Portable polarimetric underwater imaging system with a linear response

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ABSTRACT

Polarized light plays an important role in the underwater environment. Light that is scattered within the water is partially polarized. Biological and artificial systems can exploit this phenomenon. We aim to utilize this phenomenon in a new generation of underwater imaging systems in order to partially compensate for the loss of color and visibility. In order to obtain quantitative measurement of radiance and polarization, the imaging system should have a linear radiometric response and low noise. In addition, the interface of the camera with the water should have a minimum effect on the polarization. In this paper, we describe a portable lightweight imaging system that addresses these conditions. We detail the design considerations and empirical verifications.

Keywords: polarization, underwater imaging, polarimetric imaging, remote sensing, photoelastic effect

1. INTRODUCTION

Polarized light plays an important role in the underwater environment. There are some artificial as well as biological systems that can exploit polarization underwater. Biological research has found some underwater animals that use the polarization of light for navigation,[1,2] communication[3] and preying.[4] Imaging as suggested in this article is helpful for polarization related visibility improvement. Some previous studies[5–9] have used polarization of scattered light underwater in order to improve visibility and contrast*.

Polarization of light in the water can stem from different reasons.

1. Refraction through the water surface. According to the Fresnel equations[13] light that enters the water generally becomes polarized.
2. Scattering light in water (at angles other then $0°$ or $180°$) partially polarizes light.[2,5,14–19]
3. Refraction / reflection by polarizing objets.
4. Emission from a polarized light source, as a torch.

To study and exploit polarization phenomena underwater, we seek an imaging system capable of quantitative measurement of radiance and polarization. The imaging system should have a known (preferably linear) radiometric response and low noise. In order to use it easily, the system should be portable, and should not need external devices or power supply. The camera parameters should be easily controlled underwater. In addition, the interface of the camera with the water should least distort intensity and polarization readings. Physical effects as the photo-elastic effect, reflection and refraction should be taken into consideration. A specific off-the-shelf camera and housing combined with some custom made accessories were chosen by us to meet these requirements.

2. THE AQUA-POLARICAM

We have built a custom system for underwater polarimetric imaging, which we term the Aqua-Polaricam. We built the system shown in Figs. 1 and 2. The system is composed of a digital camera, an underwater camera housing and a circular polarizer. Each of the Aqua-polaricam components was carefully chosen to meet our requirements, and the considerations are specified in the following.

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*In this context it is worth mentioning that polarimetric imaging has proved helpful in open-air scenarios.[10–12]

Figure 1. The Aqua-Polaricam mounted on a tripod.

Figure 2. The system was used during scuba dives.

2.1. Required underwater camera housing specifications

This section describes the specifications we imposed on the underwater camera housing. We then describe our selection. The specifications are:

1. **No intensity and polarization distortions.** The camera lens views the scene through a *port*, i.e., a transparent window in the housing.[20,21] The port of the underwater housing is an optical component by itself. We must ensure that the image would be least subject to intensity or polarization distortion caused by the window. This issue is described in detail in the following.

2. **Watertight at high pressure.** To enable dives at depths.

3. **Control of required camera options.** The housing must have an interface to control the camera parameters.

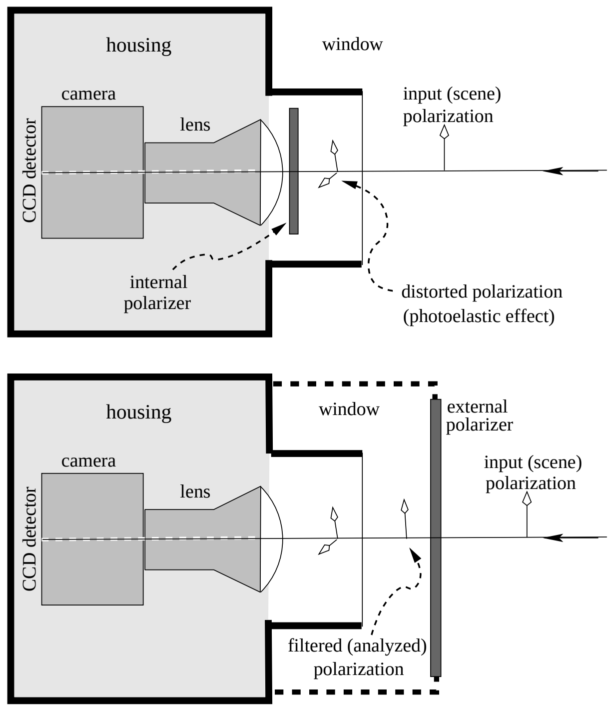

Figure 3. [Top] An unwanted effect: photoelasticity in the window changes the polarization. When light passes through an internal polarizer, this manifests in changes of image intensity and color. [Bottom] The preferred design: placing the polarizer externally to the window minimizes this effect.

4. **No stray light.** Most housings have multiple windows through which one can check the digital camera settings. We need to make sure that there would be no stray light coming from these windows (or any other source) to our image. Preliminary experiments on the commercial housing we used, revealed that stray light enters the housing from its back viewing ports and then reflects into the lens. We blocked the stray light by slightly modifying the internal structure of the commercial housing.

Polarization Considerations

The main concern in the optical design is its affect on polarization. We use a polarizer to analyze the scene. However, we would like the *rest* of the optical system components to have *minimal effects* or sensitivities related to polarization. We achieve this by making the following decisions:

An external polarizer. Stress in the transparent port's material changes the polarization of the light it transmits. This phenomenon is called the *photoelastic effect.*[13] Due to inhomogeneities in the material, this polarization effect is spatially varying. If the polarizer is inserted inside the housing (Fig. 3), this photoelasticity could induce spatial variations in the transmittance though the polarizer, depending[13] on the wavelength λ and the polarization state. Moreover, the effect may vary with the underwater depth, due to changes in the external water pressures.

In principle, placing the polarizer externally should eliminate visible photoelastic effects. We thus decided to place the polarizing filter *outside* the housing. Consider Fig. 3. The filter is the first optical component the light from the scene encounters as it enters the imaging system. The space between the external polarizer and the dome is filled with the water coming from the surroundings. In practice, the photoelastic visible effects are indeed greatly diminished, but not completely eliminated. Residual effects persist due to complicated refractions in the transparent materials. To minimize such residual effects, we make the following decisions.

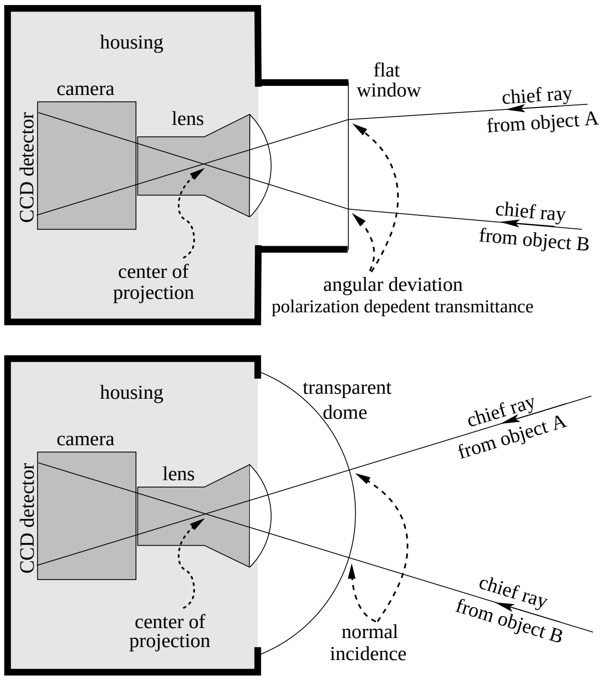

Figure 4. [Top] An unwanted effect: the transmittance of a flat port (window) is polarization dependent at oblique incidence. [Bottom] The preferred design: a spherical dome concentric with the center of projection nearly eliminates this effect by creating normal incidence angles.

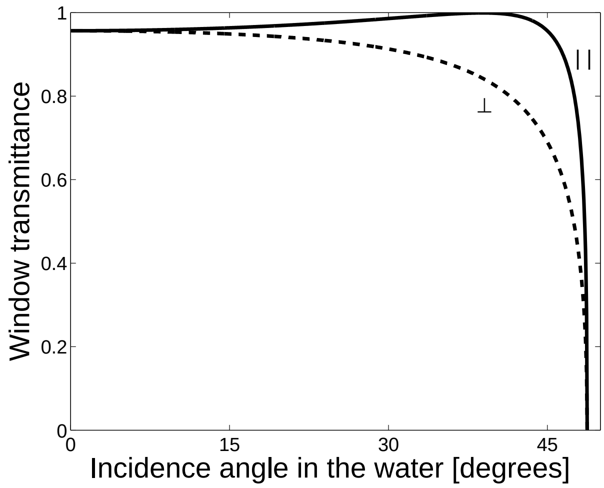

Figure 5. The transmittance of the parallel and perpendicular polarization components.

A glass windows. The photoelastic effect is much smaller in glass than in polycarbonate (plastics) materials.[13] We thus decided to use a *glass port*. We avoid the use of crystal glass windows, which are commercially available, since they may posses birefringence, affecting the polarization readout.

A dome port. Typical ports are flat or spherical. Consider Fig. 4. The chief ray from an object point in the water to the detector undergoes an angular deviation[20, 21] at flat window interfaces. In this case, the window transmittance depends on the polarization of the passing light[13] (see Fig. 5). This polarization dependence

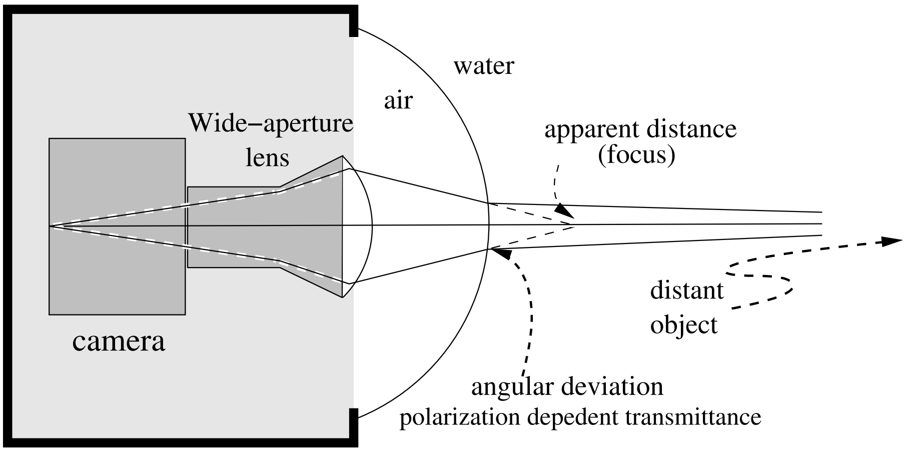

Figure 6. In practice, the dome port creates an effective lens in front of the camera lens, when the housing is underwater. This causes far objects to appear very close, with regard to focusing. Due to the refraction of the beam, there are non-normal incidences even when using a dome port.

distorts the intensity and therefore the polarization readout values. On the other hand, dome ports alleviate most of this problem, if the dome's center coincides with the center of projection of the camera lens. Then, the chief ray from an object point to the detector is normal to the dome interface. For this reason, we decided to use a *dome port* .[22, 23]

The dome's exterior is in water while its interior is in air. This difference of refraction index across the curved surface creates a simple lens,[20] placed in from of the camera lens. This is shown in Fig. 6. Although the dome port allows the lens to retain its full field of view, the dome "induced lens" creates a virtual image very close to the housing.[20] The distance from the dome to the virtual object is given by[24]

$$z' = \frac{R \cdot n_{air}}{(n_{water} - n_{air}) + n_{air}\frac{R}{z}} \quad , \tag{1}$$

where R is the curvature radius of the dome (R=90mm in our case), while $n_{air} = 1$ and $n_{water} = 1.33$ are the refraction indices of air and water. Here z is the distance from the dome to the object. For far objects ($z \gg R$), the distance to the virtual object, is

$$z' = \frac{R \cdot 1}{(1.33 - 1)} \approx 3R = 270mm \quad . \tag{2}$$

A circular or linear polarizer? Even if we use a dome port, not all light rays have a normal incidence. One reason is that the dome may not be precisely concentric with the center of projection. In addition, each pixel corresponds to a *beam* rather than a single ray (Fig. 6), due to the finite lens aperture. In non-normal incidence, different polarization components are differently transmitted, affecting the intensity readouts. To reduce this effect, we decided to use a *circular polarizer.* A circular polarizer (Fig. 7) is composed of a linear polarizer and a $\lambda/4$ plate oriented at 45° to the polarization direction. It filters the linear polarization of its input (scene) while it outputs circular polarization[13] to the dome. In this case, the light transmittance of the dome is independent of the filter orientation. Yet, circular polarizers are tuned to a narrow band (typically "green"), and do not perform perfectly across the spectrum. So, while this measure helps in minimizing unwanted polarization effects, the other considerations listed above should be employed as well.

We selected a housing which satisfies these considerations. The housing is manufactured by Sealux and is commercially available. For the reasons explained previously, we close the housing with a *dome* port made of *glass*, while a *circular* polarizer is attached *externally* to it. The surrounding water flows to the space between the external polarizer and the dome, through several openings in the housing's interface to the polarizer mount.

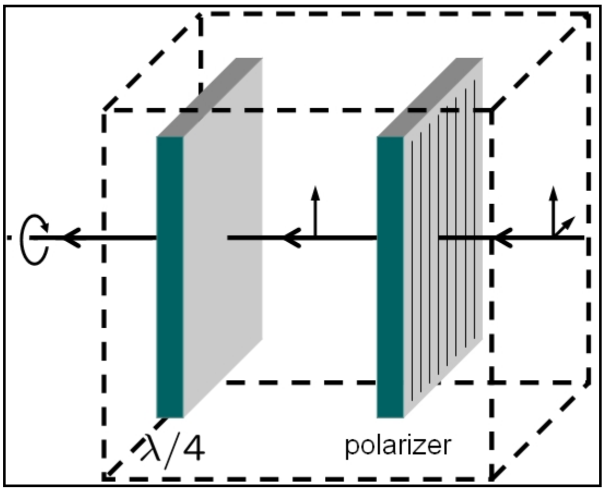

Figure 7. A circular polarizer is composed of a linear polarizer and a $\lambda/4$ plate oriented at 45° to the polarization direction, it filters the linear polarization of its input (scene) while it outputs circular polarization.

2.2. Required camera specifications

This section describes the specifications we imposed for selecting a digital still camera for our work. We then describe our selection. The specifications are:

1. **Portability.** There are numerous cameras in the market which provide linear response, full control and avoid internal image processing. However, almost all of them are designed for laboratory use or applications in industrialized machine vision. This means that they must be connected to an external power source and an external recording medium (a PC). All this stands in contrast to our need to perform experiments underwater without limitations. This practically rules out such cameras. On the other hand, all the consumer-grade cameras are portable - they work on small internal batteries and have an internal recording media. Yet, consumer cameras typically suffer from nonlinear response and automatic processing. In the bottom line, we require the camera to be portable (as consumer cameras), while maintaining the rest of the specifications written below.

2. **A Linear radiometric response.** To sense polarization, several images are taken, corresponding to different states of the polarizing filter. To calculate the polarization, we assume that the scene radiance corresponds to the recorded digital value according to a known function (the *radiometric response*). If this function is nonlinear, then the scene radiance can be recovered using nonlinear compensation. However, this process increases noise in some ranges of the image readout. For this reason, it is best to use a camera which has a linear radiometric response, which rules out many consumer digital cameras.

3. **No internal image processing.** Some cameras process the images automatically before sending the images to the camera output. Examples include color de-mosaicking, white balancing, highlight/shadow softening and spatial noise reduction. These processes distort the assumed relationship between the scene radiance and the output recorded digital values. For this reason, we require the camera to avoid these processes altogether.

4. **Full control.** While we wish to avoid automatic processes by the camera, we require having full manual control over the camera parameters.

5. **Low noise.** There are a few cameras which meet the above mentioned specifications. We then seek the one which has the lowest noise levels.

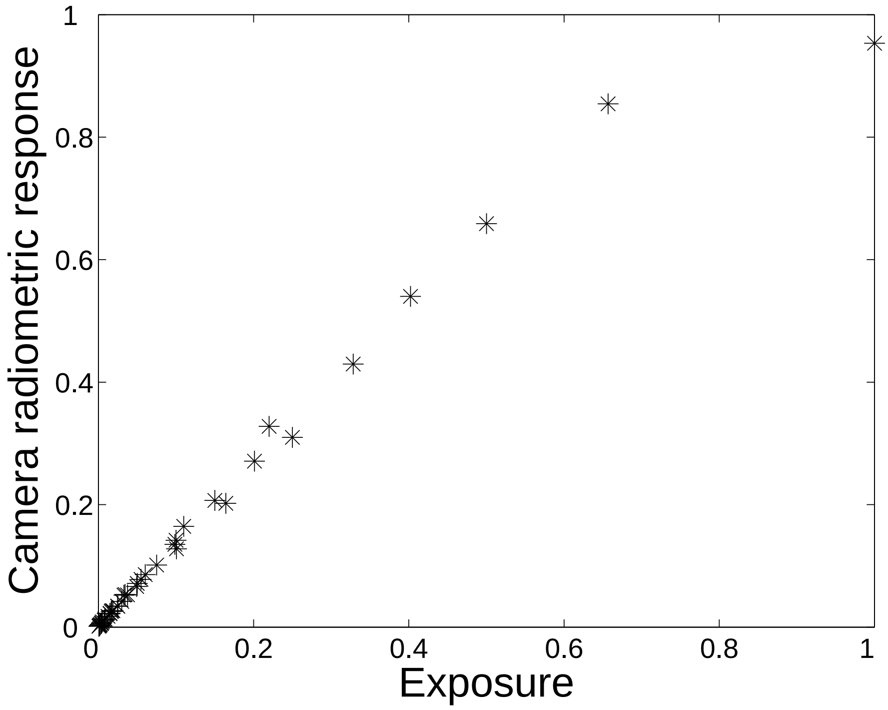

Figure 8. The camera readout as a function of exposure. Linearity exists up to at least 85% of the dynamic range of the camera output.

There are several digital single-lens-reflex (SLR) cameras which meet the above mentioned specifications. They provide an option to output a RAW format image. This format is company specific. However, some of the companies explicitly state that their format records the image irradiance without any processing, i.e, without gamma-correction, color de-mosaicing, white balancing etc. We thus select the camera having the lowest noise level. The leading models at the time of purchase were the Nikon D1H and the Nikon D100. The former has slightly lower noise for a given camera gain. However, the latter has many more pixels. These in turn can be averaged in a sub-sampling scheme we wrote, to reduce noise. Considering the resolution/noise tradeoff, the Nikon D100 digital SLR is superior. For this reason, we selected this camera.

Extraction of Data

To confirm the linearity and noise performance of the camera, we took images of a standard calibration target. The results of the validation experiments are shown in Fig. 8. Linearity of the radiometric response exists up to at least 85% of the dynamic range. The conclusion is that the Nikon-D100 indeed yields images linearly related to the scene radiance. However, in order to achieve this, we should use a 3^{rd} party software to extract the data from the camera[†]. We use the Nikon D100 digital SLR camera, which allows for raw output data having a linear response (i.e., no gamma correction) without automatic white balancing.

When setting the camera parameters, the issue of gain level (ISO) and noise should be dealt with. Setting the camera to a high gain level results in noise amplification. On the other hand, using long exposures rather than high gain might lead to high dark current. After conducting some daylight experiments underwater in the scuba-dive depth range, we tested the Nikon D100 camera in the lab, at typical underwater environment lightning and temperature conditions. We found out that it is preferable to adjust the camera to a gain level of 800ISO to 1000ISO, to obtaining minimum overall noise.

[†]We found out that the software *Bibble labs 2002* by Bibble Labs extracts the images without gamma correction. This is in contrast to the software provided by Nikon, which extracts the images with gamma correction.

3. DISCUSSION

Underwater imaging is used in various applications,[14, 25–33] such as mine detection, inspection of underwater power and telecommunication cables, pipelines,[34, 35] nuclear reactors, and columns of offshore platforms.[34] Underwater computer vision is commercially used to help swimming pool life guards.[36] As in conventional computer vision, algorithms are sought for navigation and control[37] of submerged robots. In addition, underwater imaging is used for research in marine biology,[2, 33, 38, 39] archaeology[40–43] and mapping.[37] Moreover, underwater photography[20, 21] is becoming more accessible to the wider public. Therefore it is important to find ways to study effects in underwater imaging and to improve underwater visibility.

We have introduced an imaging system named the Aqua-Polaricam, which is designed to obtain quantitative measurements of radiance and polarization underwater. The system is lightweight, portable, has a linear radiometric response and low noise. The system has been especially designed to have minimal distortions of intensity and polarization, taking into consideration optical effects that may affect these readings. We plan to use this system to develop methods for improving underwater visibility.

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