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Improving the Repeatability of a Color Sensor by Integrating an FSM for Scanning-based Areal Measurements

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***Abstract*— This work presents the design, alignment algorithm and validation of an optical scanning color sensor system capable of precisely aligning itself to a sample without additional external sensors, improving the repeatability of the color measurement. The proposed system design enables to scan the optical path of the color sensor by a fast steering mirror (FSM), such that the angle of incidence can be varied within $\pm 3°$. A color characterisation is performed to determine the parameter of the CIELAB color space, which can be used to correctly align the color sensor with respect to the sample. An alignment algorithm automatically determines the correct measurement distance and angle of incidence, based on the measured brightness value L^*. Experimental results show that the alignment algorithm can precisely align the sensor with a deviation of 9.3 µm and 8 mdeg. To evaluate the repeatability of the system, ten measurements with various start positions are performed, resulting in a maximum color difference of 0.0741 between the measurements. Additionally, the measurement data acquired during the alignment process can be used to characterize the surface finish.**

I. Introduction

Color is an essential quality feature for many product types, such that color control is applied in multiple industries, like the paper, textile, pharmacy, and automotive industry [1], [2]. However, the color perception strongly depends on the angle of incidence of the illuminating light beam as well as the viewing angle, which contributes to correct color measurement being a challenging task [3], [4]. Particularly metallic paint used in the automotive field requires to measure the color at several angles of incidence, to characterize the color effects caused by metal flakes [5], [6]. Therefore, color sensors are commonly attached to industrial robots, such that multiple points over the entire bodywork can be measured with different angles of incidence [7]. To correctly align the color sensor with respect to the sample, additional external sensors are used which measure the distance and angle between them. These color measurements are generally performed in-line to ensure a consistent product quality [8]. Due to the point-wise measurement and alignment procedure a long measurement time is required, which limits the achievable throughput. To overcome this limitation several robots with color sensors are typically used to obtain the required amount of measurement points within a given time frame [9]. However, as the number of produced goods is constantly increasing, also the need for advanced, fast and accurate color measurement systems rises.

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Optical scanning systems have the potential to reduce the measurement time, since the moving mass of the scanning mirror is low compared to the entire color sensor. Such systems have already been realized for triangulation sensors [10] and confocal chromatic sensors [11]. By manipulating the optical path of the color sensor, multiple angles of incidence can also be quickly measured, which enables a fast characterization of color effects.

The contribution of this paper is the system design, alignment algorithm and evaluation of an FSM based areal scanning color sensor system, which improves the repeatability of the color measurement. Section II describes the system design and used color space. The experimental setup, and system hardware is developed in Section III, while the color characterisation is shown in Section IV. The flowchart used to determine the optimal measurement distance and angle of incidence is presented in Section V, followed by the measurement results and the determination of the surface finish shown in Section VI. Finally, Section VII concludes the paper.

II. System Design

The color measurement is influenced by the angle of incidence, viewing angle and distance between sensor and sample [2], such that an optical beam steering device able to manipulate the optical path in both rotational DoFs and an actuator to change the measurement distance are required to align the sensor with respect to the sample. A fast steering mirror (FSM) supports such a two dimensional scanning and has the same point of rotation for both axes, which enables a simplified and more compact setup compared to a scanning system with two 1D scanners, such as galvanometers. By using a color sensor with an identical illumination and reflection path an FSM with a small aperture size can be used to scan both optical paths, such that a high scan speed and subsequent high throughput can be achieved. Figure 1 depicts the resulting schematic of the optical scanning system. The measurement distance d_{meas} between sensor and sample composes out of the fixed distance d_1 between the optic and FSM, and the distance d_2 between FSM and sample, which can be changed by an actuator. Additionally, a rotatory stage is integrated to position the sample at an offset angle α_x.

In the manufacturing industry multiple colorspaces, like RGB, CMYK, XYZ and CIELAB, are used [12], [13]. However, not all perceptible colors can be represented in all colorspaces [14]. Since the CIELAB can represent all perceptible colors and enables to determine the correct alignment between

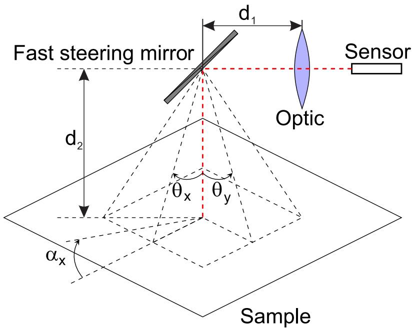


Fig. 1. Schematic of the scanning color sensor system. An FSM is used to manipulate the angle of incidence of the color sensor, which has an identical illumination and reflection path. The distance d_2 between the FSM and sample can be manipulated with an actuator.

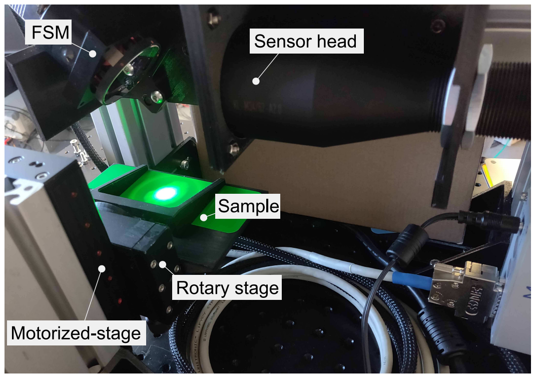


Fig. 2. Experimental setup of the optical scanning color sensor system. The sample holder is attached to a rotary stage, which enables to rotate the sample by a defined angle α_x. With a motorized stage the distance between sensor and sample can be changed within 50 mm. The FSM enables to manipulate the angle of incidence by $\pm 3°$ in tip and tilt direction.

sensor and sample, which is further described in Section IV, this color space is used. If, however, the measured color is required in a different color space, it can generally be converted [15]. The CIELAB is a three-dimensional colorspace in which the brightness value L^* is perpendicular to the color plane formed by a^* and b^*, which represent the red-green and yellow-blue axis, respectively.

To determine color differences, the color distance ΔE can be used, in the following form

$$\Delta E = \sqrt{\left(\Delta L_1^* - L_2^*\right)^2 + \left(\Delta a_1^* - a_2^*\right)^2 + \left(\Delta b_1^* - b_2^*\right)^2}, \quad (1)$$

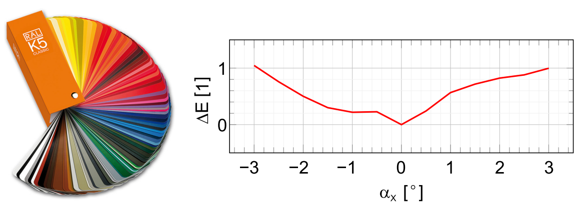
with $(\Delta L_1^*, \Delta a_1^*, \Delta b_1^*)$ and $(\Delta L_2^*, \Delta a_2^*, \Delta b_2^*)$ being the CIELAB coordinates of the two colors, which should be compared [16].

III. Experimental Setup

The experimental setup of the optical scanning system is shown in Fig. 2 and consists of a color sensor (type: CFO 200, Micro-Epsilon GmbH, Germany), with a repeatability of $\Delta E \leqslant 0.3$, an objective (type: KL-M34/62-A2.0, Micro-Epsilon GmbH, Germany), which expands the optimal measurement distance to $d_{meas,opt}$=140 mm and an FSM (type: OIM102, Optics In Motion LLC, Long Beach, USA), used to change the angle of incidence. The FSM has a built in feedback position control with a closed-loop bandwidth of 750 Hz and a angular resolution of 2 µrad. Due to the large aperture size of the attachment optic of 62 mm, an FSM with an aperture size of two inches is required. The FSM is tilted by 45° with respect to the optical axis of the attachment optic, such that the optical path is perpendicular to the sample, if the FSM is in the zero position. The distance between the optic and FSM is selected to d_1=76 mm, such that the optimal distance between FSM and sample is $d_{2,opt}$=64 mm. The sample is held by a sample holder which is mounted onto a rotary adjustment stage (type: DV 65-D37, OWIS GmbH, Germany) and a position controlled stage (type: VT-80 62309120, Physik Instrumente GmbH, Germany), which enables to rotate and move the sample by a defined value. The translational stage has a travel range of 50 mm and is paced at a distance d_2=97 mm, such that the sample can be positioned too far away as well as too close to sensor. The optimal measurement distance is reached at a set position of 33 mm. The experimental setup is controlled by a graphical user interface (type: Matlab, Mathworks, USA), which uses a data acquisition device (type: USB-6211, National Instruments, USA) to set and read the angular positions of the FSM.

IV. Color Characterisation

Standardized color cards (type: RAL K5 classic, RAL GmbH, Germany), shown in Figure 3(a), are used as samples, to provide a constant color over the entire measurement area. To demonstrate the impact of a slight angular misalignment between sensor and sample, the position of the rotary adjustment stage was varied between $\pm 3°$. Figure 3(b) depicts the calculated color distance over the angular misalignment for the color card pearl night blue (RAL 5026), which already leads to a ΔE of 1. The human eye is able to detect color differences of $\Delta E \approx 0.3$ for achromatic dark colors [14]. In [17] and [18] the maximum color differences for plain and metallic car paints are defined to $0.6 \leq \Delta E \leq 1.8$ and $1.5 \leq \Delta E \leq 1.8$. A small misalignment



(a) (b)

Fig. 3. Sample and angular sensitivity. (a) shows the standardized color cards used as sample. (b) depicts the influence of a tilted sample on the measured color pearl night blue (RAL 5026). An angle of 3° already causes a color difference ΔE of 1.

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of 1° already lead to a color difference noticeable for the human perception, such that a correct alignment between sensor and sample is mandatory for the color measurement.

To determine which color axis of the CIELAB colorspace is suitable to determine the correct alignment between sensor and sample, a color characterisation was performed. Therefore, measurements with multiple measurement distances and angles of incidence were performed. The measurement results of the color card pearl night blue (RAL 5026) are depicted in Fig. 4. As can be observed, only the brightness value L^* shows a maximum for the correct position of the stage and angle of incidence, which should be 33 mm and 0°, respectively. The color axes a^* and b^* show neither a maximum nor a minimum for the correct distance or angle of incidence. Furthermore, the surface shape and gradient of a^* and b^* changes with the used color card (data not shown), such that a correct alignment can not obtained from these parameters. However, for the brightness value L^* the position of the maximum does not depend on the used color card, such that this parameter can be used to determine the correct alignment. L^* shows for almost all angle of incidence a maximum at a stage position of 33 mm, such that the alignment algorithm can determine the correct measurement distance and angle of incidence independently. This strongly reduces the overall measurement time since only one optical scan over the entire solid angle is required.

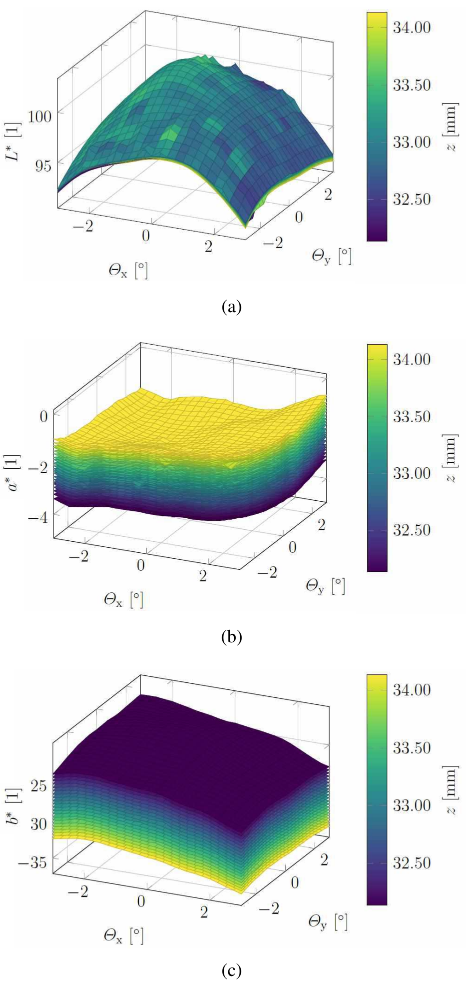

Fig. 4. The measured L^* a^* and b^* values are shown for various measurement distances and angles of incidence. If the measurement distance is increased, the value of a^* is steadily increasing, while b^* is steadily decreasing. Only the brightness value L^* shows a permanent maximum for a stage position of 33 mm, which corresponds to the correct distance between sensor and sample. The brightness value L^* also enables to determine the angle of incidence since the maximum corresponds to the correct angles of incidence.

V. Alignment Algorithm

To automatically align the scanning color measurement system with respect to the sample, the correct measurement distance, i.e. the position of the stage, is determined first, for which the flowchart depicted in Fig. 5 is used. Initially, the brightness value L^* is determined. Afterwards the distance between the sensor and sample is increased by 2 mm. This step size was selected to enable a fast convergence to the correct measurement distance. If the brightness value has

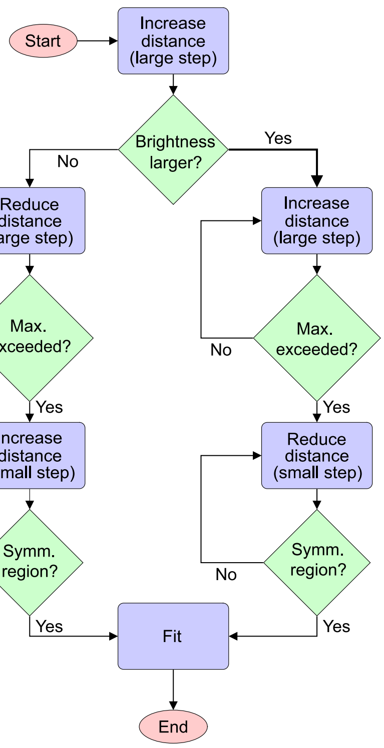

Fig. 5. Flowchart to determine the correct measurement distance. The algorithm uses only the measured brightness value L^* of the color sensor. Initially, a large step size is used to find the region with the highest value. Subsequent, this region is rescanned with a smaller step size. Finally, the measurement points are fitted to a Gaussian function. The expected value of this function represents the calculated measurement distance.

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increased/decreased compared to the initial measurement the distance is increased/decreased by 2 mm. The measurement distance is further monotonically increased/decreased by 2 mm until the maximum brightness value is exceeded. The step direction is inverted and smaller steps are performed, e.g. decreased/increased with a step size of 500 µm, until a symmetric region around the maximum is obtained. The step size of 500 µm was chosen to provide enough measurement points to precisely calculate the correct measurement distance. Finally, all measurement points are used to fit to a Gaussian function, with the least squares method [19]. The expectancy value of this function represent the calculated set position of the stage.

After the measurement distance is determined by the algorithm, a scan over the entire solid angle of incidence ($\pm 3°$) is performed. Based on the measurement, the centre of gravity of the brightness value L^* is calculated, which represents the correct angle of incidence. If the correct angle of incidence can not be reached within the actuation range of the FSM, a manual realignment would be required. This is the case if the centre of gravity is located at the edge of the actuation range.

VI. Experimental Results

To validate the performance of the alignment algorithm and the scanning system, multiple measurements are conducted. In addition, the data acquired during the alignment algorithm are used to characterize the surface finish.

A. Validation of the alignment algorithm

Figure 6 shows the procedure to determine the measurement distance, described in Section V, for the color card pearl dark gray (RAL 9023). The set position calculated from the alignment algorithm is 33.0093 mm, which is almost equal to the optimal measurement distance reached at a set position of 33 mm (see Section III).

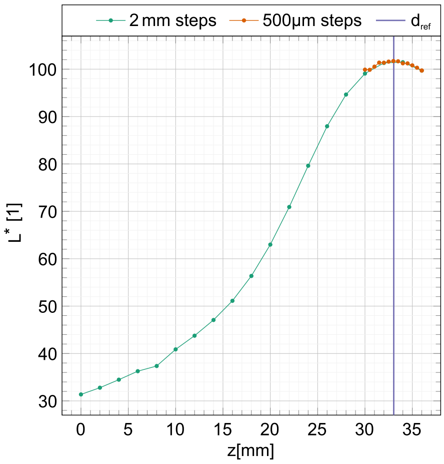

Fig. 6. Procedure to find the correct measurement distance. Initially, the distance between the sensor and sample is increased with a step size of 2 mm till the brightness value L^* decreases. Subsequent the distance between the sensor and sample is decreased with a step size of 500 µm until a symmetric region is scanned. Based on the measurement data the measurement distance is calculated.

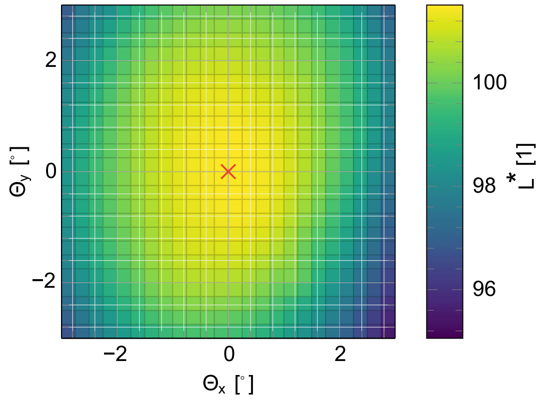

Fig. 7. The centre of gravity of L^* (shown by a red cross) corresponds to the correct angle of incidence, such that the entire alignment of the sensor can be determined with the brightness value L^*.

After obtaining the right measurement distance, the algorithm to obtain the correct angle of incidence is performed. Initially, the stage is moved to the calculated measurement distance, with an angular scan over the entire scan area being performed thereafter. Figure 7 depicts the measured brightness value L^* over the scan area. The centre of gravity was calculated to 1.9 mdeg and 8 mdeg for θ_x and θ_y, respectively. The calculated centre of gravity is also depicted in Fig. 7 (red cross) and shows good agreement to the reference position, which is 0° for θ_x and θ_y.

B. Measurement series

To validate the repeatability of the scanning color sensor system, ten measurements with different starting positions are performed. Figure 8 depicts the measured color values L^*, a^*

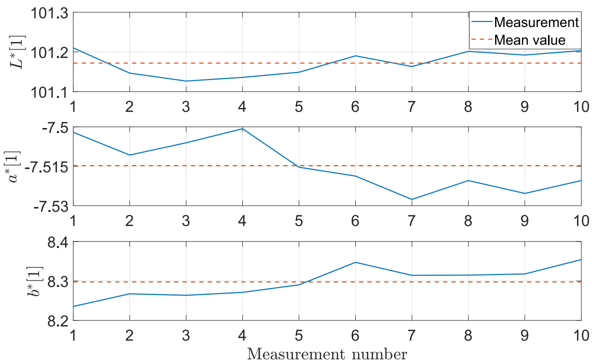

Fig. 8. To validate the effectiveness of the alignment algorithm ten measurements with different starting distances are performed. The measured L^* a^* and b^* after the alignment procedure are shown. As can be observed only slight deviations between the measurements are visible.

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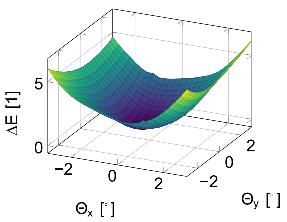
and b^* of each pass. As can be observed, only small deviations occur between all the measurements. In addition, the color difference ΔE between the mean value over all measurements and the measurement with the largest deviation (No. 1) was calculated to 0.0741. This deviation is significantly smaller compared to the repeatability of the color sensor, which is $\Delta E \leqslant 0.3$, demonstrating the improved repeatability of the FSM based scanning color sensor system.

C. Surface finish characterisation

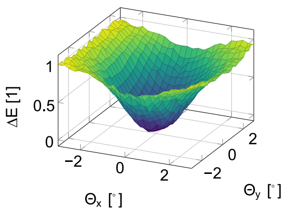
As described in Section I, metallic and effect paints require color measurements at several angles of incidence, to characterize the color effects. Since the alignment algorithm already performs an optical scan with different angles of incidence, the obtained measurement data can also be used for this characterization.

To further analyze the effects of a metallic color compared to a matte color on the obtained color, measurements on both samples were performed. Figure 9(a) shows the used color cards, which are pearl night blue (RAL 5026, metallic) and luminous light red (RAL 3026, matte). For both color cards the color deviations with respect to the ideal measurement position were calculated. In Fig. 9(b) the color deviations for the metallic color card (pearl night blue) are depicted, while in Fig. 9(c) the results of the matte color card (luminous light red) are shown. As can be observed, the metallic color features a large color distance over the scan area of up to $\Delta E = 5$. In addition, the gradient of the color deviation increases towards the edges of the scan area, such that even higher color deviations can be expected for larger angles of incidence. In comparison the matte surface shows only a small color distance of 1 over the scan area and the gradient of the color distance decreases with increasing scan angles. The measurement results on the metallic and matte color card demonstrate that the optical scanning system is able to characterize the surface finish.

(a) Metallic and matte sample



(b) Metallic sample



(c) Matte sample

Fig. 9. Surface finish characterisation. (a) shows the used metallic and matte color cards, which are pearl night blue (RAL 5026) and luminous light red (RAL 3026), respectively. (b,c) depict the color distance over the angle of incidence. The metallic surface has a large color distance ΔE of 5 for a large angle of incidence, while the color distance of the matte surface stays within a ΔE of 1.

In summary, the design of an FSM based optical scanning color sensor system is successfully validated, enabling color measurements with an improved repeatability of $\Delta E \leqslant 0.0741$ between ten measurements.

VII. Conclusion

In this paper the design, alignment algorithm and validation of an optical scanning color sensor system are presented, which can precisely align itself without additional external sensor. The optical path of the color sensor is scanned by an FSM, such that the angle of incidence can be varied by $\pm 3°$ in tip and tilt directions. A position controlled stage with a travel range of 50 mm is used to manipulate the measurement distance between sensor and sample. The color characterisation reveals that the correct alignment can be observed from the brightness value L^*, such that no additional external sensors are required. To automatically align the color sensor with respect to the sample, an alignment algorithm is presented, which initially determines the correct measurement distance and subsequently the angle of incidence. Measurement results show that the scanning color sensor system is capable of correctly aligning the sensor with respect to the sample. To validate the repeatability of the FSM based scanning system, ten measurements with different starting positions were performed, resulting in a maximum color difference of $\Delta E \leqslant 0.0741$, which is significantly smaller as compared to the repeatability of the color sensor of $\Delta E \leqslant 0.3$. Finally measurements on metallic and matte samples were performed, revealing that a change of the angle of incidence leads to a large color distance of 5 for the metallic sample, while the color distance is only 1 for the matte sample. This demonstrates that the optical scanning system is also able to characterize the surface finish of a sample.

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