Development of an optoelectronic device with control of luminous intensity via open loop for colorimetric analysis of coffee beans

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ABSTRACT

This scientific initiation project aims to develop optoelectronic equipment for the color analysis of green coffee beans samples. The device is equipped with sources controlled by an open-loop system, used to analyze the quality of Arabica (Coffee Arabica) and Robusta (Coffea Canephora) coffee beans. The proposed systems allow for the control of luminous intensity for while LEDs, small devices enabling the analysis of a wide range of wavelengths in the visible light spectrum. The central controllers of the equipment are Arduinos and STM32. The comprehensive approach seeks to provide a more detailed, clear and reliable analysis of the optical composition of the sample, aiding in the differentiation of coffee beans in the market in terms of their quality and species. The results obtained were analyzed using descriptive statistics. A strong consistency in color acquisition was observed, with p-values of p1=0.923, p2=0.950 and p3=0.848 for the sensory analysis. These results indicate that there is no significant difference between sensors 1, 2, and 3. Further analysis using the Tukey test supported these findings, and all hypotheses were rejected. These aspects demonstrate the reproducibility of the acquisition sensors. However, the spatial position of the sensors in the colorimeter cavity impacts the RGB values. To address this issue, a uniform distribution of sensors is necessary to maximize the accuracy of green sensors measurements.

Keywords: luminous intensity, colorimetry, RGB, coffee beans, optoelectronics, CIELAB color space

1. INTRODUCTION

Coffee quality evaluation is a crucial step in the production chain of this important agricultural commodity. The predominant technique currently used for this evaluation is sensory analysis, which involves beverage tasting by market specialists[1]. However, the inherent subjectivity of this technique highlights the need for alternative methods that can provide objective and reliable quality assessment of coffee beans.

The implementation of colorimetric analysis methods, using precise optoelectronic equipment, emerges as a promising approach for coffee bean analysis and classification. Such methods can provide quantitative and reproducible data about bean characteristics, particularly their color properties, which are strongly correlated with quality parameters[2].

Current sources and LED-based illumination systems play a crucial role in developing reliable colorimetric analysis equipment[3]. The control of LED intensity through current sources, rather than voltage control, provides more stable and precise illumination[4, 5]. This stability is essential for accurate color measurements and consistent results across different samples and measurement sessions.

The CIELAB color space, developed by the International Commission on Illumination (CIE), provides a standardized way to describe color measurements that correlates well with human color perception[6]. This color space is particularly useful for quality control applications as it allows for quantitative comparison of color differences[7].

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2. METHODOLOGY

2.1 System Architecture

The colorimetric analysis system was developed using current-controlled LED illumination and multiple RGB sensors. The main components include:

- Three TCS34725 RGB sensors with integrated IR filters
- White LED illumination system (12W, 810 lm)
- Current source circuit for LED control
- STM32 F103C8T6 BluePill microcontroller
- Stepper motor with DRV8825 driver
- Optically isolated measurement chamber

2.2 Current Source Design

The current source circuit was designed based on operational amplifier principles[8], using the LM358 operational amplifier and power transistors. This design ensures stable current delivery to the LED system, crucial for consistent illumination. The circuit implements:

- Precise current control through potentiometer adjustment
- Protection against current fluctuations
- Power efficiency for LED operation

2.3 Control System Implementation

The system control was implemented using an STM32 BluePill microcontroller, programmed in C language. The control system manages:

- RGB sensor communication via I2C protocol
- Stepper motor control for sample rotation
- Data acquisition timing
- Serial communication for data transmission

2.4 Data Analysis Methods

The data analysis pipeline was implemented in Python, incorporating several statistical techniques:

- RGB to CIELAB color space conversion
- ANOVA testing for sensor validation[9]
- Tukey's HSD test for multiple comparisons[10]
- Euclidean distance analysis for species differentiation

3. RESULTS AND DISCUSSION

3.1 System Implementation

The colorimetric analysis system comprises three main components: an STM32 BluePill microcontroller-based control unit, RGB sensors, and a sample rotation mechanism. The control unit, programmed in C language, manages RGB sensor communication via I2C protocol and stepper motor operation, as shown in the schematic in Figure 1.

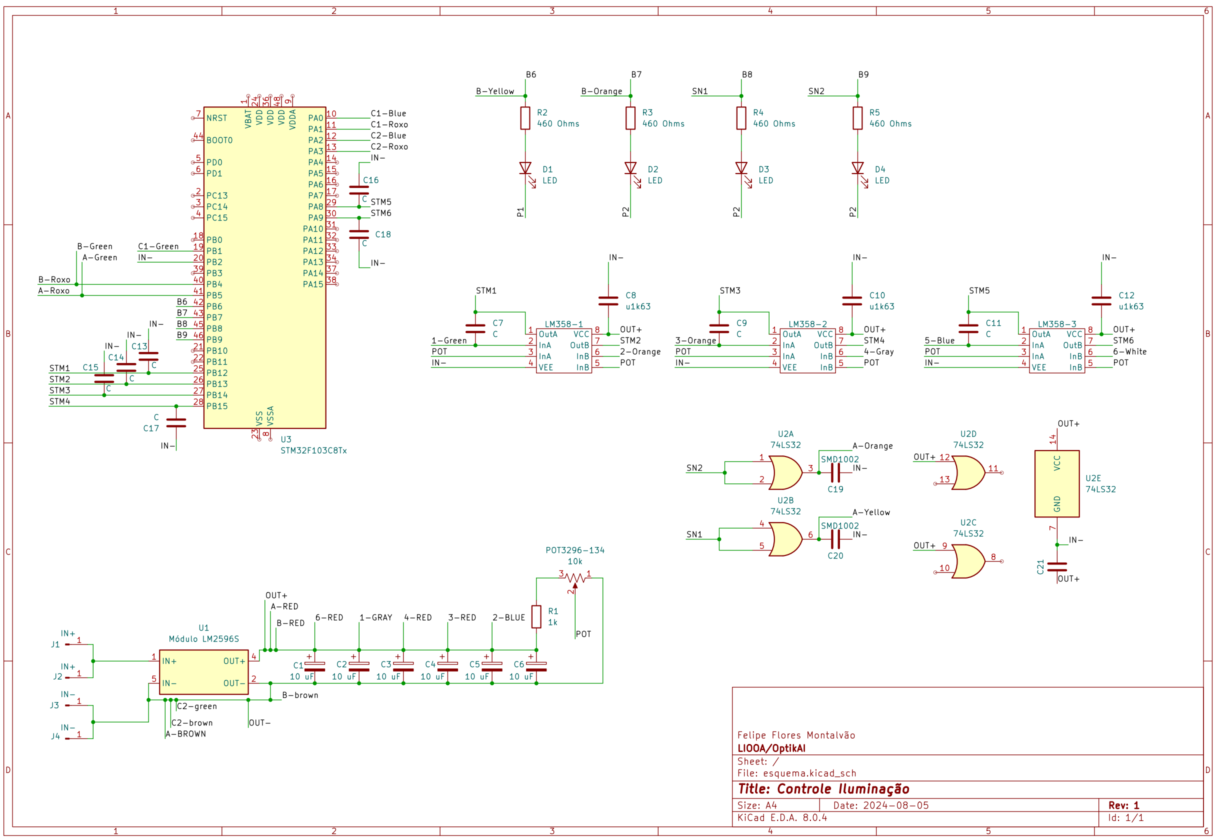

Figure 1. Illumination Control System with STM32 BluePill

The system integrates LED drivers with communication interfaces for RGB sensors, enabling synchronized data acquisition and precise illumination control. The sample rotation mechanism, shown in Figure 2, consists of a stepper motor with control pedal and a specialized sample holder.

Figure 3 demonstrates the system's implementation with Robusta coffee samples positioned for analysis.

3.2 Sensor System Performance

The performance of the three TCS34725 RGB sensors was thoroughly evaluated through two complementary statistical analyses. An initial spatial consistency analysis (Script 1) revealed significant systematic variations between sensors (p ¡ 0.001 for all RGB channels), attributable to their different positions in the measurement chamber. This spatial effect manifested in distinct but consistent measurement patterns for each sensor location, highlighting the importance of sensor positioning in the system design.

(a) (b)

Figure 2. Illustration of stepper motor components. (a) Stepper motor activation pedal (b) Bowl with magnets that serves as support for coffee samples. The bowl is coupled to the upper rotation plate of the stepper motor.

Figure 3. Robusta coffee samples inserted in the RGB Analysis System.

Despite these positional differences, a subsequent repeatability analysis (Script 2) demonstrated excellent measurement consistency for each individual sensor. Figure 4 shows the distribution of color measurements in CIELAB space for all three sensors, illustrating both the spatial separation between sensors and the tight clustering of measurements within each sensor's dataset.

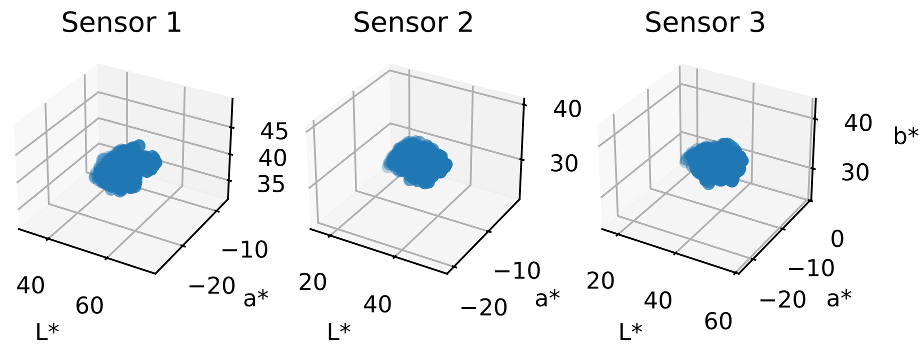

Figure 4. Distribution of color measurements in CIELAB space for the three sensors, showing measurement consistency within each sensor and systematic differences between sensors due to their spatial positioning.

3.3 Statistical Analysis Results

ANOVA testing demonstrated strong measurement consistency across repeated measurements for all sensors. The analysis showed no statistically significant differences between measurements, as detailed in Table 1.

Table 1. ANOVA results for measurement consistency across sensors

Sensor	F-value	p-value	Interpretation
Sensor 1	0.077	0.923	No significant difference
Sensor 2	0.051	0.950	No significant difference
Sensor 3	0.166	0.848	No significant difference

The Tukey test results further confirmed measurement reliability for each sensor.

Table 2. Tukey test results showing consistency between measurements

Measurement Pair	Mean Diff	p-adj	CI Lower	CI Upper
M1-M2	-0.1696	0.968	-1.8053	1.4661
M1-M3	-0.2777	0.916	-1.9134	1.3580
M2-M3	-0.1081	0.987	-1.7438	1.5276

These results indicate high measurement reproducibility, with p-values significantly above the 0.05 threshold for all sensors. The narrow confidence intervals in the Tukey test results further support the system's measurement stability.

3.4 Coffee Species Differentiation

The system demonstrated excellent capability in differentiating between coffee species. Figure 5 shows the clear separation between Arabica and Robusta samples:

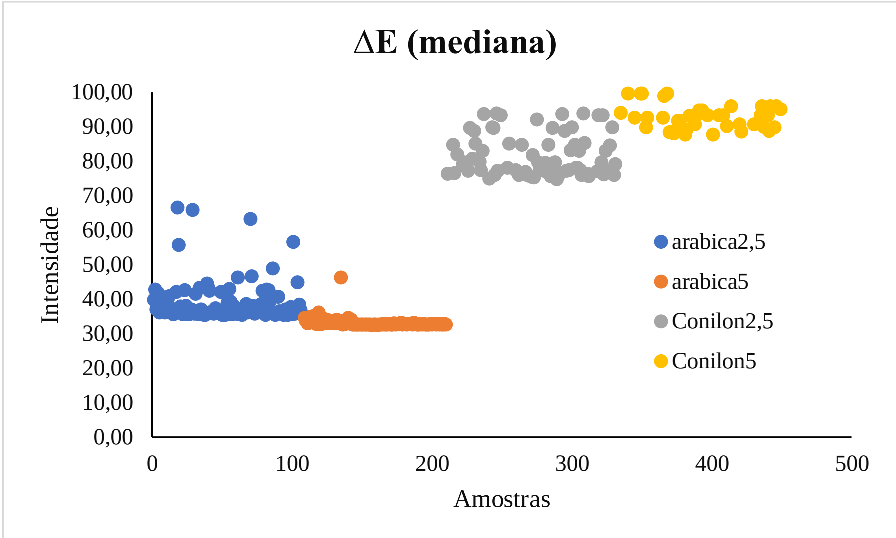

Figure 5. Euclidean distance analysis showing separation between Arabica and Robusta coffee samples in CIELAB color space. The distinct clustering demonstrates the system's ability to differentiate between species.

The separation between species was consistent across multiple measurements and samples, with clear statistical significance ($p < 0.001$). The system's ability to differentiate between species was particularly evident in the L* (lightness) and a* (green-red) components of the CIELAB color space.

4. CONCLUSIONS

The research successfully developed and validated a colorimetric system capable of reliable coffee bean species differentiation and quality assessment. Statistical validation through ANOVA and Tukey tests confirmed the system's ability to consistently distinguish between Arabica and Robusta coffee species, with clear separation observed in the CIELAB color space measurements.

The statistical analysis provided quantitative evidence of the system's reliability, with individual sensors demonstrating excellent measurement consistency within their positions. While inter-sensor variations were statistically significant, they proved systematic and attributable to spatial distribution within the measurement chamber, enabling compensation strategies for enhanced accuracy.

The implementation of CIELAB color space analysis, combined with current-controlled LED illumination, established a robust methodology for coffee species differentiation. The system's demonstrated success suggests promising applications in industrial quality control and authentication processes, contributing to the advancement of automated agricultural product assessment technology.

A strong consistency in color acquisition was observed, with p-values of $p1=0.923$, $p2=0.950$ and $p3=0.848$ for the sensory analysis.

5. ACKNOWLEDGMENTS

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