUVs for mapping the associated 3D scattered acoustic field. The spatial and temporal structure of the acoustic field is subsequently processed using SAS algorithms with dynamic pattern recognition and tracking for concurrent detection and classification. The proposed classification method has been shown to be readily implemented in real-time, as demonstrated both in simulations and in post-processing of the experimental data. More recent improvements include additional processing that supports producing images with a resolution of 1 m at a 40 m range using only ambient noise (Buckingham et al., 1996). A second-generation system, the Remotely Operated Ambient Noise Imaging System (ROMANIS), was subsequently developed by the Acoustic Research Laboratory in Singapore. Signal processing for ROMANIS has been generalized to include several new imaging concepts beyond ADONIS intensity-based imaging, including Kalman filtering (Potter and Chitre, 1999). ROMANIS operates over the 25-85 KHz range with 504 sensors (Figure 6) and an aggregate data rate of 1.6 Gb/s, 10 times that of the Norwegian VHF system, and has produced images at 70 m range with 1 m resolution using only ambient noise (Venugopalan et al., 2003). ROMANIS uses 54 Pentium computers in the wet-end array, linked by 4 fibre-channel communications loops to provide full raw data, recorded on 54 fibre-channel hard drives on the surface. A 36-cpu parallel computing platform is being built to and omni-directional source transmitting FM pulses at 2-12 kHz for sub-bottom imaging of buried objects (Schock et al., 2001). The Buried Object Scanning Sonar (BOSS) processes each transmission event using coherent nearfield focusing to generate a 3-D map of acoustic intensity. As the sonar passes over the seabed, the 3-D intensities are combined in a matrix representation that is locally geo-refer- target reacquisition and acoustic field prediction (Nave and Edwards, 2003; Edwards and Schmidt, 2003).

Passive Acoustic Imaging

In 1994, a prototype system called the Acoustic Daylight Ocean Noise Imaging System (ADONIS) was developed at SIO. ADONIS was successfully tested on various targets, perform the beamforming and imaging in near real-time. ROMANIS won the Singapore Defence Technology Prize (DTP) in 2004.

Acoustic Algorithms based on Image Processing Techniques

Acoustic imaging systems are associated with many of the processing tasks found in optical image formation systems. Image pro-

cessing algorithms are applicable for automated object recognition (Foresti et al., 1997; **Boulinquez** and **Quinquis**, 1999; **Boulinquez** and **Quinquis**, 2002), segmentation and feature tracking (Trucco et al., 2000; Cutter et al., 2002), enhancement and noise reduction (Murino and Trucco, 1999; Tu and Jiang, 2004), image compression (Hoaq et al., 1997; Barbosa and Barroso, 2000; Cunha et al., 2000), motion estimation and discrimination (Petillot et al., 2001; Fernandez et al., 2004), and others. Processing trends have included classify-before-detect (CBD) algorithms where target classes are distinguished from the target echo using *a priori*information. One reported method uses a supervised statistical principal component classifier to produce a reduced feature vector,which is then sent to a supervised al., 2000c; Trucco et al., 2002). Specifically, Independent Component Analysis (ICA) has been used on subsampled data sets to allow real-time operation at 5 fps and the Marching Intersection Algorithm (Rocchini et al., 2001) was used for online geometric fusion on border grid cells.

A Vision of the Future

"Nothing ages so quickly as yesterday'svision of the future."

Richard Corliss (1944-present)

"Vision is the art of seeing the invisible."

Jonathan Swift (1667-1745)

Regulations and issues relating to Home- mimic biological vision systems of some animals and provide more robust detection or navigation capability for undersea vehicles. Some of these include combined signal processing at the local (pixel) level for velocity estimation (speed of motion and direction), improved tracking ability, simplified identification, and adaptive functionality.

New techniques in computer vision and pattern recognition algorithms may include automatic target recognition on compressed imagery; improved compression or encoding methods for higher bandwidth transmission of multi-dimensional data sets to multiple locations including the Internet; fusion of data from multiple platforms and data types requiring a combination of robust algorithms (also called algorithm fusion); behavior recogstatistical classifier (Trucco, 2001). Another recent processing method employs PCA to reduce the dimensionality of the feature vector, which is filtered using best basis wavelet decomposition to classify seabed composition using a linear discriminant analysis approach (Barat and Rendas, 2002).

Several developments in acoustic image mosaicking have also been reported (Murino et al., 2000b; Repetto et al., 2002; Kim et al., 2004; Castellani et al., 2004; Negahdaripour et al., 2005). The problem of matching and positioning successive images has been approached using various projection methods including a precision ray tracing approach and an analytic solution. The former requires a reduction of the number of rays for optimum results with minimum computational load, while the latter uses an interpolation method based on generation of virtual beam signals to obtain high quality mosaics (Repetto et al., 2002). Another approach (Negahdaripour et al., 2005) uses a projective transformation for 2-D image registration correcting for rotational and translational motion of images produced by an acoustic camera. Fusion algorithms were demonstrated to reduce errors due to rapid image motion thereby increasing resolution and reducing blur (Kim et al., 2004).

Techniques for reconstructing 3-D representations from range images obtained from multiple views have also been proposed (Castellani et al., 2004), with processing methods discussed in detail (Murino and Trucco et land Security, security and safety of ships and ports, monitoring and conservation of our environment, surveillance and defense systems will drive future research in underwater imaging. Emphasis will be placed on automating and optimizing the processing—using both hardware and software measures—to increase throughput, robustness, and data assimilation affording maximum resolution with minimum delay. As moreand more sensory information is gathered, emphasis will continue to be placed on methods to fuse similar and disparate sensor data and to display, archive, transmit and share this data to achieve real-time awareness at multiple sites. This observation holds particularly when an instantaneous decision must be based on up-to-the-minute information. As we have seen in some present research, multiple sensor systems are becoming increasingly important. Thus, simplified data usage and automated detection/processing based on data fusion is needed. All data, however,should be made available in an unprocessed format with an option to invoke image processing algorithms for improving the representation.

Although conventional methods of image processing are well suited for target recognition, identification, location, and tracking, there is a need for future systems to make physical and biological measurements over large survey areas for species monitoring, differentiation, and health assessment through spectral analysis. Sensors using advanced concepts are expected to nition and automated scene understanding processes applied to an image sequence; storage of metadata including geo-coordinates with individual sensor data; and improved methods of database management and information retrieval, particularly with LIDAR and sonar bathymetric data. As data becomes available on the Internet, needs arise for interpretation of visual contents, storage and indexing information for search engines, filtering undesired contents and encrypting sensitive information, and handling video streams. Future advancements will include real-time watermarking of such data into the video image to link still image and video data archive, as well as to allay copyright and security concerns related to dispersal of such material over the Internet.

The future of acoustic imaging should allow a high degree of integration and cost reduction to provide a truly covert capability at target standoff distances exceeding those of advanced optical imaging systems which operate at 4 to 7 optical attenuation lengths (300-400 m in clear water). The future also promises sensor fusion between passive and active imaging systems using both acoustic and optical methodologies. (Refer to Sloan et al. [2003] for an extensive review of acoustic and optical-based imaging techniques that have provided ecological insights and information about marine benthic systems. Hewitt et. al [2004] provide a similar case study.) The ability to combine data in different formats and data rates for online decision making will evolve, as well as processing techniques to coordinate, present, and interpret multiplatform and multidimensional sensor data. Acoustic imaging sensors may be used in distributed networks at harbor choke points, similar to deployable underwater surveillance systems (DUSS). In one such system, an active sonar concept based on distributed network of small multistatic transmitter/receiver nodes has been deployed and tested (Mozzone et al., 1999). Due to the large volume of data in these multisensor systems, data archival and access continues to be important. Geographic information systems (GIS) are becoming widely used as a tool for visualization and analysis (NOAA, 2003; Hamano, 2004; Mitchell, 2004). In benthic surveys, for example, multibeam bathymetry data can be collected over a large survey area and mapped into a GIS Benthic Terrain Modeler (BTM) tool, as described in Lundblad et al. (2005). In this technique, both a fine and broad scale Bathymetric Position Index (BPI) can be estimated as a second-order derivative along with surface slope measures and rugosity estimates. The BPI maps are then standardized and a classification dictionary is used to produce the benthic structures and zones. The resulting classification in features will preserve rich color and tones and offer automatic image correction and enhancement, as is just beginning in the commercial market. These systems will be tailored to the entire range of lighting conditions; however, there will be a trend toward self-contained, high efficiency LED illumination.

Signal processing integrated onboard imaging semiconductor chips and local processing at the pixel level for sensitivity normalization, contrast enhancement, and filtering will be just a few of the future enhancements. More advanced features such as the discrimination of temporally variant signatures may also evolve to provide enhanced detection and monitoring systems.

As for applications, the need for land-based imaging systems for close observation of vessel traffic, ports and harbors, offshore platforms, oil and gas fields, fisheries, and coastal waterways is already becoming increasingly important. In addition, unattended offshore platforms and buoys face dangers from pirates or terrorists due to their remoteness. Since operation of these platforms is expensive and technologically demanding, protecting them is a top priority. Planned monitoring systems range from simple, single radar installations to fully networked multiple radar or multiple moni- around ports, between ports and over the horizon. The goal is to create reliable technology that can monitor activities, connect diverse events that suggest potential threats and alert security personnel when necessary (BAE, 2005; Quintas, 2005).

Long-range imaging systems have considerable value for inspection, search and rescue, and species assessment. In the past, these systems were large, expensive, and power consumptive, requiring dedicated support programs. The future promises reduction below the current 150-200 watt power levels and further reduction in packaging size—thereby allowing deployment on smaller ROVs or AUVs. With current trends toward higher data storage density, the potential exists for replacing current real-time imaging capabilities with onboard image storage for later off-loading and processing. These advancements are expected to allow increased usage for biological assessment of population densities, e.g. patterns in distribution and abundance, especially for low population density species. In addition, archival recording of data can allow image post-processing for a variety of applications and uses beyond current interest. The further embellishment of these systems with multi-wavelength lasers, could al-maps provide a better understanding of species–habitat relationships that can assist in establishing and monitoring marine protected areas. The BTM methodology is most useful when combined with *in situ*data sets.

Advances in image sensor technology will yield smaller size, distributed networking and smart processors (e.g., autonomous "smart dust" sensors [Kahn et al., 1999]). A distribution of underwater imaging sensors in a self-formed or other network architecture would provide ubiquitous coverage affording multiple perspective views for robust identification and rapid detection. These advanced systems could also mimic swarming or schooling behaviors of biological organisms for cooperative problem solving given the mission at hand.

Weare already seeing a wide range of small, affordable camera systems with greater resolution and capability due to CMOS sensors and onboard processors. In the future, the imagers will maintain compatibility across a wide range of software, hardware and image types. Built-toring systems with integrated video/thermal imaging cameras, radio and direction finding (DF), GPS and other transponders and meteorological, hydrological and geographical information databases. One developing system from Sidus Solutions integrates radar information with video or still camera position control to provide disparate views of a given location, then transmits the images to a remote command center via satellite communications for evaluation (Flakus, 2005). Enhanced perception at night or in poor visibility situations is achieved using ISIT, ICCD, or thermal cameras.

Another prototype development underway, the Department of Homeland Security's (DHS) Project Hawkeye Intelligent Video Analysis, is aimed at assisting the U.S. Coast Guard in South Florida with maritime surveillance by integrating a host of different imaging technologies into an intelligent system capable of automating the detection, tracking and evaluation of vessel traffic low spectral differentiation, as well as fluorescence measurements and other data to be acquired for more accurate detection, differentiation, species assessment, and health monitoring.

Summary

It is clear that imaging and image analysis will play an increasing role in remote sensing with applications in Homeland Security, environmental monitoring and assessment, and basic biological and geological research, with perhaps the most emphasis being applied to collection, transmission, storage, cataloging, and retrieval of information collected over vast distances and areas. The adage "apicture is worth a thousand words" is perhaps more appropriately today rephrased as "information is worth a thousand images" and tasks such as data/image collection, management and analysis will certainly lead our future endeavors.

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