MICRO-EPSILON

Basics of colorimetry

Guide for industrial color measurement

What is **color?**

Color is individual, visual sensation elicited by light.

Human color impression is subjective and depends on age, sex and daily mood, while factors such as illumination, background and surface structure also play an important role for color impression.

Color sensors imitate human color perception.

Industrial color measurement is a great challenge since color is an individual, visual sensation elicited by light. Therefore, everything is about comparing the measured color with the actual color perceived by the human eye. The crux of the matter in most measurement tasks is to detect very slight deviations in color as even these can be perceived by the human eye.

Why **industrial color measurement?**

In many industries, color implies quality. Particularly with consumer goods that arrive at the final customer, the exact color shade affects the value and identity of the product and the brand. Therefore, it is crucial to match the correct color shade in the production process and to produce it homogeneously throughout numerous batches.

Color not only leaves behind a quality impression but can also be used as indirect quantity to control the process. For example, color sensors are used to monitor the presence of adhesive beading, to sort parts or to determine active ingredients.

More than just color measurement

- Detection of color rings
- Color values can be read and statistically evaluated
- Color mark recognition in printing industry
- Color and gray-scale detection
- Packaging control
- Color sorting tasks (e.g., O-ring control, closures, crown caps, labels)
- Color recognition on interior/exterior parts
- Coloring of liquids
- Gray shades of concrete blocks and paving stones
- Internal coating of cans
- Surface finishing
- Distinction of materials and coatings

What **types of color measurement** are there?

Industrial color measurement technology is based on two principles for color determination:
Absolute color measurement determines the color of objects.
Relative color measurement compares the detected color with a reference color.

The sensor measures and evaluates the reflection of wavelengths in the visible range. Depending on the distribution and composition of wavelength parts, a measurable color shade is produced. However, certain conditions (observer, illumination, distance, ...) must remain as constant as possible (see page 6).

Absolute color measurement

Absolute color measurement means that the color distance is determined between the target and the absolute, device-independent coordinates of a reference color (Delta E_{abs}). Measurements must be performed with the same but not necessarily standardized light source.
If all standard conditions for color measurement are adhered to, this is referred to as standardized color measurement.

The most important feature of color-measuring sensors from Micro-Epsilon is their high accuracy. As the colors from the entire color spectrum are determined, these absolute measuring systems can be used for control and regulation tasks.

For absolute color measurements, the colorCONTROL ACS7000 measuring system is used.

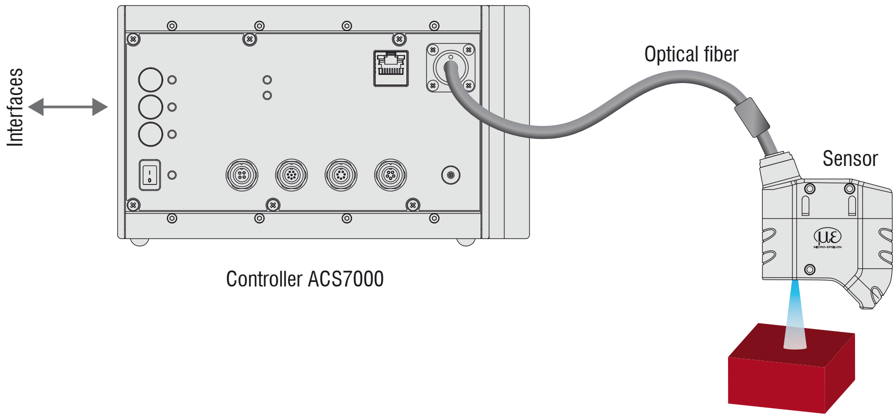
Relative color measurement

Relative color measurement is often referred to as color inspection. The color distance between the target and the reference sample is determined using the same sensor (Delta E_{rel}, see page 9).

One important feature of color-inspecting sensors from Micro-Epsilon is their primary purpose: comparing colors directly in the sensor with a reference color taught in advance. The user receives a good/bad evaluation as an output/switching signal.

For relative color measurement, the colorSENSOR CFO100 & CFO200 True Color sensors are used.

Sensors **for absolute color measurement**



colorCONTROL ACS7000 for absolute color measurement with high accuracy

Micro-Epsilon offers the colorCONTROL ACS7000 measuring system which is intended for absolute color measurements. The controller can be operated with three different sensor types. The sensor cables consist of optical fibers (glass fibers) which are firmly connected to the sensor.

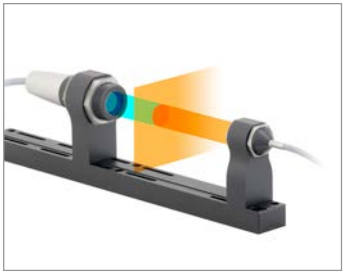
Sensors and adapters for tactile color measurement offer multiple application possibilities for inline color measurement. And due to its high precision, the device is ideally suited to laboratory applications and quality assurance.

colorCONTROL ACS7000

- Absolute color measurement, ideal for precise measurements in laboratories, quality assurance and production lines
- Measurement speed up to max. 2 kHz
- High repeatability: $\Delta E \leq 0.08$ (5 nm)
- Color space: XYZ; L*a*b*; L*C*h° or L* u* v*
- Interfaces: Ethernet, EtherCAT, RS422, digital I/O

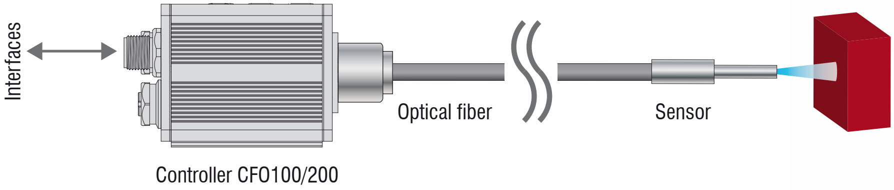
ACS1 Standard sensor
for standard measurement tasks

ACS2 Circular sensor
for structured, highly reflective and shiny metallic surfaces



ACS3 Transmission sensor
for (semi-)transparent objects

Sensors **for relative color measurement**



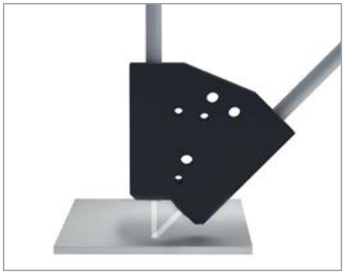
colorSENSOR CFO100 / CFO200
True Color sensors for precise color recognition

The colorSENSOR CFO series from Micro-Epsilon is designed for relative color measurement (color inspection). A channel usually consists of sensor, optical fiber and controller.

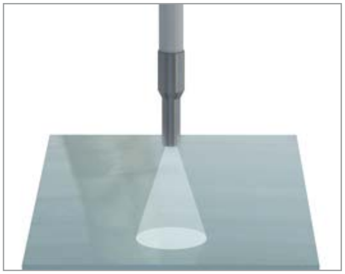
The high-performance light source and the evaluation unit are housed in the controller. The controller guides the light via the optical fiber to the sensor (or probe head/sensor head). The sensor widens the light on the measuring point of the target. Various sensors with a different measurement arrangement, measurement spot size and distances are available. The light reflected by the target is guided back into the controller via the optical fiber where it is evaluated by the True Color chip.

colorSENSOR CFO100 / CFO200

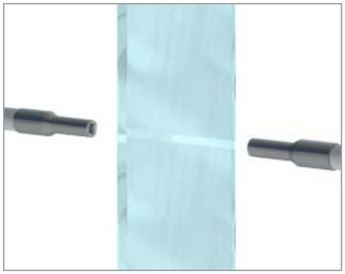
- Relative color measurement, ideal for fast color recognition in automation, production monitoring and quality control
- Measurement speed up to max. 30 kHz
- High color resolution: $\Delta E \leq 0.3$
- Operation: Web browser, foil keyboard



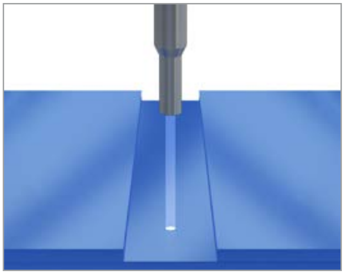
CFS1 Standard sensor
Measuring high-gloss surfaces



CFS2 Circular sensor
Measuring structured surfaces, metallic-effect paints and high-gloss surfaces



CFS3 Transmission sensor
Measuring color changes of liquids, color measurement of translucent films



CFS4 Reflex sensor
Ideally suited to metals, plastic parts, coatings and packaging; ideal for direct reflection incl. gloss

How to measure **colors correctly?**

In order to receive constant results, a reproducible measuring method with the following conditions is required:

Please note:

- The sample surface must be as clean as possible. Finger prints, scratches, dust and residues of cleaning agents distort the measured results.
- Curved surfaces: always measure at the same location on the target with the least amount of curvature to achieve a reproducible result.
- Make sure that the sample is optimally positioned. If the distance from the sample changes slightly the measurement results will be influenced.
- Constant surface temperature is important for comparable results as different temperatures can lead to deviations. Samples in best quality should be qualified as representative master.
- Regular calibration is a prerequisite for reproducible results and should be performed under the same ambient conditions prevailing during the subsequent measurement.

Reproducible measuring methods and conditions

- Definition of sample (body or light)

- Definition of measuring points

- Definition of permissible tolerance

- Measurement conditions to be defined:
- Color space / color values (L*a*b*, XYZ, Luv, …)
- Distance models (ΔE, ΔEcmc, cylinder, box …)
- Illuminant (D50, D65, A or others)
- Standard observer (2° or 10°)
- Measurement geometry (specular or diffuse illumination)
- Measurement mode (reflection in reflex mode or transmission in transmitted light mode)
- Number of measurements

- Referencing with white/black/green standards

Only measurements performed under the same conditions are comparable.

Ensure constant measurement conditions.

Multi-channel color measurement

Synchronous color measurement using multiple sensors

With synchronous color inspection of an identical target using colorSENSOR CFO sensors, the color value display, e.g. in the web interface, can vary. As the color measurement is relative to an identical reference, this deviation does not matter in process monitoring.
In order to obtain identical colors in the display, factory calibration for the controller is recommended. Using several colorCONTROL ACS controllers for synchronous data collection requires no calibration, as each controller determines absolute color values.

Basics of color measurement

Standard observer

There are two different types defined by three cone sensitivity curves:

2° standard observer (1931)

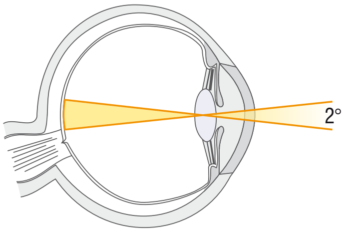
- Distance 30 cm = 1 cm visual field
- Focus onto small area of retina (macula of retina)
- Hardly corresponds to visual perception

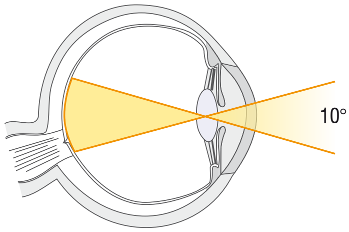
At the end of an outstretched arm, an object the size of a thumbnail has an aperture angle of approx. 2°.

10° standard observer (1964)

- Distance 30 cm = 5 cm visual field (standard practice)
- Focus onto large area of retina (macula of retina + edges)
- Corresponds to visual perception

At the end of an outstretched arm, this approximately corresponds to the palm without fingers. The sensitivity curves of the standard observers are standard spectral sensitivity curves/functions. The spectral values for $\bar{x}$ $\bar{y}$ $\bar{z}$ defined in DIN 5033 are the calculation basis for the chosen observer.





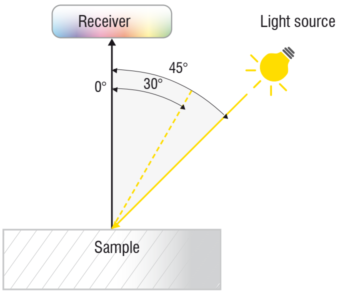
Standard observer

People perceive colors differently. In order to achieve perceptual uniformity, the International Commission on Illumination (CIE) stipulates spectral weighting functions.

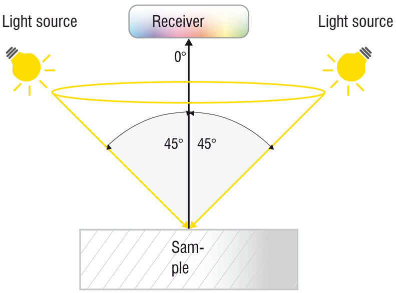
These functions describe how people perceive colors. They are based on experimentally determined sensitivity curves of the long-wave L-cone (X), medium-wave M-cone (Y) and short-wave S-cone (Z).

Measurement geometries

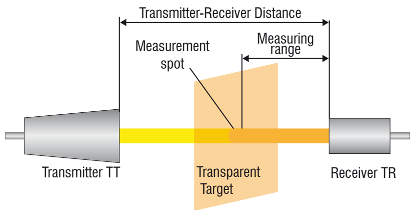
The measurement geometries described correspond to the color vision of the human eye.



Measurement geometry 30°x:0°; 45°x:0°
The sample is illuminated at 30°/45° and measured at 0°.



Measurement geometry R45°c:0°
The sample is illuminated at 45° and measured at 0°. All-round lighting minimizes structural influences by the surface. No orientation must be specified.



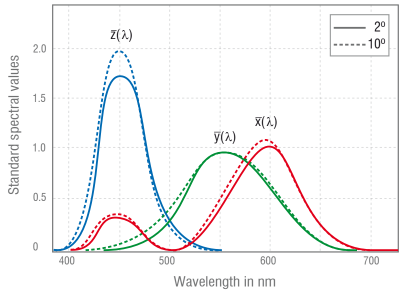
Transmission sensor with transmitter (TT) and receiver (TR) 0°:180°

Basics of color measurement

In order to create a basis for worldwide color communication and standardized color measurement systems, the CIE (Commission internationale de l'éclairage, International Commission on Illumination) was founded in 1931 and is responsible for monitoring and inspection of internationally recognized color values. The observer was defined (see "Standard observer") in a study based on individual color impression. Furthermore, light sources such as fluorescent lamps, candles, the sun etc. were defined as illuminants. If a sample is measured using a color measurement device, the factors illuminant and observer are standardized, adjustable parameters with international validity. The color perception of the test persons was defined in the standard spectral sensitivity functions $\bar{x}$ (long-), $\bar{y}$ (medium-) and $\bar{z}$ (short-wave).

Color assessment based on:

- **Hue:** Color differentiation, e.g., red, green, blue, yellow, etc.
- **Brightness:** Intensity of light perception, color appears darker or brighter
- **Colorfulness:** Intensity of the color compared with a gray color (not colored) with the same brightness
- **Saturation:** Describes the relation between colorfulness and brightness



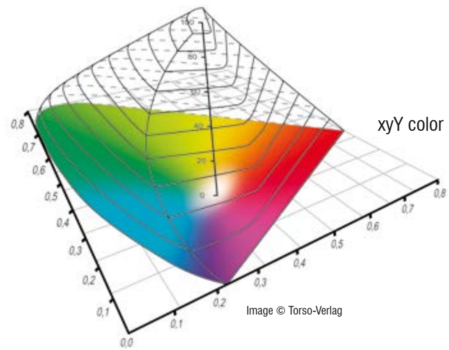
This is how each perceivable color can, due to its characteristics, be assigned an exact location in a color space and be communicated worldwide.

Spectrum

We perceive color stimulus between 380 nm violet and 780 nm red and can distinguish up to 10 million color shades.

Color spaces

The human eye has three color receptors (L = long, M = middle, S = short). This is why 3D color models are used in order to clearly identify colors and to compare these with other colors (see color distance). In the industry, particularly the L*a*b* color space has become established.



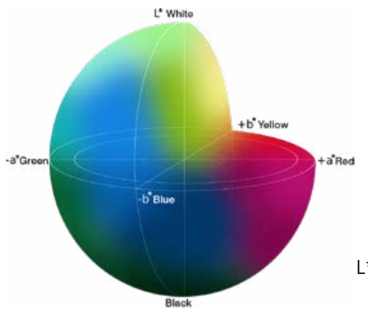
xyY color space

Standard color space CIE 1931 (xyY color space)

This color space is based on perceived color in human color vision.
(very large green and small blue/red range).
x and y = color vectors describing hue and saturation
Y = value (brightness) scaled from 0 to 100
W = white point (x=y=z=1/3)
Spectral lines = "pure" colors
Black body curve = color as temperature of an ideal, black radiator
Suitable for testing green and white LEDs.

Standard color space CIELAB76

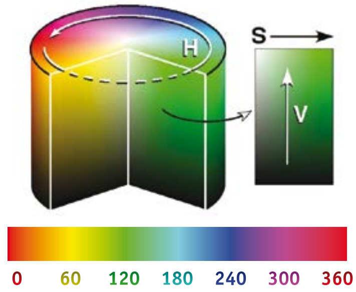
The L*a*b color space comprises all colors perceptible to the human eye. In this 3D color model, each hue is described with approximately the same volume of space. The L*a*b* color space has established itself in the industry and is used by device manufactures for color inspection.
Each color is described by the color location (L*; a*; b*).
L* = lightness (black = 0; white = 100)
a* = green/red colors (green = -100; red = +100)
b* = blue/yellow colors (blue = -100; yellow = +100)



L*a*b* color space

HSV/ HSI color space

The colors in the HSV color space are defined by hue, saturation and brightness combining several color models such as HSV/HSL/HSI.
Each color is defined by the color coordinates (H, S, V)
H= Hue (red = 0°; green = 120°; blue = 240°)
S= (Saturation) Colorfulness (neutral gray = 0%; „pure“ color = 100 %)
V= (Value) Brightness
I = (Intensity) Light intensity (dark = 0%; very bright = 100%)



HSV/ HSI color space

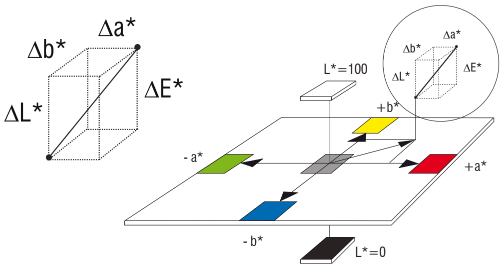
Color distance ΔE

The larger the difference between the colors within the color space, the more clearly the difference can be perceived with the human eye. This is defined as ΔE color distance.
Delta E; ΔE; dE = is a metric for the perceived color distance between colors (DIN 5033)

$$\Delta E=\sqrt{(L^*_p - L^*_v)^2 + (a^*_p - a^*_v)^2 + (b^*_p - b^*_v)^2}$$

ΔE of 11.61 corresponds to the difference between sample (p) and comparison (v)

$$\Delta E=\sqrt{(60^*_p - 55^*_v)^2 + (-38.6^*_p - (-30)^*_v)^2 + (-46^*_p - (-52)^*_v)^2} = 11.62$$



Sample (p)

Comparison (v)

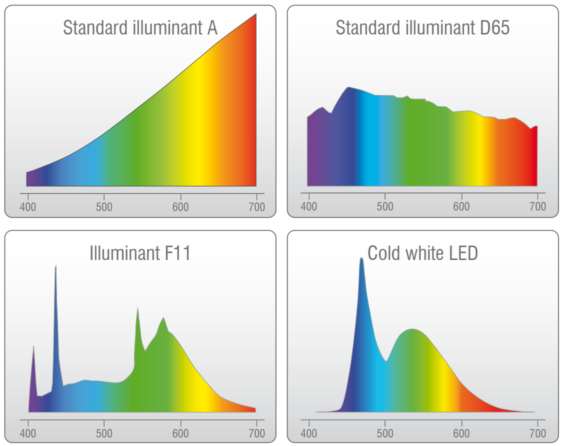
Interpretation:

ΔE > 5 Large color difference
ΔE 0.5 … 1 Limits of human perception
ΔE < 0.3 Required by the paper industry
ΔE < 0.1 Required by the automotive industry

Standard illuminants and light sources

Standard illuminants are defined from 380 to 780 nm.

- **Illuminant A** = light bulb with 2865 k
- **Illuminant D65** = medium daylight with approx. 6500 k
- **Illuminant F11** = fluorescent lamp
- **Cold white LED**

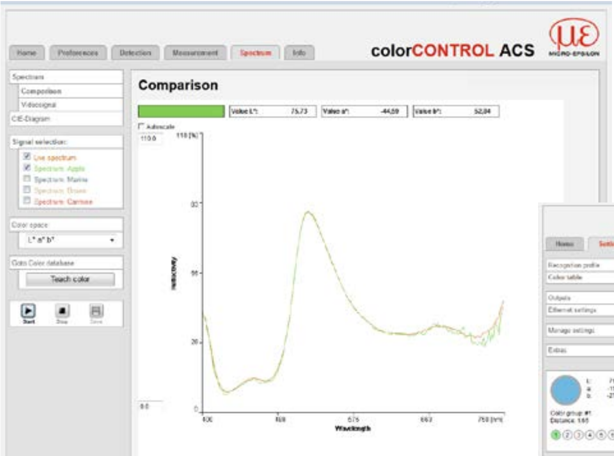


Web interface for intuitive operation

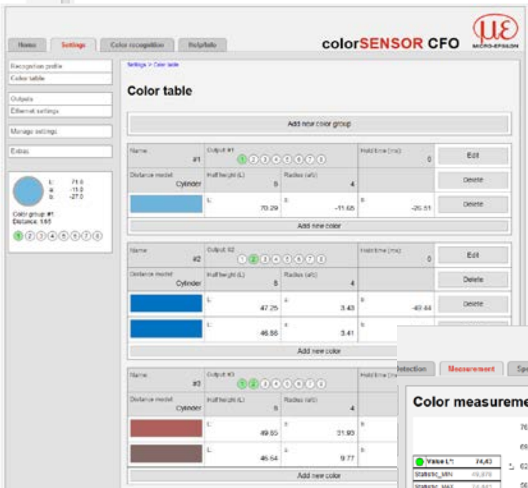
The integrated, intuitive web interface enables user-friendly configuration of the colorSENSOR and colorCONTROL systems. The sensor is connected to a PC via an Ethernet interface. The web interface features measurement value display, set up and configuration of e.g. exposure and measurement frequency. Furthermore, the sensor can be adapted to suit different color groups and tolerance space for each color.

Ideal for fast measuring data display

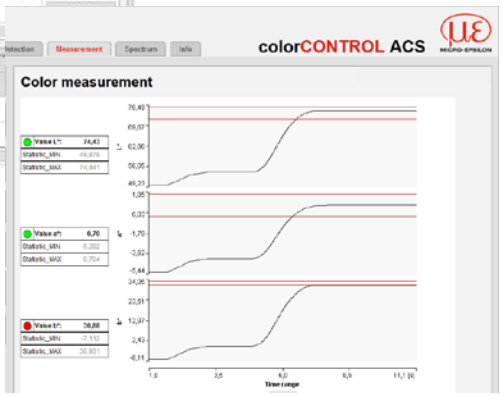
The web interface is, for example, an advantage for laboratories or test applications, as parameter can be set and read quickly. For high-speed real-time monitoring, the web interface is only suitable to a limited extent as the display of measured values via the browser is limited.



Spectrum and color location in user interface



Configuration of color groups



Measurements of XYZ, L*a*b*, L*u*v*, L*c*h shown over time

General

Metamerism means that a pair of samples looks the same under one light source but different under another light source.

With **structured surfaces**, it is recommended to perform the inspection from all four directions (north, east, south, west on one side) and to calculate the average on different positions or to illuminate the specimen from all directions (ring illumination (R45°c:0°) and to measure only one position.

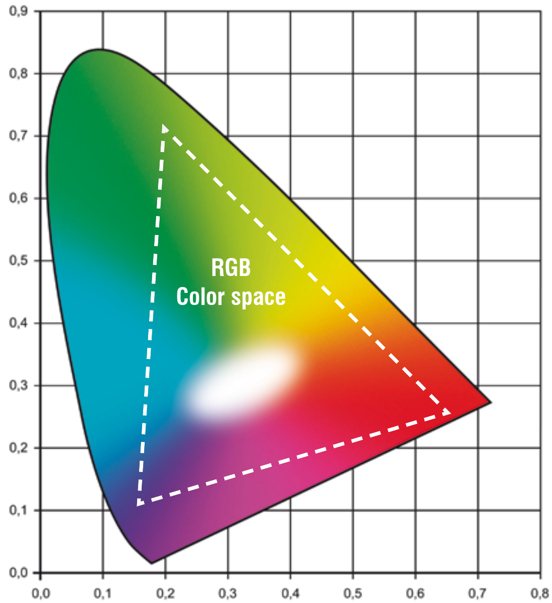
With **translucent samples**, a defined background or folding the sample should provide sufficient layer thickness for the inspection. You can alternatively use some illumination as background in order to inspect in transmission (0°:180°) mode.

The average is calculated with several measurements on different positions or only one position of the sample and by evaluating these values.

The **color temperature** refers to the temperature by which black bodies would have to be heated theoretically in order to emit light with the same color. Color temperature is measured in Kelvin (K).

RGB color space: The RGB color space combines the colors red (R), green (G) and blue (B) into one. It is an additive color space, i.e. all three colors as one result in the color white. Black color is produced when R/G/B = 0/0/0.

The RGB color space has established itself in the display industry but is of no interest for industrial measurement technology since not every color can be displayed and measured.



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