Smart Cuvette: An Integrated Optical System for Ethanol Measurement in Liquid Samples for Enological Applications

Ivana Kovačević, Ivan Aleksi, Tomislav Matić, Josip Zidar
Faculty of Electrical Engineering, Computer Science and Information Technology Osijek
Department of Computer Engineering and Automation
Kneza Trpimira 2B, 31000 Osijek, Croatia
{ivana.kovacevic, ivan.aleksi, tomislav.matic1, josip.zidar}@ferit.hr

Abstract. *This paper presents the development and testing of a compact measurement system prototype, called Smart Cuvette, used to determine ethanol concentration in liquid samples. The device uses light-emitting diodes (LEDs) with different wavelengths as selective light sources, and photodetectors to monitor changes in light transmission through a cuvette containing the sample. The calibration was performed using ethanol-water mixtures over a wide concentration range. The developed sensor response showed a generally linear trend with increasing ethanol concentration, still accompanied by noticeable oscillations. Although no validation with real wine samples has been conducted at this stage, the system demonstrated consistent performance under controlled conditions. The results suggest that the prototype offers a modular and accessible approach for rapid ethanol estimation, with the potential for further applications in enology.*

Keywords. wine ethanol measurement, spectroscopy, optoelectronic sensor, NIR, transmittance measurement

1 Introduction

Winemaking is a complicated process, where every step is important for maintaining the quality of the final product. The process is divided into several phases where the fermentation is the most significant one and should be carefully monitored. During the fermentation process sugars, fructose, and glucose, are converted into ethanol, carbon dioxide, and glycerol by the action of yeast metabolism. Ethanol is the main product of wine fermentation, and its measuring is not only important for monitoring fermentation kinetics and progression but also for legal classification, product labeling, and quality control [1].

Various methods for measuring ethanol in liquid samples have been developed and applied both in research and in industry. Enzymatic methods are based on specific biochemical reactions, such as alcohol dehydrogenase (ADH), which converts ethanol into acetaldehyde that can be quantified spectrophotometrically. These methods are selective and relatively easy to perform but require expensive reagents and are sensitive to temperature and pH fluctuations [14]. Raman spectroscopy has been proposed as a non-invasive and reagent-free method for ethanol analysis due to its ability to identify the molecular vibrations characteristic of ethanol. However, its application in complex solutions, like wine can be challenging because of weak Raman scattering signals and significant fluorescence interference [17]. Refractive index analysis (RI) is another traditional method that takes advantage of the lower refractive index of ethanol compared to water. Although RI methods are simple and cost-effective, their precision decreases in the presence of other solutions and with temperature fluctuations [15]. Gas chromatography (GC) and high-performance liquid chromatography (HPLC) are still the standard methods due to their precision and ability to separate ethanol from other volatile or non-volatile compounds. However, both methods require expensive equipment, trained personnel and a considerable amount of time, which makes them impractical for continuous monitoring [13]. Densimetry, which is based on the change in liquid density with ethanol content, is widely used in commercial alcohol analyzers. However, it lacks specificity and can be inaccurate in complex mixtures due to interference from sugars and other dissolved substances [16]. An overview of ethanol measurement methods, along with their main advantages and disadvantages, is presented in Table 1.

In response to the limitations of conventional and laboratory-based techniques, authors in [2] proposed an optoelectronic sensor device that utilizes light absorption measurements to monitor ethanol concentration during grape must fermentation. Their system is based on near-infrared (NIR) spectroscopy with LEDs and photodetectors at specific wavelengths, demonstrating the possibility of real-time monitoring through absorbance changes. However, this proposed system lacks modularity and practical accessibility for small-scale producers. Authors in [18] have explored the potential of optoelectronic systems for monitoring key

Table 1. Overview of ethanol measurement methods with advantages and limitations

Method	Advantages	Limitations
Enzymatic (ADH-based)	Selective, relatively easy to perform	Requires expensive reagents, sensitive to temperature and pH fluctuations [14]
Raman Spectroscopy	Non-invasive, reagent-free, detects molecular vibrations	Limited applicability in complex mixtures [17]
Refractive Index (RI) Analysis	Simple, cost-effective	Low precision in mixed solutions and affected by temperature variations [15]
Gas Chromatography (GC)	High precision, capable of separating volatile compounds	Requires expensive equipment, trained personnel, and is time-consuming [13]
High-Performance Liquid Chromatography (HPLC)	High precision, separates non-volatile compounds	Requires expensive equipment, trained personnel, and is time-consuming [13]
Densimetry	Widely used, fast and straightforward	Lacks specificity, interference from sugars and other dissolved substances [16]

processes in winemaking. In their study, the authors developed an optoelectronic device for monitoring device for monitoring the maceration process of red wine. This sensor focused on capturing optical changes related to phenolic and color compound extraction, relying on NIR LED photodiode configurations and validating its performance through comparative testing. Additionally, the same authors outlined the system architecture and design considerations for their NIR-based ethanol monitoring prototype [19]. Their work highlights emitter selection, photodetector pairing, and signal processing required for accurate optical sensing in a winemaking context. These papers confirm the possibility of NIR-based systems for noninvasive ethanol monitoring, and possibilities for further enhancements in terms of open hardware design, cost-effectiveness, and scalability in different production environments.

In this paper, we present a prototype of the device for the determination of ethanol concentration in liquid samples. The proposed prototype is a compact optoelectronic device based on LED light transmission through a liquid sample, measured by a photodetector and processed via a microcontroller. Its modular design enables simple integration, portability, and real-time data acquisition. In this work, several tests are carried out with different levels of ethanol-water samples. The obtained results validate the purpose of the system and provide a foundation for further development and application of the device for the specific application in enology and process monitoring.

The rest of the paper is organized as follows. Section 2 describes the proposed prototype of a device for ethanol measurement. Section 3 presents the experimental analysis setup and discusses the results of testing. Section 4 concludes the paper and gives remarks for future work.

2 System development

2.1 Device prototype architecture

This paper proposes a prototype of an ethanol detection device that uses light transmission through a liquid sample to estimate the ethanol concentration. The system is based on the ESP32 microcontroller, which features integrated Wi-Fi, Bluetooth, and multiple digital interfaces for peripheral control. Three pairs of light-emitting diodes (LEDs) with wavelengths of $980\,nm$ (MTE9730CP), $1200\,nm$ (MTSM1200MT2-BK), and $1310\,nm$ (MTE1301C1) are used in the suggested prototype system. These wavelengths are selected due to their sensitivity to changes in the optical properties of ethanol-water mixtures in the near-infrared (NIR) region. Selected diodes provide reliable output within the NIR range, making them suitable for detecting subtle changes in transmission caused by varying ethanol concentrations [8] [9] [10]. The transmitted light is measured by photo diodes, which are sensitive to changes in light intensity and enable accurate detection of sample absorbance variations.

The measured sample is placed in a quartz cuvette, housed in a custom holder that ensures stable alignment between the light sources and the photodetector.

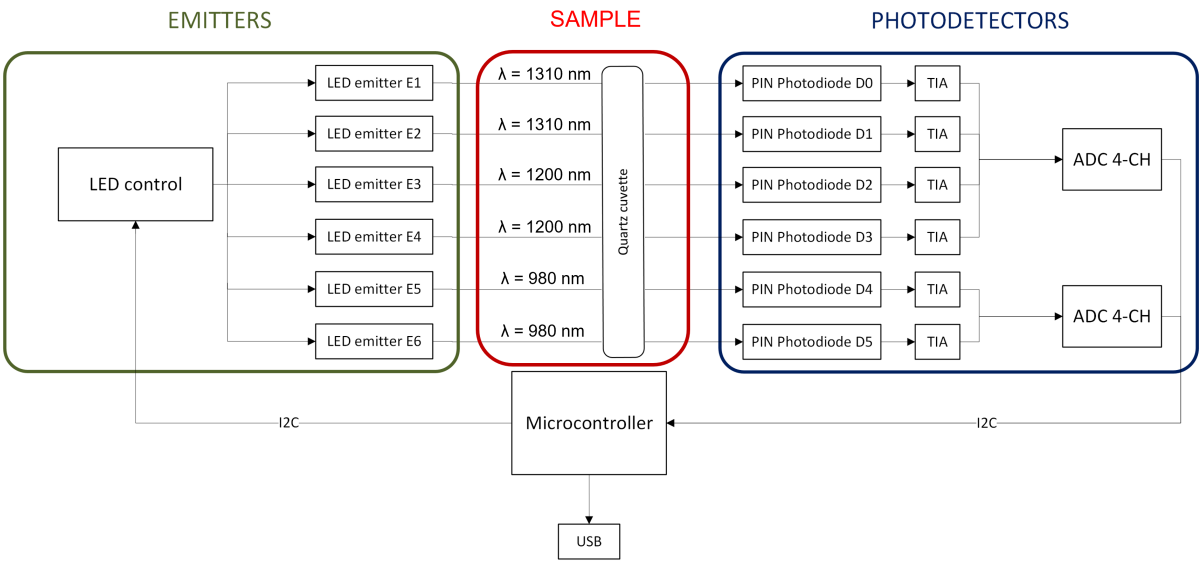


Figure 1. Architecture of the proposed prototype for ethanol measurement

A quartz cuvette is selected because of its high optical transparency in the near-infrared range, $190\,nm - 2500\,nm$, which enables accurate and repetitive measurements of ethanol at the wavelengths mentioned above [4].

The proposed prototype bases its measurements on the correlation between ethanol concentration and the optical transmission properties of ethanol-water samples in the NIR range. As the light emitted by LEDs passes through the sample contained in a quartz cuvette, it is partially absorbed and scattered depending on the chemical composition and concentration of ethanol. The part of the light that is not absorbed is transmitted through the sample and reaches the photodetector, an MTPD1309D3-030 [11] InGAs PIN photodiode, which provides high responsivity from 900 nm to 1700 nm and is placed directly opposite the light source.

The photodiode converts the transmitted light into a current through an internal photoelectric effect [3]. The magnitude of the generated photocurrent I_{ph} in (1) is directly proportional to the intensity of transmitted light P_{opt}, as expressed in (1):

$$I_{ph} = R \cdot P_{opt}, \tag{1}$$

where R is the responsivity of the photo diode. A higher light intensity results in a greater current, whereas increased absorption by ethanol reduces the transmitted light, leading to a lower value of I_{ph}, cf. (1). Because the photocurrent generated by the photodiode is typically in the microampere range, it must be converted into a voltage signal suitable for digital acquisition. This is achieved using a transimpedance amplifier (TIA) configuration, where the AD8601 precision operational amplifier converts a small current into a proportional voltage. The TIA ensures low noise amplification and maintains signal integrity [12]. The resulting analog voltage is then digitized by the ADS1115, a 16-bit analog-to-digital converter (ADC) which communicates with the microcontroller over an I^{2}C interface [20]. Diode switching is handled via the ULN2803 transistor array, which enables stable and sequential LED activation. Emitters E1 to E6 correspond to LED Emitters 1 to 6, while D0 to D5 denote the corresponding photodetectors aligned with each light source. The overall system architecture is illustrated in Fig. 1.

The sensor system transmits data via a serial communication interface using a UART module. During measurements, the microcontroller continuously sends sensor readings, one set for all six diodes per sampling cycle, over a USB connection. On the receiving side, a Python-based graphical interface was developed to handle data acquisition and visualization. The Python script establishes a serial connection to the microcontroller, reads incoming data lines, decodes them, and parses six values corresponding to the six photodetectors (D0-D5). The data collection loop was configured to capture 100 measurements per sample for each diode. Once this number was reached, the program automatically closed the serial connection and finalized the CSV file. This enables synchronized, consistent, and identifiable data logging across all sensor channels. This USB-UART-Python pipeline provides a reliable method for real-time analog sensor data acquisition from analog sensors, allowing easy recording and visualization of measurements.

The measured voltage corresponds to the amount of light that has passed through the sample, and it is typically expected to be inversely proportional to ethanol concentration due to increased absorbance. However, in our measurements, an opposite trend was observed at certain wavelengths. In our experiment, increased

ethanol concentration resulted in higher transmitted light and consequently higher voltage. The relationship between ethanol content and the signal is nonlinear, affected by a combination of refractive index changes, changes in the operating wavelength-dependent absorbance, and light dispersion within the sample. The elemental causes of this atypical response will be discussed in more detail in the following sections.

2.2 Data sampling

The developed prototype uses a microcontroller in combination with an external 16-bit analog-to-digital converter (ADC) to acquire photo diode signals corresponding to transmitted light intensity at each LED wavelength. The microcontroller collects raw digital values from the photo diodes without any on-board signal processing and transmits them directly to the PC via UART for further analysis. Sampling was performed at a fixed frequency of approximately $0.5\,Hz$, which was sufficient for capturing gradual changes in ethanol concentration under controlled conditions. This rate is limited by intentional delays for LED switching and signal stabilization. However, it can be increased to $5\,Hz - 10\,Hz$ by reducing these delays and optimizing the acquisition loop, depending on system noise and measurement stability.

The experimental procedure involved preparing a series of samples with ethanol concentration ranging from $0\,\%$ to $96\,\%$ (v/v), in $10\,\%$ increments. Each sample was prepared with $96\,\%$ pure ethanol with distilled water to achieve the appropriate solution concentration. The volume of ethanol and water required for each concentration using the standard dilution formula:

$$C_1 \cdot V_1 = C_2 \cdot V_2 \tag{2}$$

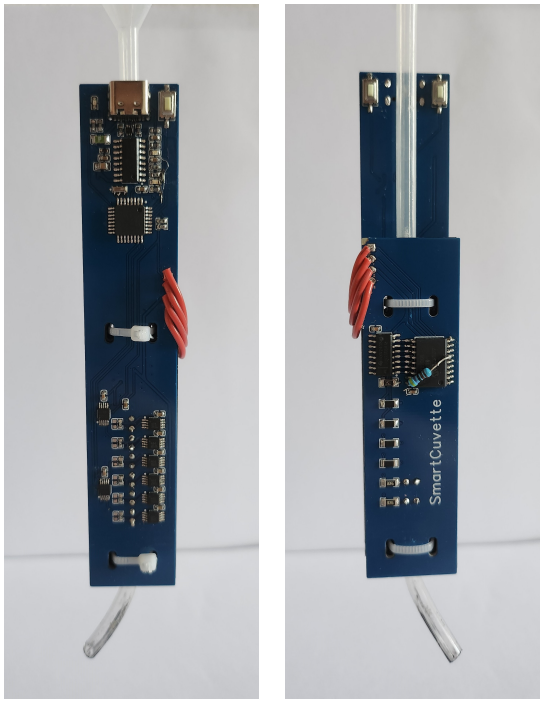
where C_1 is the initial ethanol concentration (96%), V_1 is the volume of ethanol used, C_2 is the target concentration, and V_2 is the final total volume of the prepared sample. This approach ensures consistency and the possibility of repetition across all tested concentrations, as recommended in standard analytical procedures for solution preparation [5].

All measurements were carried out inside a closed, black enclosure designed to eliminate the influence of external light. This type of repetitive sampling combined with averaging is frequently used in low-cost sensing systems to reduce the impact of electrical noise, mechanical disturbances, and ambient light fluctuations [6]. A detailed view of the prototype device, including the integrated measuring section with aligned LED and photo diode components, is shown in Fig. 2, illustrating both the front (a) and back (b) sides of the proposed system.

3 Data analysis and results

To evaluate the system's sensitivity to ethanol concentration, voltage signals from six photodetectors (D0-D5) each paired with a specific infrared LED source, were recorded for each prepared sample. The sensors were grouped by the wavelength of the light source, with D0 and D1 operating at $1310\,nm$, D2 and D3 at $1200\,nm$, and D4 and D5 at $980\,nm$. Fig. 3 compares the mean voltage values of all sensors, D0 to D5, and shows how the response varies depending on the wavelength. Significant variations in output can be observed between sensor pairings that operate at the same wavelength, such as D0 and D1. Although these sensors use identical components and are exposed to the same sample, the signal variation is likely caused by mechanical or optical asymmetries in the current prototype. This limitation affects the comparability of signals between certain channels and highlights the need for improved alignment and calibration in future iterations of the device. The measurement showed a clear relationship between ethanol concentration and output voltage, most notably in detectors operating at $1200\,nm$. Sensors D2 and D3 demonstrated a consistent increase in voltage with rising ethanol concentration up to $80\,\%$, followed by a slight decrease at the highest concentrations, which is shown in Fig. 4.

The nonlinear behavior observed in D2 and D3 sensors, especially the initial rise in voltage up to $80\,\%$ ethanol, followed by a slight drop, may be closely related to changes in hydrogen bonding and molec-

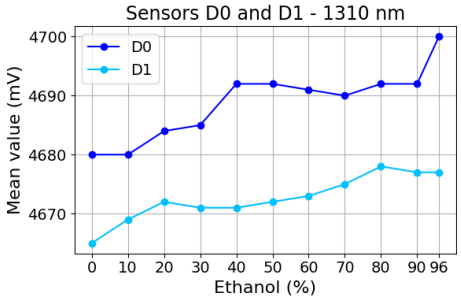


(a) **(b)**

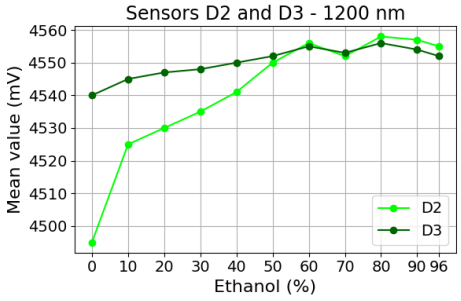
Figure 2. Front (a) and back (b) views of the device prototype.

ular structure within the liquid. According to [7], the strength of inter-molecular hydrogen bonds between ethanol and water peaks around $40\,\%$ ethanol concentration. Beyond this point, ethanol tends to self-associate, reducing the number of hydrogen bonds formed with water molecules.

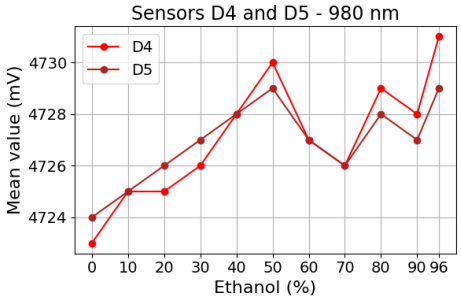
The shift in molecular interaction alters the NIR absorption profile of the sample. As ethanol concentration increases and ethanol-water hydrogen bonding decreases, the overall absorbance in specific NIR bands decreases. The reduced absorbance allows more light to pass through the sample, resulting in increased photodetector voltage, especially at wavelengths like 1200 nm, where ethanol displays relatively low absorbance. At very high concentrations, ethanol structures may absorb less effectively in the NIR range, contributing to signal variations. These results are promising for tested wavelengths, showing a sensitivity to ethanol concentrations. However, the response remains nonlinear in certain concentration ranges. Additional testing and analysis through a broader range of wavelengths and concentration intervals are needed to refine the calibration and better understand the system's behavior.



(a)



(b)



(c)

Figure 3. Mean voltage responses for all sensor pairs (a) D0 and D1 (b) D2 and D3 (c) D4 and D5 at different ethanol concentrations

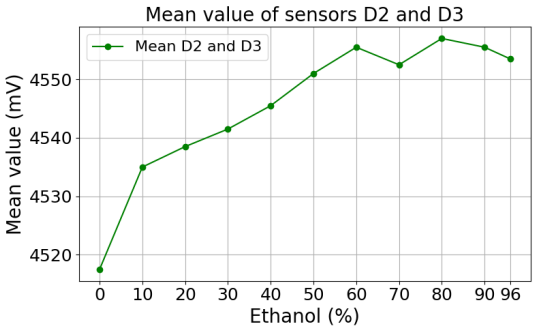


Figure 4. Mean output voltage of sensors D2 and D3

In addition to the previously mentioned nonlinear response patterns, the unexpected signal levels observed for sensors D4 and D5 at high ethanol concentrations may also be influenced by saturation effects or possible measurement errors in the acquisition system. These effects require further investigation to determine whether they stem from hardware limitations or optical phenomena at extreme concentration values.

This interpretation is by the obtained results and explains the observed signal rise as ethanol content increases. They confirm that optical sensor response is not driven only by ethanol concentration, but also by underlying molecular structure and interaction dynamics of the liquid.

4 Conclusion and Future work

In this paper, a prototype of a modular optoelectronic system was developed for determining ethanol concentration in liquid sampled using infrared LED photodetector pairs operating at $980\,nm$, $1200\,nm$, and $1310\,nm$. The system integrates analog signal acquisition through a microcontroller with real-time data visualization and storage via a custom Python interface. Measurements were performed on a series of ethanol samples, $0\,\% - 96\,\%$ v/v, prepared by dilution with distilled water, with each sample measured 100 times per sensor under controlled ambient conditions in the closed black enclosure.

Analysis of the recorded data showed that the sensors operating at $1200\,nm$ (D2) and (D3) provided the most stable response, exhibiting an increasing voltage trend with rising ethanol content. This behavior was attributed to refractive index changes, molecular changes, and light transmission that depends on wavelength. At high ethanol concentrations, a slight decrease in signal was observed, consistent with literature findings related to reduced hydrogen bonding and self-association of ethanol molecules.

The results confirm the sustainability of the proposed approach for ethanol quantification using low-complexity hardware and NIR sensor principles.

Future work will follow two main directions. First, a more comprehensive calibration model will be developed using nonlinear fitting or machine learning methods to better interpret sensor responses. Second, the system will be validated using real wine samples and benchmarked with reference methods. In addition, further experimental work will explore the device's performance at other NIR wavelengths. Extending the optical spectrum and concentration range will help reduce nonlinearity and broaden the application of the system in different ethanol detection scenarios.

Acknowledgments

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