

Spectral and Angular Analysis of Reflectance in Mobile Robot Prototypes under Controlled Artificial Lighting

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Abstract—Environmental monitoring in sports arenas presents challenges related to light interference in optical sensors. This study experimentally investigated the influence of different color spectra and angles of incidence on light reflection in scaled prototypes of a mobile robot. Polylactic Acid (PLA) was used as the base material for constructing six conceptual models. The analyses considered representative colors from the visible light spectrum (380–750 nm), also including conditions with black light (ultraviolet, outside the visible spectrum) and white light (a combination of the entire visible spectrum). The tests were conducted in a controlled environment, with Light Emitting Diode (LED) lighting and light intensity measured by a lux meter, using a reference baseline of 10.76 lux. The light incidence angles ranged from 30° to 120°. The results showed that the white color exhibited the highest reflectance (MGI: 17.53 lux; +62.92%), with a reflection peak at 30° (+150.09%). In contrast, the black color reflected the least amount of light (MGI: 10.46 lux; -2.79%), with the lowest value recorded at 90° (-9.94%). Intermediate colors, such as yellow (+27.23%) and orange (+12.92%), showed moderate levels of reflection.

Keywords—Light reflection; Robotic design; Optical sensors; Environmental monitoring; Sports arenas.

I. INTRODUCTION

Environmental monitoring in sports arenas—such as football fields, gymnasiums, and courts—is essential to ensure appropriate conditions during events, especially in environments with variable light from sunlight or spotlights. Robots equipped with optical sensors have been used to measure temperature, humidity, and air quality, contributing to operational efficiency and safety during large-scale sporting events [1]. However, the interaction between ambient light and robot surfaces presents a challenge: light reflection on chassis materials may interfere with sensor accuracy, resulting in errors in data collection or autonomous navigation. This issue is particularly relevant in sports arenas, where lighting variations influence the choice of materials and designs to reduce interference.

Light reflection on robot surfaces can affect the performance of optical sensors responsible for detecting environmental variables, especially under dynamic lighting conditions. The choice of colors and materials directly impacts reflected illuminance and can compromise data reading accuracy or task execution, such as navigation. This study experimentally analyzes light reflection on conceptual 3D PLA models simulating robots, to assess how color and angle of incidence affect reflected illuminance. Conceptual models were produced in six colors

(Yellow, White, Orange, Green, Blue, Black) and tested at seven incidence angles (30° to 120°) inside a dark chamber measuring 60 cm × 26 cm × 20 cm, painted matte black to minimize external reflections. An LED lamp emitted light, and illuminance was measured using a Vonder LDV 2000 lux meter, with a reference baseline of 10.76 lux in the empty chamber. This paper aims to discuss the selection of materials' colors for robot design, seeking to reduce interference and improve sensor efficiency in environmental monitoring within sports arenas. This paper aims to discuss the selection of materials' colors for robot design, seeking to reduce interference and improve sensor efficiency in environmental monitoring within sports arenas. In Section 2, related works are reviewed to provide the theoretical and experimental context of the study. Section 3 introduces the Spectral Analysis System Architecture, describing the experimental setup and measurement procedures. The obtained data and their interpretation are presented in Section 4, Results and Discussion. Finally, Section 5 concludes the paper by summarizing the key findings and outlining directions for future research.

II. RELATED WORK

The use of robots in sports and environmental contexts has gained prominence in the scientific literature. In the sports domain, Siegel and Morris [2] analyzed the impact of automation and robotics on sports, addressing refereeing, field maintenance, and audience experiences, highlighting the potential of robots in sports arenas. Hameed et al. [3] focused on robots for grass cutting and automatic field marking, presenting algorithms for line generation and operational guidance, thus connecting environmental robotics to sports arenas.

In environmental monitoring, Dunbabin and Marques [4] presented advances in robots to monitor terrestrial, aquatic, and aerial environments, emphasizing applications and challenges. Bogue [1] examined the role of robots in environmental monitoring, including drones and ground robots, with applications in data collection and pollution detection. Hegde et al. [5] explored sensors in soft robotics, emphasizing flexibility and the integration of lightweight electronic systems, while Keicher and Seufert [6] analyzed automatic guidance technologies in agricultural vehicles, applicable to robot navigation on sports fields.

Regarding material selection, Ullah and Harib [7] proposed an intelligent method based on performance, cost, and sustainability. Coyle et al. [8] discussed biologically inspired soft robotics, addressing material selection and design, while Hussain et al. [9] reviewed materials and fabrication techniques in robotic exoskeletons. In terms of design, Bechthold and King [10] discussed the integration of robotics into design and architecture, focusing on digital fabrication.

There is a noticeable gap in the literature regarding the experimental analysis of the interaction between light and robotic surfaces in sports contexts. This study investigates how colors and incidence angles affect light reflection on 3D PLA conceptual models, providing insights for more effective robot design in sports arenas.

III. SPECTRAL ANALYSIS SYSTEM ARCHITECTURE

The experimental architecture was developed to evaluate the impact of light reflection on environmental monitoring robots in sports arenas. The *setup* consisted of a dark chamber measuring 60 cm × 26 cm × 20 cm, painted matte black to minimize external reflections, and equipped with a LED lamp (Elgin Smart Color, white mode, 100% intensity) as the light source, as presented in Figure 1. Conceptual robot models, 3D-printed in PLA in six colors (yellow, white, orange, green, blue, and black), were individually placed in the chamber to simulate robotic surfaces. Reflected illuminance was measured using a Vonder LDV 2000 lux meter positioned 35 cm from the conceptual model, with seven incidence angles tested (30° to 120°). Three measurements were taken for each condition, all yielding identical results, confirming experimental stability. The empty chamber established a baseline reference of 10.76 lux.



Figure 1. General schematic of the experiment, showing the dark chamber with the LED lamp, a conceptual robot model, and the lux meter.

A. Dark Chamber

A dark chamber, with dimensions of 60 cm × 26 cm × 20 cm, was constructed to ensure a controlled environment with standardized lighting for

evaluation. The inner walls were painted matte black and an LED lamp was mounted on the roof as a light source. The conceptual model was placed in the center and the lux meter, placed 13 cm away, to measure the reflected illuminance. The region responsible for data acquisition (part of the sensor) is indicated in Figure 2.

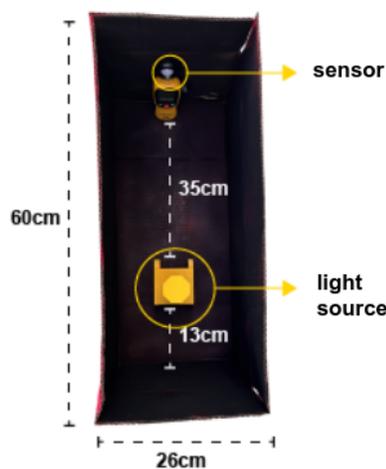


Figure 2. Top view of the dark chamber.

B. Conceptual Models

Six conceptual robot models were 3D printed using polylactic acid (PLA) filament, each with a height of 20 cm, in the colors yellow, white, orange, green, blue and black, as shown in Figure 3.

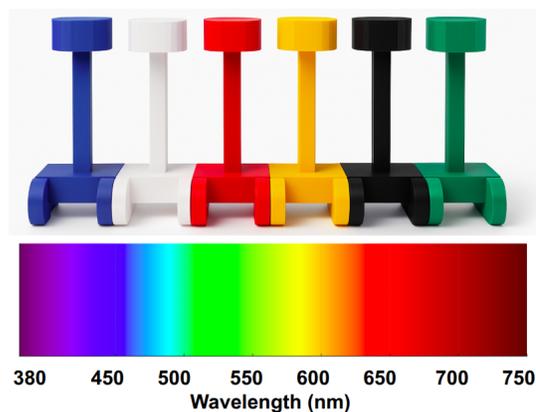


Figure 3. Conceptual models with color labels: Yellow, White, Orange, Green, Blue, Black, and the visible spectrum.

PLA was selected as the base material due to its high market availability, low cost, ease of printing, and good dimensional stability—characteristics that make it widely used in rapid prototyping projects and experimental robot development. Furthermore, as a thermoplastic derived from renewable resources and biodegradable, PLA presents environmental advantages compared to other commonly used materials, such as ABS.

The material has a slightly glossy and homogeneous surface finish, which favors optical reflectance analysis under controlled

lighting conditions. The selected colors were carefully chosen to represent different optical behaviors, ranging from light tones, such as white and yellow, which tend to reflect a greater amount of light, to darker tones, such as blue and black, which absorb light more intensely. Intermediate colors, such as green and orange, complete the sample set, enabling comparative analysis of the light response across a representative range of the visible spectrum. This chromatic variety is essential to evaluate the impact of surface color on the efficiency of optical sensors embedded in mobile robots.

Regarding illumination and light reflection, the visible spectrum extends approximately 380 nm to 750 nm. Black light, such as that emitted by ultraviolet lamps, is not part of the visible spectrum and lies in the ultraviolet (UV) range, which includes the following wavelength subcategories:

- UV-A: 315–400 nm;
- UV-B: 280–315 nm;
- UV-C: 100–280 nm.

Thus, from a wavelength perspective, black light falls below 380 nm and is not visible to the human eye. White light, on the other hand, does not have a single wavelength, as it results from the balanced combination of all colors in the visible spectrum. White light spans the entire visible range, from 380 nm to 750 nm. Therefore, white light does not occupy a specific position within the spectrum but is a mixture of multiple visible light frequencies.

C. Light Source and Sensing

The light source used in the experiment was an Elgin Smart Color LED lamp, operating in white mode at 100% intensity, ensuring consistent and controlled illumination. This lamp has a power rating of 10 W and a luminous flux ranging between 800 and 1,000 lumens, providing adequate brightness for testing in controlled environments. This light source was selected based on its ability to deliver efficient and uniform lighting, which is essential for analyzing the reflectance of robotic model surfaces. The white mode was chosen to ensure coverage of the entire visible spectrum, from the shortest wavelengths (violet) to the longest (red), simulating daylight-like illumination and enabling a comprehensive study of light–surface interactions. The lamp was positioned outside the dark chamber to allow light to be directed at the required angles while maintaining an illuminance level of 10.76 lux inside the empty chamber.

Reflected illuminance from the model surfaces was measured using a Vonder LDV 2000 lux meter, a high-precision device that quantifies the luminous intensity reflected by different prototype colors. This lux meter features a measurement range from 0.1 to 200,000 lux, enabling readings across a wide range of lighting conditions, from low-intensity environments to brightly lit scenarios. The device has an accuracy of $\pm 3\%$, ensuring minimal error in the readings and guaranteeing the reliability of the experimental data. Using this measurement instrument contributes to obtaining consistent and comparable results, which is essential for analyzing the reflectance behavior of different colors and light incidence angles on the conceptual models.

D. Experimental Conditions

The light source was systematically positioned at seven distinct incidence angles (30° , 45° , 60° , 75° , 90° , 105° , and 120°), as illustrated in Figures 4 and 5.

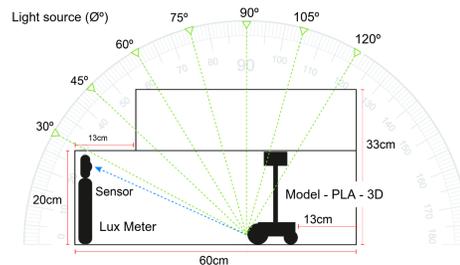


Figure 4. Side view of the dark chamber, showing the angles of incidence.

For each angular configuration, three independent measurements were conducted, all of which demonstrated complete reproducibility of the results.

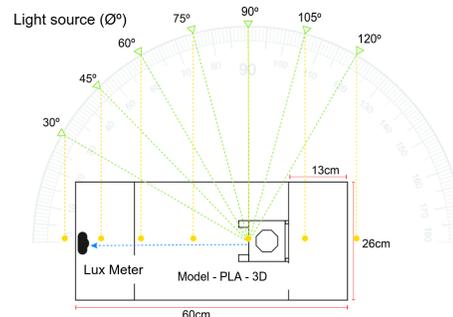


Figure 5. Top view of the dark chamber, with labels: Lamp, conceptual model, Luxmeter; distance from conceptual model to luxmeter: 13 cm.

IV. RESULTS AND DISCUSSION

The experimental results demonstrated clear differences in light reflection across the colors of the conceptual 3D-printed PLA models, as illustrated in Figure 6.

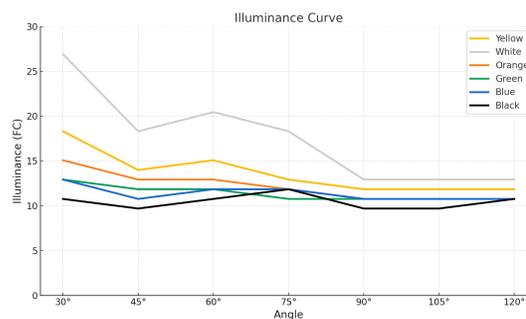


Figure 6. Illuminance curve as a function of the angle of incidence (30° to 120°), with lines representing each color.

The white model presented the highest reflectance, with a General Mean Illuminance (GMI) of 17.53 Lux and a peak of 26.91 Lux at 30° , while the black model exhibited the lowest performance, with a GMI of 10.46 Lux and minimum values of 9.69 Lux at 45° , 90° , and 105° . The other colors

showed intermediate behaviors: yellow (GMI 13.69 Lux), orange (GMI 12.15 Lux), and green and blue (both GMI 11.38 Lux). In practical terms, illuminance consistently varied with the incidence angle, reaching maximum values at 30° and dropping to a minimum at 90°. This angular dependence, summarized in Table I, highlights the importance of material color and geometry in applications where light distribution and efficiency are critical design parameters.

TABLE I. AVERAGE ILLUMINANCE (FC)

	30°	45°	60°	75°	90°	105°	120°	MGI	Notes
EMPTY	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8	
YELLOW	18.3	14.0	15.1	13.0	11.9	11.9	11.9	13.7	
WHITE	27.0	18.3	20.5	18.3	12.9	12.9	12.9	17.5	HIGHEST REFLEC.
ORANGE	15.1	12.9	12.9	11.8	10.8	10.8	10.8	12.2	
GREEN	12.9	11.8	11.8	10.8	10.8	10.8	10.8	11.4	
BLUE	12.9	10.8	11.8	11.8	10.8	10.8	10.8	11.4	
BLACK	10.8	9.7	10.8	11.8	9.7	9.7	10.8	10.5	LOWEST REFLEC.

The distribution of reflection values, illustrated in the histogram (Figure) 7, shows a clear trend: light-colored models (white and yellow) reflect significantly more light than darker ones (black, blue, and green), with orange exhibiting intermediate behavior.

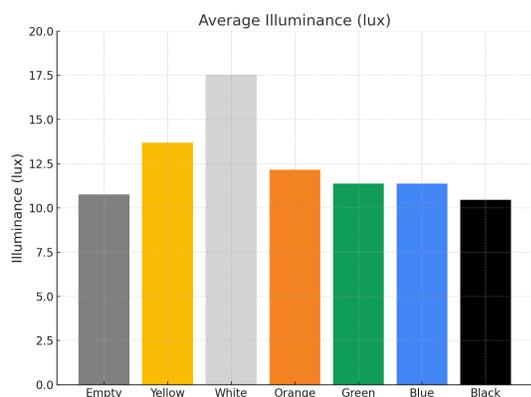


Figure 7. Histogram of overall average illuminance (MGI) by color.

This distinction emphasizes the role of material color in influencing light performance, an important factor when selecting polymers for applications requiring controlled reflection or optimized illumination.

V. CONCLUSION AND FUTURE WORK

This study revealed that light colors, such as White (GMI 17.53 Lux, +62.92% compared to the baseline of 10.76 Lux), reflect more light than dark colors, such as Black (GMI 10.46 Lux, -2.79%), with reflection being more intense at grazing angles (30°, White: +150.09%) and lower at perpendicular angles (90°, Black: -9.94%). Intermediate colors exhibited behavior between these extremes. These findings contribute to the design of robots in sports arenas, indicating that color selection can optimize the accuracy of optical sensors. Future research may explore other materials and natural lighting conditions.

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