3D Reconstruction Model of Underwater Environment in Stereo Vision System

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***Abstract*—Underwater 3D reconstruction has shown great prospects in ocean investigations. In this paper, the stereo vision system has been set up to explore the 3D reconstruction scheme of the underwater environment at small scale and high density. The dense disparity map will be first developed in a fast stereo matching algorithm with the biocular consistency checking and uniqueness validation, and then 3D surface model can be completed on the basis of the depth map and further adjusted by the image quality enhancement combined with the homomorphic filtering and wavelet decomposition. It has been shown in the simulation experiments that the proposed model could get good performances in both robustness and effectiveness, and the colors and textures in the 3D reconstruction process could be corrected against the underwater light propagation**

Keywords—3D reconstruction; Dense disparity map; Depth map; Image quality enhancement

I. INTRODUCTION

3D reconstruction, the course to capture and recreate the shapes and appearances of the real objects in three-dimensional space [1-3], has shown great prospects in ocean investigations [4-8].

Dating back to history, 3D reconstruction has achieved remarkable success for the land-based systems [1-3]. However, there are still a variety of difficulties in the accurate 3D reconstruction from images captured by underwater cameras due to the imaging visibility, light absorption, non-uniform illumination, etc. [9-13]. For the underwater imaging system itself, the quality of image degrades because of the effects of light attenuation and scattering [13-16]. Besides, the refraction of light occurs and causes the image distortion problem when a light ray passes through the water-glass and air-glass interface, rendering the conventional pin-hole camera model invalid in theory.

Among the process of 3D reconstruction, stereo matching is vital and fundamental [17, 18]. Generally, the matching techniques can be divided into the area-based methods, the feature-based methods, and their combination. The Scale Invariant Feature Transform (SIFT) [19], the Speeded Up Robust Features (SURF) [20] and the Sum Absolute Differences (SAD) [21, 22] etc., are among the most widespread techniques. The objective of the stereo matching depends on the balance between the complex computation and the stereo problem formulation at a reasonable cost.

In this paper, we further develop the underwater 3D reconstruction model and enhance the quality of the environment understanding in the stereo vision system. The paper is organized as follows: section II describes the basic framework of 3D reconstruction in our system. Section III introduces the stereo image acquisition and preprocessing. Section IV is about the stereo matching principle and Section V refers to the 3D reconstruction algorithm. Section VI shows the experimental results and Section VII comes to the conclusions.

II. GENERAL FRAMEWORK

The underwater stereo vision system is specially designed to allow seamless swapping of multiple views in the sea with one stereo camera. A brief flow chart of the 3D reconstruction model is shown in Fig.1, which is made up of several steps, including the camera calibration and package, the stereo image acquisition, some preprocessing, the stereo matching, the dense disparity map formation, the depth map generation, the quality enhancement, and 3D surface reconstruction, etc. The setup of the underwater vision system needs to protect the image collection process against mechanical shock and vibration. The stereo matching algorithm in this paper consists of the disparity value search, the cost calculation for each pixel, the integral calculation of the difference accumulation, the window statistical computation, and the sub pixel interpolation. Both the consistency checking and uniqueness validation will be used to recognize and rectify the false matching. After this, 3D surface model can be reconstructed by the depth map computed from the disparity map. Due to the impacts on the stereo vision quality in the sea, a generic parameter-free enhancement method will be taken to make a total abstraction of the image formation process at small scale and with high quality.

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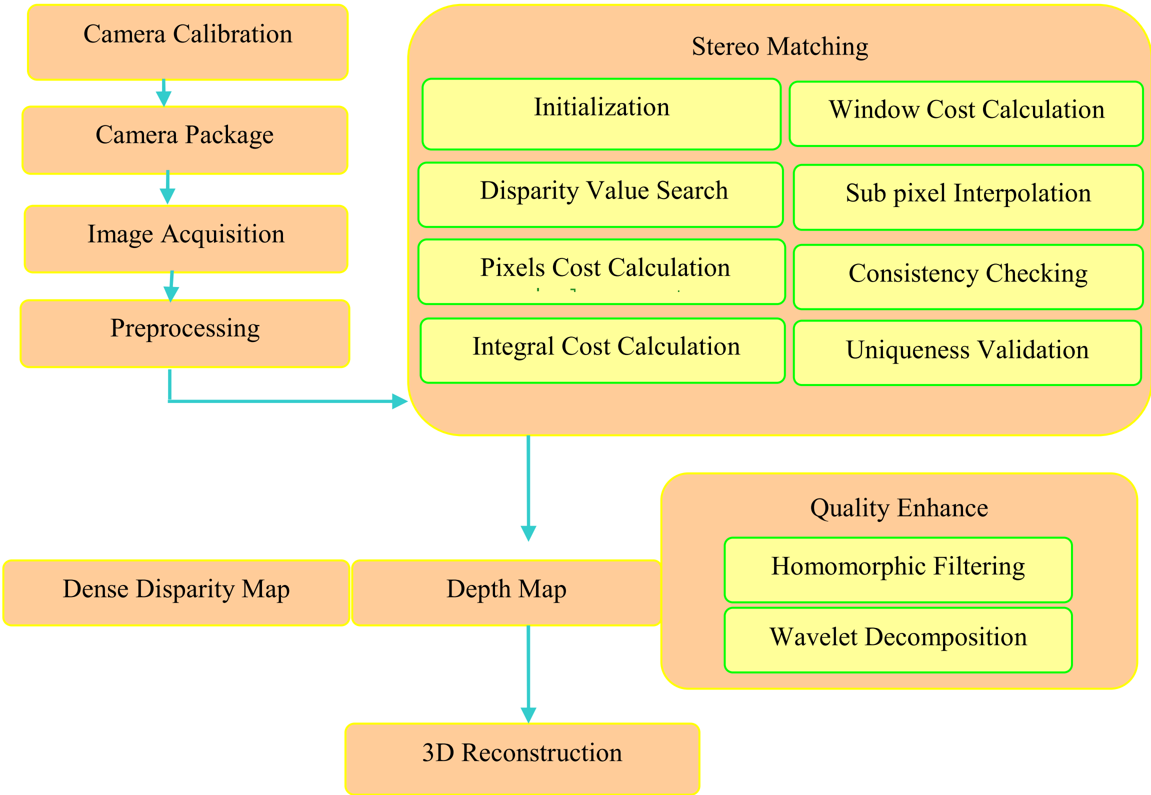

Fig. 1. The flow chart of the 3D reconstruction model

III. STEREO IMAGE REPRESENTATION

The stereo images observing from multiple view angles will be collected in the sea. Suppose that there is one pair of underwater images I_L, I_R taken by our stereo vision system. Let there be one spatial point P in the real world space, and O_L, O_R are respectively the left and right projection centers of the stereo vision camera. The distance between O_L and O_R is defined as the baseline distance B. The corresponding pixels of the left and right images I_L, I_R taken from the spatial point P in the sea are represented as p_L, p_R, provided that the underlying hypothesis is that the corresponding epipolar lines of the stereo vision system are horizontal and at the same height. Fig.2. is the stereo imaging process in our system.

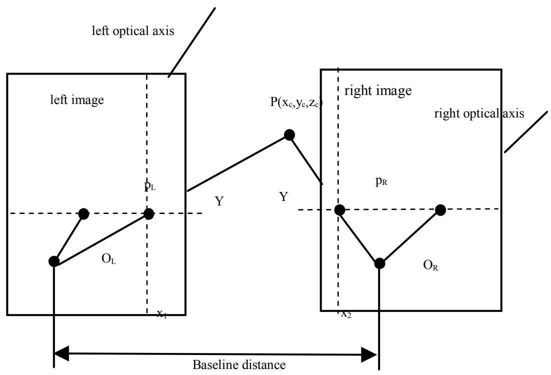

Fig. 2. Stereo imaging process

IV. STEREO MATCHING

The stereo matching in our system involves the process of fast similarity measure and best matching by decomposing the image into blocks. Let the size of each searching block in the underwater images I_L, I_R be $M \times N$. For any current image block A at the absolute location (x, y) of the target image I_R, we look for its corresponding reference block B at the relative location (i, j) around (x, y) from the original image I_L. The searching criterion is defined as,

$$f(x,y,i,j)=\sum_{l=0}^{M-1}\sum_{k=0}^{N-1}\left|A_{(x+l,y+k)}-B_{(x+i+l,y+j+k)}\right| \quad (1)$$

where $A_{(x+l,y+k)}$ and $B_{(x+i+l,y+j+k)}$ respectively indicate the image pixels of the current block and the reference frame, and the searching area is relatively located by (i,j) with the displacement of the candidate reference block from the current block. The candidate reference block yielding the minimum determines the motion vector (i,j) for the location of the current image block (x,y).

Both the biocular consistency checking and uniqueness validation strategies are taken to detect the occlusions, the unreliable matches, and to eliminate the false matches for the underwater vision system. First, given a corresponding pair (x_L,y_L) and (x_R,y_R), both the matching results retrieved from left-to-right and right-to-left will be compared and checked about their fitting to consistency. So for all the pixels in the stereo images, the uniqueness of the correct matching will then be validated. The disparity map, i.e., the relative depth information of the stereo vision in the sea, will be constructed except the occlusion with the correct matching pairs included and the false matching abandoned. The disparities of the occlusion can be further obtained by curve fitting with the disparities of their neighborhood area. In this way, the dense disparity map will be implemented accurately and efficiently.

V. 3D Reconstruction

The disparity map from our stereo vision system further provides the reason to perceive the depth information around the underwater environment, and translate into the distance sense in the sea. The dense depth map between the projection center of the camera and the underwater 3D points in the scene can then be easily computed from the disparity map and the 3D coordinates of the space points, and generated by the vector addition on the overlapped areas. As the intensity gradient in a disparity map describes the contour of underwater environment in a particular view, it can be done by surfing over the surface of the disparity map proportional to the depth associated with each pixel. 3D surface model can then be reconstructed by maintaining the color and texture in originally collected underwater images as well as combining the depth map computed from the disparity map.

For 3D reconstruction, due to a great many impacts on the stereo vision quality in the sea, one generic parameter-free enhancement method is presented here to make a total abstraction of the image formation process at small scale, reduce the underwater perturbations, and correct the contrast disparities caused by the attenuation and backscattering, without the prior knowledge of the depth, the distance and the water quality. The color space model of the image will be converted into the YCbCr space to concentrate only on the luminance channel which corresponds to the intensity component. The homomorphic filtering is adopted to correct non uniform illumination, enhance contrasts and sharpen the edges at the same time. Wavelet decomposition is further introduced to the homomorphic filtering for image denoising. The wavelet base is nearly symmetric orthogonal with a bivariate shrinkage exploiting interscale dependency.

VI. Simulation Experiment

In our simulation experiment, one kind of stereo vision camera, Bumblebee XB3, was packaged to engage in the underwater image collection at regular intervals as well as the pre-calibrated against distortion and misalignment, as is shown in Fig.3. The camera parameter matrices could be directly retrieved from the stereo vision system. Fig.4. displays one pair of example underwater images collected in our system. The dense disparity map from the example images is shown in Fig.5. A complete 3D surface model was then generated by the depth map with the color and texture information. The quality of the underwater 3D reconstruction was further improved and interactively visualized in a 3D viewer through the homomorphic filtering, the wavelet decomposition, and other rectification. Fig.6 shows the 3D reconstruction performance of the example images. We could see from the simulation results that the proposed model has shown good performances in both robustness and effectiveness. At the same time, the colors and textures in the 3D reconstruction process could be corrected against the underwater light propagation.

Fig. 3. Bumblebee XB3

(a) Left image

(b) Right image

Fig. 4. Example stereo images

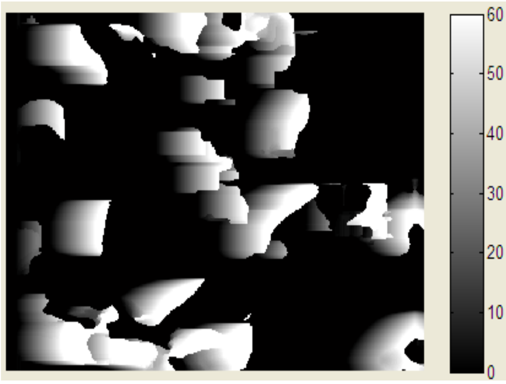

Fig. 5. Disparity map

Fig. 6. 3D reconstruction performance

VII. CONCLUSIONS

In this paper, we have focused on the 3D reconstruction scheme in the stereo vision system under the sea. When capturing the underwater scene from multiple views with the stereo camera, 3D reconstruction at small scale and high density has been well implemented by a set of strategies during the stereo matching, the dense disparity map formation, the depth map generation, and 3D surface modeling, such as the consistency checking, the uniqueness validation, the quality enhancement with the homomorphic filtering and wavelet decomposition, etc. Simulation experiments have shown high quality performances with robustness and effectiveness for underwater environment understanding in the proposed model.

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