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Optical Identification and Digital Monitoring of the State of Subsoil-use Sites

Dzhumelia Elvira, *PhD, ORCID ID 0000-0003-3146-8725, elviradzhumelia@gmail.com;*
Fechan Andrii, *Dr. Sc., Prof., ORCID ID 0000-0001-9970-5497, andrii.v.fechan@lpnu.ua;*
Khoverko Yurii, *Dr. Sc., Prof., ORCID ID 0000-0002-7045-2729, yurii.m.khoverko@lpnu.ua;*

Lviv Polytechnic National University, Lviv, Ukraine

The paper proposes an approach to digital monitoring of the physicochemical state of subsoil-use sites based on passive optical sensors, digital image processing, and automated identification techniques. The relevance of the approach is driven by the development of digital technologies in the mining industry and the need to obtain timely information on changes in the state of environmental components, particularly water bodies within areas affected by mining activities. A sensor tag based on an optically active polyaniline film, whose colour changes depending on environmental conditions, is proposed in combination with a QR code for sensor identification and storage of additional information about the monitored site. A digital reading algorithm has been developed that includes QR code detection and decoding, determination of the spatial position of the sensor tag, image preprocessing, and determination of its colour characteristics. The software implementation was carried out using the OpenCV library. Laboratory tests demonstrated the possibility of automated reading of encoded information and determination of the colour parameters of sensor tags. The proposed approach is considered a basis for further development of low-cost, remote, and non-destructive environmental monitoring tools for subsoil-use sites.

Keywords: subsoil use, environmental monitoring, optical sensor, colorimetry, digital identification, QR code

1. Introduction

The current development of the mineral resource sector involves not only the efficient use of subsoil resources but also adequate control of the impact of mining activities on environmental components. Timely acquisition of information on changes in the physicochemical parameters of water bodies, soils, and other components of the natural environment in areas associated with mineral extraction and processing is of particular importance. The digitalisation of the mining industry contributes to the wider adoption of sensor technologies, automated data collection, and real-time monitoring systems. In this context, the use of low-cost sensors is considered one of the directions for the development of digital and sustainable subsoil use (Cacciuttolo et al., 2023).

One of the important tasks of environmental monitoring in mining areas is water quality control. Changes in acidity, concentrations of dissolved substances, metals, and other parameters may be associated both with ongoing extraction processes and with abandoned or decommissioned mining sites. Acid mine drainage is a representative example, for which monitoring pH and other parameters is important when assessing the effectiveness of remediation measures. The application of optical methods for *in situ* monitoring of pH and oxygen has already been demonstrated in studies of acid mine drainage treatment processes (Reuß et al., 2023).

A promising direction for the development of such systems is the use of colorimetric sensors, in which changes in a controlled environmental parameter are accompanied by a change in the colour of the sensitive material. Colorimetric sensors offer the possibility of rapid detection of various pollutants and have potential for environmental monitoring, partly due to the simplicity of visual signal assessment (Liu et al., 2020).

The further development of digital cameras and mobile devices creates an opportunity to replace subjective visual colour assessment with digital analysis. Image-based digital colorimetry involves acquiring an image of a sensor element, extracting its colour characteristics, and converting them into numerical parameters. Current studies consider various colour spaces, including RGB, HSV, CIE XYZ, and L*a*b*, while digital colorimetry is regarded as a promising rapid and relatively low-cost approach for on-site analysis (Fan et al., 2021).

At the same time, the reliability of digital colour determination depends on image acquisition conditions, imaging geometry, illumination, and camera characteristics. Studies of smartphone colorimetry demonstrate the possibility of using built-in cameras for quantitative determination of colour characteristics, while also highlighting the need to assess measurement error and control measurement conditions (Ciaccheri et al., 2023).

The practical application of digital colorimetry for environmental monitoring has also been demonstrated for water parameter determination. In particular, a mobile multi-channel colorimetric system has been proposed for field determination of water quality parameters, including turbidity, ammonium nitrogen, orthophosphates, and certain heavy metals (Xing et al., 2022). This confirms the potential of combining optical sensing principles with digital methods for data acquisition and processing.

In previous studies by the authors (Fechan et al., 2026), optical identification and passive sensor systems based on optically active materials were investigated. Non-contact sensors for optical identification and passive sensor elements for monitoring environmental parameters were studied. The results of these studies provide a basis for further development of digital reading of the optical signal from a sensor element.

However, for the practical use of a network of optical sensors, it is not sufficient to determine only the colour of an individual sensor tag. It is also necessary to establish which sensor, observation point, and monitoring site the obtained signal corresponds to. One way of addressing this issue is to combine a colour sensor tag with a QR code that can contain the sensor identifier, information about its location, and additional data on the controlled parameter. In this case, a digital camera simultaneously performs the functions of an identification and optical signal recording device.

The aim of the study is to investigate an algorithm for optical identification of sensor tags and digital reading of their colour parameters as a basis for digital monitoring of the state of subsoil-use sites.

2. Materials and Methods

The study is based on an optical sensor tag formed using a polyaniline film and a PVA–PANi composite material (polyvinyl alcohol–polyaniline). The sensor element is characterised by changes in its optical properties depending on environmental conditions, which makes it suitable as a basis for non-contact recording of changes in the controlled parameter. The methodology for obtaining and investigating polyaniline-based sensor films is described in previous studies by the authors (Tsizh et al., 2016; Aksimentyeva et al., 2018).

For digital identification of the sensor element, its combination with a QR code is proposed. This structure makes it possible to simultaneously obtain information about the sensor identifier, its spatial position, colour characteristics, and the value of the controlled parameter. In this study, pH was used as an example of the controlled parameter.

Digital information reading is performed from an image acquired using a digital camera. The algorithm consists of the following sequential operations:

1. detection of the QR code in the image;
2. determination of the coordinates of its corner points and geometric parameters;
3. decoding of the information encoded in the QR code;
4. determination of the location of the corresponding sensor tag;
5. image preprocessing;
6. extraction of the sensor-tag region based on its geometric characteristics;
7. determination of the colour parameters of the sensor element.

The OpenCV library, specifically the QRCodeDetector function, was used for QR code detection and decoding. If the quality of the original image is insufficient, additional conversion to grayscale and binarisation are applied. This approach improves the reliability of QR code detection under varying image acquisition conditions.

The position of the colour sensor tag is determined relative to the coordinates of the QR code. Since the QR code and sensor tag form a spatially fixed pair, the sensor search area can be restricted to the corresponding image region after the QR code has been identified. This reduces the amount of image data requiring further processing and simplifies subsequent extraction of the sensor element.

To determine the boundaries of the sensor tag, grayscale conversion, binarisation, and contour detection are applied. The presence of a contrasting frame around the coloured area is used as an additional feature for its localisation. After the sensor region has been extracted, its colour characteristics are determined and represented by the R, G, and B components.

Three test samples of sensor tags were used to verify the algorithm. The QR codes contained the position identifier, the colour value in the RGB system, and the corresponding pH value (Table 1).

Table 1

Test samples of sensor tags

No	RGB values	pH
1	R = 97, G = 157, B = 125	13.5
2	R = 21, G = 48, B = 77	6
3	R = 231, G = 56, B = 41	18

Thus, the research methodology combines a passive optical sensor element, QR-based identification, and digital image analysis. The obtained results are used to assess the feasibility of applying this approach as a basis for digital monitoring of the state of subsoil-use sites.

3. Research Results

To assess the performance of the proposed approach, digital reading of information from test sensor tags was performed, with each tag spatially coupled with a QR code. The QR code contained the sensor tag identifier, its colour characteristics in the RGB system, and the value of the controlled parameter, pH. This data structure made it possible to verify not only the correctness of QR code decoding but also the possibility of associating the obtained information with the corresponding sensor tag region in the digital image.

At the first stage, automatic detection of the QR code and decoding of the encoded information were performed. The QRCodeDetector functionality of the OpenCV library was used for this purpose. After successful recognition, the obtained information string was divided into separate blocks corresponding to the tag identifier, colour characteristics, and pH value. This format makes it possible to associate the optical measurement result with a specific sensor element.

The next stage involved determining the spatial position of the sensor tag. Its width, height, and orientation in the image were determined from the coordinates of the QR code corner points. Taking into account the predefined relative position of the QR code and the sensor tag, a search region for the colour sensor element was formed. Restricting the search region reduced the amount of image information requiring further processing.

To localise the colour region, the image was converted to grayscale, followed by binarisation and contour detection. The contrasting frame around the sensor tag was used as an additional geometric feature for its extraction. After determining the sensor element region, its colour characteristics were evaluated using the RGB components.

To verify the accuracy of digital reading, the values encoded in the QR code were compared with the values obtained from image analysis. For the second test sample, the encoded value of the *R* component was 21, whereas digital colour determination yielded a value of approximately 21.4. The relative deviation was approximately 1.9%.

The obtained result demonstrates the feasibility of using digital image processing for quantitative assessment of changes in the colour of the sensor element. At the same time, the accuracy of colour determination depends on illumination conditions, camera characteristics, imaging geometry, and the properties of the sensor surface. Therefore, practical application requires calibration of the sensor tags and standardisation of image acquisition conditions.

An important feature of the proposed approach is the combination of sensor identification and recording of its optical signal within a single digital reading process. The QR code can contain identification information, whereas the colour of the sensor tag serves as an information carrier reflecting the current state of the monitored environment. This creates an opportunity to generate structured data for further accumulation, comparison, and spatial analysis of monitoring results.

For subsoil-use sites, this approach could potentially be used to organise distributed observation points. In particular, sensor tags can be considered as elements of a system for monitoring physicochemical parameters of water-related environmental components in areas associated with mineral extraction, as well as for monitoring disturbed areas after the cessation of deposit exploitation. However, the laboratory results should not be considered field validation of the approach. Further studies using natural environmental samples and assessing the influence of external factors are required to confirm the applicability of the technology under real-world conditions.

4. Conclusions

An approach to digital reading of information from optical sensor tags combined with QR codes has been proposed for sensor element identification and determination of its colour characteristics. This structure makes it possible to associate the optical signal with a specific sensor and encoded information about the controlled parameter.

An image processing algorithm has been investigated, including QR code detection and decoding, determination of the spatial position of the sensor tag, localisation of its region, and evaluation of colour characteristics using the RGB components. The software implementation using OpenCV enabled automated reading of the test sensor tags.

For the test sample, a relative deviation of approximately 1.9% was obtained for the *R* component compared with the encoded value. This result confirms the feasibility of using digital image analysis for quantitative assessment of the optical signal from sensor tags.

At the same time, the accuracy of digital colour determination depends on illumination conditions, camera characteristics, and image acquisition geometry. Therefore, further research should focus on calibration of sensor tags, standardisation of image acquisition conditions, and validation of the method using real environmental samples.

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