Real-time polarization difference imaging (rPDI) reveals surface details and textures in harsh environments

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Abstract

Extensive peer reviewed scientific research has demonstrated the utility of polarization difference imaging (PDI) to reveal subtle surface details and textures in poor lighting conditions caused by fog, smoke, clouds or turbid water. We present sample results of a new real time PDI camera showing the ability of the camera to enhanced imaging harsh environments, particularly in turbid water.

Keywords: Polarization, sensors, underwater imaging

1. INTRODUCTION

It has been known for a few decades that using polarization difference imaging (PDI) can greatly improve the background discrimination in underwater object detection and imaging [1]. However, real world use of polarization difference imaging has been limited by the sequential rather than simultaneous capture of the polarization states. Our team has built and tested a prototype of a custom polarization beam-splitting assembly developed and patented by Q5 Innovations Inc. from COTS components. This real-time polarization difference imaging camera (Detect POL™) offers high polarization segregation across a wide field of view, and allows the simultaneous separation and routing of orthogonal states of linear polarization to two separate sensors. The purpose of this paper is to present the ability of the Detect POL™ camera for real-time underwater object detection and imaging under turbid conditions. The performance of the camera is tested with both linear and circular polarized lighting of the targets and two different types of induced turbidity agents (Maalox® and water-soluble cutting oil).

2. EXPERIMENTAL SETUP

2.1 The Detect POL™ camera

The Detect POL™ camera used in the experiments is a prototype of a real-time Polarization Difference Imaging (rPDI) video system. It selectively and simultaneously splits the horizontal and vertical planes of polarized light from an input signal using a custom beam-splitter design. Once segregated, the two polarized signals are imaged on two CCD cameras. Software, based on the CCD camera's manufacturer, was developed in order to perform real-time operations on the two polarized images. The resulting processed image of a scene can be displayed in real-time, thus enhancing contrast and improving target detection, as well as improving visibility in optically dense or poor lighting conditions.

Fig. 1 shows a functional schematic and a picture of the Detect POL™ camera. The camera can be customized for imaging at specific wavelengths by inserting a band-pass filter inside the camera body at a position provided by the design. The Detect POL™ camera specifications are listed in Table 1.

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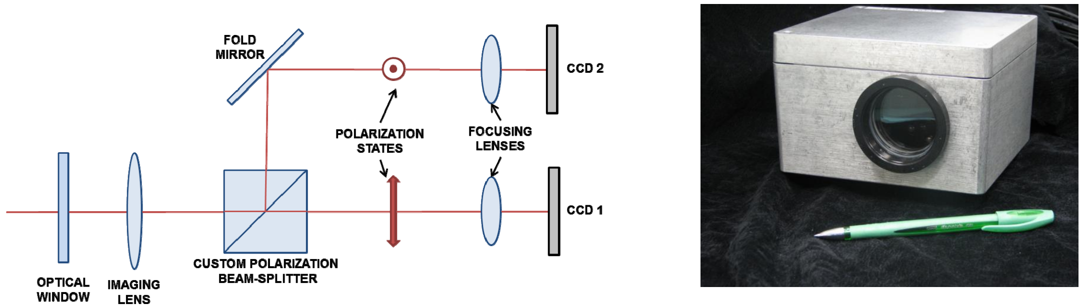

Figure 1. Schematic (left) and picture (right) of the prototype rPDI camera (left). Each CCD captures a different polarization state: CCD 1 captures the horizontal polarization component while CCD 2 captures the vertical one. (Under US 7,446,871; CDN 2,550,692; UK GB2, 427,975 patents).

Table 1. Specifications of the rPDI prototype camera.

Specification	Value
Image resolution	800 x 600 pixels / 8-bit
Pixel size	4.65 um
Frame rate (max.)	30 Hz
Field of view	20 deg.
F-number	f/1.9
Resolution (full field)	160 lp/mm @ 20% contrast
Work range	0 - infinity

2.2 Experimental setup for the aquarium tests

All imaging tests were done using the setup showed in Fig. 2. The aquarium used is a consumer retail unit having a 15 gallons capacity and external dimensions of 24"(L) x 12"(D) x 14"(H). The sides of the aquarium were covered with sheets of black Coroplast® to keep the imaging of the different sample targets from undesired reflections. The Detect POL™ camera is held by a bracket and faces down to the bottom of the aquarium which resides at a distance of 30 cm from the entrance window of the camera. The front end of the camera is waterproof so it is kept immerged when doing the tests. The samples are illuminated using a 300W Tungsten lamp plugged to a rheostat used to control its light output. A linear polarizing sheet is held in place by the aquarium edges to provide a source of linear polarized light. For the series of experiments involving circular polarizers, the linear polarizing sheet is replaced by a right-handed circular polarizing sheet and a left-handed circular polarizer is inserted inside the Detect POL™ camera body at the position provided for a band-pass filter. A LaMotte 2020we portable turbidity meter is used to monitor the turbidity levels during the experiments.

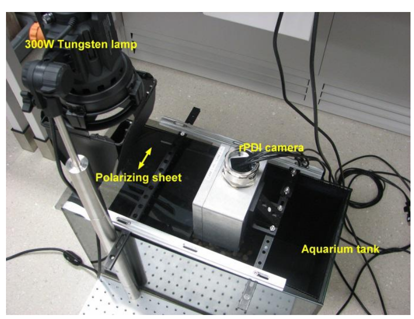

Figure 2. Image of the aquarium tests setup. The 300W Tungsten lamp is connected to a rheostat to adjust its light output, and is positioned relative to the camera to approximate typical illumination geometry used with many underwater cameras. Samples to image are placed at the bottom of the aquarium, below the prototype rPDI camera at a distance of 30 cm. Note that the aquarium is shown empty.

3. AQUARIUM TESTS WITH MAGNESIUM HYDROXIDE AND LINEAR POLARIZER

3.1 Objectives

The approach was to evaluate how the Detect POL™ camera enhances image contrast when imaging underwater targets under conditions of high turbidity. The underlying assumption is based on the fact that linear polarized light that is scattered backwards by suspended particulate in ocean water is much less depolarized than the light scattered by the object [1]. The Detect POL™ camera should help to discriminate the signal coming back from the turbid water in respect of the light coming back from the target. The Detect POL™ camera channel oriented perpendicular to the transmitted light will reject the backscatter signal while recovering a portion of the target reflected light. Such imaging tests under turbid conditions are often done using magnesium hydroxide (Maalox®) dispersed in water and is well documented in the literature [2]. In our tests, we had to rely on a generic brand because the original Maalox® supplier had been back-ordered for some months. We thus performed measurements of the turbidity at different concentrations of a generic brand in water to calibrate the mL/L ratio to obtain specific values of turbidity during our experiments. We found the linear relation turbidity [NTU] = 571.67*concentration of generic formula [mg/L] to hold particularly well.

3.2 Results

When imaging using the prototype camera, the contrast is calculated using the following equation [3]:

$$contrast = \frac{\left(I_{vert.} - I_{horiz.}\right)}{\left(I_{vert.} + I_{horiz.}\right)}, \tag{1.1}$$

where $I_{vert.}$ and $I_{horiz.}$ are the vertical and horizontal polarization intensity signals recorded by channel 2 and channel 1 of the Detect POL™ camera. The 8-bit images are converted to 32-bit when computing the contrast using Eq. (1) and a color-mapping is then applied to the results.

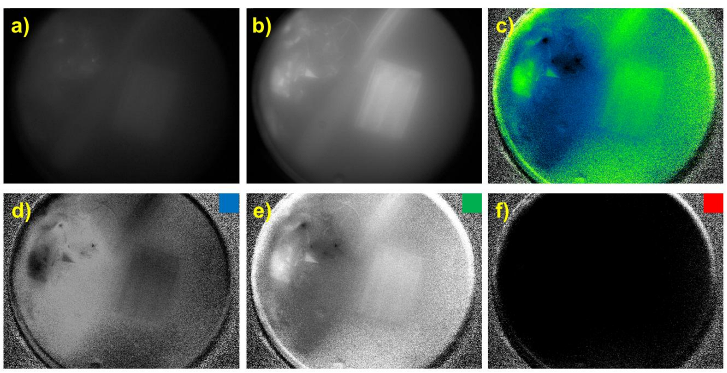

Figure 3. Results of aquarium test with magnesium hydroxide at a turbidity level of 10 NTU using linear polarized light and the Detect POL™ camera unit; a) is the image from camera 1 showing horizontal polarization information; b) is the image from camera 2 showing vertical polarization information; c) shows the polarization contrast computed using Eq. (1); d), e), and f) show the blue, green, and red channels of image c).

3.3 Conclusion

The difference in the amount of exposure in Figs. 3a and 3b clearly highlights the fact that a large proportion of backscattered illumination in magnesium hydroxide induced turbidity maintains a substantial linearly polarized component. Such "polarization noise" significantly reduces the spatial contrast of the image, and attempts were made to investigate methods of reducing this polarization artifact.

4. AQUARIUM TESTS WITH MAGNESIUM HYDROXIDE AND CIRCULAR POLARIZER

4.1 Objectives

Previous studies have highlighted the potential utility of applying left and right handed circular polarizers in imaging in scattering media [3]. The illumination source is circular polarized with one handedness, and imaging is carried out through a circular polarizer of opposite handedness. In the case of using a Detect POL™ rPDI camera, it is critical that the orientation of the circular polarizer inside the camera is such that the retarded component of the circular polarizer is closest to the input of the rPDI beam-splitting component.

4.2 Results

With the circular polarizer, we were able to see significant improvements in image detail with a decrease in the differential exposure between the two cameras (see Fig. 4a in comparison to Fig. 4b). It is important to note that, although the targets are illuminated by circular polarized light, the pixel intensity differences, and the ability to resolve surface textural and geometric details, are still based on imaging linear polarization information. Even at 10 NTU, fine surface details can be resolved as shown on Fig. 4e insert that shows scratches on an aluminum block.

At 22 NTU, although it is still possible to see that there are objects in the field of view, all details are obscured. Preliminary off line tests of frame averaging (see Fig. 6) resulted in a stronger signal for the detection of the presence of objects, but all textural and surface details were still obscured.

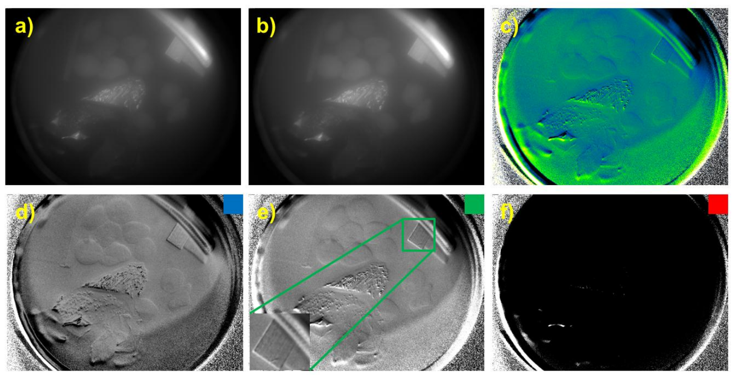

Figure 4. Results of aquarium test with magnesium hydroxide at a turbidity level of 10 NTU using right-handed circular polarized light and a left-handed circular polarizer inside the Detect POL™ camera unit; a) is the image from camera 1 showing horizontal polarization information; b) is the image from camera 2 showing vertical polarization information; c) shows the polarization contrast computed using Eq. (1); d), e), and f) show the blue, green, and red channels of image c). The insert in e) clearly shows that fine scratches on an aluminum block can be resolved.

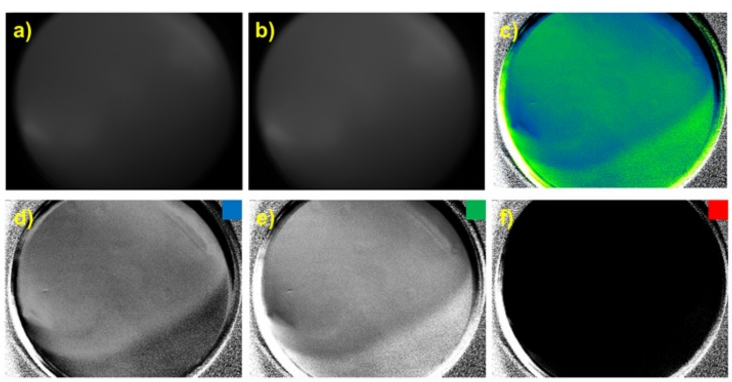

Figure 5. Results of aquarium test with magnesium hydroxide at a turbidity level of 22 NTU using right-handed circular polarized light and a left-handed circular polarizer inside the Detect POL™ camera unit; a) and b) show the recorded images by camera 1 and camera 2 respectively; c) shows the polarization contrast computed using Eq. (1); d), e), and f) show the blue, green, and red channels of image c).

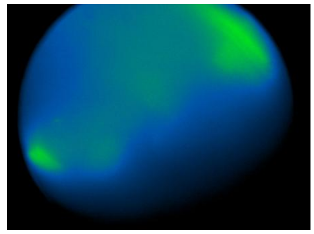

Figure 6. Results of aquarium test with magnesium hydroxide at a turbidity level of 22 NTU using right-handed circular polarized light and a left-handed circular polarizer inside the Detect POL™ camera unit. An rPDI image was computed "off-line" using ImageJ software to assess the potential future utility of implementing frame averaging to reduce image noise associated with high turbidity low light level imaging. It can be seen that even simple averaging of three consecutive video frames results in a significant image improvement, and suggests promise for future implementation of real-time image processing algorithms.

4.3 Conclusions

The results obtained using a pair of circular polarizers clearly confirms the results already obtained in section 3, that although magnesium hydroxide is good at producing seawater-like attenuation length factors, its high albedo results in a high amount of backscattered light to the camera. The use of the circular polarizer pair reduces the amount of backscattered light contamination, resulting in enhanced details on the rPDI processed images.

5. AQUARIUM TESTS USING CUTTING OIL

5.1 Objectives

In section 3.3, it was mentioned that a large proportion of backscattered illumination in magnesium hydroxide induced turbidity maintains a substantial linearly polarized component. A recent experiment has shown that diluted hydrophilic cutting oil into water can be used as a stable, homogeneous and nonorganic induced turbidity medium [4]. We were able to get some cutting oil from our department machine shop and perform a series of aquarium tests with the Detect POL™ camera. We noticed that cutting oil indeed produces induced turbidity that is highly homogeneous and stable.

5.2 Results

Figs. 7 and 8 show the results obtained when using water-soluble cutting as the turbid agent to produce a turbidity level of 35 NTU inside the aquarium. Fig. 7 shows the images obtained when using the pair of circular polarizers and Fig. 8 shows the images obtained when using the linear polarizer in front of the light source. Fig. 8b shows a frame sample extracted from a live video recorded at a 15 NTU turbidity level when using the Detect POL™ camera and a linear polarized light source. A reference image of the target was shoot using a standard digital camera and is shown in Fig. 8a.

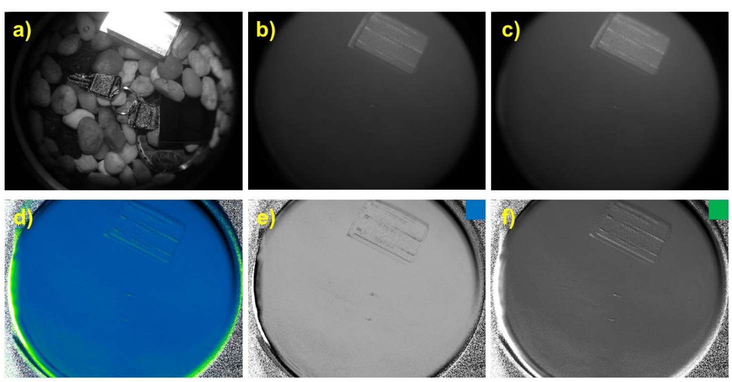

Figure 7. Results of aquarium test with cutting oil at a turbidity level of 35 NTU using right-handed circular polarized light and a left-handed circular polarizer inside the Detect POL™ camera unit. Image a) show a reference image taken at 0 NTU while b) and c) show the recorded images by camera 1 and camera 2 respectively; d) shows the polarization contrast computed using Eq. (1); e) and f) show the blue and green channels of image d).

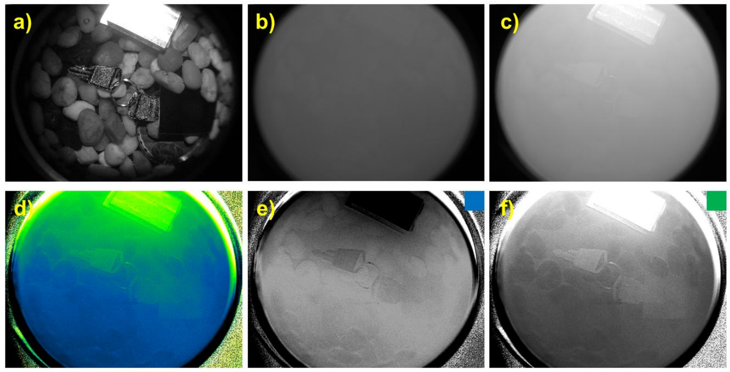

Figure 8. Results of aquarium test with cutting oil at a turbidity level of 35 NTU using linear polarized light and the Detect POL™ camera unit. Image a) show a reference image taken at 0 NTU while b) and c) show the recorded images by camera 1 (horizontal polarization information) and camera 2 (vertical polarization information) respectively; d) shows the polarization contrast computed using Eq. (1); e) and f) show the blue and green channels of image d).

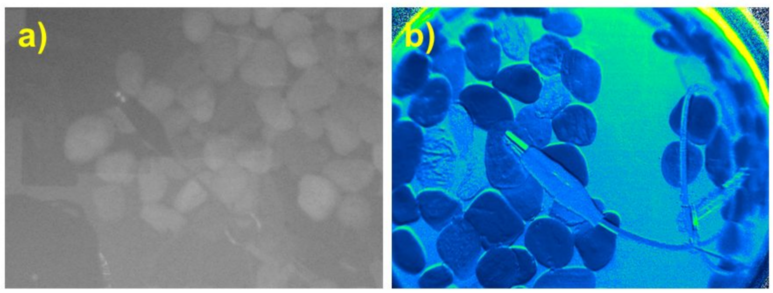

Figure 9. Results of aquarium test with cutting at a turbidity level of 15 NTU using linear polarized light and the Detect POL™ camera unit when imaging an alligator clip. Image a) show a reference image taken with a regular Canon S20 digital camera while b) shows the polarization contrast computed using Eq. (1). Rock details can easily be seen in b).

5.3 Conclusions

The rPDI images, taken using water-soluble cutting oil to induce turbidity, show that the albedo issue that is present when using magnesium hydroxide is greatly reduced. The use of the circular polarizer pair to reduce the amount of backscattered light contamination is in this case less significant to enhance the rPDI signal. However, when using a linear polarized source oriented along the vertical channel of the Detect POL™camera, a highly contrasted rPDI image can be obtained. These high contrast color-channels images results in fine visible detail structures on the target not visible otherwise.

6. SUMMARY AND CONCLUSIONS

We performed a number of experiments using the Detect POL™ camera for imaging under turbid conditions. We noticed that using the Detect POL™ camera in a turbid medium requires that the scene be illuminated by a polarized light source. It is clear that using the contrast ratio between the horizontal and vertical channels of the Detect POL™ camera enhance the object detection under turbid conditions.

While magnesium hydroxide is commonly used as the turbid agent in several other experiments, its albedo is high and so it does not necessarily represents real-world conditions [5]. The results that were obtained using magnesium hydroxide and a pair of circular polarizers tend to confirm this assertion as better structure details can be seen in Fig. 4 than in Fig. 3. The circular polarizers are thus better to help discriminate the amount of backscattered light resulting from the magnesium hydroxide high albedo.

Although there is no actual literature to be found on using water-soluble cutting oil for induced turbidity experiments in underwater imaging situations, other than presented in [4] for an instrument calibration, the results presented here illustrate that it alleviated the reflecting issues of Maalox® high albedo. While it would require further characterization, a close examination of Figs. 6 and 7 point to the fact that the cutting oil setup is a suitable and more stable solution to reproduce seawater-like environments.

The difference between using a linear or circular polarized light source will greatly depend on the exact structure of the turbid environment the camera will be used in. Considering the fact that the cutting oil scenario seems to closely reproduce real-world backscattering conditions, the combined used of a linear polarized light source and the Detect POL™ camera lend to greatly improved object detection at a turbidity level of 35 NTU at a 0.30 m distance (or 10.5 NTU at 1.5 m).

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