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IMAGING SYSTEMS FOR ADVANCED UNDERWATER VEHICLES

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ABSTRACT

Exploration of the underwater environment either by human operated or by autonomous vehicles can highly benefit from using a visual imaging system. When a vision system for an underwater vehicle has to be designed, some specific characteristics of the image formation in sub-sea conditions should be taken into account. This paper presents an extensive survey of components, techniques and methods used to build underwater vision systems. First, most of the phenomena that affect the image formation in submersed conditions are described; second, some significant illumination techniques and light sources, including laser, are presented; and third, the review follows with a list of relevant underwater visual installations and submarine vehicles with vision-based infrastructures recently developed and commercially available. Furthermore, the paper finally introduces some techniques for improving the quality of underwater images. Among all these techniques, a special attention has been paid to the effect of employing polarized light to overcome the undesired scatter present in images. This last section includes some experiments carried out by the authors to test the usefulness of polarization-based methods in robotic applications.

Key words: Autonomous Underwater Vehicles, Robot Vision, Polarization, Underwater Installation.

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INTRODUCTION

Thanks to recent technological advances, the subaquatic world is more accessible for exploration, scientific research and industrial activity. When the tasks involved in missions are repetitive, hazardous or too long to be carried out by divers or human guided vehicles, the use of unmanned vehicles becomes more suitable. At present, remotely operated vehicles (ROVs) are commonly used in a variety of applications such as surveying, biological, archaeological and geological sampling, rescue operations or infrastructure inspection and maintenance (Ortiz and Antich, 2009). Trying to overcome some of the intrinsic limitations of ROVs, such as their limited operative range or the need of a support vessel, autonomous underwater vehicles (AUVs) are progressively being introduced.

Improving the sensorial capabilities of underwater vehicles is a key point to increase the variety and the feasibility of missions that can be carried out by ROVs and AUVs.

Optical imaging sensors can provide dense information updated at high speed and they are commonly used in many terrestrial and air robotic applications. However, due to the interaction between water and electromagnetic waves, optical imaging systems and vision systems need to be specifically designed to be used in underwater scenarios, whether their output images and videos are going to feed an autonomous system or a human operated one. Sub-sea images have specific characteristics that should be taken into account during the gathering process. Light attenuation and scattering, non-uniform lighting and shadows, colour filtering, suspended particles or abundance of marine life on top or surrounding the target of interest are frequently found in typical sub-sea scenes. Some improvements specifically designed for the described situations, including specialized lighting systems, filtering methods, ultra-sensitive and wide-spectrum cameras or multi-camera systems have been described in the literature. From the image acquisition point of view, research in underwater optical imaging has recently proposed novel solutions that achieve significant advances in image quality (Kocak, et al., 2008). It has also been proved that vision algorithms performance can be improved if the physical process of image formation is appropriately modelled and taken into account (Singh, *et al.*, 2004) (Negahdaripour, 1998). Physics-based image formation models, including information from the radiant source, the nature of the surface of scene objects or the imaging hardware has been extensively studied in recent years (Ortiz and Oliver, 2006)(Ortiz and Oliver, 2010).

This paper focuses its attention on presenting a study of available cameras and different possibilities for illuminating the environment, to get the best image quality and performance in underwater optical imaging systems. Moreover, a list of underwater installations and submarine vehicles recently developed and commercially available has been included as a reference of previous experiences. Besides, among all the known techniques devoted to improve the image quality, those that use polarized light have been analyzed in detail and experimentally tested.

UNDERWATER OPTICAL IMAGE FORMATION

When electromagnetic waves propagate in a sub-aquatic medium they interact with water molecules and with dissolved and particulate matter. As a consequence, the distance this radiation travels in the underwater environment is dramatically reduced compared to air. A general exposition of this situation from a physical point of view can be found in (Gordon, 1994) and (Mobley, 1994). Detailed analysis regarding the underwater light propagation problem, focused on computer vision and its applications in robotics are presented in (Ortiz, A., 1998) and (Horgan and Toal, 2009), respectively. Among all the optical issues known, refraction, scattering and absorption seem to play a more significant role in underwater optical image formation and computer vision, thus, they are described below.

Underwater cameras are housed in watertight enclosures including a depth rated lens. Before reaching the sensitive area of the camera, the refraction causes the light rays coming from the scene to bent as they pass from water to glass and then from glass to air. The refraction modifies the apparent size and position of objects. This effect combined with the imperfections of the housing system, including lens defects and misalignments, lead to non-linear image distortion that must be compensated with a proper calibration process.

When a photon hits a particle suspended in the water its original path is deflected. Depending on the angle the light ray is deviated, this phenomenon is known as forward scatter or backscatter. Forward scatter occurs when the angle of deflection is small, resulting in image blurring and contrast reduction. Backscatter occurs when the light from the light source is reflected to the camera before reaching the object to be illuminated. Backscatter may cause bright points in the image usually known as marine snow. However, the main problem of backscatter, also referred to as veiling light, is that it can highly reduce the image contrast, causing serious problems in underwater imaging systems. The general term for this problem, that also appears in other media than water, is path radiance. The referred effects of backscatter, forward scatter and refraction are illustrated in Figure 1.

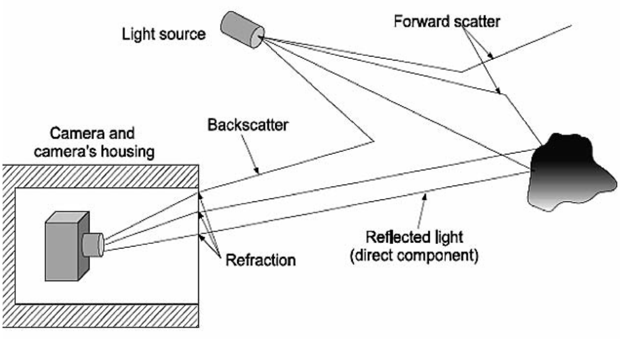

Figure 1: Example of backscatter, forward scatter and refraction.

Both backscatter and forward scatter depend on the volume of illuminated water inside the camera's field of view. In general, this means that the negative effects of scatter in underwater imaging increase with the distance from the camera to the object to be viewed. Moreover, as it will be exposed later, some veiling and snow effect reduction can be obtained increasing the distance from the light source to the camera in an opportune way.

The absorption causes the electromagnetic waves traversing water to be quickly attenuated. Furthermore, the spectral components of light are differently absorbed. Thus, in clear water long wavelength (red light) is lost first. In turbid waters, or in places with high concentration of plankton red light may be better transmitted than blue light. As a consequence, two problems arise as they have important consequences for optical imaging and computer vision systems. First, the use of artificial lighting is needed in most cases and dramatically limits the distance at which objects are perceived. Second, the natural colours are distorted and the perception of the scene can be altered.

The overall effect of absorption, scatter and other phenomena not described in this work such as the fluorescence, produces an attenuation of light. The attenuation factor depends on the specific characteristics of the water, the dissolved components and the particles in suspension. A common measure of this effect is the attenuation length, which is the distance where the intensity of the light has dropped by a 1/e factor. In other words, the attenuation length is the distance after which about the 64% of the light intensity is lost. Visibility in water ranges between one and two attenuation lengths. This means, in general, ranges from 30 to 60 meters in clear waters, from 6 to 15 meters in deep waters and from 1.5 to 6 meters in coastal waters. As it will be shown throughout this document, the visibility range can be significantly increased by using the appropriate illumination and camera.

ILLUMINATION TECHNIQUES

Illumination Sources

Choosing the proper light sources for an efficient underwater visual system becomes and important issue because illumination conditions always determine certain imaging effects and results. Natural light sources, like daylight, can be used at low depths, but they completely attenuate before they reach significant depths. Artificial light is necessary at deeper environments, and since a single visible light source illuminates the scene producing a central bright spot surrounded by a poorly illuminated area, it is common to use different light sources strategically located, specially if they emit structured light.

From the illumination type point of view, underwater visual systems can be classified according to different concepts. In a first approximation, illumination systems can be roughly classified as active or passive. On the one hand, passive Illumination systems image scenes illuminated by some kind of natural lighting source (sunlight or bio-luminescence sources) or by some artificial source non specifically placed to illuminate that environment (light coming from a nearby stations, ships or whatever that is generating and/or consuming energy). Passive imaging is especially attractive for covering operations such as fish seeking prey or in Navy secret inspecting or surveillance tasks. On the other hand, active Illumination and structured lighting systems take advantage of artificially generated light with one or more sources strategically placed and configured, These systems offer substantial benefits for underwater imaging in the sense that the incident light can be either continuously emitted (standard visible light sources), collimated into very narrow or wide beams, be monochromatic (lasers), or can also be flashed and sent in a sequence of very short duration pulses (strobe, pulsed lasers). These more sophisticated lighting systems typically allow imaging at greater ranges and/or higher depths than passive systems. The most significant of the advanced techniques that use the effects of light at specific frequencies to overcome harmful effects as scatter, refraction or absorption, among others, are:

Synchronous scanning systems: The illumination source emits a collimated light (rays are nearly parallel) with a minimal beam section. This causes minimum backscatter and it results in hight contrast images. To compute target range, triangulation can be used (B. Zheng, *et al.*, 2009).

Light Stripe Range Scanning (LSRS): A plane or sheet of light, typically generated by a laser diode, scans the environment or an object to be imaged to obtain its 3D reconstruction (Narasimhan and Nayar, 2005), (Taylor and Kleeman, 2006). In the presence of scattering, the light sheet becomes visible and it makes the detection of the obstacle surface more complicated. This technique reduces backscatter and permits to recover 3D information by means of triangulation.

Photometric Stereo (PS): Photometric Stereo techniques are a good alternative to LSRS techniques when the last take too long, for example, in dynamic environments. In the absence of scattering, it is well known that three images obtained illuminating the scene from three different but known directions are enough to reconstruct the surfaces of the different scene objects. The challenging problem arises when it is necessary to determine how many sources are needed to infer the scene features in the presence of scattering (Negahdaripour *et al.,* 2002), (Narasimhan and Nayar, 2005).

Range Gated Systems: The source emits a pulse of light and the camera shutter waits for the time the light takes to propagate from the emitter to the target, scatter in the target surface and back again to the camera. Only the light scattered by the target is received and considered for imaging. The main difficulty that these systems entail is that a very precise light gating is needed in the camera receptor.

Obviously, the light pulse is much shorter than the total light propagation time. The cost of these systems is hight but they considerably reduce the backscatter and augment the contrast (Han, *et al.*, 2009), (Tan *et al., 2006*).

Selection of the light source position

When using conventional illumination systems, the amount of backscatter depends on the volume of water where the light field and the camera's field of view intersect. Because of this, it is common to separate the light source as much as possible from the camera in order to reduce the aforementioned volume of water. Figure (2-a) exemplifies the volume of water producing backscatter when the camera and the light source are close between them, and Figure (2-b) shows the difference when increasing this distance. Jaffe (Jaffe, 1990) emphasizes the importance of this aspect by stating that the basic trade-offs in underwater imaging design are between camera-light separation, contrast and power. As a matter of fact, the rough classification of underwater imaging systems provided in (Jaffe, 1990) is widely referenced by the underwater vision community. According to this classification, underwater imaging systems fall in one of the following three groups:

Conventional systems: The light source is placed close to the camera. This configuration makes it possible to obtain images up to 2 attenuation lengths.

Increased camera/light separation: The light source is separated from the camera as much as possible in small underwater vehicles (3-5 meters). This configuration allows the acquisition of images up to 3 attenuation lengths.

Exotic systems: These systems used range gated or laser based systems, increasing their complexity and price, and also their power consumption.

Thus, increasing the separation between the light source and the camera is a very simple and cheap way to obtain images one attenuation length farther than conventional systems, neither involving major changes in the imaging architecture nor requiring more power. Although this idea has been widely used and is considered common knowledge, very few studies have quantified the effects of such increase in separation. Jaffe models the behaviour of light in water as well as the image formation process and performs several computer simulations in (Jaffe, 1988) and (Jaffe, 1990). These simulations assume a camera pointing to the sea floor and evaluate the image contrast for different separations between the camera and the light source, moving the light source vertically and horizontally.

Simulations show that separating the light source horizontally dramatically increases the image contrast. Separations up to 10 to 20 meters considerably increases the contrast, but it tends to slightly decrease at large distances, mainly due to the light attenuation. For example, for a camera altitude of 40m, increasing the separation 3 to 5 m results in an approximate doubling of the image contrast. The results provided by (Jaffe, 1990) are summarized in figure 3. The image contrast also increases when separating the light source vertically. This may seem counter-intuitive as this kind of separation does not decrease the volume of water where backscatter may appear. According to Jaffe, this improvement appears because the area directly in front of the camera is not illuminated as intensely as in the case that no separation exists.

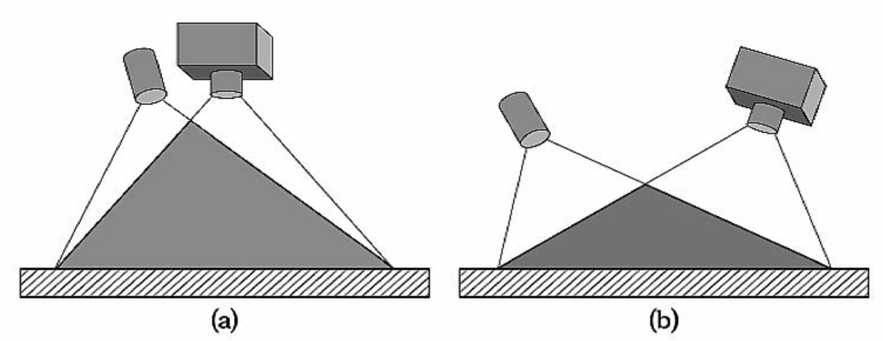

Figure 2: (a) Conventional system (b) Increased camera to light source separation. The grey area depicts the volume of water where backscatter appears.

Nevertheless, the improvements in image contrast are much smaller when moving the light source vertically than horizontally. For example, for a camera altitude of 60m, there is almost no difference in putting the light source very close to the camera or separating it vertically. Increasing the horizontal separation between the light source and the camera is a worthwhile improvement for some underwater imaging systems, but it can be difficult to apply in vehicles, depending on their shape and size. However, it is always possible to place the light source and the camera in different vehicles and coordinate their navigation (Jaffe, 2007). These systems increase cost and complexity in their coordination and can generate moving shadows in the image.

Illuminating Systems

At the time of choosing a proper light source for an undersea visual installation, one has to search a balance between the cost consumption and the quality of the produced light. These terms are all reflected in the parameter *efficacy* (lumens/Watt). Efficacy is an important term, specially in autonomous vehicles which need to optimize the power consumption to generate the maximum light. Underwater visual systems have progressively evolved towards the use of more effective technology, and that obviously includes the illuminating systems. Different types of light emitters with different levels of efficacy are listed next:

Halogens: They use a filament to ignite halogen gas. Halogen lamps are more effective than incandescents since they emit a 30% in average whiter and more brilliant light consuming less watts and irradiating less infrared heat. Halogens do not produce blackening of the bulb glass in usage and they are smaller compared with a standard incandescence emitter. Halogens have a longer live-time than standard incandescence.

HID (High Intensity Discharge or also know as Xenon): These lamps use an electrical discharge between two electrodes for igniting xenon gas in a sealed bulb. They emit a blue-white light closer to the natural daylight. This technology improves halogens durability and security in 10 times and also increases efficiency producing much more light (measured in lumens or lux) than halogens with the same power consumption and emitting much less heat. HIDs emit light that penetrates darkness better than halogens. HIDs are extensively used in underwater applications such as ROVs (where the power can be supplied via its umbilical) or static underwater stations.

HMI (Hydrargyrum medium-arc Iodide lamp): In this lamps, bulbs are filled with mercury vapor which is excited by creating an electrical arc between two electrodes. They are useful in imaging systems that need a long time light exposure. They are typically used in the film industry, but since 1996 they have been used in underwater photography. They are usually expensive and high power consumers (more than 600watts) although some manufacturers are beginning to produce low consumption HMI lights. They produce extraordinary illumination quality and are used in some ROVs for underwater filming at high depths.

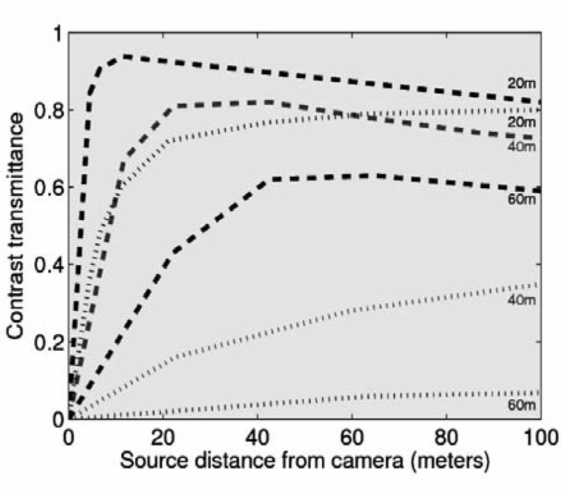

Figure 3: Contrast transmittance vs. separation. (...) Vertical separation. (- - -) Horizontal separation. Source: Jaffe, 1990.

HIF (High Intensity Fluorescent): In many cases, these systems are more energy-efficient than HID solutions. They generate lower lumen depreciation rates, present better dimming options and reduce the glare. They are able to illuminate a more extensive area than HID lamps do. Fluorescent solutions are applied in underwater for attracting fish but rarely for underwater vehicles.

LEDS: These systems are supplied with direct and continuous current, (12V or 24V). The power consumption is 4 times less, in average, than the halogens. LEDS can emit light in a wide range of wavelengths, they have a small spectral bandwidth, their live time is much longer than halogens and, in general, they have a higher efficiency than HIDs. Although they can be expensive, LEDs have become specially important and suitable for underwater autonomous vehicles equipped with batteries since they considerably reduce the power consumption.

Infrared: Light is considered to be infrared for wavelengths in the 700nm-1mm range. Infrared imaging is extensively used for night vision and in some underwater applications. Infrared light emitting must be accompanied with the use of cameras with infrared receivers (IR cameras). Infrared light is very useful for filming marine fauna, since it can be used to remotely determine the temperature of targets and it is no visible. Infrared light penetrates shallower than orange, yellow or green light, but it has been demonstrated to still be suitable for some underwater imaging applications (Lam *et al.*, 2007), (Sedlazeck *et al.*, 2009). In some cases, the undesired scatter can be filtered-out in the receptor if the wavelength of the received energy is different than the emitted one.

Laser: Laser usual operation wavelength is in the 350nm-630nm range. Laser are usually used in underwater extended range techniques, since it permits to illuminate at further distances than light with lower or higher wavelength. Laser permits also to calculate distances and object sizes with a high degree of precision. Laser has two main problems: a) emitters are considerable more expensive than HID, LEDs or infrared, and b) emitters generate a very narrow beam which makes necessary to scan the environment to take an image, delaying the process and reducing the frame rate.

Although these systems are considerably more expensive than the rest, they deserve and special attention for the wide range of benefits that offer.

LASER-BASED TECHNIQUES

Techniques using laser emitters and receptors are intended to considerably extend the range of the captured scenes thanks to the laser scattering and absorption properties, improving contrast and resolution beyond that offered by other means such as infrared or systems with visible light (Funk *et al.*, 1972). Laser emitters concentrate intense light over a very small and narrow area, but this light propagates longer. Although laser-based solutions are of difficult implementation, they need an important post-processing software, and can be more expensive than standard solutions. They are the best choice for long range imaging since they can be effective up to 5,6 or 7 attenuation lengths, while with visible light images are clear up to 2-3 attenuation lengths. The most outstanding techniques involving laser infrastructures are detailed next.

Laser Range-Gating (LRG) Methods

These systems scan the scene with laser pulses emitted at frequencies lower than 100Hz (short pulses of approximately 6ns). Special cameras must be provided with ICCD sensors that are able to synchronously capture laser light in time gates. Knowing the speed of light in water and the distance to the target, the time that the light pulses need to go from the emitter to the target and return to the receptor can be easily calculated. Therefore, using a gateable receiver with a sufficiently high temporal resolution the most of the undesired scatter can be filtered out leaving only the signal returned by the target. In 1994, Range-Gating was already a consolidated technique for extending underwater imaging range (Swartz, 1994) (Weidemann *et al.*, 2005). More recently, Shan *et al* proposed a new method for the synchronization control of the laser emitter and the camera receptor in a LRG system. Improving the synchronization between the emitter and receiver helped to precisely improve the image resolution (He *et al.*, 2009).

Recently, Wu *et al* (Wu *et al.,* 2009*)* have simulated and evaluated the performance of gated ICCD cameras to be applied in LRG-based underwater imaging applications.

Laser Line Scan (LLS) Methods

LLS systems scan the environment with a narrow laser beam perpendicularly to the direction of the sensor support platform and sweeping out light rays as the vehicle moves. LLS techniques can use either continuous or pulsed laser reducing the backscatter effect by displacing the receiver from the laser source. Pulsed LLS can reduce the undesired scatter by time gating the receptor aperture to capture the light only at certain time intervals. Caimi *et al* (Caimi *et al.*, 2007) and Dalgleish *et al* (Dalgleish *et al.*, 2008) demonstrated that pulse-gated LLS provide a much better performance than previous continuous wave (CW) LLS configurations. CW-LLS systems, under certain conditions, are limited by multiple backscatter caused by an increase of turbidity or an increase of the illumination distance (Dalgleish *et al.*, 2009).

LLS has lately been considered as the optimal technology for extended range underwater imaging.

Scattered Light Rejection using modulation/demodulation techniques

Modulation/demodulation consist in displacing the frequency spectrum of a signal, and it can be used, for example, to discriminate useful components from noise, or to transmit several digital channels in an unique physical infrastructure. Coherent demodulation implies that the receiver is equipped with a Phase-Locked-Loop (PLL) that tracks the phase and the frequency of the received signal. The fact that sea water particles cause an important dispersion on the light (specially at high optical frequencies) has motivated many researches to question if coherent/non-coherent modulation/demodulation techniques could be efficient in underwater imaging systems. Illuminating with laser or infrared light (for example, at 99K MHz) has the advantage that the frequency, wavelength, phase or amplitude of the emitted light are known and can be demodulated in the receptor separating the signal spectrum from the scatter frequency components. Infrared light has been scarcely considered because it is absorbed by water at closer distances than laser. Other systems demonstrated that it is possible to enhance contrast and image quality at large distances by coherently modulating and demodulating the illuminating laser signal in phase (B-PSK or Q-PSK) (Cochenour *et al.*, 2007) (Laux *et al.*, 2007).

SOME UNDERWATER IMAGING INFRASTRUCTURES

Surveying different existing imaging systems, such as underwater vehicles or visual infrastructures shall be convenient to learn from previous experiences and to plan an effective design, anticipating already identified problems. Many of the existing systems improve their features using several cameras for different purposes and/or various light sources:

1. Eye-in-the-sea: It is an unobtrusive deep-sea observatory and uses a LED which emits red light (wavelength 680nm) in combination with a low-light-level (LLL) camera (Widder, 2007).
2. (Rosenkranz *et al.*, 2008) Underwater imaging system designed for fisheries detection and observatory. A Gigabit ethernet high resolution camera is connected via optical fiber to the control computer. The environment is illuminated with strobe light to eliminate motion.
3. (Lam *et al.*, 2007): Underwater camera system for monitoring marine fauna in coral reefs. The system is provided with a wide angle infrared (IR) sensitive camera connected via optical fiber to a on-land controlling computer.
4. The submarine observatory NEPTUNE (pacific ocean) needs to integrate station nodes and static imaging systems to support ROVs in their surveillance tasks. Imaging platforms have been equipped with a high definition camera, and three different light sources: i) a 3 beam laser system to provide range information to the user, ii) two dimmable LEDS with more than 406 lumens of a equivalent power of 250 Watts, and a life of 50000 hours, and iii) a 150 Watts HID light to extend range of visualization (Roston *et al.*, 2007).
5. Sedlazeck *at al* (Sedlazeck *et al.*, 2009) presented a 3D reconstruction system based on feature tracking. Images were provided by the ROV Kiel 6000, equipped with 3 cameras: i) a high definition camera, ii) a standard colour PAL still camera and, iii) a slave-mode controlled camera with automatic flash shot. The ROV is also equipped with a 250 Watts halogen lamp, another 70 Watts HID light and a 400 watts HMI dimmable focus.

6. In (Negahdaripour and Firoozfam, 2006) Negahdaripour and Firoozfam presented a vision system for automatic ship hull inspection, applicable to UAV but firstly tested with images provided by a ROV. The ROV was equipped with a stereo camera.
7. Negahdaripour *et al* (Negahdaripour *et al.*, 2007) explored the possibility and results of using optical-acoustic stereo imaging for 3D shape recovery of underwater targets. DIDSON (DIDSON, 2009) acoustic cameras provide acoustic images with such a high degree of reliability that they can be analyzed and processed in the same way as standard images.
8. The CSIRO Marine and Atmospheric Research in Australia (Shortis *et al.*, 2007) developed a ROV for sea bottom underwater map construction, fisheries study, detection and surveillance. The ROV was equipped with: i) two standard PAL cameras in stereo configuration for video recording to geolocate images with the vessel GPS, ii) a high resolution still camera for computing mosaicking and, iii) a forward-looking camera for obstacle detection and avoidance. Concerning to illumination, two 250 watts incandescent lamps were used for the video recording and two strobes for the still camera.
9. Recently, an underwater docking station was developed for enhancing the UAV REMUS (Allen *et al.*, 2006) performance. The vehicle incorporated several cameras for different purposes: i) one ethernet video camera to provide real-time information about the process of entering and leaving the docking station, and, ii) a periscope camera for the sea surface observation.

This camera was mounted in a housing that could be deployed and retracted above and below the sea surface.

10. Hercules (IFE, 2009) is a ROV specially designed for working in the deep sea, manipulating, recovering or digging in ancient shipwrecks. Hercules is equipped with one high definition video camera for monitoring the sea bottom and two still cameras for mosaicking tasks.

11 ARGUS is a ROV produced by Woods Hole Marine Systems, Inc, (Woods Hole Oceanographic Institution) which can operate independently or as a partner of other ROVs and it is equipped with cameras and HMI lighting for underwater image registration (WHMS, 2009).

12 Phantom DHD2+2 and Phantom HD2+2, (Deep Ocean Engineering) (DOE, 2009), are two ROVS designed for fisheries and scientific research, military missions, gas/oil pipes inspection or underwater filming, and specially suitable for deep water and strong currents. Both vehicles incorporate a high resolution PAL/NTSC colour camera with a wide angle lens, and two 250 watts halogen lamps to illuminate the area of inspection.

POLARIZATION

A fraction of the light that passes through water is scattered back to the camera before reaching the object. This phenomenon, which is known as *backscatter*, significantly reduces the contrast in the resulting image. The effects of backscatter depend on the amount of water in the line of sight and, thus, on the distance to the object being observed. Moreover, the backscatter is magnified when artificial illumination is used (Treibitz and Schechner, 2009). As artificial illumination is a common requirement for sub-sea operation, backscatter happens to be an important problem in underwater robotics.

Fortunately, the media responsible for the backscatter behaves differently to the objects in the environment in front of polarized light. However, there is not a consensus in the research community regarding this subject. According to (Treibitz and Schechner, 2006) and (Treibitz and Schechner, 2009) some studies assume that objects in the scene preserve polarization whilst backscatter do not, and some other studies state that polarization is preserved only by the backscatter. In spite of these opposed points of view, polarization can be used to reduce the negative effects of backscatter because, either in one sense or another, backscatter behaves differently to the objects in the scene in front of polarized light.

This section focuses on the potential benefits of using polarization to increase contrast in underwater images. To this end, it first introduces some basic concepts, then surveys some relevant studies on the subject and finally shows some tests conducted in our laboratory.

Basic Concepts

Light can be regarded as a wave that oscillates in an arbitrary direction perpendicular to its direction of motion. Polarization is, in this context, a property of light that indicates the direction of these oscillations. Light is said to be polarized if it oscillates in a single direction (*linear polarization*, Figure 4 left) or if it rotates as the wave travels (*circular* and *elliptical polarization*, Figure 4 right).

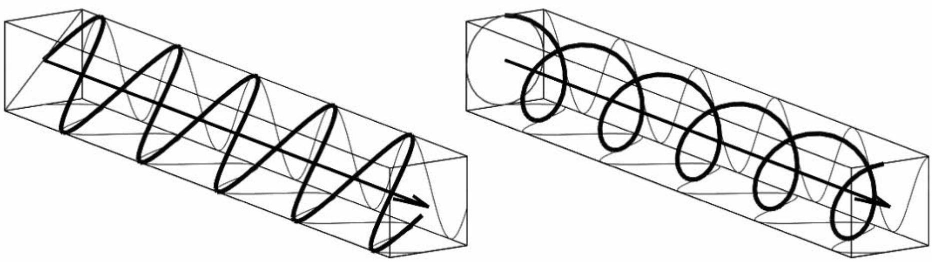

Figure 4: Illustration of linear polarization (left) and circular polarization (right).

Most of the light found in nature, as well as the light produced by most artificial light sources, is a superposition of waves oscillating in different planes. The *degree of polarization* (DOP) measures the correlation between the different oscillation planes. Accordingly, it is possible to classify light according to its degree of polarization, ranging from *unpolarized light* (no correlation) to *polarized light* (maximum correlation) through a continuum of *partially polarized* states.

Although uncommon, light with very high DOP can be found in nature. For example, according to (Schechner and Karpel, 2005), the sun light gets polarized in underwater environments when traversing the interface between air and water. Also, some animals, especially in the marine fauna, take advantage of polarization by perceiving it analogously to color vision in humans (Wolff, 1997).

A *polarizer* is a device that converts unpolarized or partially polarized light into polarized light. This is commonly accomplished by filtering out those waves not meeting some restrictions in their oscillation plane. That is why polarizers are commonly referred to as *polarizing filters*. The cost of this approach is a very important loss of light intensity. Off-the-shelf polarizing filters reduce the light intensity more than 50%.

Polarizing filters are classified as *linear* and *circular*. A linear polarizing filter lets pass through it only those light waves with a certain, linear, polarization. Circular polarizing filters convert unpolarized light to circularly polarized light. This is accomplished by firstly performing a linear filtering and then shifting 45 degrees one of the two orthogonal components of the linearly polarized light. Accordingly, if the goal is to filter a certain oscillation plane, linear and circular polarizers are equivalent. However, cameras having auto-focus, auto-exposure or TTL light measurement cannot properly operate with linearly polarized light. Thus, if a polarizing filter has to be mounted on a digital camera, it has to be a circular polarizing filter.

Extended Range Using Polarization

The different behaviour of objects and backscatter in front of polarized light can be used to improve contrast in underwater imaging. Some studies exploit this idea in underwater environments where sun light is sufficient and no artificial illumination is required (Karpel and Schechner, 2004; Schechner and Karpel, 2004; Schechner and Karpel, 2005). These studies are based on the following two assumptions. First, that the interface between air and water partially polarizes the sun light. Second, that backscatter preserves polarization whilst the observed objects do not. The author's proposal is to attach a polarizing filter to the camera and capture two images of the same scene using orthogonal polarization angles. By properly combining the resulting two images, backscatter can be significantly removed.

Similar approaches have been proposed (Morgan et al, 1997; Treibitz and Schechner, 2009) to deal with those underwater environments where sun light is not sufficient. In these cases, the artificial light source is endowed with a linear polarizer so that the scene is illuminated with polarized light, similarly to the previous case.

The aforementioned approaches have some problems, that are clearly described in the provided references. The most important one, especially when using these techniques in underwater robotics, is the need for two images to filter out backscatter. On the one hand, this reduces the available frame rate to the half. On the other hand, as the underwater robot moves, the two images may not correspond to the same scene.

Other approaches, such as the *polarized light stripping* (Gupta *et al.*, 2008) or the *polarization vision* (Wolff, 1997) are also useful in order to remove backscatter at the cost of additional, expensive hardware in the first case, or the requirement of three images per scene in the second case.

Housing

An important issue when designing an underwater imaging system involving polarization is related to the interface of the camera with the water, as it should have a minimum effect on the polarization. In (Karpel and Schechner, 2004) some details regarding this issue are provided.

First, the housing must guarantee that the only light going through the camera lens comes from the viewing port. Other light sources must be blocked. Second, the stress in the transparent port's material changes the polarization of the light that it transmits due to the so called *photoelastic* effect. In order to reduce this effect, glass ports should be used instead of plastic ones and, more importantly, the polarizer should be placed outside the port, in contact with water.

Regarding the port's shape, the optimal choice is a dome whose center coincides with the center of projection of the camera lens.

Experimental Evaluation

In order to evaluate the advantages and drawbacks of using a polarization-based system in underwater scenarios, we have implemented the proposal in (Treibitz and Schechner, 2009) and tested it in a water tank in our lab. As stated previously, this proposal consists in attaching a polarizing filter to the artificial light source and another polarizing filter to the camera. Then, one image is taken using orthogonal states for both polarizers and a second image is obtained being both polarizers in a parallel state. By combining both images, the effects of backscatter can be reduced.

The water tank size is 1.5m x 0.4m x 0.45m and contains 240 l of water. The only light source during the experiments was a 3Watt LED lamp endowed with a HOYA linear polarizer. The images were taken using an Olympus E510 camera with a circular polarizer attached to it. A calibrated sheet, as well as some other objects, were placed inside water. Also, in order to check the effects of water turbidity, different amounts of milk were dropped into water. Figure 5 illustrates our experimental setup.

Figure 5: The experimental setup.

Some of the obtained results are shown in Figure 6, where the two images taken for each scene, as well as the image resulting of the descatter process, are shown. The figure shows the results for different levels of water turbidity. Next, some analysis is provided.

The first thing that has to be taken into account when evaluating the obtained results is that this technique requires a very simple and cheap hardware. Thus, the question we want to answer is not if polarization based methods are better than other complex and expensive techniques such as laser based ones, because the answer is probably that they are not. The question we want to answer is if polarization methods provide sufficient benefits with respect to simply using a camera with no filters and an unpolarized light source.

The main problem that we have observed is that polarizing filters strongly attenuate the light and this influences the quality of the images. In most cases, low illumination introduces noise in the image as the CCD performs poorly under these conditions. Because of that, using polarizers makes necessary to use stronger light sources involving more power consumption, and this may be problematic for an autonomous vehicle.

As it can be observed in Figure 6, the reconstructed image contains less backscatter than the two original ones. However, a detailed analysis of the images shows that the resulting image has more noise and is saturated in some areas. This observation is consistent with (Treibitz and Schechner, 2009), where it is stated that keeping the camera's exposure time constant, which is usual in video acquisition, never improves the *signal to noise ratio* (SNR) of the resulting images. Moreover, they also show that even using automatic exposure and assuming optimal exposure times there is SNR gain only in rare cases. We have also observed that the algorithm's results strongly depend on two parameters, named *pscat* and *pobj*. These parameters denote the expected amount of polarization preserved by backscatter and objects in the scene respectively and may change from one scenario to another.

The authors propose a method to obtain these values from one image, however, the method requires human intervention to select some particular areas in the images.

Finally, a requirement of this proposal is to use two images per scene obtained from the same camera position. This requirement is especially problematic for two reasons. On the one hand, using two images per scene reduces the available frame rate to the half. On the other hand, if the camera is attached to a moving underwater robot, it is not possible to guarantee that both images have been obtained from the same camera position.

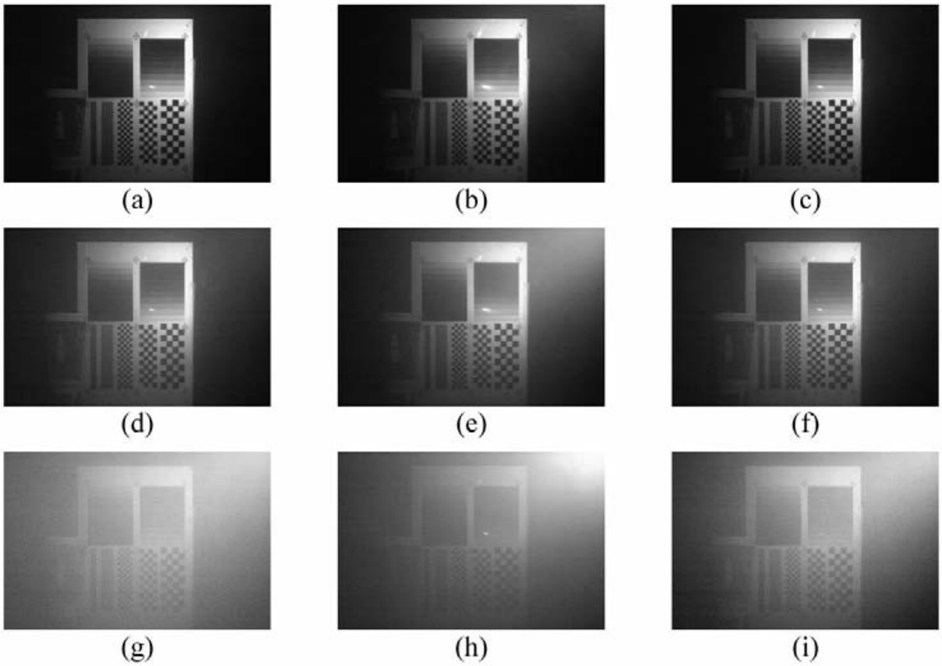

Figure 6: Some results using polarization. Left column: light and camera polarizers perpendicular. Central column: light and camera polarizers parallel. Right column: reconstructed image. First row: 10cc of milk. Second row: 20cc of milk. Third row: 50cc of milk.

As a conclusion, the studied approach is able to significantly reduce the negative effects of backscatter in the image formation at the cost of strongly reducing the light intensity and, thus, at the cost of reducing the SNR. Although this technique may be useful to obtain clear images using a stationary camera, additional problems appear when mounting it onto an underwater mobile robot. On the one hand, the proposed method to estimate the algorithm parameters requires human intervention and, thus, are not suitable for autonomous operation. On the other hand, as the robot is continuously moving, it is not possible to guarantee that the two required images are obtained from the same position.

CONCLUSIONS

Due to the different interactions between water and light, sub-sea images have some special characteristics that have to be taken into account when designing an underwater optical imaging system. Aspects such as the illumination type or the camera's housing shape and material, which are generally not relevant in many terrestrial applications, become of crucial importance when going under water.

Additionally, if the imaging system has to be mounted on a ROV or an AUV, some additional constraints appear. In these cases, autonomy is very important and human intervention has to be reduced to the minimum. Thus, systems requiring some manual configuration during the image acquisition have to be avoided. Also, in AUVs that have no physical link with the support vessel, power consumption has to be considered. In these cases, power-demanding illumination systems should not be used.

This paper has surveyed different illumination techniques. Among the described approaches, the best way to improve the image quality while not dramatically increasing the AUV cost or power consumption, is to keep the light source and the camera as separated as possible. In this way, the volume of water where the emitted light and the camera's field of view intersect is reduced. This leads to a reduction of backscatter and, thus, to a higher contrast in the resulting image.

Also, the camera's housing has been analysed in this paper. The optimal shape is a dome whose center coincides with the center of projection of the camera lens. Also, in order to reduce the photoelastic effect, glass ports are preferred over those made of plastic materials. Finally, if some technique based on light polarization is used, the polarizing filter should be placed outside the dome, in contact with water, and special attention has to be paid to light sources not coming from the viewing port, as they have to be blocked.

Concerning to polarization, some studies have been surveyed. These studies are based on the assumption that backscatter behaves differently to the objects in the scene in front of polarized light. Some of the studies rely on the partial polarization produced when the sun light traverses the interface between air and water, whilst some other are meant to be used in areas where no sun light is available.

In both cases, the camera has to be endowed with a polarizing filter and the ability to switch it between two orthogonal states is needed. If images are taken by a human operator, this may be an easy task, but difficulties arise when the task has to be accomplished autonomously. Also, the requirement of two images per scene poses two problems. First, frame rate is reduced to the half. Second, obtaining two images of the same scene is difficult when the system is mounted on an AUV.

One of the surveyed polarization based methods has been tested in our lab. Results show some reduction of the backscatter effects in the image, meaning that the contrast is increased. However, due to the strong light attenuation produced by polarizers, the SNR is decreased. This reduction of the SNR reduces the performance of image analysis algorithms and, thus, it may lead to problems in autonomous systems.

To conclude, from the author's point of view, the best choice to improve image quality in underwater scenarios using an AUV, is to keep light source and camera as separated as possible and use a glass dome port. Polarization based techniques should be considered only when the vehicle is not moving and the resulting images are meant to be analysed off-line by human operators.

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