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Underwater Image Recovery Using Structured Light

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ABSTRACT Structured lighting techniques have increasingly been employed in underwater imaging. Except for the limitation in underwater illumination, the desire of underwater image acquisition comes from the applicability of removal of the back scattered light, the critical problem of underwater imaging, using structured lighting techniques. This paper presents an approach for underwater image recovery using structured light and CCD camera. By integrating the scanned frame images, we generate an integration image which can be formulated as the convolution of the surface albedo and the illumination function. Thus, underwater image acquisition is addressed as an optimization problem of image recovery and resolved by deconvolution, rather than the traditional geometric manipulation of frame tiling. The significance of the proposed method is that the forward scattering effect in the recovered image is fully eliminated by the integration operation and collection of the forward scattered light enhances the total imaging energy. By means of the structured lighting technique, an algorithm of using virtual aperture to limit the field of view is proposed to eliminate the back scattered light in frame images. Concerned with applicability of using the broad lighting pattern in structured light systems, the coded structured light with binary pseudo-random sequence is introduced, by which the high-frequency details in image recovery can be preserved through deconvolution. The results of underwater experiments are given.

INDEX TERMS Structured light, image recovery, elimination of back scattered light, coded structured light.

I. INTRODUCTION

In general, structured light techniques modulate the appearance of a surface by projecting a particular pattern of light onto it [1]. The correspondence of the image pattern and the surface points enables accurate computation of the range of the surface points. Structured light techniques can be classified into multiple-shot (sequential) or single-shot categories. As one of the essential 3D measurement technologies, structured light has found growing application in underwater imaging, such as seabed mapping, pipeline or dock detection, target localization and ROV/AUV navigation. A variety of structured lighting techniques have been developed [2]–[7]. However, optical imaging in scattering media suffers from the scattering problems [8], [9]. The back scattered light, which is scattered back from the medium before projecting onto the object surface, veils the scene and degrades the image contrast. The forward scattered light, which comes from the illuminated object surface but deviates during the transmission to the camera, blurs the details of the scene and degrades the sharpness of the image. Due to such scattering effects, together with light attenuation, an optical image taken in underwater usually loses meaningful image features of scene. So most single-shot structured light techniques can not be applied in turbid water medium, since the lighting features with the designed specific complex patterns are indistinguishable due to the poor image qualities. In practice, structured light of multiple-shot mode, i.e., sequential imaging by way of scanning a simple line/beam lighting pattern, is the reliable implementation of the structured light technique in underwater, but with time cost.

Although 2D image can be obtained using flood light with CCD camera in underwater, it is strongly desired to acquire 2D image with the structured light while 3D measurement is implemented. One of the most important reasons is that the elimination of the back scattered light, commonly concerned in underwater imaging systems, can be realized by structured lighting techniques. Classical is the synchronous laser line scanning system (SLL) [2], [5], [12], [13]. The system works with the laser line (stripe) illumination and the

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aperture-coupled optoelectronic sensor, both of which scan synchronously. Since the overlapped volume of the illuminated field of the laser and the view filed of the aperture, i.e., the observable portion of the medium, is very limited, the amount of the back scattered light received by the sensor is thus very limited; most of the back scattered light generated outside the overlapped volume are spatially separated from the reflected light of the object. The 2D image of the scene is consequently obtained by tiling the sequentially scanned outputs of the image sensor. The SLL system is very effective to physically remove the back scattered light, but with the cost of hardware complexes.

Benefited from the developed image processing techniques, the compact device consisting of the CCD camera and the structured (or flood) illumination source have become the popular imaging system in underwater applications. In [8], a comprehensive analysis of structured light in underwater imaging is given. In their method, an analytic image formation model is derived to describe the interactions of light with the medium and the scene. Applying the model for strip lighting pattern, a simple algorithm is developed to obtain the 3D reconstruction of the scene in the presence of scattering. The calibration is preset by measurement of the known 3D world coordinates of points on planes and the attenuation coefficient are estimated by fitting observations to the model in the measurements as well. Once the attenuation coefficient is evaluated and the 3D surface is reconstructed, the clear-air appearance of the scene is computed for each object intersection strip and all the intersection strips are geometrically tiled to form the 2D image. That method can fully remove the back scattered light in 2D imaging by computations, but requires the priors of the attenuation coefficient of the medium and the calibration process with extra in-situ measurements.

The issue of the structured light has been fully discussed for 3D reconstruction, but less concerned for 2D image acquisition until now. It is noticed that a few existing methods for 2D image acquisition using structured light, such as that of the SLL system and that of the implementation of [10], commonly utilize the tiling approach, i.e., simply stacking all the scanned frames to output the 2D image. Although the tilting approach is a straightforward manipulation, the output image preserves the forward scattering effect in the output image, causing blurs of image details. In practice, the forward scattering effect may not introduce significant degradation of the image quality in weakly scattering media. However, the forward scattering effect is still a notable problem in underwater imaging, particular in turbid water, which could prevent the detection of the image details.

In this paper, we present a new approach for 2D image acquisition using structured light. The structured light projects onto the object surface and scans in one dimensional direction (aligned with the row direction in the image coordinate). In each frame image, the row pixels are integrated to form each column of the integrated image with respect to each scanning position. Thus all those column elements can be formulated as the outputs of one dimensional convolution integration of the object albedo and the illumination distribution of the structured light along the row coordinate. Therefore, the 2D image acquisition of the object albedo can be issued as the optimization problem of image recovery and is approached by the deconvolution routines. Concerned with the robustness of deconvolution operation, the coded structured light is further proposed. The significance of the proposed method is that the forward scattering effect in the recovered image is fully eliminated through the integration operation. From another point of view, the integration operation enables us to collect the forward scattered light during the transmission from the object to the camera, enhancing the total imaging energy of the object. In order to remove the back scattered light in each frame image, an algorithm of using virtual aperture to limit the field of view is proposed, by the same physical mechanism of the synchronous scanning imaging system but implemented through computation.

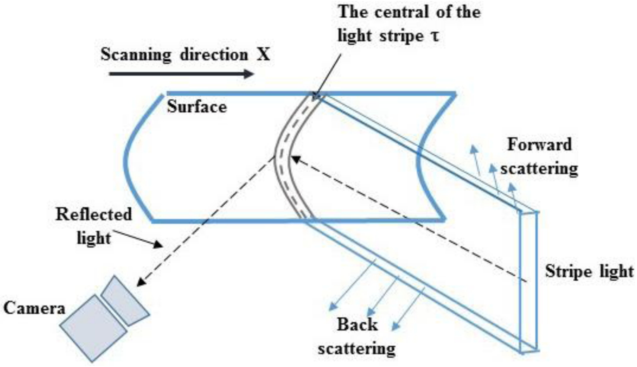


FIGURE 1. Typical structured lighting technique.

II. THE PRINCIPLE OF IMAGE RECOVERY WITH SCANNING STRUCTURED LIGHT

Figure 1 shows a schematic illustration of the structured light technique. The projector projects a stripe light and sweeps across the object surface while the CCD acquires the sequential images. By detecting the image position of the intersection curve of the light plane and the surface, the 3D coordinates of each point on this curve can be computed once the correspondence between the CCD coordinate and the projector coordinate is setup.

It should be noted that in real implementations, stripe light usually refers to a strip-like illumination which intensity distributions has a very narrow support. Thus the commonly used model in term of light plane, i.e., vanishing thin stripe, is just an ideal description of the strip light. In this paper, we consider the general description of the illumination distribution of the stripe light; the sectional distribution of light illumination, observed from the CCD image coordinate, is denoted $I(x)$, where x is the same with the image row coordinate. Thus we can represent the image formation with respect to one dimensional description associated to a single image row. All image rows stack to form the complete 2D image.

For an image row, suppose the albedo of the object surface is $O(x)$. At a moment during the scanning, the central of the lighting distribution is positioned at τ. Thus the one dimensional image with respect to the variable τ can be expressed as

$$f\,(x,\tau) = I(x-\tau)\mathrm{O}(x) \tag{1}$$

In underwater imaging, however, the forward scattering occurs during light transmission from the object to the camera, whose imaging effect can be expressed by the PSF (point spread function), denoted $h(x)$, while the back scattering induces the added background, denoted $b(x)$. Thus the general image formation is

$$f\,(x,\tau) = h\,(x) * [I\,(x-\tau)\,O\,(x)] + b(x,\tau) \tag{2}$$

where $*$ is the convolution operation. Taking integration operation on both sides of (2) with respect of the variable x, we obtain the integration image defined as

$$\begin{aligned} \mathrm{g}\,(\tau) &= \int_{\Omega} f\,(x,\tau)\,dx \\ &= \int_{\Omega} h\,(x) * [I\,(x-\tau)\,\mathrm{O}\,(x)]\,dx + \int_{\Omega} b\,(x,\tau)\,dx \end{aligned} \tag{3}$$

where Ω is the image domain. Noting the equivalent expressions:

$$\int_{\Omega} h(x)dx = 1 \text{ and } \int_{\Omega} h(x) * f\,(x)\,dx = \int_{\Omega} f(x)dx \tag{4}$$

we can formulate (3) as

$$\begin{aligned} \mathrm{g}\,(\tau) &= \int_{\Omega} I(x-\tau)O(x)dx + \int_{\Omega} b(x,\tau)dx \\ &= I\,(\tau) * O\,(\tau) + B(\tau) \end{aligned} \tag{5}$$

The form of (5) suggests that the function $O(x)$ can be obtained by the deconvolution operation once we generate the integration image $g(\tau)$ by integrating the sequential frame images. Consequently, the whole image is obtained by the recovered $O(x)$ row by row.

It is noted that the function $I(x)$ in (5) is actually the projected light distribution observed from the view of the camera, which distribution may slightly differ from that of the input distribution of projector. It implies that the recovery of $O(x)$ is relevant to the blind deconvolution mathematically. Whatsoever, the estimation of $O(x)$ is straightforward since the prior of the input light distribution of projector provides with a precise initial estimate of $I(x)$. In addition, the attenuation factor is omitted in image formation of (2) and is treated as a multiplicative scalar of $O(x)$, which can be restored once the 3D reconstruction be implemented using structure light and the attenuation coefficient be available.

Alternatively, if the integration of (2) is manipulated with respect to the variable τ rather than the variable x, then we have the tiling result, expressed as

$$\mathrm{g}'(x) = A \cdot h\,(x) * O\,(x) + B'(x) \tag{6}$$

where $A = \sum I(x)$. So the commonly used tilting approach results in a blurred version of the object $O(x)$ due to the forward scattering effect of $h(x)$. Instead, the proposed approach by model of (5) eliminates the forward scattered effect through integration of $h(x)$; the non-blurred version of the object $O(x)$ is recovered through optimal estimation with deconvolution routines.

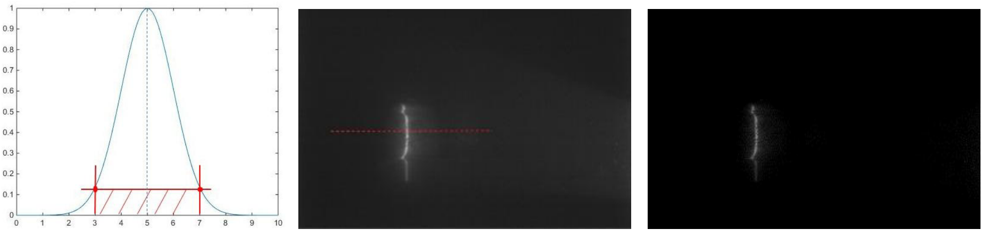
III. REMOVAL OF BACK SCATTERED LIGHT

Eliminating the back scattered light is critical in underwater imaging systems, for which the gating techniques such as the synchronous scanning technique were well-developed [11]–[14]. The synchronous scanning system utilizes the stripe/beam structured light and the aperture-coupled sensor to limit the received back scattered light within the small volume during scanning and to cut out the back scattered light generated outside the overlapped volume in each frame image. Although such a physically valid gating technique is very effective to eliminate the back scattered light, it requires high cost of hardware implementations. Concerned with the same gating mechanism, however, eliminating the back scattered light can be realized using an alternative computational approach.

As illustrated in Figure 1, when stripe light propagates in scattering medium, the back scattered background appears as a light sheet which brightness falls off exponentially along the projecting direction, ending at the intersection of the object surface. By detection of the end of the light sheet, we can cut off the back scattered light sheet from the surface light using a window mask on the frame image. Such a window mask works as a virtual "aperture" to limit the field of view, instead of the real aperture in the synchronous scanning system.

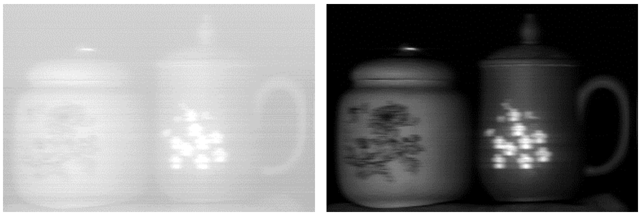
The position and the scale of the window mask should be determined so to cover the surface reflected light and to separate the back scattered light as much as possible. Since the sectional distribution of the projected stripe light is known as the prior, we can first position the far end of the window mask outside the back scattered light sheet simply by thresholding. Then the near end is determined accordingly, keeping the same scale of the support of the sectional distribution of the strip light. Considering the uncertainties of the reflected surface light induced by the noise and texture of the surface, we apply the smoothing filter to the frame image before window masking.

Figure 2 shows the illustration of the window masking method and Figure 3 shows the results of the integration images before and after elimination of the back scattered light by the proposed method. It can be shown that the proposed method can effectively eliminate the back scattered light in the frame images and significantly improves the quality of the integration image. It should be noted that the masking operation inevitably involves loss of the scene information in each frame image. However, it does not induce any deficiency of the recovery of the object $O(x)$ by the model of (5), since the masking operation can be specified as the modification of the illumination function $I(x)$ with a windowed cut-off and



(a) (b) (c)

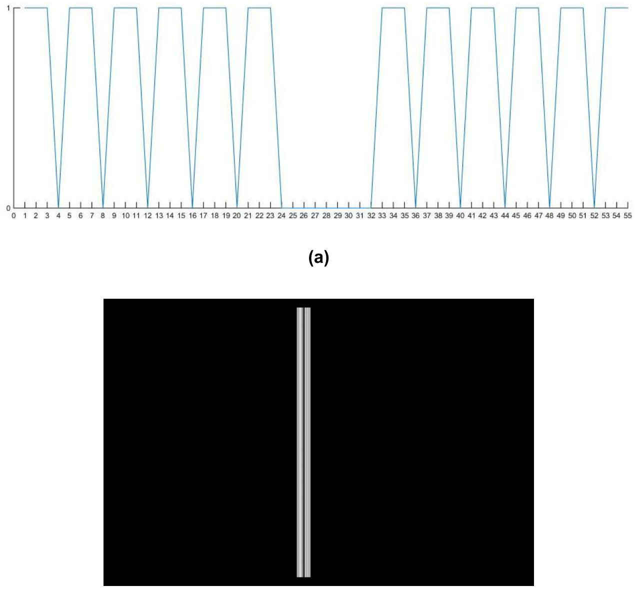
FIGURE 2. Illustration of window masking. (a) The sectional intensity distribution of the projected stripe light and the preset threshold. (b) The frame image obtained in underwater. The scanning is along x direction (dotted line). (c) The frame image after the elimination of the back scattered light.



(a) (b)

FIGURE 3. The integration images of (a) result before elimination of the back scattered light and (b) result after elimination of the back scattered light.

just involves the estimation of the modified $I(x)$ through blind deconvolution.



(a)

(b)

FIGURE 4. (a) The coding pattern of the structured light; (b) Coded structured light PPT.

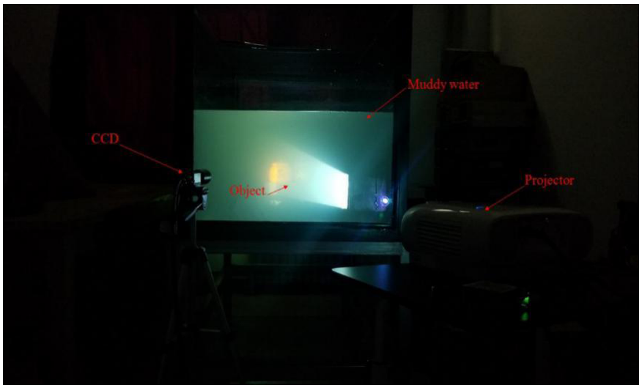


FIGURE 5. Experimental setup.

IV. CODED STRUCTURED LIGHT

Although structured light system usually utilizes a very thin strip projection pattern, broad lighting patterns are also frequently encountered in applications. Except for the inevitably light spread during transmission caused by the forward scattering, manually-specific broad lighting is useful to exploit the inter-frame coherence, e.g., to facilitate frame registration or feature detection. However, broad light distribution means loss of high frequency components of the function $I(x)$ of (5). Since the recovery of the object via deconvolution involves the inversion of the frequency spectrum of $I(x)$, image recovery may fail due to the ill-posedness of the deconvolution.

Inspired by the coded exposure techniques in motion deblurring [15], [16], we introduce the specific lighting pattern with the binary pseudo-random sequence in structured light for 2D image recovery. Instead of the conventional smoothly distributed lighting pattern, the specific coded lighting pattern changes the low-band illumination function $I(x)$ of (5) to a wide-band function that preserves high-frequency details in the integration image $g(\tau)$, so that the recovery of the object $O(x)$ becomes a well-posed problem. In fact, binary and continuous codes are commonly used in signal processing for modulation as broadband substitutes for an ideal impulse signal. Normally the m-sequences and the so-called modified uniformly redundant arrays (MURA) are popular choices for coding and decoding by circular convolution [15]. We apply the improved coding method proposed by [16] to specify the structured light pattern. The spatial distribution of the coding pattern is illustrated in Figure 4.

V. EXPERIMENTAL RESULTS

Following the descriptions in section 2 and section 3, the steps of the system implementation are described below:

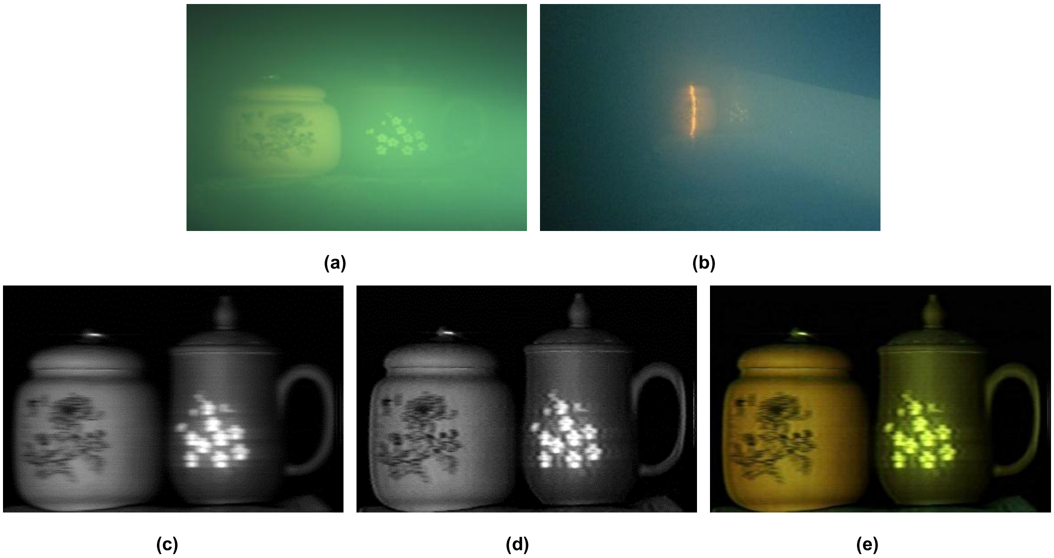


FIGURE 6. Results of image recovery with weak turbidity of the water. (a) The floodlit image. (b) The frame image. (c) The integration image after removal of the back scattered light using the proposed method. (d) The recovered image using L-R algorithm of blind deconvolution. (e) The colored version of image recovery.

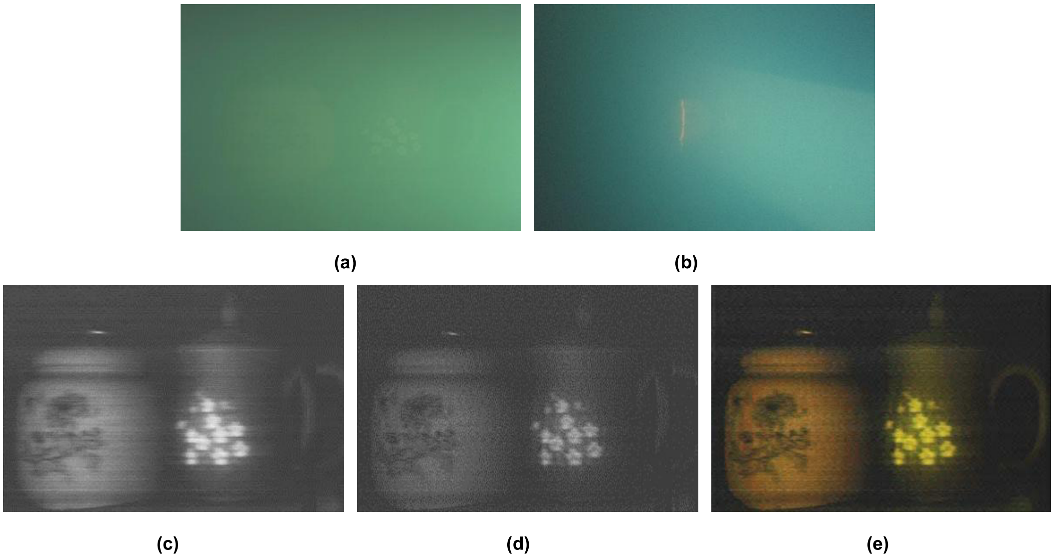


FIGURE 7. Results of image recovery with heavy turbidity of the water. (a) The floodlit image (b) The frame image. (c) The integration image after removal of the back scattered light using the proposed method. (d) The recovered image using L-R algorithm of blind deconvolution. (e) The color version of image recovery.

(i) Project the designed illumination pattern and record the frame image synchronously;

(ii) Complete the scanning process by sequentially translating the illumination pattern with 1-pixel displacement at the projector and obtain the sequential frame images accordingly;

(iii) Apply the virtual aperture to each frame image to remove back scattered light;

(iv) Complete the convolutional integration by integrating each frame image in one dimension, i.e., to sum up the row of pixel values to output a single pixel value, and one frame image outputs one column of the image $g(\tau)$ of Equation (5); all frame images give rise to the complete $g(\tau)$;

(v) Apply the deconvolution routine to recover the albedo O(x) of Equation (5); the initial estimate of I(x) is given by the designed illumination pattern.

The experimental setup is shown in Figure 5. The objects were placed in a 150 × 150 × 300cm glass tank whose faces are anti-reflection coated. The scattering medium is emulated using water mixed with different quantities of milk and aluminum hydroxide. The CCD video camera and an DLP projector were placed outside the tank without 3D calibrations. The scanning was aligned with the direction of the x coordinate on the image plane (the row coordinate).

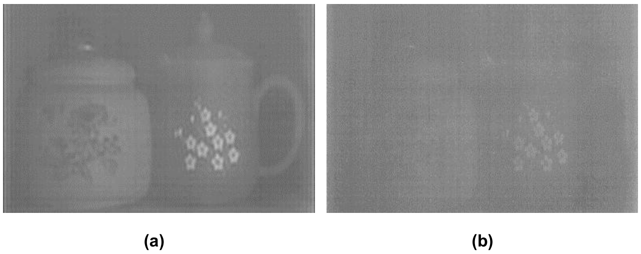


FIGURE 8. Results of tiling the sequential frame images of the same used in Fig.6 and Fig.7 after removal of the back scattered light. (a) The result with weak turbidity of water. (b) The result with heavy turbidity of water.

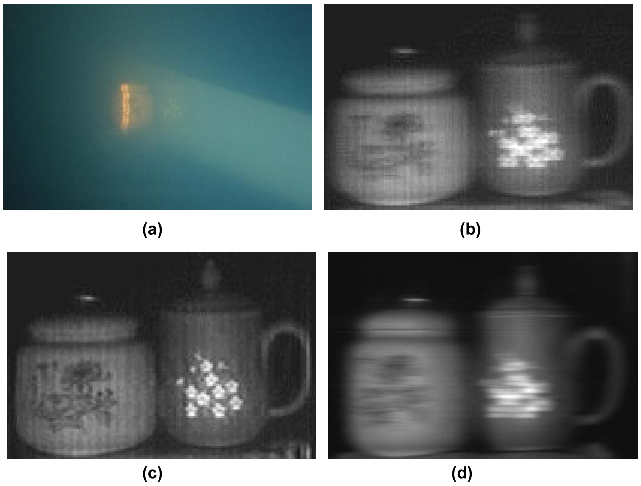


FIGURE 9. Results of image recovery using coded structure light. (a) The frame image. (b) The integration image. (c) The recovered image. (d) The recovered image using Gaussian lighting pattern with the same scale of spatial distribution of the coded one.

As the preprocessing stag, the proposed method of removal of back scattered light was applied to the collected frame images. The integration image was then computed by the model of (5) row by row. For image recovery, the well-developed blind deconvolution algorithm of Lucy-Richardson method (L-R) was applied [17], [18].

We first use the narrow stripe pattern in structured light imaging. The sectional intensity distribution of the light is designed as the Gaussian distribution, so the shape of projected $I(x)$ could facilitate the detection of the center of the stripe light in 3D measurements. The value of parameter σ, describing the scale of the distribution, was 9 pixels. The experimental results are shown in Figure 6 and Figure 7 with different turbidity of the water. Considering the wavelength-dependent transmission in underwater imaging, we also applied the algorithm to RGB channels respectively and the colored versions of image recovery are given, as well as the gray-scale versions. For a comparison, the tiling result using the model of (6) are shown in Figure 8. It can be seen that the results of using the tiling method show better smoothness but less contrast than that of using the proposed image recovery method. The improvement of contrast enhancement by the proposed method can be understood that the integration operation collects the forward scattered light in each frame image so to enhance the whole imaging energy while eliminating the image blur induced by the forward scattering effect. It should be noticed that the disturbances in the recovered image (as shown in Figure 7 (d)) were mainly caused by the randomness of light transmission in different frame images.

We further applied the coded light pattern to substitute for the Gaussian distributed pattern in structured light imaging, as proposed in Section 4. The experimental results are shown in Figure 9 with a broad lighting pattern which intensity distribution is coded with the binary pseudo-random sequences. The results of image recovery using Gaussian lighting pattern with the same scale of spatial distribution are also given for a comparison. As expected, the recovered results using the coded lighting pattern preserved high-frequency details of the object. In contrast, the results of using the traditional Gaussian distributed pattern failed to recover high-frequency components due to the low-band illumination function.

VI. CONCLUSION

This paper presents a new approach for 2D image recovery using structured light in underwater. Unlike the traditional method of tiling the sequentially lighted pixels to assemble the whole image, scanning by striping light is interpreted as the implementation of convolution operation and the image acquisition is addressed as image recovery by deconvolution. The proposed approach possesses the advantages of integrating the forward scattered light into recovered image so that the forward scatter induced image blur is fully eliminated in image recovery.

As the preprocessing stage, a simple method to remove the back scattered light in each frame image is proposed. By the same physical mechanism of the synchronous scanning system, a virtual aperture is applied to eliminate the back scattered light outside the field of view by window masking operation. Concerned with applicability of using the broad lighting pattern in structured light systems, the coded light pattern with binary pseudo-random sequence in is introduced in the proposed method. Such a specific lighting pattern with a broad frequency band preserves the high-frequency details in deconvolution and the image recovery becomes a well-posed problem. Further potentials of image recovery by optimal estimation can be expected in use of the proposed method, at least to tackle the uncertainties in underwater imaging applications.

In the proposed approach, 2D image acquisition does not require 3D calibration of the system. Therefore, 3D reconstruction is not considered in this paper. Obviously, 2D image acquisition can sensibly improve 3D reconstruction with structured light techniques; the recovery of the surface albedo enables the recovery of the lighting distribution on the surface in each frame image so that the central detection of structured light becomes straightforward, particularly in case of employing broad lighting patterns in real implementations.

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