# Development of an underwater multispectral imaging system based on narrowband color filters

Chaopeng Wu[1], YiChun Shentu [1], Chaofan Wu[1], Yilu Guo[1], Yunfei Zhang[1], He Wei[1], Ping Yang[2], Hui Huang[1], Hong Song[1,*]
1.Ocean College, Zhejiang University, Zhoushan, 316021, China
2. School of Digital Media, Hangzhou Dianzi University, Hangzhou, 310018, China
*Corresponding author: hongsong@zju.edu.cn

***Abstract*—Underwater spectral imaging technology is of potential significance to marine research fields. This paper presents a novel underwater multispectral imaging system based on 31 narrowband color filters installed on double filter wheels. A set of underwater spectral imaging systems are initially developed containing an optical principle, imaging module, a control, and software. A pool experiment is conducted to evaluate the performance of the underwater multispectral imaging system, and 31-channel spectral images with wavelengths of 400 to 700 nm at intervals of 10 nm are obtained. The spectral responses of similar color objects are analyzed and discussed, and the results show that the underwater multispectral imager has advantages in distinguishing color, which aids the identification of similar color objects.**

***Keywords—co-underwater multispectral imaging; narrowband color filter; color discrimination***

## I. INTRODUCTION

Spectral imaging has been applied in many terrestrial fields as it can effectively obtain information about an object of interest in the spectral dimension. Due to the influence of water absorption and scattering on underwater light transmission, which is wavelength dependent, it is difficult to apply spectral imaging underwater [1]. However, underwater spectral imaging technology is of potential significance to marine research fields, such as the identification and classification of seafloor objects [2] and the protection and monitoring of the ecological marine environment [3].

Recently, underwater hyperspectral imaging systems with a push-broom structure have been developed for the identification or mapping of seafloor objects [4], and has advantages including high spatial, spectral, and radiometric resolutions, but they must be used along with a stable platform, such as seafloor tracks or an underwater vehicle, and their complex optical structure may influence their reliability and affect focusing requirements. An underwater spectral imaging system based on eight tunable color LED (light-emitting diode) light sources has also been proposed [5], which is novel for achieving multispectral imaging through emitting a narrow band spectrum and makes better use of the limited light energy. A filter-based spectral imaging system with a staring structure has been demonstrated to be feasible [6], however, the filter system is too large, which may limit its application underwater.

In this paper, the development of a novel underwater multi-spectral imaging system (hereinafter referred to as UMSI) with 31 narrowband color filters is proposed. UMSI should contain spectral information with 31 channels across the visible spectrum (400 - 700 nm), i.e., the spectral resolution is 10 nm. Using an underwater LED lighting system for artificial lighting, an underwater experiment is conducted to evaluate the performance of the UMSI. Underwater spectral images with an imaging distance of 5 m were successfully captured, and the UMSI has an effective capacity to distinguish between similar colors. The main contribution of this paper is on the design of a naval underwater multispectral imaging system, which adopts double filter wheels, so that the diameter of the UMSI is greatly reduced allowing the system to be well carried and applied underwater, .

## II. SYSTEM DESIGN

### *A. The principle of multispectral imaging*

The UMSI is designed for the visible light wavelength ranges, which should have 31 bands between 400 and 700 nm in increments of 10 nm. To cover the spectral range, 31 narrowband color filters are selected as the light splitter, which is used to extract the required narrowband spectrum from the whole band; their center transmission wavelengths are 400, 410, …, and 700 nm, respectively. The narrowband color filter is installed into a rotatable filter wheel, and the wavelength is altered by rotating the wheel so that color filters with different central wavelengths are inserted in the imaging optical path according to the demand.

Fig. 1 depicts the imaging principle of the UMSI. The light reflected or emitted by the underwater object of interest penetrates the water column, passes through the glass window, and is focused by the imaging lens. Before being collected by the camera sensor, the full band of visible light is filtered by a narrowband color filter so that only specific wavelengths with weak spectral energy can transmit to the camera sensor and other wavelengths are blocked. After reaching the shutter, the camera sensor produces a single wavelength image. By switching color filters with different center transmission wavelengths, the camera sensor can generate a sequence of monochrome images from 400 to 700 nm in turn. In addition, the spectral cube data consist of all these spectral images, therefore the spectral and spatial (pixel) dimensions are combined, which allows the spectral response curve of any pixel position to be extracted.

### *B. Hardware description*

Fig. 2 shows the prototype UMSI; the whole system is sealed in a hard aluminum, water-tight housing. The internal hardware includes a monochrome CCD camera, an improved autofocus lens, 31 narrowband color filters, and an aluminum frame for fixing the various components.

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Due to the strong absorption and scattering of light in water, and the limitation of the low transmittance of narrow-band color filters, spectral energy is attenuated exponentially with the underwater imaging distance [7], which reduces image quality. A camera sensor with a large photosensitive area can partially enhance image quality, so a monochrome CCD camera (Lm165m, Lumenera, USA) with a 1392×1040 pixel resolution (2/3") and a dynamic range of 66 dB is selected as a detector as it is suitable for low-light conditions.

In the case of a fixed focal length, switching color filters with different refractive indexes may change the optical imaging path, which requires a lens with a great depth of field to allow high-definition spectral images. Moreover, different water columns have different limits on imaging distance, which requires the ability to adjust the focal length according to actual needs. Considering the above factors, an autofocus (AF) lens (EF-S 18-135 mm f/3.5-5.6 IS STM, Canon, Japan) is selected, which not only has a large depth of field, but can also be manually adjusted to change the field of view.

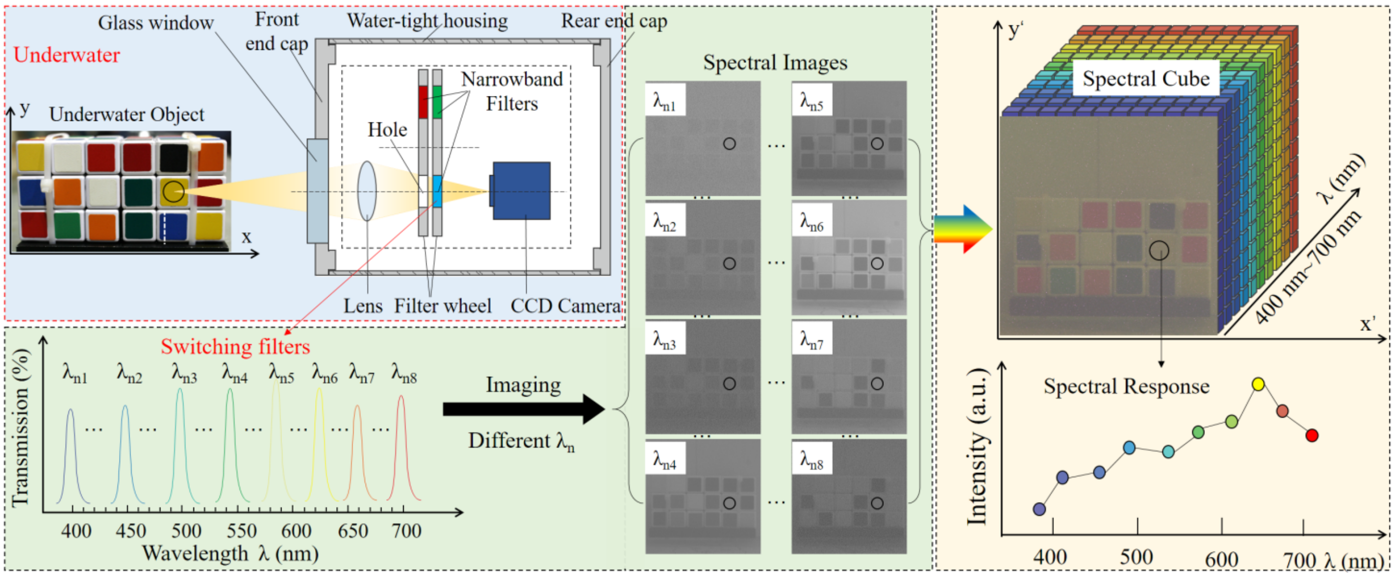


Fig. 1 Illustration of narrowband spectral imaging underwater

The aperture, spectral transmittance, and bandwidth of the color filters are the major factors that may influence the image quality and imaging distance. In addition, the large number of color filters may significantly increase the volume of the system. Considering the above conditions, the Thorlabs' narrow band-pass filter, which is a thin film Fabry-Pérot filter, is selected; this series of filters has 37-50% transmittance on the passband, and the higher spectral transmittance than that of other staring multispectral imagers that are based on a liquid crystal tunable or acousto-optic tunable filter is advantageous for underwater imaging. Color filters (FB series Filter, Thorlabs, USA) have 10±2 nm full-width-half-maximum (FWHM), with the center transmission wavelength ranging from 400±2 nm, 410±2 nm, …, 700±2 nm at intervals of 10 nm.

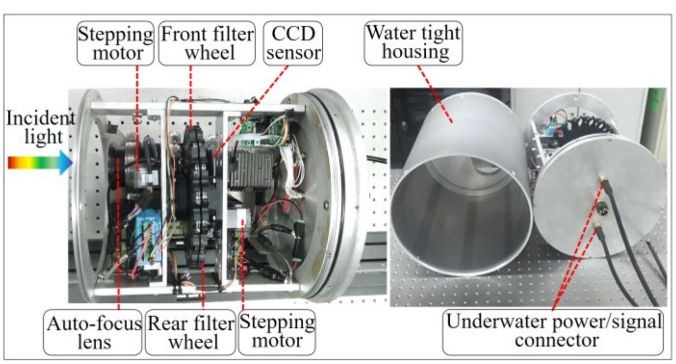


Fig. 2 Prototype of the UMSI

In order to reduce the dimension of the imaging system, a double-wheel design is adopted. All color filters are arranged in a circular array on two rotatable filter wheels with the same size, and each filter wheel has 18 mounting holes for color filters. Sixteen color filters are installed in the front wheel, which is closer to the lens, and the other fifteen color filters are installed in the rear wheel, thus, there are some vacant holes in both wheels with no filters. To ensure that only one color filter is inserted into the optical imaging path, a vacant hole in the other wheel is inserted at the same time. Both wheels are synchronized and each filter wheel is driven by a separate stepper motor (DG60, Oriental Motor, Japan).

As two filter wheels are used, the diameter of the filter wheel is reduced to 200 mm, thus, the volume of the system is reduced, allowing it to be well sealed and carried underwater. The water-tight housing is a thin-wall cylinder with front and rear end caps; the outside diameter and length of the cylinder are 300 and 330 mm, respectively. As the designed depth rating is 50 m, the wall thickness of the cylinder is calculated as 6 mm and the central thickness of the end cap is approximately 20 mm. An optical plexiglass window is included on the front end cap of the water-tight housing. The whole water-tight housing is designed to achieve a static seal with an O-ring.

## C. *Control and software*

Fig. 3 illustrates the software and hardware structure of the UMSI. The CCD camera equipped with mini USB 2.0 digital interface includes a complete software development kit (SDK), which makes it easy to integrate camera functions, such as parameter setting and image acquisition, into the application of the upper computer by secondary development. The AF lens controlled by a small stepper motor can automatically focus, and the stepped size and direction are estimated from the feedback of the quality of the final image, the stepper motor can be driven by the autofocus circuit, which serves as its driver. The rotation motion of both filter wheels is precisely controlled by a stepper motor, which is also driven by the stepper motor's driver. The I/O controller can act as a relay station between the software and hardware, which distributes a control signal from the upper computer to the corresponding stepper motor driver. These communication and control programs are developed based on the Modbus protocol and SDK.

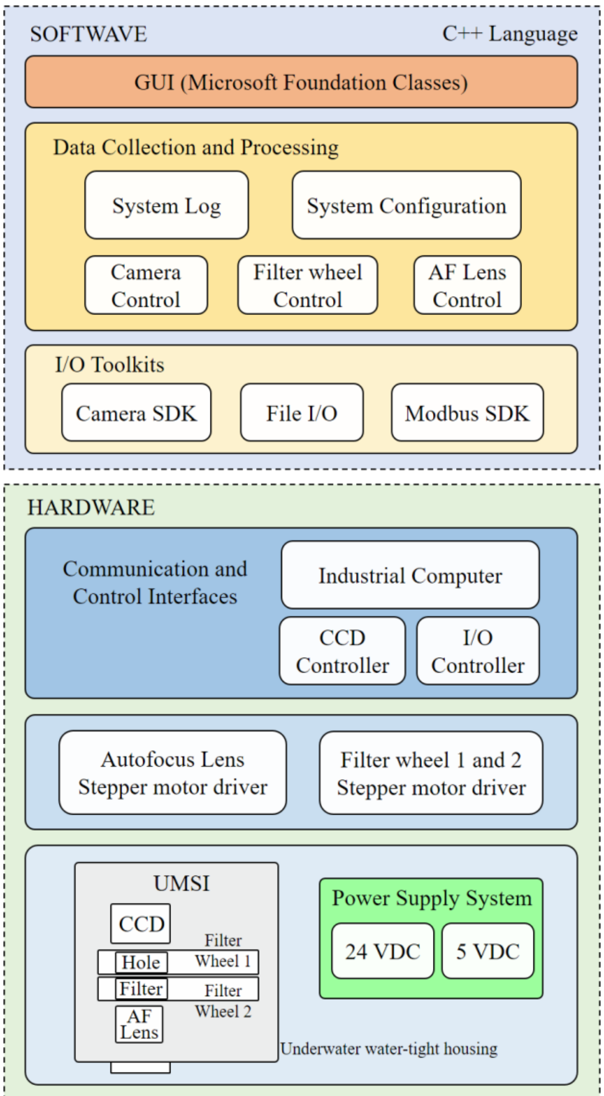


Fig. 3 Architecture of the control system

The functions of the software mainly include image acquisition and storage from the CCD sensor, the control of the filter wheels, lens autofocus, automatic exposure setting for different imaging wavelength bands, and the display and preprocessing of spectral images. These functions are developed based on the camera and Modbus SDKs, and the OpenCV image processing technology. The graphical user interface (GUI) is created using the Microsoft VS2010 software development platform and Microsoft Foundation Classes (MFC).

## III. Experiment and Results

To evaluate the performance of the UMSI, an underwater experiment is conducted in a standard indoor swimming pool with a length of 100 m, width of 50 m, and water depth of 1.8 m. As shown in Fig. 4, the underwater experimental setup includes an underwater illumination system, the UMSI, an upper computer (Thinkpad, Lenovo, China), and a plastic color board.

The underwater illumination system includes three LED light sources (Huaming, China) mounted together with the UMSI on an aluminum combination bracket. Each LED light source is powered by a LED driver that can transform 220 VAC power into a stable 48 VDC voltage source. The color board used as the underwater imaging object consists of 60 different color pieces aligned into 6 rows and 10 columns.

After the initial configuration of the system, light covering wavelengths of 400 to 700 nm is emitted from the underwater illumination system. After propagating in the water for a certain distance, $L$, the light is reflected by the color board, propagates in the water for the same distance, and is captured by the UMSI during spectral imaging. Once the imaging distance is changed, the lens needs to be adjusted for autofocus and the exposure time of the camera is automatically reset. The procedures are controlled by an upper computer that runs the system software and stores the spectral images.

When the color board is located 5 m in front of the UMSI, i.e., $L$=5 m, 31 underwater spectral images are sequentially captured by the UMSI in at wavelengths of 400, 410, ..., 700 nm as shown in Fig. 5. Each spectral image has a resolution of 1392*1040 pixels, and all 31 images form a set of raw spectral images. Fig. 5 illustrates that the response of the UMSI to the same color piece varies with imaging wavelength, and the responses curves of different color pieces are different,

In addition, to collect dark background images at the same distance, all LED light sources are turned off, and a further 31 underwater spectral images are captured by the UMSI, forming a set of background spectral images. After collecting the high-definition spectral images, image processing can be conducted to analyze the imaging performance of the UMSI as follows.

i) Sets of raw and background spectral images are read into MATLAB R2017b (MathWorks, USA).

ii) A simple median filtering algorithm is performed on all images to reduce impulse noise, and each image is then normalized so the image brightness ranges from 0 to 1.

iii) A spectral image of the object is obtained by subtracting the corresponding background spectral image from each raw spectral image, so 31 object spectral images at wavelengths of 400, 410, ..., 700 nm can be generated.

iv) The spectral response curve is defined as a set, $S$, i.e.,

$$S=\{I_n(L, t_n, \lambda_n, r_x, c_y)\}|_{n=1,2,\ldots,31},$$

where, $I_n$ represents spectral image brightness with where $I_n$ represents the brightness of the spectral image with a wavelength of $\lambda_n$, $r_x$, and $c_y$ represent the row and column pixel positions on the object spectral image, respectively, $\lambda_n$ ranges from 400 to 700 nm at an interval of 10 nm, $t_n$ represents exposure time, and $L$ represents imaging distance.

v) Due to the inconsistent exposure times for different imaging wavelength, it should be normalized. Considering the linear relationship between camera response and exposure time, the brightness of an object spectral image is scaled according to the following formula,

$$S_N=\{t_{min}*I_n(L, t_n, \lambda_n, r_x, c_y)/t_n\}|_{n=1,2,\ldots,31},$$

where, $S_N$ represents the normalized spectral response, and $t_{min}$ represents minimum value of $\{t_n\}|_{n=1,2,\ldots,31}$.

vi) Normalized spectral response curves are compared, which can reflect the spectral imaging differences of the UMSI for different colors.

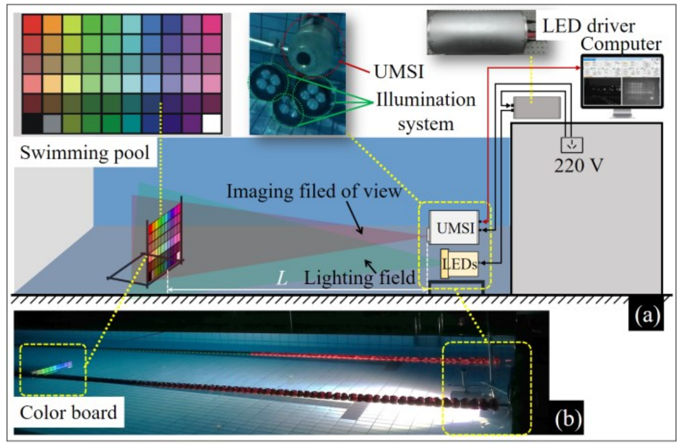


Fig. 4 Experimental setup
(a) Schematic diagram, (b) Image of the setup

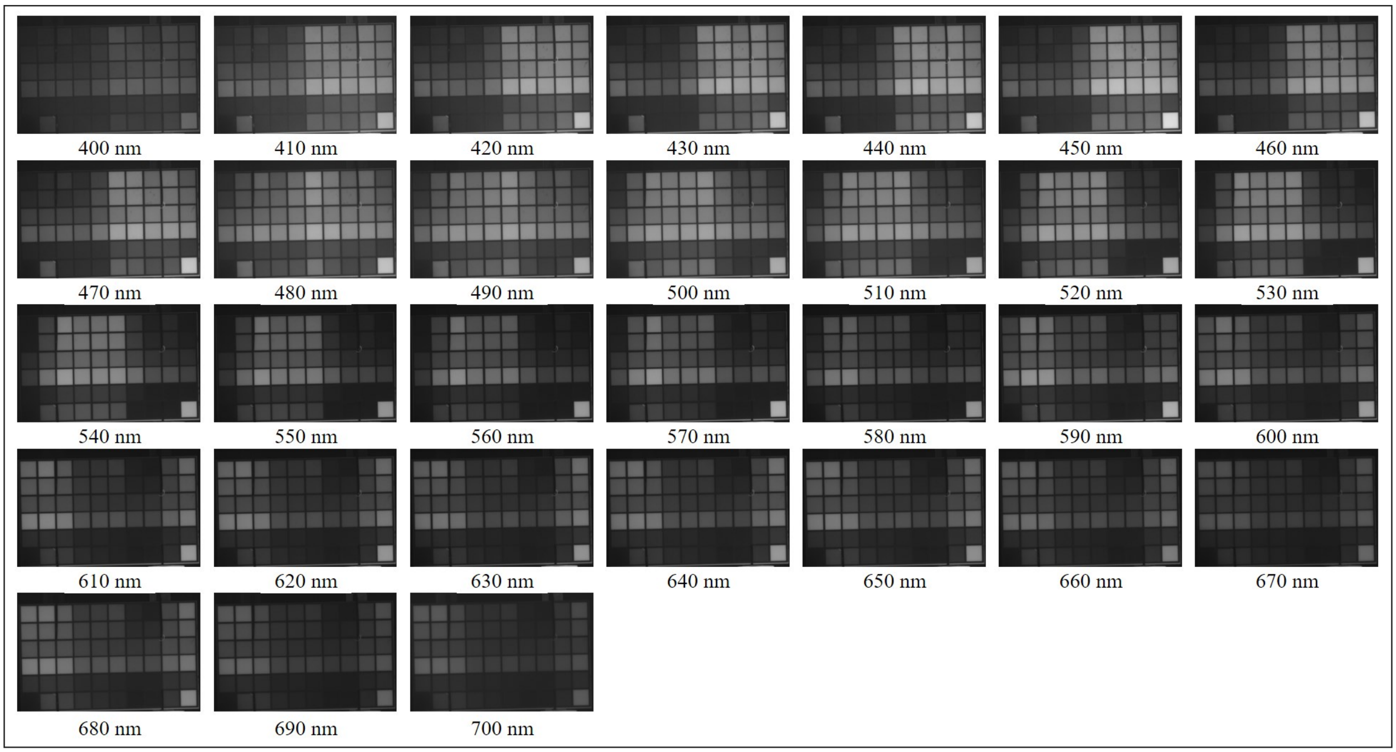


Fig. 5 Underwater spectral images captured at a distance of 5 m

Fig. 6 shows the normalized spectral response curves of different color pieces, marked as 1, 2, …, 5. The selected pixel position is the center of each color piece. The result indicates that the spectral differences in the color pieces with different Munsell hues can be clearly distinguished based on the multispectral images. In addition, the curve of the color piece, marked as 5, reflects the relative energy distribution of the spectrum of the light source at a distance of 5 m.

In the case of underwater imaging, especially with a long imaging distance, it is difficult to distinguish similar colors using a color camera, because color is distorted by water attenuation. Fig. 7 shows the color discrimination capacity of the UMSI for similar colors.

The normalized spectral response curves of five different points on the same green color piece, as shown in Fig. 7(a), are drawn in Fig. 7(b), and the curves are close. Curve 1 is taken as a reference, thus,

$$S_{ratio,m}=\{I_n(L, t_n, \lambda_n, r_m, c_m)/I_n(L, t_n, \lambda_n, r_1, c_1)\}|_{n=1,2,\ldots,31},$$

where $m$ represents the color point marked as $m$, $m$=1, 2, 3, 4, or 5, and $S_{ratio,m}$ represents the ratio of the spectral responses of color point *m* to color point *1*. The results (Fig. 7(c)) show that the difference between curve *m* and reference curve *1* is below 5%, except for two abnormal points. Hence, the observation by the UMSI is uniform for the same color piece, and differences are attributed to uneven illumination and unevenly coated materials.

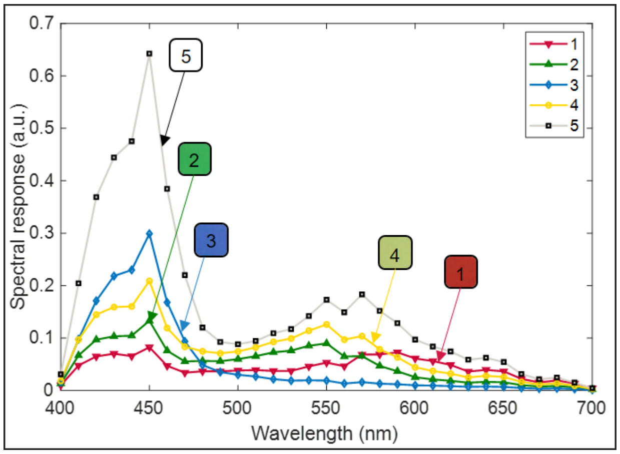


Fig. 6 Normalized spectral response curves of different color pieces

Five different color points, marked as points *1-5* on the adjacent five color pieces shown in Fig. 7(d), are green in hue, but have different saturations and lightness. Fig. 7(e) shows the normalized spectral response curves, and compared with those in Fig. 7(b), multispectral imaging responded differently to these similar colors. The influence of wavelength on spectral differences is indicated in Fig. 7(f). The main difference between color pieces *1* and *2* is their lightness, and the normalized spectral response of color point *2* is approximately scaled down compared with that of color point *1*. Color piece *3* contains more blue components, so its normalized spectral response is stronger than that of color point *1* in the wavelength range of 400 to 490 nm. Similarly, the normalized spectral response of color point *5* is stronger than that of color point *1* in the wavelength range of 560 to 700 nm, because the hue of color piece *5* is closer to red. Thus, the UMSI can highlight the spectral signatures of similar colors.

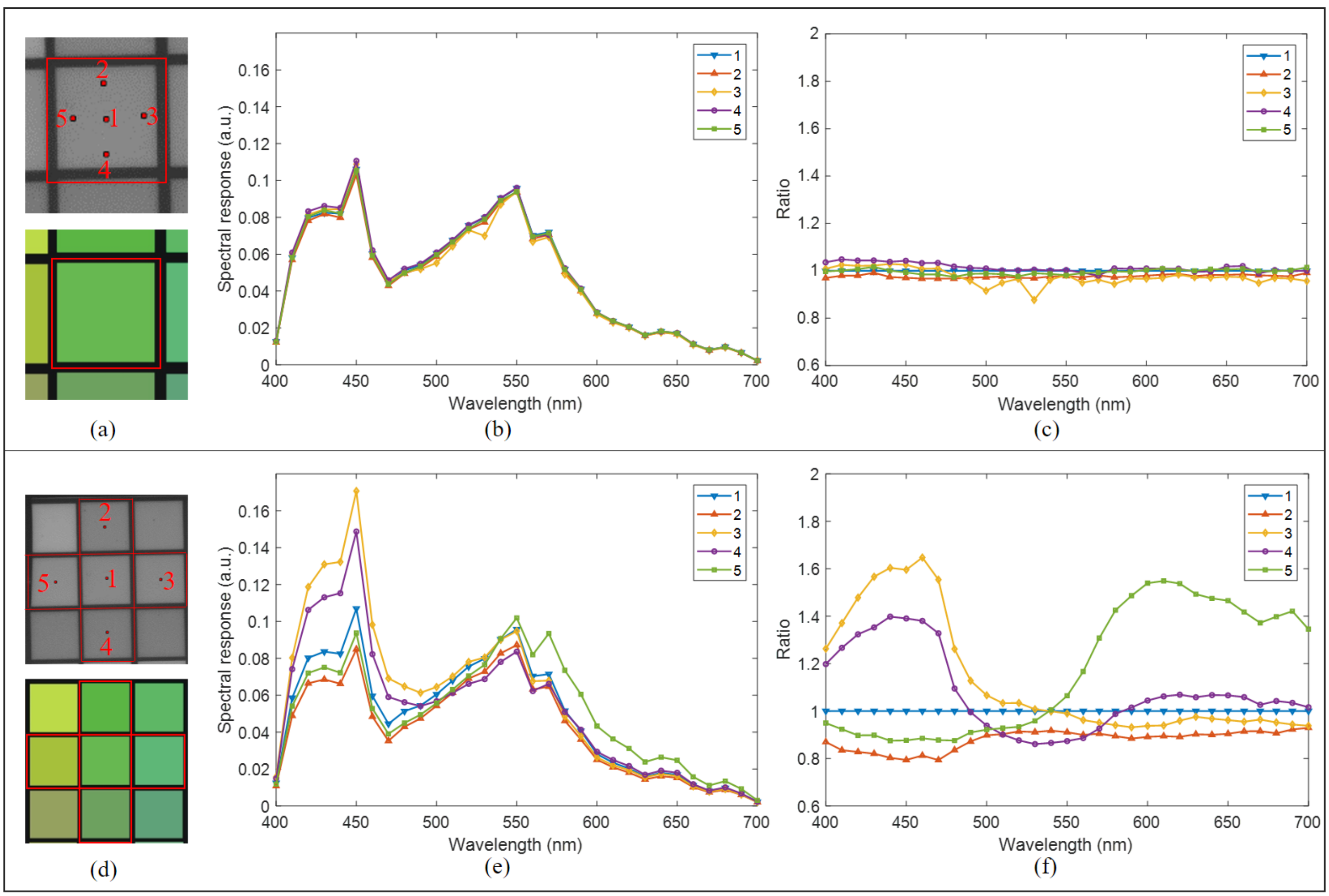


Fig. 7 (a): Spectral and color photos, points on the same color piece, (b)&(e): the normalized spectral response curves of similar color points, (d): Spectral and color photos, points on the adjacent five color pieces, (c)&(f): the ratio curves obtained from curves *1-5* with curve *1*

## IV. CONCLUSION

In this paper, an underwater multispectral imager using narrowband color filters is presented, and the multispectral imaging method is simple and suitable for *in-situ* underwater local target detection and recognition. Thirty-one color filters are installed into double filter wheels to reduce the size and weight of the UMSI, making it more convenient to seal the system, but this will increase the power consumption. The color filters are changeable for different specific applications, i.e., the category and passband of the filters and the spectral range of interest are changeable. The results of the underwater experiment show that the spectra and as spatial information of the object can be completely acquired by the UMSI. In addition, the UMSI can highlight the spectral signature for similar colors, which is of great significance to the identification and classification of underwater objects with similar appearances.

## ACKNOWLEDGMENT

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