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MULTISPECTRAL ECOLOGICAL CONTROL OF BIOMASS OF PHYTOPLANKTON IN AQUEOUS MEDIA IN SITU USING A QUADROCOPTER

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Abstract. The aim of the work is to improve the method and means of multi-spectral ecological control of phytoplankton biomass in water environments in situ using a quadrocopter with a multi-spectral camera. The instrumental and methodological errors of indirect measurements of phytoplankton biomass in the near-surface layer of the aquatic environment using the developed means of environmental control have been analyzed.

Key words: ecological monitoring, multi-spectral measurements, water, phytoplankton, bio-indication.

1. Introduction

When harmonizing the environmental protection system of Ukraine with EU legislation, it is necessary to improve the monitoring system for anthropogenic pollution of aquatic environments [1]. In this case, an integral parameter characterizing the toxic effect of all the pollutants present in the water – toxicity, can be obtained only by bio-testing. In order to obtain high reliability of ecological control of the toxicity of aquatic environments, it is necessary to select bio-indication test objects, their test parameters, methods and means for measuring them and to ensure sufficient accuracy of measurement of these test parameters. For further research in this work, phytoplankton has been chosen as a test object, and the test parameter is the concentration of phytoplankton biomass in the near-surface water layer. At the same time, optical methods of control, in particular, the multi-spectral method is the perspective direction of improving the means of ecological control of the phytoplankton biomass concentration in water bodies. Unmanned aerial vehicles (UAVs) have been widely used all over the world since the 1970s to investigate and determine the locations of the “blossoming spots” of cyanobacteria in the near-surface water layer. Complex solution of the tasks of ecological safety management of water bodies requires the improvement of methods and tools for multi-spectral environmental measurement of water parameters. The aim of this work is to increase the accuracy of measurements of phytoplankton biomass in aqueous media in situ using a quadrocopter and a multi-spectral method.

2. Materials and methods

The essence of the method of multi-spectral measurement control is the analysis of digital images of the investigated object, obtained in several spectral ranges [2–6]. Conventionally, spectral television measurements are divided into one-spectral (panchromatic, number of channels $N=1$), multi-spectral (number of channels is $2 \leq N \leq 99$), hyper-spectral (number of channels is $100 \leq N \leq 999$), and ultra-spectral (number of channels is $N>1000$) [7]. After processing the received array of multi-spectral images, it is necessary to indirectly measure the parameters of heterogeneous aqueous media in each pixel of the image. This is done on the basis of the solution of the inverse optical problem [8], taking into account the mathematical model of inhomogeneous aqueous media [9].

Mathematical models of light transformation in the near-surface layer of inhomogeneous aqueous media take into account the concentrations of the main pigments, the structural features of the near-surface layer, the wavelength of the incident radiation and the degree of its polarization. The method of experimental research and environmental measurement control based on the processing of multi-spectral images of an object obtained by a CCD camera at characteristic wavelengths should provide high probability of monitoring of the state of the object and its near-surface structure. The concentration of the main pigments in the near-surface layer of heterogeneous aqueous media is measured by analyzing the array of multi-spectral images of the test object and comparing them with an array of multi-spectral images of model media with the known concentrations of pigments obtained under certain specified experimental conditions [10].

The coordinates in the multi-spectral n-dimensional space are determined on the basis of the spectral characteristics of the radiation sources, filters, photo-matrix and the object of control. When using a multi-spectral camera with light filters at the inputs of photo-matrix elements, the system of equations for determining the coordinates in the n-dimensional multi-spectral space will be the following:

$$\begin{cases} M_1 = \sum_{i=1}^{i_{\max}} P(l_i) s_1(l_i) R_d(l_i) \Delta l, \\ M_2 = \sum_{i=1}^{i_{\max}} P(l_i) s_2(l_i) R_d(l_i) \Delta l \\ \ldots \\ M_n = \sum_{i=1}^{i_{\max}} P(l_i) s_n(l_i) R_d(l_i) \Delta l, \end{cases} \quad (1)$$

where $P(l_i)$ is a spectral characteristic of a radiation source; $s_i(l_i)$ – spectral characteristic of the *i*-th channel of the multi-spectral camera; $R_d(l_i)$ – spectral characteristic of the diffuse reflection coefficient of the object of study.

2.1. Experimental part

The spectral characteristics of the diffuse reflectance coefficient on the surface of the natural aqueous environment are calculated in [11] in a small-angle approximation for the following parameters of phytoplankton: biomass of phytoplankton varies from 17.7 to 35.4 mg/l; the ratio between chlorophyll *a* and total chlorophyll in phytoplankton is 0.8; the ratio between carotenoids and total chlorophyll is 0.27. The content of chlorophyll *a* in the crude mass of phytoplankton is assumed to be 0.5 %. The spectral characteristics of the absorption index, the scattering index and the anisotropy factor for the aquatic environment without phytoplankton but with the presence of suspended particles of organic origin are introduced into the mathematical model by means of approximation from the results of experimental studies. Natural solar radiation is used as a source of radiation, the averaged spectral characteristic of the radiation density of which, taking into account the absorption in the atmosphere, is shown in Fig. 1, *a*. The multi-spectral environmental monitoring tool uses eight-channel multi-spectral cameras of the CMS series (Silios Technologies, France) with the following main parameters [12]: the spectral range of CMS-C is 400–700 nm, CMS-V – 550–850 nm, CMS-S – 650–950 nm; monochromatic channel resolution is 1280×1024; resolution of spectral channels is 426×339; the size of one pixel is 5.3 μm; ADC is 10 bit; exposure time is from 10 μs to 2 s; weight – 59 g. The spectral sensitivity characteristic of the multi-spectral cameras of the CMS series is shown in Fig. 1, *b*–*d*.

The results of calculation of multi-spectral parameters according to the known spectral characteristics when phytoplankton biomass is changed and using eight-channel multi-spectral cameras of the CMS series of various types are shown in Fig. 2. Since the spectral characteristics of natural solar radiation at the water surface level are constantly changing, it is necessary to normalize the results of multi-spectral measurements from a quadrocopter relative to an object with the known spectral characteristics, for example, a floating platform with a white diffusely reflecting surface with barium sulfate coating. The need for a part of this surface always to fall into the multi-spectral image reduces the real resolution of the control object image. For indirect measurement of phytoplankton biomass, based on the results of multi-spectral measurements, only the normalized values of multi-spectral parameters are used.

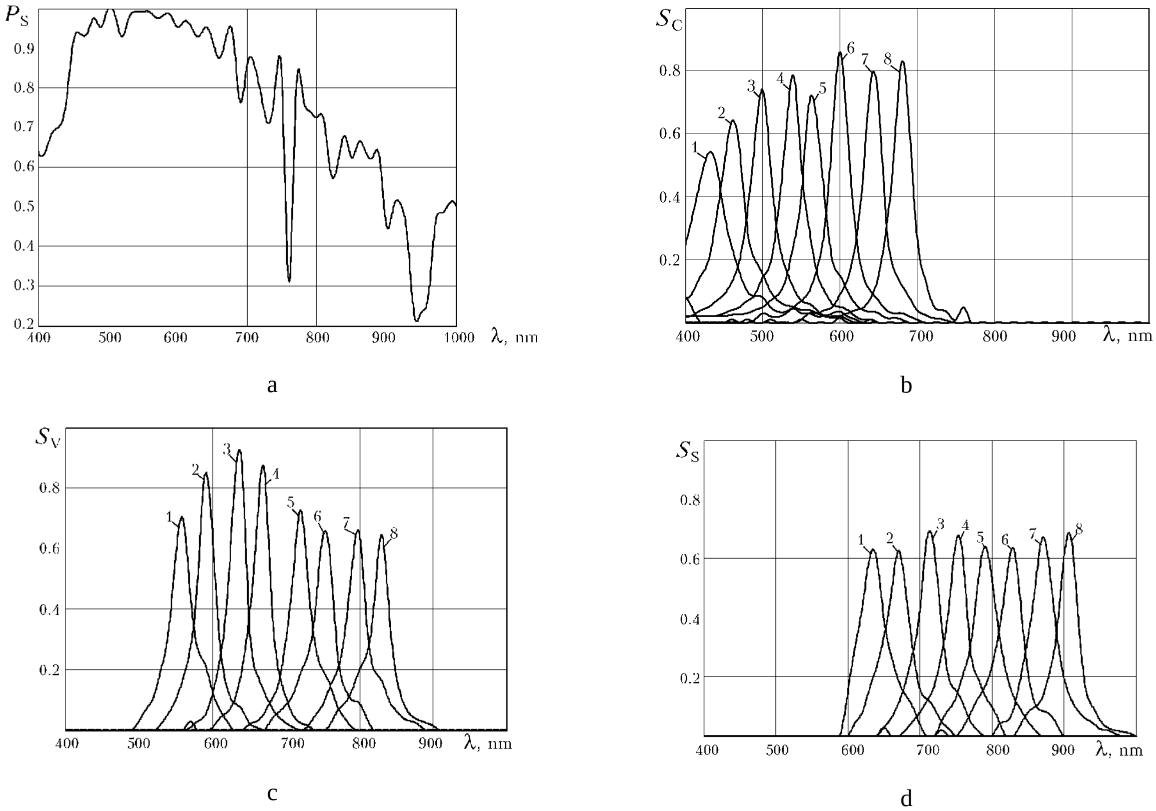

Fig. 1. Normalized spectral characteristics: a – natural solar radiation;
b – sensitivity of the spectral channels of the camera CMS-C (400–700 nm);
c – sensitivity of the spectral channels of the camera CMS-V (550–850 nm);
d – sensitivity of the spectral channels of the camera CMS-S (650–950 nm)

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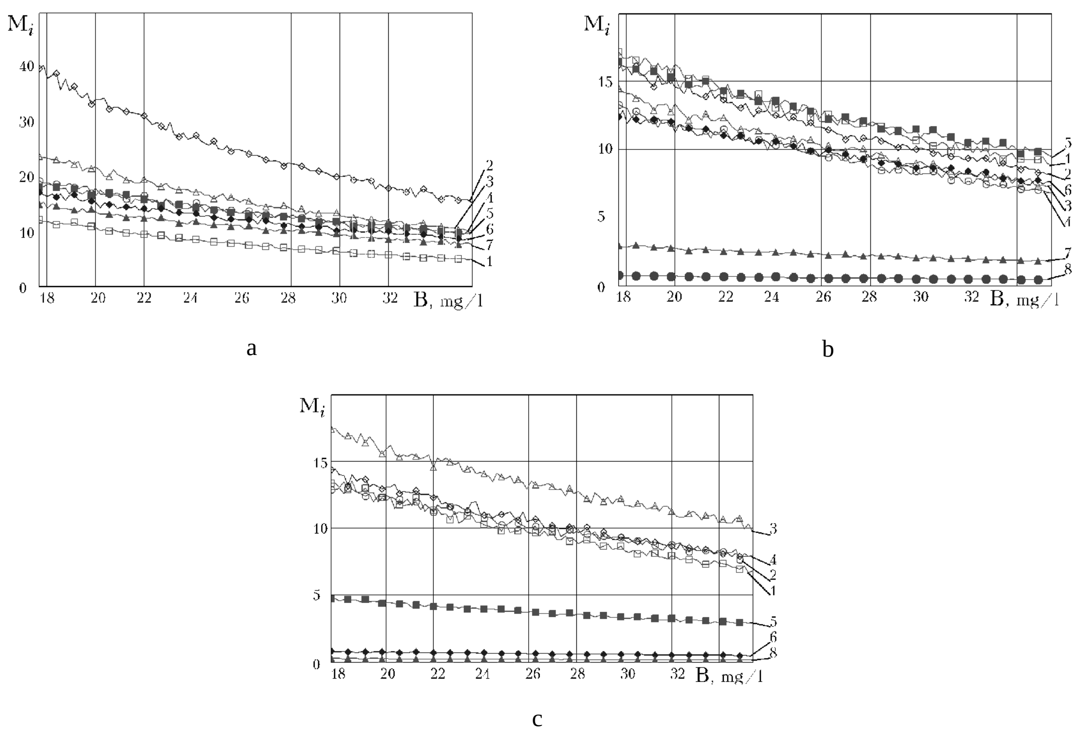

Fig. 2. Dependences of multi-spectral parameters when the biomass of phytoplankton varies from 17.7 to 35.4 mg/l and using multi-specral cameras of the series CMS: a – CMS-C; b – CMS-V; c – CMS-S

3. Results and discussion

The solution of the inverse optical problem for the determination of phytoplankton biomass in aqueous media based on the results of multi-spectral measurements is carried out by means of multiple regression in the STATISTICA 6.0.Program. Using step-by-step regression, we analyze the multi-spectral parameters that allow the most accurate determination of the biomass of phytoplankton.

In the multiple regression for indirect measuring of the phytoplankton biomass in water bodies using CMS series multi-spectral cameras, the following regression equations have been obtained:

$$B_{CMS\_C} = 0{,}057154618 - 0{,}475979M_{C\_7\_642} - 0{,}472422M_{C\_5\_563} - 0{,}287206M_{C\_6\_600} + 0{,}345161M_{C\_2\_461} - 0{,}343838M_{C\_4\_536} + 0{,}237081M_{C\_1\_430}, \quad (2)$$

$$B_{CMS\_V} = 0{,}058691384 - 0{,}196036M_{V\_4\_669} - 0{,}283101M_{V\_6\_752} - 0{,}150405M_{V\_8\_829} - 0{,}131900M_{V\_7\_795} - 0{,}122064M_{V\_5\_719} - 0{,}118101M_{V\_3\_635}, \quad (3)$$

$$B_{CMS\_S} = 0{,}062431853 - 0{,}330180M_{S\_5\_790} - 0{,}283269M_{S\_6\_827} - 0{,}170174M_{S\_7\_871} - 0{,}138106M_{S\_3\_713} - 0{,}107677M_{S\_4\_752} + 0{,}153303M_{S\_1\_635} - 0{,}126370M_{S\_2\_669}, \quad (4)$$

where B_{CMS_C}, B_{CMS_V}, B_{CMS_S} is the biomass of phytoplankton, determined with the help of multi-spectral cameras CMS-C, CMS-V, CMS-S; $M_{i\_j\_k}$ – multi-spectral parameters of the i-th type camera, of the j-th spectral channel and the k-th wavelength value in nm.

Table 1

Results of multiple regression calculation for multi-spectral measurements

N	λ, nm	F	δ_m, %	R
camera type CMS-C (400 – 700 nm)				
1	642	4144.709	0.0792326	0.98838330
2	642, 563	3012.789	0.0659567	0.99204687
3	642, 563, 600	2134.479	0.0640159	0.99258727
4	642, 563, 600, 461	1721.980	0.0617600	0.99317439
5	642, 563, 600, 461, 536	1473.263	0.0597513	0.99368003
6	642, 563, 600, 461, 536, 430	1261.884	0.0589508	0.99391440
camera type CMS-V (550 – 850 nm)				
1	669	5077.319	0.0717393	0.99048673
2	669, 752	3993.504	0.0574001	0.99398240
3	669, 752, 829	2982.531	0.0542694	0.99467822
4	669, 752, 829, 795	2378.076	0.0526532	0.99504356
5	669, 752, 829, 795, 719	1966.259	0.0518029	0.99525336
6	669, 752, 829, 795, 719, 635	1648.677	0.0516476	0.99533215
camera type CMS-S (650 – 950 nm)				
1	790	5508.512	0.0689254	0.99122163
2	790, 827	4191.557	0.0560435	0.99426429
3	790, 827, 871	3336.031	0.0513425	0.99523811
4	790, 827, 871, 713	2644.500	0.0499554	0.99553957
5	790, 827, 871, 713, 752	2156.245	0.0494888	0.99566887
6	790, 827, 871, 713, 752, 635	1797.086	0.0494881	0.99571516
7	790, 827, 871, 713, 752, 635, 669	1562.387	0.0491432	0.99582033

Let us analyze the instrumental component of the error of multi-spectral measurements using multi-spectral cameras of the CMS series with a bit depth of 10 bits and a signal-to-noise ratio of 60 dB [13]. In this case, the analog-to-digital conversion error arises from a finite number of allowed signal levels in the level-quantization $d_{ADC\,ccd}$ and instrumental error due to the presence of noise and random interference in the camera $d_{noise\,ccd}$. We calculate the instrumental error due to the presence of noise and random interference in the photomatrix

$$d_{noise\,ccd} = 100\,\%/\left(10^{D_{s/n}/20}\right) = = 100\,\%/\left(10^{60/20}\right) = 0.1\,\%. \quad (5)$$

Quantization error $d_{ADC\,ccd}$ with a large number of discharges can be described by a rectangular distribution law, corresponding to an equal probability density of the quantization error within $\pm h_k/2$, where h_k is a quantization step. Taking into account the maximum and minimum signal levels on the elements of the matrix:

$$d_{ADC\,ccd} = \frac{F_H}{2 \cdot F_{X\max} \cdot 2^n} \cdot 100\,\% = = \frac{1}{2 \cdot 2^{10}} \cdot 100\,\% = 0.049\,\%. \quad (6)$$

Mean square error of quantization [14]

$$d_{SD\,ADC\,ccd} = \frac{d_{ADC\,ccd}}{\sqrt{12}} = 0.014\,\%. \quad (7)$$

Let us determine the random component of the measurement error of each coordinate in the n-dimensional multi-spectral space on the basis of the root-mean-square values of the components:

$$d_{rand.Mi} = \sqrt{d^2_{noise\,ccd} + d^2_{ADC\,ccd}} = = \sqrt{0{,}1^2 + 0{,}014^2} \approx 0.101\,\%. \quad (8)$$

The random component of the measurement error is determined by the random components of the measurement error in each of the spectral channels, so the total random component of the error of the indirect measurements will be determined by the random errors of the corresponding multi-spectral parameters that fall into the common regression equation [15]

$$d_{\text{instr.}} = \sqrt{\sum_{i=1}^{N} d^2_{rand.Mi} + 2\sum_{i=1}^{N}\sum_{j<i} R_{ij} d_{rand.Mi} d_{rand.Mj}}, \quad (9)$$

where $d_{rand.Mi}$, $d_{rand.Mj}$ is the random error component in the i-th and j-th channels; R_{ij} – correlation coefficient between multi-spectral parameters obtained after multiple regression; N – total number of channels.

For a three-channel instrument, the instrumental error component, taking into account the correlation coefficients between the measurement results from different channels, was 0.303 %, for a four-channel instrument is was 0.35 % and for a six-channel – 0.428 %.

The total error in measuring the biomass of phytoplankton will be determined by the sum of the instrumental and methodological errors:

$$d_{gen} = d_{\text{instr.}} + d_m. \quad (10)$$

At the same time, the value of the total biomass measurement error of phytoplankton for the three-channel agent was 0.367 %, for the four-channel it was 0.412 % and for the six-channel – 0.487 %. Therefore, since the instrumental component of the measurement error increases with the increase in the number of channels, the lower the methodological component of the error, the overall error in measuring the biomass of phytoplankton will increase with the increase in the number of spectral channels of the multi-spectral control.

Conclusions

The method of ecological control of phytoplankton biomass concentration in the near-surface layer of natural water environments in situ using a quadrocopter with multi-spectral chamber has been improved. The inverse optical problem for the determination of phytoplankton biomass in natural aqueous media has been solved based on the results of multi-spectral measurements using eight-channel multi-spectral cameras of the CMS series (Silios Technologies) and the corresponding regression equations have been obtained. Comparing the values of the methodological error in measuring phytoplankton biomass for cameras of this series operating in different wavelength ranges, the smallest value has been obtained for the camera working in the range of 650–950 nm (CMS-S). It has been analyzed how the methodical and instrumental component of the biomass measurement error of phytoplankton changes with the growth of the number of spectral channels. Optimal wavelengths of spectral channels and their number in the indirect measurement of phytoplankton biomass in natural aqueous media in situ are selected from the condition of ensuring a minimum value of the total error.

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