

Underwater Three-Dimensional Microscope for Marine Benthic Organism Monitoring

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I. ABSTRACT

In-situ microscopic imaging of coral reefs or other benthic organisms allows us to monitor how microscale features change in response to the natural environment. However, underwater microscopic imaging remains in its nascent stages, constrained by the complex seafloor environments, and requires a more flexible working distance for microscope, a challenge that this paper addresses. In this work, we develop an underwater three-dimensional microscope for marine benthic organism monitoring. Specifically, we redesigned the optical path structure of the microscope by incorporating an electrically tunable lens, enabling dynamic adjustment of the working distance. This allows each scan of the microscope to produce an image stack rather than a single image, which contains different views of the specimen at each focus plane change. We then use image fusion algorithms to generate a fully clear image and a 3D model from the image stack. The proposed microscope enables long-term, in-situ, real-time monitoring of benthic marine environments, providing researchers with micrometer-resolution, clear, high-quality 2D and 3D image data of microbenthos and meiobenthos.

II. INTRODUCTION

Marine benthic organisms are an essential part of the marine ecosystem [1]. They not only occupy different ecological positions in the marine food web but are also closely linked to the material and energy flows of the marine ecosystem [2]. In addition, benthic organisms play an important role in indicating environmental pollutants [3].

Systematically observing and researching microbenthos and meiobenthos poses challenges due to their small size, especially when compared to macrobenthos. Consequently, a common approach to study them involves initial sampling in the marine environment, followed by the transportation of collected specimens to the laboratory for observation and

analysis using specific imaging tools such as optical microscopes [4] or fluorescence microscopes [5]. While the laboratory provides controlled and replicable conditions for studying the biological characteristics, ecological behaviors, and environmental adaptability of these benthic organisms, there are limitations associated with conducting research in this controlled setting.

The marine environment is highly complex, with dynamic changes in physical and chemical parameters. Laboratories are unable to fully replicate the intricacies and dynamics of the real marine environment, this limitation may potentially impact the normal physiological activities and ecological behaviors of benthic organisms. Moreover, the sampling and processing procedures in the laboratory environment may inflict certain damages or disturbances to the organisms.

In recent years, there has been a trend towards directly observing and studying marine benthic organisms in their natural habitats to minimize human impacts [6]–[9]. This approach takes into consideration the integrity and dynamism of marine ecosystems, providing a more authentic understanding of the survival status and adaptive mechanisms of benthic organisms in their natural environment. Therefore, there is an urgent need to develop imaging devices capable of directly observing and recording high-definition images of benthic organisms in their natural marine habitats. This paper presents an underwater microscope that enables long-term, in-situ, real-time monitoring of benthic marine environments on the seafloor, providing high-resolution 2D and 3D image data.

III. METHOD

A. Imaging system

The system adopts a modular design, allowing the replacement of each key component as required. It incorporates a white LED ring light as the primary illumination source, a 3X long-working-distance microscope objective, and an Electrically Tunable Lens (ETL) as the imaging unit [10]–[12]. The ETL is strategically positioned after the objective

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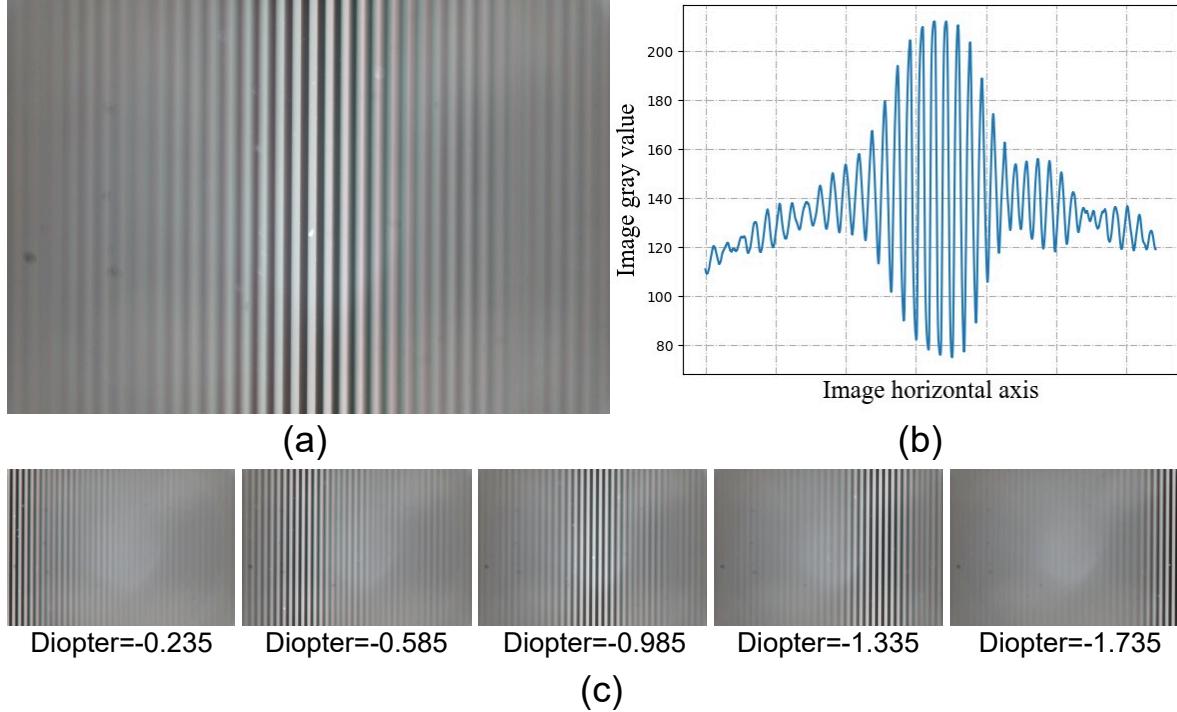


Fig. 1. Schematic diagram of depth of field position changing with changes in the diopter of the ETL.

lens. After imaging and modulation, the image of the object is projected onto the CCD.

To achieve rapid scanning and acquisition of objects, mitigating distortion caused by the movement of benthic organisms, this system employs a global shutter camera with a frame rate of up to 30 fps and a resolution of 12.0 MP (4096×3000 pixels), which can capture enough details at the same time. Additionally, to do some data preprocessing work and rebuilding the three-dimensional models with the underwater three-dimensional microscope, the control unit employed is the NVIDIA Jetson TX2, which is powerful enough to do these edge-computing tasks. The optical resolution of the imaging system attained $1.03 \mu\text{m}$ with a $4.23 \text{ mm} \times 3.10 \text{ mm}$ field of view.

Fig. 1a, 1b and 1c illustrate the captured image with diopter = -0.985, the color contrast differences inside and outside the depth of field and the image stack with different diopter of ETL, respectively. From Fig. 1a and 1b, it can be seen that the depth of field of the image is only about $600 \mu\text{m}$. As the diopter (focal length of the ETL) changes, the imaging position of the system moves from left to right, which can be found in Fig. 1c. Technically the diopter of ETL can be changed from -4 to 5, thus with the help of the ETL, the imaging depth of the microscope can be scanned in 1s, and the scanned depth can be reached to 25 mm.

The housing of the microscope is 48 cm in length and 12.9 cm in diameter, which is extremely compact and portable. The housing is constructed from a brass alloy cylinder, which is

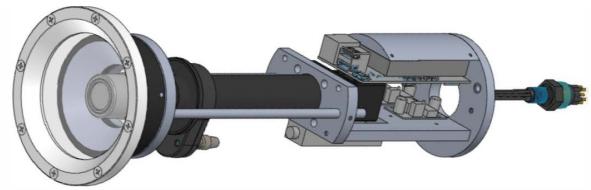


Fig. 2. The structure of the designed underwater three-dimensional microscope.

designed to be deployed up to 500 m, and has been pressure tested to a depth of 750 m. Additionally, the optical window is K9 optical glass with 12 mm thickness x 92 mm diameter.

The microscope is connected to the underwater in-situ coupling platform via a 6-core submarine cable, where 2 cores are dedicated to supplying 24V DC power, and the remaining 4 cores are utilized for communication and control between the instrument and the platform. The diagram of the designed microscope is shown in Fig. 2.

B. Image stack fusion and 3D modeling

Every time the microscope scans, since the focal plane is constantly changing, it will capture a stack of images with different clear regions. We can synthesize the image stack into a full-clear image through multi-focus image fusion algorithms [13]. Considering that the captured image stack has good spatial continuity in each scan, we use the image fusion algorithm in [14] to synthesize full-clear images and 3D models. The details of this algorithm are as follows:

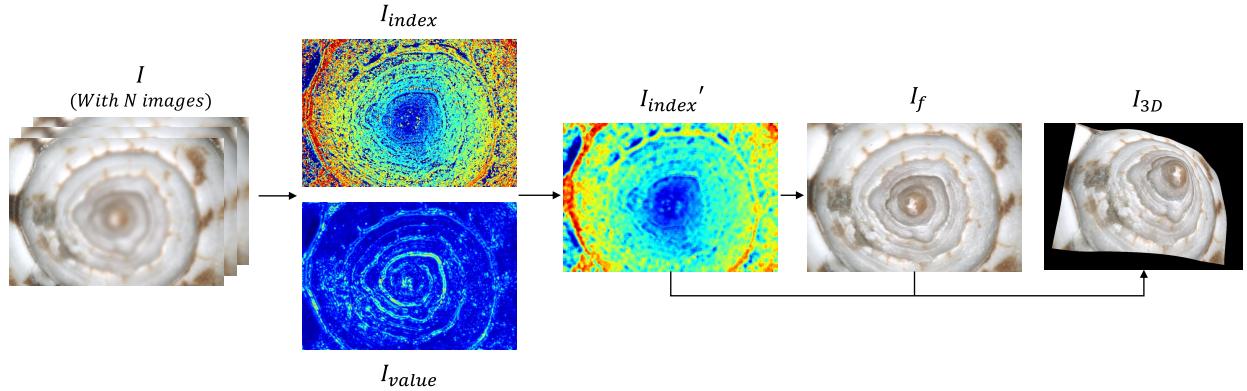


Fig. 3. The employed multi-focus image stack fusion algorithm and 3D modeling method.

Given a set of image stack $I = \{I_1, I_2, \dots, I_{N-1}, I_N\}$ containing N images, gaussian filtering is applied to each image in I to obtain I_B . The unsharp masking stack I_{usm} can be obtained by computing the absolute difference between the original image stack I and the blurred image stack I_B . For the majority of regions in the image stack I_{usm} , a higher element value indicates a clearer pixel in the corresponding position for most regions.

$$I_{usm} = |I - I_B| \quad (1)$$

Gaussian filtering is then applied to the obtained smoothed I_{usm} to decrease noise. By taking the maximum value along the depth direction of I_{usm} and obtaining the layer index of the maximum value, we can obtain I_{value} and I_{index} . I_{value} can reflect the clarity of each position of the image to some extent, while I_{index} indicates the layer from which these pixels come, namely the depth map. The depth map calculated in this way is often noisy, especially in regions with low color contrast, so we need to further smooth I_{index} to reduce obvious errors in the final fused image. The degree of smoothing for each pixel is determined by I_{value} . For a pixel at a certain position, the smaller the value in I_{value} , the less certain the clearest layer is calculated, so it needs more smoothing. The optimized I'_{index} can be calculated by the following formula:

$$I_{tra} = Norm(\text{Max}(I_{value}) - I_{value}) \quad (2)$$

$$mask = I_{tra} \times K \quad (3)$$

$$I'_{index} = Gaussian\ blur(I_{index}, mask) \quad (4)$$

Where Max is the maximum operation, Norm is the normalization operation, I_{tra} is the transition matrix, K is the predefined maximum blur kernel size, and Eq. 4 indicates that a mask is used to perform different degrees of Gaussian blur at each location of I_{index} . According to the depth map I'_{index} , we can extract the corresponding pixels from the original image stack I to form the final fused image I_f . By combining the fused image I_f and the depth map I'_{index} , the 3D model I_{3D}

of the original image stack I can be obtained. Therefore, each image stack obtained from a single scan of this underwater microscope can be used to generate a full-clear image and a 3D model of the observed object.

IV. RESULT

The system has a high resolution of up to $1.03\ \mu\text{m}$ and is capable of long-term observation and recording of benthic organisms at a speed of 30 fps in an in-situ marine environment. Fig. 4 presents a set of conch images captured at different focal lengths by this underwater microscope. In contrast to images obtained by traditional underwater cameras [15], which typically have a large field of view, this system can accurately record structures that are difficult to observe with the naked eye. Additionally, the microscope's continuous imaging capability enables the recording of the complete behavioral process of observed benthic organisms over time. These images provide scientists with valuable insights into the ecological, physiological, and behavioral characteristics of benthic organisms. Furthermore, the system facilitates the observation and interpretation of the global phenomenon of coral reef bleaching at a finer scale, shedding light on recent widespread occurrences worldwide.

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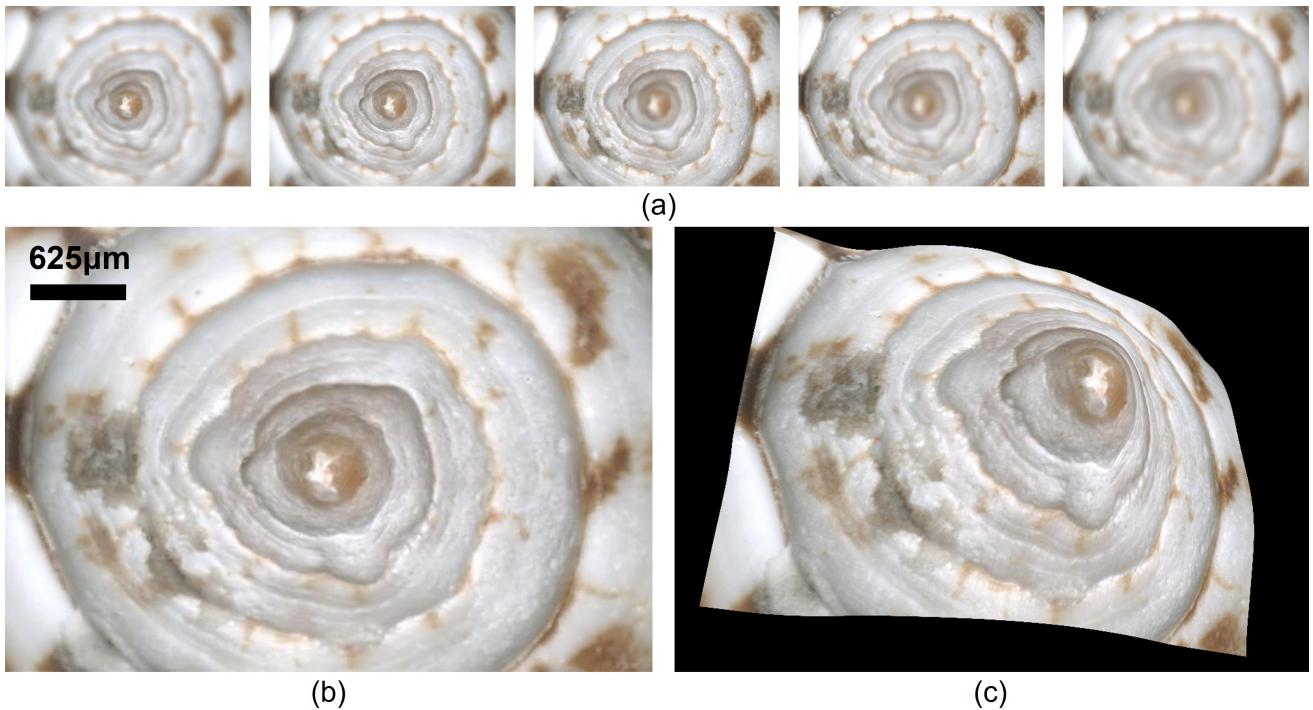


Fig. 4. Conch images captured by this system.

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