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TCS230 color sensor: operating principles, calibration, applications, and performance limitations

Anggit Pamungkas[1], Hendril Satrian Purnama[1], Danang Sulistia Aji[2]
[1]Embedded Systems and Power Electronics Research Group, Yogyakarta, Indonesia
[2]Faculty of Industrial Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia

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ABSTRACT

The TCS230 is a programmable light-to-frequency color sensor widely used in low-cost color detection, sorting, and portable measurement systems. Its photodiode array contains red-, green-, blue-, and clear-filtered elements, while its output frequency varies with the intensity of the selected light component. This architecture offers a simple interface to microcontrollers because color information can be acquired by counting pulses rather than measuring a small analog voltage. However, practical accuracy depends on more than the sensor itself, including illumination spectrum, object distance, viewing geometry, surface reflectance, calibration, and signal acquisition. This review examines the TCS230 operating principle, internal architecture, interfacing methods, calibration procedures, application areas, and principal sources of measurement error using literature published no later than 2018. Research on TCS230-based instruments demonstrates their suitability for color comparison, educational devices, and automated sorting, while related colorimetry studies clarify the importance of controlled illumination and reference standards. The review finds that the sensor is best suited to repeatable, application-specific classification rather than universal, traceable color measurement. Future systems should emphasize optical shielding, stable illumination, calibration transfer, uncertainty evaluation, and validation against reference instruments.

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1. INTRODUCTION

Color detection is an important requirement in industrial inspection, agricultural grading, educational devices, and analytical instrumentation. Conventional color measurement systems can provide detailed spectral information, but their cost and complexity may restrict their use in small-scale or embedded applications. Low-cost integrated color sensors offer an alternative by converting reflected light into electrical signals that can be processed by microcontrollers. The TCS230 is one such device, combining photodiode arrays and programmable frequency conversion in a compact integrated circuit [1]–[4].

Despite its accessibility, the TCS230 does not automatically provide standardized or universally accurate color measurements. Its output is influenced by illumination, sensor-to-object distance, surface characteristics, optical alignment, and the electronic configuration used to count its output pulses. These factors can cause two objects with similar visual appearances to produce different readings, or different objects to produce overlapping readings. This review therefore examines the sensor's operating principle, system architecture, calibration, applications, and technical limitations, connecting specific TCS230 implementations with broader research on colorimetric measurement.

2. OPERATING PRINCIPLE AND INTERNAL ARCHITECTURE

2.1. Photodiode array and color selection

The TCS230 operates by converting incident light into a frequency-modulated electrical output. Its internal photodiode array contains 64 photodiodes arranged in an eight-by-eight structure, with groups

incorporating red, green, blue, and clear filters. The photodiodes respond to the intensity of incoming light within their respective spectral sensitivity ranges. By selecting a particular photodiode group, the device produces an output corresponding to the selected color channel [1], [5].

The sensor uses a current-to-frequency conversion architecture to simplify the measurement of optical intensity. The photocurrent generated by the selected photodiodes is converted into a square-wave output whose frequency increases with incident light intensity. The output frequency can be measured by a microcontroller using a digital input and pulse-counting or frequency-measurement routines. This approach avoids the need for a conventional analog-to-digital conversion stage for the sensor output and makes the device convenient for embedded applications [3], [6].

2.2. Programmable configuration

The TCS230 provides digital selection of both the photodiode group and output-frequency scaling. Two selection inputs determine which filtered photodiodes are active, allowing the system to measure red, green, blue, or clear responses. Two additional inputs select the output-frequency scaling, which helps adapt the signal to the timing capabilities of the receiving microcontroller. These programmable features make the device flexible for different illumination levels and measurement arrangements [1], [4].

A practical measurement cycle normally reads the output frequency for each selected color channel in sequence. The microcontroller stores the readings and uses them to estimate the relative color response of the measured object. The clear channel can provide additional information about overall light intensity, although it does not independently identify the object's color. Researchers using related color-to-frequency devices have demonstrated that this measurement architecture can be incorporated into compact educational and laboratory colorimeters [6], [7].

3. ELECTRONIC INTEGRATION AND MEASUREMENT PROCEDURE

3.1. Microcontroller interface

The TCS230 can be integrated with common microcontroller platforms through its digital control and output pins. A typical system includes the sensor module, a microcontroller, a regulated power supply, an optical enclosure, and a display or communication interface. Some commercial modules also include white LEDs to illuminate the target, although the illumination arrangement depends on the module design rather than being an inherent requirement of the sensor chip. The microcontroller selects the color channel, measures the output frequency, and stores the resulting readings for subsequent processing [2], [3], [8].

Signal acquisition must be configured carefully because the measured frequency depends on both light intensity and the selected frequency-scaling setting. A short measurement interval allows faster operation but may increase reading variation, particularly when the signal frequency is low. A longer measurement interval generally improves pulse-counting resolution but reduces the maximum measurement speed. The appropriate acquisition strategy therefore depends on the required response time, illumination level, and expected range of object colors [6], [9].

3.2. Calibration and color classification

Calibration is essential when the TCS230 is expected to distinguish colors consistently rather than simply detect changes in light intensity. A basic calibration procedure uses reference objects with known colors and records the corresponding red, green, and blue output responses. These readings can then be used to establish thresholds or reference ranges for classifying unknown objects. Aruan *et al.* demonstrated the use of TCS230 measurements to construct a color album, while Martenius and Wibowo developed a portable RGB comparison instrument based on the same sensor [2], [3].

A reliable calibration procedure should control the optical conditions under which the reference and unknown objects are measured. The sensor should maintain a fixed distance and orientation relative to the target, while the illumination source should remain stable throughout the measurement process. A white reference can help monitor changes in illumination, while a dark reference can help identify unwanted background signals. Standard colorimetric guidance also emphasizes the importance of defined illumination, viewing geometry, reference conditions, and appropriate color-difference evaluation [10], [11].

4. APPLICATIONS OF THE TCS230

4.1. Color comparison and educational instruments

One practical application of the TCS230 is comparing the color of a sample against a predefined reference. A portable instrument can measure the RGB response of a printed object and determine whether it falls within an accepted tolerance range. This approach is relevant to printing inspection, product identification, and simple quality-control tasks where rapid comparison is more important than full spectral

characterization. The portable RGB comparison system reported by Martenius and Wibowo illustrates this type of implementation [3].

The sensor can also support educational tools that introduce color recognition and embedded instrumentation. A microcontroller-based device can identify selected colors and provide visual or audio feedback to the user. Such systems demonstrate how optical sensing, digital processing, and human-interface components can be combined in a relatively simple platform. Nevertheless, educational demonstrations should distinguish between recognition of a limited set of calibrated colors and accurate measurement of arbitrary colors [6], [12].

4.2. Automated sorting and industrial control

Color-based sorting is another relevant application because products can often be grouped according to their visible surface color. A TCS230-based system can be connected to a programmable controller or microcontroller that activates a motor, conveyor diverter, or pneumatic mechanism after identifying an object. Tarigan and Setiono reported a TCS230-based sorting-control design, illustrating the use of color sensing within an automated handling system. Related work using the TCS3200, a closely related color-to-frequency sensor, has also demonstrated object sorting based on predefined color categories [4], [13].

The performance of an automated sorting system depends on the consistency of the entire measurement and handling process. Objects should pass the sensing position at a controlled distance and under repeatable illumination conditions. The control system must also account for conveyor speed, object spacing, processing delay, and actuator response time. These requirements indicate that successful color sorting is not determined by sensor sensitivity alone, but by the integration of optical, electronic, mechanical, and control subsystems [4], [13], [14].

4.3. Colorimetric and analytical measurement

The TCS230 can also serve as a detector in compact colorimetric instruments, where chemical reactions produce measurable changes in sample color. De Morais *et al.* developed a low-cost microcontrolled photometer using a TCS230 sensor and LED illumination for selective lead detection with gold nanoparticles. Their work demonstrates that the sensor can be used beyond simple object classification, including optical measurements associated with chemical analysis. However, quantitative analytical applications require careful control of the optical path, blank measurements, reference standards, and repeatability [15].

Other portable colorimeters provide useful comparisons for designing TCS230-based analytical systems. Research on miniaturized colorimeters has demonstrated the value of compact optical arrangements, controlled light sources, and stable photodetection for quantitative measurements. Studies of portable LED-based colorimeters have also shown that low-cost instruments can produce useful analytical results when their optical and electronic components are properly designed. These developments provide a broader engineering context for adapting the TCS230 to laboratory and field measurements [7], [8], [16].

5. PERFORMANCE LIMITATIONS AND RESEARCH CHALLENGES

The principal limitation of the TCS230 is its dependence on the optical environment. Ambient light can enter the sensing region and change the measured frequency, particularly when the sensor is used without an enclosure. Variations in LED intensity, target distance, surface gloss, and object orientation can also influence the amount of reflected light reaching the photodiodes. Research on colorimetric sensors and portable measurement systems confirms that illumination control and measurement geometry are essential for obtaining reproducible color data [9], [10], [17].

Another challenge is the difference between RGB sensor readings and standardized color measurement. The TCS230 produces channel responses determined by its spectral filters and detector characteristics, rather than directly reporting a complete spectral reflectance curve. Consequently, two samples with different spectral properties may produce similar RGB responses under a particular illumination condition. Research on colorimetric accuracy has shown that calibration and correction methods can improve the agreement between inexpensive color instruments and reference spectrophotometers [9], [10], [11].

Future development should therefore focus on improving measurement repeatability and application-specific calibration. Optical shielding, regulated illumination, fixed sensor positioning, and periodic reference measurements can reduce major sources of variation. More advanced processing methods may also improve classification by considering normalized channel responses and validated decision boundaries. Ultimately, TCS230-based instruments should be evaluated against suitable reference devices and tested with representative samples under the conditions in which they will actually operate [8], [9], [16], [18].

6. CONCLUSION

The TCS230 is a practical color sensor for low-cost systems because it combines filtered photodiodes with programmable light-to-frequency conversion. Its digital output simplifies integration with microcontrollers and supports applications such as color comparison, educational instruments, automated sorting, and compact colorimetric measurement. However, its measurement reliability depends strongly on illumination stability, optical geometry, calibration quality, and signal acquisition. The sensor is therefore most appropriate for controlled, application-specific color recognition rather than universal or traceable color measurement, and future designs should prioritize repeatability, optical control, and validation against reference instruments.

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