KURSOR Journal
Research on Computing and its Aplications

Vol. 7, No. 1, January 2013 **ISSN 0216 – 0544**

ENHANCEMENT OF 3D SURFACE RECONSTRUCTION OF UNDERWATER CORAL REEF BASE ON SIFT IMAGE MATCHING USING CONTRAST LIMITED ADAPTIVE HISTOGRAM EQUALIZATION AND OUTLIER REMOVAL

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Abstrak

Penelitian ini menggambarkan peningkatan kualitas rekonstruksi 3D permukaan terumbu karang bawah laut menggunakan sistem kamera stereo. Algoritma Contrast Limited Adaptive Histogram image Equalization (CLAHE) diusulkan untuk meningkatkan kualitas citra bawah laut tersebut, karena menurunnya kualitas citra bawah laut dapat disebabkan oleh penyerapan dan hamburan sinar matahari. Dalam mengembangkan rekonstruksi 3D permukaan bawah laut, pasangan citra stereo diekstrak secara manual dari rekaman video yang diperoleh, yang kemudian dilakukan proses pencocokan citra stereo menggunakan algoritma SIFT. Kelebihan algoritma SIFT tersebut adalah tahan terhadap perubahan skala, transformasi, dan rotasi dari sepasang citra tersebut. Banyaknya matching point antar 2 citra stereo dijadikan ukuran untuk mengetahui kinerja CLAHE terhadap algoritma SIFT. Hasil penelitian menunjukan bahwa penggunaan CLAHE dan outlier removal mampu meningkatkan jumlah matching point sebesar 56%. Keberhasilan CLAHE tersebut perlu diujikan ke beberapa algoritma matching point yang lain. Perbandingan beberapa algoritma matching point yang menerapkan CLAHE dapat membuktikan bahwa CLAHE sangat cocok dalam meningkatkan kinerja algoritma matching point dan rekonstruksi permukaan 3D citra bawah laut.

Kata kunci: Rekonstruksi 3D, Citra Bawah Laut, SIFT, CLAHE.

Abstract

This research describes an enhancement of 3D Reconstruction coral reef images using stereo camera system. Contrast Limited Adaptive Histogram image Equalization (CLAHE) algorithm was proposed to enhance the image quality in preprocessing area, since the quality of underwater images degrades by the absorption and scattering of light. To develop a 3D-representation of the seafloor, image-pairs were first extracted from the video footage manually, then corresponding points are automatically extracted from the stereo-pairs by SIFT matching algorithm, which is invariant to scale, translation, and rotation. Number of matching points is used to evaluate the performance of SIFT with and without CLAHE. As a result, the promising techniques provides better 3D reconstruction details of coral reef imagesin total, the combination of CLAHE and outlier removal performs the enhancement for 56%. For further, CLAHE need to be performed to other image matching techniques. The comparison of different image matching techniques with and without CLAHE can prove that CLAHE is appropriate as image enhancement method for image matching and 3D surface reconstruction.

Key words: 3D Reconstruction, Underwater Image, SIFT, CLAHE.

INTRODUCTION

Underwater ecosystems have become an international attention since its effect on environmental changes that includes the evolution of coral reef environments. Indonesia as part of the coral-reef triangle has 18% of coral reefs around the world and placed as one of the countries where coral reefs are most threatened according to reefs a risk [1]. The survey result of the Indonesian Institute of Science [2] states that only 5.23% of coral reefs in Indonesia are in good condition.

With the advances in underwater robotics, it become a cost-effective technology to monitoring critical and endangered benthic cover such as coral reefs environment that caused by various sources of hazards [3]. In the field of ocean study, 3D reconstruction and measurement of underwater images can be generated by 3D visual observations [4]. Reconstruction of 3D structures is useful in underwater applications. 3D mosaicking is one important tool for exploration, visualization, underwater navigation, and can estimate the size of the objects of interest such as organisms and structures [5].

However, underwater images are suffering from image quality due to the absorption and scattering of light as it reaches the seafloor[6]. This condition gives problem in 3D reconstruction process, since some pixels become brighter than others (shimmering) and colors degrade as light at longer wavelengths (green, red) is largely filtered in the first 4 meters of the water column [7]. Figure 1 schematically shows the main process of light interactions in the sallow seas.

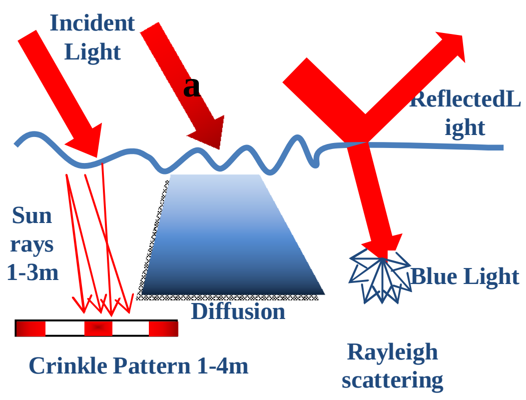


Figure 1.Water surface effects[7].

Several methods have been proposed to enhance the quality of underwater imagery in [6] proposed underwater image enhancement using an integrated color model. Iqbal *et al*[8] also proposed an Unsupervised Color Correction Method (UCM) approach for underwater image enhancement. The proposed method has produced better results compared to the existing method. In [9], comparing several filter that can be used to improve the quality of underwater image. Hogue *et al.*[10] developed a stereo vision-inertial sensing device to reconstruct complex 3D structures in both the aquatic and terrestrial domains. Other enhancement methods that used gray scale manipulation, filtering and Histogram Equalization (HE) could be seen at [11-14].

Histogram equalization is one of the popular techniques for contrast enhancement because this method is simple and effective [11]. Contrast Limited Adaptive Histogram Equalization (CLAHE) has becoming successful histogram equalization method for low contrast image enhancement [15]. The performance of Contrast Limited Adaptive Histogram Equalization (CLAHE), contrast stretching, and histogram equalization method have been compared and analyzed by Singh *et al.*[16], which revealed that CLAHE method improved image quality efficiently.

The importance thing of image quality for improving the number image matching, also resulting many researcher to concern in this field such as in [17-22]. Several researchers have conducted 3D surface reconstruction for underwater objects. In [23] proposed a novel technique to reconstruct 3D surface of an underwater object using stereo images. They focused on degradation of quality of underwater images, such as non-uniform illumination of light on the surface of objects, scattering and absorption effects.

To enhance their image quality, homomorphic, wavelet denoising and anisotropic filtering sequentially are performed. Triangulation was used to generate depth map of 3D surface underwater. However, Mahiddine et. al.[17] stated that homomorphic filter leads to poor the quality of 3D surface reconstruction. To overcome this limitation, the success of CLAHE using Rayleigh distribution in our previous research [24] is proposed to enhance the quality of 3D surface reconstruction of underwater images. CLAHE using Rayleigh distribution successfully improved the number of image matching performed by SIFT. CLAHE with Rayleigh distribution registration success of SIFT increased by 41% compared to the contrast stretching enhancement [24].

Due to the information above, there has been no any specific research that enhances the image quality to improve underwater 3D reconstruction with CLAHE. Therefore, this paper focuses on 3D reconstruction underwater seafloor improvement using CLAHE with triangulation and SIFT image matching where in the images are gathered from stereo camera system.

The remainder of this paper is organized as follows. Section II presented the theoretical background. Section III explains our method for 3D surface reconstruction. Section IV demonstrates the result of 3D surface reconstruction with/without outlier removal. The conclusion and road ahead are in final section.

METHOD

Pinhole Camera Model

This paper used pinhole camera model. The simplest camera model is the pinhole camera model. In the pinhole camera, the light of the object enter into the camera through a pinhole and projected to the image plane. As a result, the images in this plane are always in focus and size of the image relative to the actual size of the object.

Pinhole Camera model consists of image plane and the center of projection. Image plane is the place where the image is reflected, while the central projection is the place where the rays converge. The distance between the centers of projection is called the focal length (f).

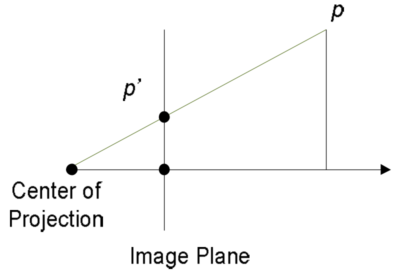


Figure 2. Pinhole Camera Model.

Figure 2 shows the model of pinhole camera. If p is the observed point, p is projected into the image plane by drawing a line from p to the center of projection. The point of intersection with the line of the image plane produces p' which is the projection of point p to the image plane.

Camera Calibration

Sample image of the dataset needs to be selected for calibrating the camera. Camera calibration has been performed using MATLAB Calibration Toolbox. Camera calibration was used to obtain intrinsic and extrinsic parameter of the camera. Intrinsic parameter consists of focal length, principle point, pixel size, and distortion coefficient. Meanwhile, extrinsic parameter describes the position of the camera in the world coordinate. Intrinsic and extrinsic matrix is shown in Equation (1) and Equation (2).

$$s.p = A.[R \mid t].P \qquad (1)$$

$$s.\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & C_x \\ 0 & f_y & C_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \qquad (2)$$

Where A is intrinsic parameter, $[R|t]$ is extrinsic parameter, $[X,Y,Z]$ is the 3D point coordinates in the world coordinate space. Figure 3 shows camera coordinate system coincides with the world coordinate system.

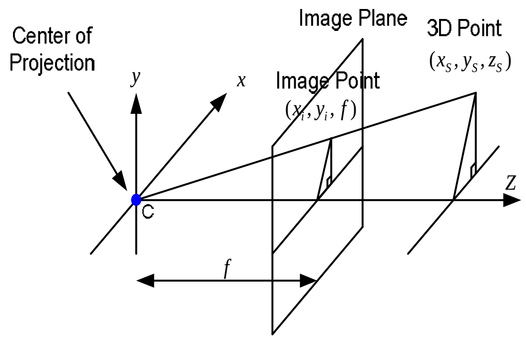


Figure 3. The camera coordinate system coincides with the world coordinate system.

Contrast Limited Adaptive Histogram Equalization

CLAHE is the extension of Adaptive Histogram Equalization method (AHE). The aim of CLAHE is to enhance the quality of image by utilizing a parameter limit value of histogram in order to handle over brightness and contrast on an image [25].

CLAHE works by divide an image into several non-overlapping regions. Then for each region, histogram is calculated. Next, histogram is clipped by a desired limit for contrast expansion. The distribution of the pixel for the histogram can be transform into uniform, exponential, and Rayleigh distribution [25].

CLAHE limits the maximum value of histogram. The clip limit β can be obtained by Equation (3).

$$\beta = \frac{M}{N}\left(1 + \frac{\alpha}{100}\left((S_{\max} - 1\right)\right) \quad (3)$$

Where α is clip limit factor, M region size, N is grayscale value. The maximum clip limit is obtained for α=100. The illustration of clipped limit is shown in figure 4.

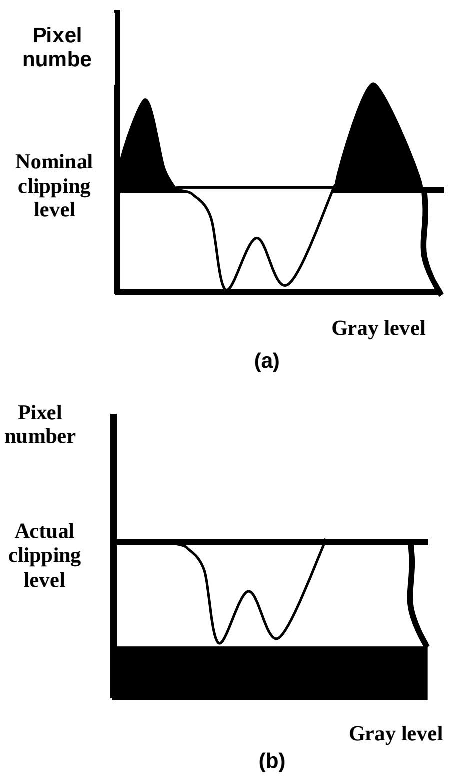


Figure 4. Histogram (a) before and (b) after clipping histogram [26].

SIFT Algorithm

Our study utilize SIFT based image matching to obtain the matching point in image pair. These matching points are useful to reconstruct 3D model. SIFT method was developed by Lowe [27]. The method includes fourphase:

Scale-space extreme detection

The first stage in the process of computing is to identify all potential key point on all scales. Scale an image space is defined as a function of $\boldsymbol{L(x,y,\sigma)}$ which is the product of convolution between the Gaussian kernel $\boldsymbol{G(x,y,\sigma)}$ with the image $\boldsymbol{I(x,y)}$. To find features on the imagery used operators Difference of Gaussian (DoG) by compiling octave image pyramid with different scales.

Keypoint localization

From the keypoint candidates obtained from a scale-space extrema detection, high stability keypoint will be selected. The emergence of feature-level stability is based on the features of each octave.

Orientation assignment

Orientation of the keypoint based on local gradient direction of each image. Any operation performed on the image based on the direction, orientation and location of the keypoint.

Keypoint descriptor

Local gradient image is computed at each scale region around the keypoint. In that situation, then transformed to local distortions and illumination changes in the area around the keypoint.

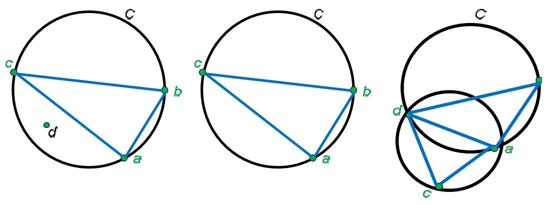
SIFT used Gaussian to develop scale space therefore it can be called Gaussian scale space. Next stage is compute the Difference of Gaussian Scale (*DoG*) as in equation (4).

$$G(x,y,\sigma) = L(x,y,k\sigma) - L(x,y,\sigma) \quad (4)$$

Where $\boldsymbol{L(x,y,\sigma)}$ is the convolution of the original image $\boldsymbol{I(x,y)}$ with Gaussian filter $\boldsymbol{L(x,y,\sigma)}$ on the scale $\boldsymbol{\sigma}$ and $\boldsymbol{L(x,y,k\sigma)}$ is the convolution of original image $\boldsymbol{I(x,y)}$ with Gaussian filter $\boldsymbol{L(x,y,k\sigma)}$ on scale $\boldsymbol{k\sigma}$, $k = \sqrt{2}$

Delaunay Triangulation

Triangulation is the process of finding coordinates and distance of a point by measuring angles between that point and two other reference points of known position and the distance between them. Triangulation is used in many fields, such as mapping, navigation, metrology, and astrometry. 3D surface reconstruction of seafloor mapping can be generated by using triangulation formulas when the coordinates and distance of the points is known. Set of features that have been reconstructed is called 3D point. Figure 5 is the visualization of Delaunay triangulation. There is no point of C in its interior of the circumcircles of a triangle in Delaunay triangulation [28].



a. b. c.

Figure 5. (a) Illegal and (b) (c) Legal Delaunay Triangulation

Outlier Removal

Removing the outlier would reduce wrong correspondence from image registration which lead to more robust 3D pattern of the coral reef. Average distance between pair of matching SIFT points is used to eliminate outliers. Let us denote N the number of matching SIFT points, d is the distance between a pair of matching SIFT points, and i is the index of current matching SIFT points. The average distance μ of matching SIFT points calculated as in Equation (5).

$$\mu = \frac{1}{N}\sum_{i=1}^{N} d_i \qquad (5)$$

The matching SIFT point is considered as outlier if the distance of matching SIFT point is higher than the average distance of matching SIFT points $d_i > \mu$.

Our 3D reconstruction is based on our two previous works: 3D reconstruction method of coral reefs using low-cost underwater cameras [29] and underwater image enhancement using adaptive filtering for enhanced SIFT-based image matching [24]. Figure 6 represents our proposed model of 3D surface reconstruction with an underwater image enhancement. This study evaluates our previous underwater image enhancement for 3D reconstruction of sea floor mapping.

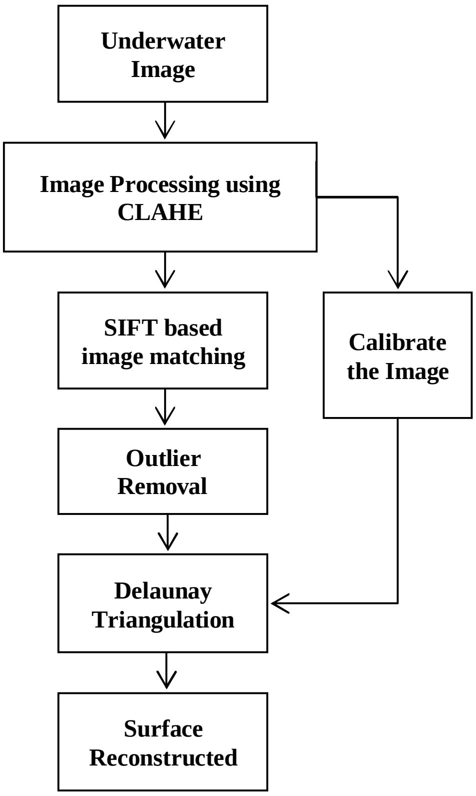


Figure 6. Proposed Model of 3D Surface Reconstruction.

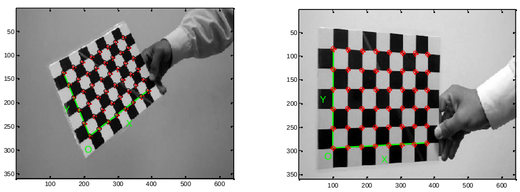


Figure 7. Camera Calibration Using Checkerboard.

Our work is defined as follows:

1. Image Processing.
   Our study selects underwater image from stereo image camera which stereo images are suitable for 3D reconstruction. This is performed to get more correspondence points between stereo images to build more accurate 3D reconstruction. CLAHE is performed to enhance the quality of image. Our study evaluates three types of CLAHE distribution: uniform, exponential, and Rayleigh distribution.

2. Camera Calibration.
   MATLAB Calibration Toolbox is performed to obtain intrinsic and extrinsic parameters. This paper used chessboard 17.5×22.5 cm to perform camera calibration. Size of square in chessboard is 2.5×2.5 cm, as shown in Figure 7.
3. SIFT Key points Detection.
   SIFT algorithm is employed to perform image matching.
4. Outlier Removal.
   Averaging the distance of match point between left and right image is the simplest way to detect the outlier of image matching. Our study remove the match point if the distance is higher than the average distance of match point.
5. 3D Reconstruction using Triangulation.
   Employing correspondence paired points and internal, external parameter that calculated with triangulation to produced 3D points.
6. Surface reconstruction using Delaunay Triangulation.
   Reconstructed 3D coordinates points that obtained by triangulation formulas. The number of 3D points is processed with Delaunay triangulation algorithm to produce surface reconstruction.

RESULT AND DISCUSSION

Data Acquisition

In this study, we use camera Olympus μ Tough-8010 cameras and resolution of 1280 × 720 pixels. Our data was collected at Karimunjawa Island Central Java Indonesia.

Karimunjawa is a National Marine Park declared as a Natural Conservation Area by Decree of the Minister of Forestry, located at 5°49'-5°57' South Latitude and 110°04'-110°40' East Longitude in the Java Sea, north of Java, Indonesia, as seen in Figure 8.We explore the underwater coral reef images in 4-5 meter deep.

Analysis

Our quantitative analysis is reported in Table 1. This table shows a significant difference with respect to the number of matching points. CLAHE with different point distributions (i.e. uniform, exponential and Rayleigh) successfully improves the number of image matching by average of 26% and 30% before and after outlier removal respectively. Detailed percentages improvement is shown in Table 2.

Figure 11 shows 3D image reconstruction developed from the sample stereo image-pair in Figure 9. In this study, we find that CLAHE and outlier removal have great influence on the 3D surface reconstruction. The accuracy of 3D surface reconstruction is greatly improved when more number of matching points is obtained. Our proposed approach produces promising result because the 3D representation of surface produce by CLAHE with Rayleigh and exponential distribution is more realistic appearance compared to before image enhancement. The 3D structure must be improved when many number of matching points is obtained. The superiority of CLAHE is shown in figure 10, which improves the number of image matching of poor original image.

Figure 8. Karimunjawa Island.

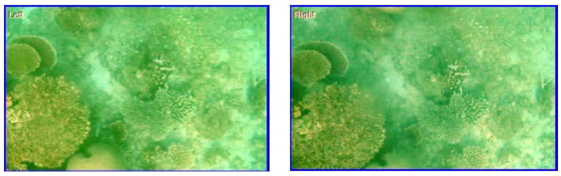


Figure 9. Sample of Stereo Image-Pair from left and Right Camera.

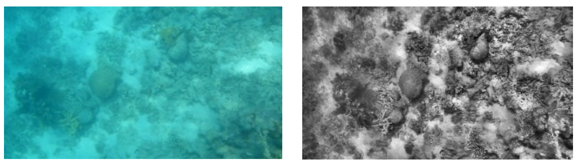


Figure 10. Image-Pair. First Column. Without CLAHE. Second Column. With CLAHE.

Table 1. Performance of SIFT with and without CLAHE before and after Outlier Removal.

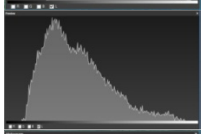
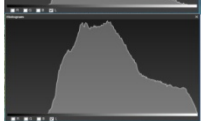
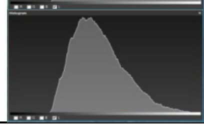
Image-pair	without CLAHE		CLAHE Exponential		CLAHE Uniform		CLAHE Rayleigh	
	Before outlier removal	**After outlier removal**	**Before outlier removal**	**After outlier removal**	**Before outlier removal**	**After outlier removal**	**Before outlier removal**	**After outlier removal**
1	652	441	1054	643	1004	639	1002	610
2	1294	1208	1363	1254	1307	1206	1430	1322
3	1617	880	2019	1139	1924	1070	1997	1053
4	1295	767	1498	907	1428	852	1420	861
5	1309	789	1788	1310	1777	1310	1733	1264

Table 2. Percentages Improvement of SIFT with and without CLAHE before and after Outlier Removal.

	Image-Pair	Percentages improvement of before and after CLAHE-Exponential	Percentages improvement of before and after CLAHE-Uniform	Percentages improvement of before and after CLAHE-Rayleigh	Average Improvement Before and After Outlier Removal
Before Outlier Removal	1	62%	54%	54%	
	2	5%	1%	11%	
	3	25%	19%	24%	
	4	16%	10%	10%	
	5	37%	36%	32%	
	Average	29%	24%	26%	26%
After Outlier Removal	1	46%	45%	38%	
	2	4%	0%	9%	
	3	29%	22%	20%	
	4	18%	11%	12%	
	5	66%	66%	60%	
	Average	33%	29%	28%	30%

Table 1 demonstrates that CLAHE-Exponential is much better than CLAHE with other distributions. Anyhow, in the case of image-pair no. 2, CLAHE-Rayleigh distribution is better than CLAHE-exponential or uniform, due to the majority of its data points are on the left side and center of the graph as seen in Table 3.

Table 3. Histogram of Original Image.

No. Image-Pair	Histogram
1	
2	
3	
4	
5	

CONCLUSION

In this study, underwater image enhancement for 3D surface reconstruction of coral reef image. High number of matching points are the results of image enhancement using CLAHE and furthermore by outlier removal. By employing CLAHE in average the image matching point increasing for 26%, while by adding outlier removal, the image matching point increasing for 30%. Therefore in total, the combination of CLAHE and outlier removal performs the enhancement for 56%.

Increasing the number of matching point improve the quality of 3D surface reconstruction of underwater images.

For the road ahead, CLAHE need to be performed to other image matching techniques. The comparison of different image matching techniques with and without CLAHE can prove that CLAHE is appropriate as image enhancement method for image matching and 3D surface reconstruction.

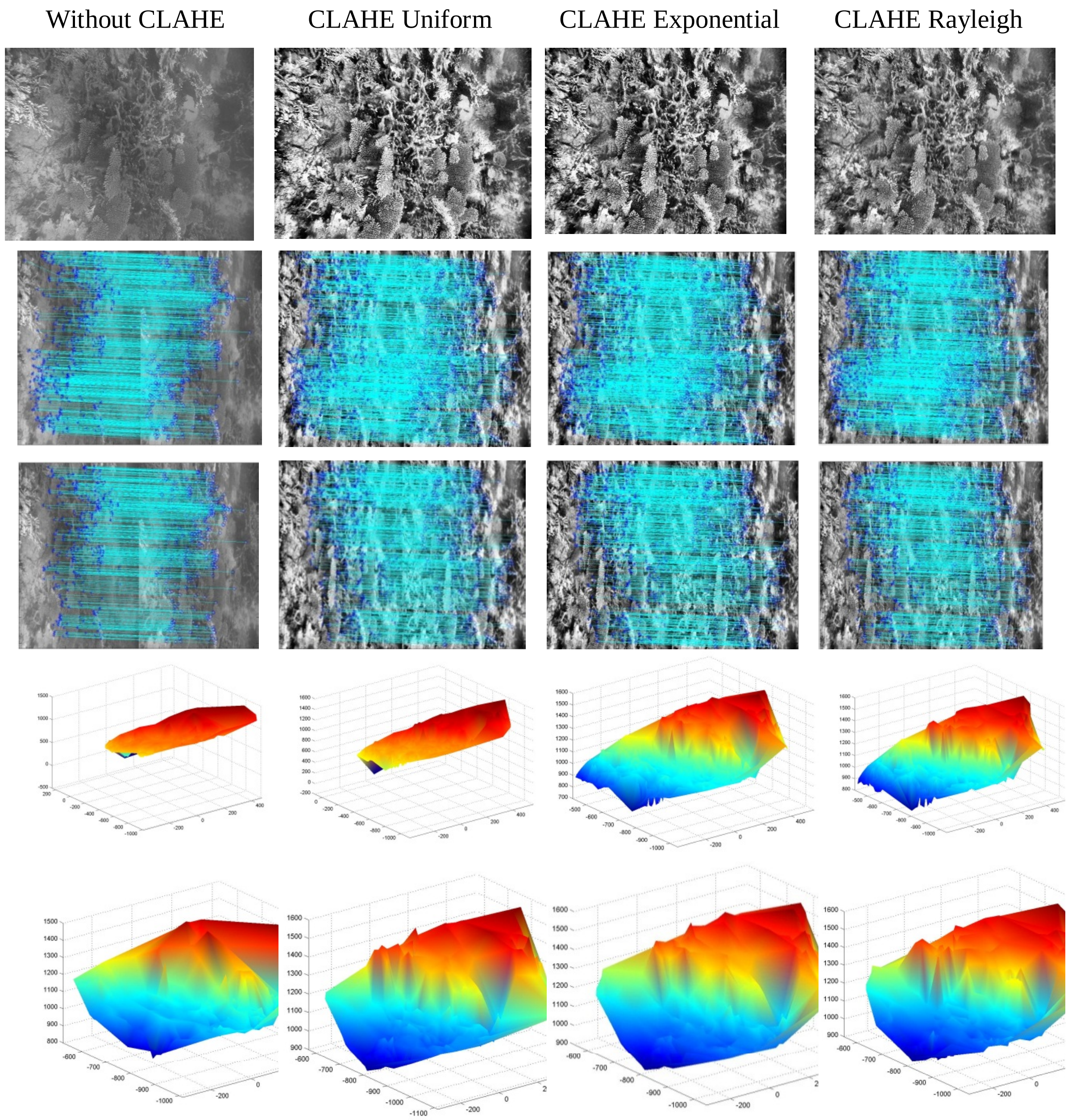


Figure 11. Sample of 3D Surface Reconstruction. First Row, Grayscale Image with and without Enhancement. Second Row, Image Matching with and without Enhancement before outlier removal. Third Row, Image Matching with and without Enhancement after Outlier removal. Fourth Row, 3D surface Reconstruction with and without Enhancement before Outlier Removal. Fifth Row, 3D Surface Reconstruction with and without enhancement after Outlier Removal.

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