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VISUALIZATION OF COLOR LABEL SENSORS IN MICROELECTROMECHANICAL SYSTEMS

Andriy Fechan[1], Yuriy Khoverko[2], Vladyslav Dalyavskii[1], Taras Dyhdalovych[1]
Lviv Polytechnic National University, Lviv, Ukraine
[1]Software department, [2]Department of semiconductor electronics
Andrii.v.fechan@lpnu.ua, Yurii.m.khoverko@lpnu.ua
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Abstract: The article presents the design and technological features of creating color labels-sensors of microelectromechanical systems intended for monitoring physico-chemical parameters under the conditions of high- level electromagnetic interference. The software module of the hardware and software complex for the visualization of spectral intensity by converting it into an RGB colour model has been created. The algorithm for carrying out the procedure for calculating the color rendering index is shown and the main parameters of temperature colors in a wide range of visible radiation waves are determined

Key words: color label sensors**,** spectral intensity distributions, color rendering index.

1. Introduction

One of the promising areas of progress of modern microelectromechanical systems (MEMS) is the development and use of microelectronic sensors, which are the result of the fusion of technologies and design of sensitive elements and organic semiconductors, i.e. liquid crystals for the creation of optically active media, on one or more crystals with hybrid or monolithic integration of electrical and optical elements [1,2]. At the same time, the development of microelectronics and the prospects of nanoelectronics [3] significantly expanded modern capabilities of microprocessor technology and features of its use in highly efficient information (intelligent) systems [4], raising the need to implement new approaches to creating sensors. On the other hand, pandemics and large-scale military actions lead to an increase in the use of disposable protective suits, containers, deployment of temporary objects of short-term use. This makes it necessary to change the monitoring system of physical and chemical parameters. In such a situation, the development of a computer monitoring system based on the methods of optical identification implementing non-contact optical primary converters based on the silicon - liquid crystal system becomes relevant. This, in turn, stimulates the development of a software and hardware complex for monitoring physico-chemical parameters based on them for working under the conditions of a high-level electromagnetic interference.

Recently, a number of studies are aimed at creating sensors whose source of information is optical radiation, rather than an electrical signal [1,2-6]. Their main advantages are the possibility of stable operation under the conditions of a high-level electromagnetic interference due to the dispersion of sensor elements in space. Optical sensors are based on optoelectronic devices consisting of a light source, a photoreceptor and an optically active environment. The change in the optical features of this environment under the influence of external factors affects the output signal of the photoreceiver used for this detection. Absolutely, the optically active medium plays a major role in the proposed structure. Liquid crystals are among the promising materials for creating this environment [7-9]. Intensity, polarization direction, change of propagation direction, etc. can be selected as information parameters, but spectral characteristics are optimal for solving the issue of immunity [10,11], as well as their monitoring due to the created hardware and software complex.

Therefore, the goal of the work is to create a software module of the hardware and software complex, intended for visualization, and color labels-sensors of the MEMS for monitoring physico-chemical parameters under the conditions of a high level of electromagnetic barrier.

2. Experiment details

Calculation of color parameters of light from the spectral range is a complex task. However, it can be significantly simplified by developing an appropriate software module that will allow processing the useful signal of color label sensors in the MEMS through a spectrometer. The software module is operable in the Windows environment. The developed system allows easy calculations of color parameters by the spectral distribution of intensity. The software supports the main color systems, namely CIE XYZ, RGB, CIE LUV and CIE LAB [12]. In addition, the calculation of other important parameters, such as the correlation color temperature [13] and the color rendering index (CRI) [14] is also supported. For flexibility and convenience, all parameters used by the system for calculations can be adjusted.

The input data for the system is the spectral intensity distribution. The spectrum can be obtained from a text, XML or JSON file, or directly from the spectrometer. The system supports a wide range of Ocean Optics spectrometers through a software interface OmniDriver [15]. The software receives and processes data from the spectrometer in real time, which allows monitoring changes in the color parameters of light. The system allows data processing results to be stored in a local database or exported to files of basic standard formats for further processing and analysis.

The main system tools are placed in the toolbar, while all others are hidden in the main menu. All graphs and charts in the program are scalable, allowing the exploration of the smallest details. The size of the application window and the aspect ratio can also be changed in a wide range, so the system is convenient to be used for most existing devices. In general, the software is developed in the C# programming language and using the .NET framework. Selected technologies and development tools are natively supported, which means there are no compatibility problems between the program and the operating system. The system consists of several software modules, a database, and a graphical user interface.

Among all software modules, the main ones are the mathematical model of light processing, the communication module with the spectrometer, and the main module of the system. The mathematical model of light processing is developed as a dynamic library that can be used separately from the software tool. The main mathematical concepts and methods on which the model is based are described in the article [16]. The transformation of the spectral intensity distribution into an RGB color is described below.

3. Experiment procedure

The basics of the technological process of creating a hybridized sensitive element of the color sensor label based on a molecular crystal-semiconductor system are the processes characteristic of the technology of integrated circuits (diffusion or ion alloying, oxidation, photolithography, vacuum metallization, various types of cleaning and heat treatment etc.). At the same time, processes are used that are not typical of semiconductor technology. First of all, these include anisotropic and isotropic chemical profiling.

The process of microprofiling of silicon substrates includes the following main stages: standard preparation of the surface of silicon wafers, growth of a film (SiO_2) masking coating on the surface of the wafer, photolithography of the mask, anisotropic etching.

The method of anisotropic etching of membranes of sensitive elements of sensors is used in the process of manufacturing the MEMS, which is the basis for creating a microelectronic color sensor label.

Considering the experimental data on the dependence of etching depth on time, the etching rate of monocrystalline silicon in an aqueous solution of KOH was calculated as a function of temperature (Fig.1). Taking into account the quality of the obtained surface of the membrane bottom depending on the concentration of the solution, as well as the rate of etching of silicon, it is possible to microprofile the plates to form the microelectronic label sensor for optical identification.

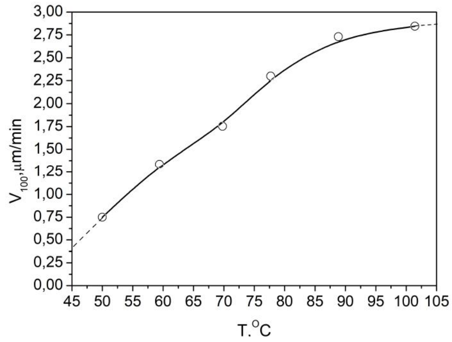

Fig.1. Dependence of the etching rate of silicon in the (100) plane on the temperature in an aqueous KOH solution.

Taking into account the above features of anisotropic etching of monocrystalline silicon, it is possible to obtain membranes for substrates with a diameter of 100 mm, whose fragment is shown in Fig. 2, as well as proposed design and technological features of the manufacture of a color sensor-label based on semiconductor liquid-crystal systems.

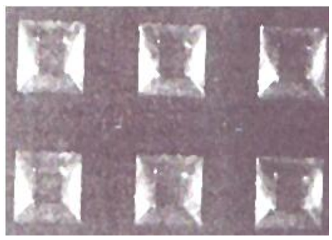

Fig.2. Appearance of membranes after deep etching of a monocrystalline substrate at x20 magnification

In this case, the features of microprofiling of silicon wafers, being intended for the formation of the chip configuration, is one of the most important stages of the MEMS manufacturing technology. At the same time, it is necessary to solve a number of problems, the main ones being the ensurance and control of the reproducibility of the geometric shape and dimensions of mechanical parts, the thickness of the membrane, the quality of the surface, etc. Fig. 3 shows a schematic representation of a microelectronic label sensor using micro-profiled monocrystalline silicon.

Liquid crystal materials with a spiral supramolecular structure, so-called cholesteric liquid crystals (CLC) were chosen for the implementation of sensors [18]. The direct effect on the spectral characteristics of optical radiation is based on the effect of selective reflection of light [19]. Selective reflection at the wave length around λ_{max} means that the flat structure of the CLC will appear colored being illuminated by white light [20].

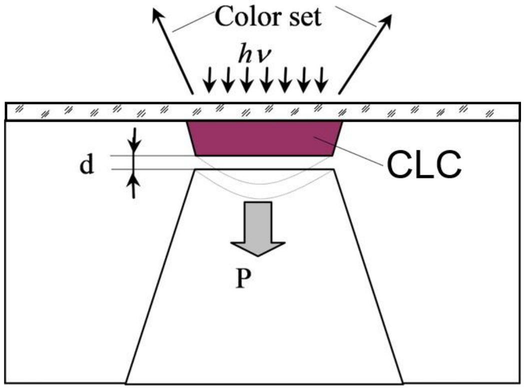

Fig.3. Schematic representation of a microelectronic label-sensor for optical identification: CLC- cholesteric liquid crystal, P-pressure, d- membrane thikness.

The coloration of a flat texture illuminated with white light can be explained by considering it as a diffraction grating with a system of parallel layers of thickness *P*/2 and an average refractive index *n*.

Then the wavelength of the light λ_{max}, which has the maximum intensity in the case of interference, corresponds to Wulff–Bragg's condition:

$$\lambda_{max} = 2\, n\, d \sin\theta, \qquad (1)$$

were $d = P/2$ is lattice period; θ is the angle between the incident beam and the cholesteric plane.

In addition, having the techniques and methods of controlled pressure change in the "membrane - liquid crystal" system, it is possible to form the color background of the microelectronic label sensor with a predetermined accuracy, or, in other words, by controlling the spectral characteristics λ_{max}= f(P) to set the required color of the device.

4. Experimental results

At the first stage, the spectral intensity distribution is normalized and converted to color in the CIE XYZ color model [12] which is the basis for all subsequent calculations and transformations. To calculate the color in the CIE XYZ model, the system uses the color finder function [21]. The function allows for easy converting the spectral intensity distribution of any visible light into color. Nowadays, there are several different color detection functions and new ones can be developed in the future, therefore, the function in the system code is not protected. In the system, the functions are stored in the database, and if necessary, the user can import a new one from a text file.

After calculating the color in the CIE XYZ model, the it is converted to the RGB color model. For this, the transformation matrix is used, which is displayed in the ratio (2).

$$\begin{bmatrix} r \\ g \\ n \end{bmatrix} = |M|^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} |M| = \begin{bmatrix} S_r X_r & S_g X_g & S_b X_b \\ S_r Y_r & S_g Y_g & S_b Y_b \\ S_r Z_r & S_g Z_g & S_b Z_b \end{bmatrix}, \qquad (2)$$

$$\begin{bmatrix} S_r \\ S_g \\ S_b \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix}^{-1} \begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix}. \qquad (3)$$

In the formulas, Xr, Yr, and Zr are the RGB parameters of the transformation matrix calculated from the chromatic coordinates of some RGB system. Xw, Yw, and Zw are the color coordinates of the reference white light of the selected RGB system.

Since there are many different RGB color systems today, the user can choose the required one from the preset systems stored in the application, or if the required color system is not available, the user can easily import it.

After calculating the linear RGB color using the matrix (3), it is converted into a more familiar, non-linear color format using the gamma transformation (4):

$$V = v^{\frac{1}{\gamma}}. \qquad (4)$$

In relation (4) V is a linear color channel, □ is non-linear RGB color channel, and γ is the gamma parameter of the corresponding color system.

The main system is designed using the Model-View-ViewModel (MVVM) architectural pattern. This was chosen because it makes it easy to update the user interface in real time. Selected .NET and Windows Presentation Foundation (WPF) frameworks [22] natively support this architectural pattern.

The SQlite database is used to save data in the software application [23]. SQLite is a relational database management system. Unlike other popular database management systems, the SQLite does not require additional installation and deployment.

To work properly, the SQLite needs only a database file and a dynamically linked library. This allows for delivering the application with the required data set and simplify the installation and deployment process. The SQLite database also has some drawbacks, but they are insignificant for the developed system.

The next part of the main system is the graphical user interface. As described above, the MVVM pattern was chosen as the main architectural design pattern, and the

WPF was chosen as the main framework for user interface development [22]. The WPF is one of the most powerful and versatile graphical user interface (GUI) frameworks for the .NET Windows platform. Another advantage is that it is supported by all popular versions of the Windows operating system.

When developing the graphical user interface, the main goal was to combine all the most important information, all the graphics and all the functionality in a one main window of the program, while all the less important things were transferred to the menu of the program and additional windows. This allows the user to always see a complete picture of the light being tested and to have easy access to the main functions. At the same time, due to the removal of everything superfluous in the menu and additional windows, the main window of the program is not overloaded with information and, therefore, not too complicated. The implementation of the main window is shown in Fig. 4.

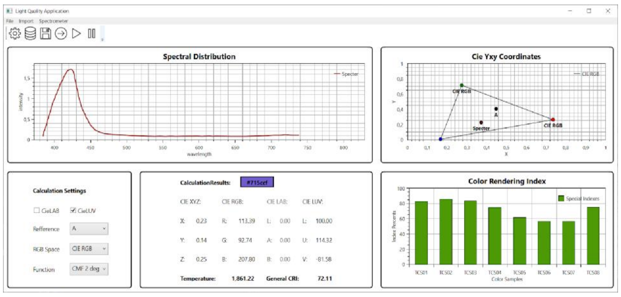

Fig. 4. The main window of the software module.

As can be seen in Fig. 4, the main window displays the spectral distribution of the intensity of the investigated light, the calculated color indicators and other light indicators. As described above, the software system directly communicates with the spectrometer. Such communication is extremely important, as it allows the elimination of several intermediate steps while investigating the color of light. The system works with most spectrometers from Ocean Optics.

The OmniDriver library [15] was used in the system to operate and configure the spectrometer. The described library supports normalization and smoothing of the intensity spectral distribution before processing. This makes the spectrum acceptable for further processing and rejects unwanted noise. Normalization and smoothing parameters can be adjusted in the corresponding system window. Also, the user can select the desired spectrometer if several of them are connected to the computer. The system receives standard parameters from the spectrometer when it is connected, so the users usually do not need to make additional settings every time they use it.

The software has two modes of working with spectrometers, namely, reading a single spectrum and periodically reading and processing the spectrum in real time within a given period. Accepting the second option, the user can dynamically change the periods and processing parameters. Reading and processing the spectral distribution in real time allows the user to monitor changes in the color parameters of light over time. It is an extremely important function, which significantly expands the scope of using the software product.

To simulate the operation of the software-hardware complex, the software module was used to find the color in the RGB model of the light emitted by the sensor in the absence of a load. A typical characteristic for T=9.68 color temperatures is shown in Fig. 5.

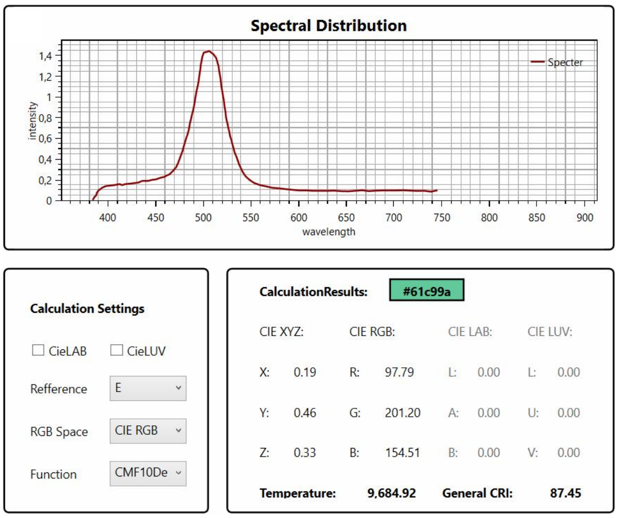

Fig. 5. Results of studies of spectral distributions for T=9.68 color temperatures.

As the research showed, there is a noticeable difference between the spectral intensity distributions which indicates a high resolution during the calculation procedure for the CRI. So, for wavelengths in the range 500÷560 nm the software module allows for estimating the intensity that constitutes the order I□1.4. At the same time, the color rendering index is within the limits CRI= 77.28 ÷ 87.45. For longer wavelengths (□ □ 420 nm) the spectral intensity distribution already corresponds to I=1.7.

6. Conclusions

As a result of the conducted research, the constructive technological element of the hardware and software complex for visualization of the color labels-sensor of the MEMS for monitoring physico-chemical parameters under the conditions of a high-level electromagnetic barrier was developed and proposed. The implementation of the sensitive element involves the complex use of bulk silicon and liquid crystal materials with a spiral supramolecular structure - cholesteric liquid crystals. A software module of the system was developed for estimating the intensity in a wide range of waves from 300 to 900 nm. The feature of the software module is the flexibility of integration with existing .NET Windows platforms. For wavelengths located in the range 500÷560 nm, the software module allows for estimating the intensity, which is the order of magnitude I□1.4. At the same time, the color rendering index is within the limits CRI= 77.28 ÷ 87.45, which indicates the high resolution of the complex during the calculation procedure for the CRI.

7. References

[1] S. Y. Han, K. S. Jeon, S. M. Seo, M. S. Seo, and S.-W. Jung, "Design of a Multifunctional Double-Active-Layer Thin-Film Transistor for Photosensing Applications", *IEEE Electron Device Letters*, Vol. 34, No. 1, pp. 66–68, 2013. doi: 10.1109/LED.2012.2223811.

[2] K.Tai, Ya-Hsiang, Lu-Sheng Chou, and Hao-Lin Chiu , "Gap-Type a-Si TFTs for Front Light Sensing Application," *Journal of Display Technology*, vol. 7, no. 12, pp. 679–683, 2011.

[3] A. Druzhinin, Yu. Khoverko, I. Kogut, and R. Koretskii, "Properties of low-dimentional polysilicon in SOI structures for low temperature sensors", *Advanced Materials Research*, Vol. 854, pp. 49–55, 2014 doi: 10.4028/www.scientific.net/AMR.854.49

[4] V. Holota, I. Kogut, A. Druzhinin, and Y. Khoverko, "High sensitive active MOS photo detector on the local 3D SOI-structure," *Advanced Materials Research*, Vol. 854, P. 45–47, 2014. doi:10.4028/www.scientific.net/amr.854.45.

[5] L. -G. Chen, D. -Y. Wu and M. S. . -C. Lu, "An integrated micromanipulation and biosensing platform built in glass-based LTPS TFT technology," *SENSORS, 2012 IEEE*, Taipei, Taiwan, 2012, pp. 1-4, doi: 10.1109/ICSENS.2012.6411063.

[6] T. R. Wolinski, W.J. Bock, and A. Jarmolik, "Development of fiber optic liquid crystal sensor for pressure measurement," *Instrumentation and Measurement Technology Conference*, p. 664, IMTC/95, 1995.

[7] J. Namkung, R. Lindquist and A. Abu-Abed, "Application to shear force sensors by homeotropic liquid crystal (LC) orientation (non-reviewed)," *IEEE SoutheastCon 2008*, Huntsville, AL, USA, 2008, pp. 80-80, doi: 10.1109/SECON.2008.4494260

[8] T. Sakuraia. T. Ohashia. H. Kitazumea, M. Kubotab,T.Suemasua, and K. Akimotoa, "Structural control of organic solar cells based on nonplanar metallophthalocyanine/ C60 heterojunctions using organic buffer layers," *Organic Electronics*, vol. 12, no. 6, pp. 966–973, 2011. doi: 10.1016/j.orgel.2011.03.016

[9] T. Miyadera, Z. Wang, T. Yamanari, K. Matsubara and Yu. Yoshida, "Efficiency limit analysis of organic solar cells: model simulation based on vanadyl phthalocyanine / C60 planar junction cell," Japanese Journal of Applied Physics, vol. 53, no. 1S, P. 01AB12, 2014. doi: 10.7567/JJAP.53.01AB12

[10] H.Seidel, L.Csepregi, A.Heuberger, and H.Baumgartel, "Anisotropic Etching of Crystalline Silicon in Alkaline Solutions", *J.Electrochem.Soc*, vol.137, no. 11, pp.3612–3625, 1990.

[11] H.Schroder, E.Obermeier, and A.Steckenborn, "Micropiramidal hillocks on KOH etched {100} silicon surfaces: formation, prevention and removal", *J.Micromech. Microeng*, vol.9, pp.139–145, 1999.

[12] J. Schanda, "CIE colorimetry", *Colorimetry: Understanding the CIE system*, pp.25-78, 2007. DOI:10.1002/9780470175637

[13] Li Changjun, Cui Guihua, Manuel Melgosa, Xiukai Ruan, Yaoju Zhang, Long Ma, Kaida Xiao, and M. Ronnier Luo, "Accurate method for computing correlated color temperature," *Opt. Express* 24, pp.14066-14078, 2016. https://doi.org/10.1364/OE.24.014066

[14] S. Jost, C. Cauwerts, and P. Avouac, "CIE 2017 color fidelity index Rf: a better index to predict perceived color difference?," *J. Opt. Soc. Am.* A 35, pp.B202-B213, 2018. https://doi.org/10.1364/JOSAA.35.00B202

[15] Ocean Optics OmniDriver Programming Guide [Electronic resource]: https://www.oceaninsight.com/globalassets/catalog-blocks-and-images/software-downloads-installers/omnidriver_programming_manual.pdf.

[16] T. Dyhdalovych, A. Fechan, S. Kutsiy and S. Melnykov, "Development of the automated system of analysis and quality assessment of visible light sources", *IEEE 16th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering* (TCSET), pp. 694-697, 2022. doi: 10.1109/TCSET55632.2022.9767066

[17] P. I. Baranskyi, A. V. Fedorov, and G. P. Gaidar, *Physical properties of silicon and germanium crystals in the fields of effective external influence*, Lutsk: Nastyrya, p. 280, 2000. (in Ukrainian)

[18] Aksimentyeva O., Konopelnik O., Cherpak V., Stakhira P., Fechan A., and Hlushyk I. , "Conjugated polyaminoarenes as electrochromic layers for non-emissive displays", *Ukrainian Journal of Physical Optics* 6(1), pp. 27 – 32, 2005.

[19] I. P. Ilchishin, O. V. Yaroshchuk, and E. A. Shaidyuk, "Phototuning of the lasing spectra of doped cholesteric liquid crystals," *Ukr. J. Phys.*, vol. 50, no.12, pp. 1333–1338, 2005.

[20] T. H. Dudok, V. I. Savaryn, O. M. Krupych, A. V. Fechan, E. Lychkovskyy, V. V. Cherpak, B. Pansu, and Yu. A. Nastishin, "Lasing in imperfectly aligned cholesterics," *Applied optics*, 54 (33), pp. 9644 – 9653, 2014.

[21] CIE. Fundamental chromaticity diagram with physiological axes. Parts 1 and 2. Technical Report 170-1. Vienna: Central Bureau of the Commission Internationale de l' Éclairage, 2006.

[22] Windows Presentation Fundation Documentation [Electronic resource]: https://docs.microsoft.com/en-us/dotnet/desktop/wpf/?view= netdesktop-6.0.

[23] SQLite Documentation [Electronic resource]: https://www.sqlite.org/docs.html

МЕТОДИ ВІЗУАЛІЗАЦІЇ КОЛІРНИХ МІТОК-СЕНСОРІВ У МІКРОЕЛЕКТРОМЕХАНІЧНИХ СИСТЕМАХ

А.Фечан, Ю.Ховерко, В. Далявський, Т. Дигладович

У поданій статті наведено конструктивно-технологічні особливості створення колірних міток-сенсорів мікроелектромеханічних систем (МЕМС) для моніторингу фізико-хімічних параметрів в умовах високого рівня електромагнітних завад. Створено програмний модуль апаратно-програмного комплексу візуалізації спектральної інтенсивності шляхом перетворення в RGB-модель. Показано алгоритм проведення процедури обчислення індексу передавання кольору (CRI) та визначено основні параметри температурних колірностей в широкому діапазоні хвиль видимого випромінювання.

Yuriy Khoverko – Dr. Sc., Prof. Department of Semiconductor Electronics of Lviv Polytechnic National University. Research interests cover the physics and technology of semiconductor devices, micro-and nanoelectronic structures and sensor electronics. Research findings are published in more than 320 scientific papers and 14 patents by Ukraine.

Andriy Fechan– Dr. Sc., Prof. Software Department of Lviv Polytechnic National University. Research interests cover optoelectronic devices based on organic materials and computer simulations of anisotropic liquids by molecular dynamics methods. Research findings are published in more than 100 scientific papers and 25 patents by Ukraine.

Vladyslav Daliavskyi - assistant professor, Software Department of Lviv Polytechnic National University. Research interests cover systems for color recognition, and microcontrollers programming. Reserch findings are published in 3 scientific papers and in 1 patent by Ukraine.

Taras Dyhdalovych - master student, Software Department of Lviv Polytechnic National University. Research interests cover the informational technologies, software engineering, internet of things, electronics. Research findings are published in 1 scientific paper.