Development Process of a Smart Code Based On Smart Materials

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Abstract

Smart materials, here especially sensitive dyes are common at several applications, e.g. time-/temperature indicating labels, smart packaging, and more. Smart Materials such as photochromic compounds have a light detecting behavior – e.g. light with a specific wavelength. Halochromic compounds respond to pH (acid - base) variances. They change their color after an induced stimulus from one color gradually to another color. These color gradations can be defined as specific limitation – in form of an inactive [0] to an active state [1], to indicate different environmental influences.

Based on this behavior, smart materials are able to store information about external conditions. Integrated into a smart code, besides static data (2D) also dynamic sensor data (3D) can be stored. Smart materials can be printed as sensors and they work autonomously without any power supply. A smart device e.g. smart phone, tablet, or wearable smart glasses can optically readout – by using the camera – the particular information of the code. By integration, various smart codes into a data network an autonomous information exchange can take place.

In this paper, the features for developing a smart code and first research results of a simplified prototype tool for the detection of position markers, static (information) and dynamic (smart materials) section will be shown. Additionally, the color switching behavior of a cluster of photochromic dots inside a smart code will be analyzed to detect differences between its states under exposure of UV light. The respective color values will be transformed into information about the intensity of a contamination.

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Introduction

Automation is an important case in the industrial sector. It requires highly efficient precision in production and delivery. Human resources are a risk factor for a fast moving industry because of their operational risks and prone to failure (Becker & Smidt, 2016). Accordingly, symbol codes are indispensable for the declaration and identification in the modern manufacturing, logistic and in the trade of goods. Symbol codes can automate technical processes and services. Depending on the application and the required storage capacity, different one- and multi-dimensional, standardized symbol codes are used in various practices. They save time at the identification of goods and reduce the risk of erroneous entries.

One-dimensional symbol codes, such as GTIN and ISBN are predominantly used in retail trade. Two-dimensional codes, such as composite-, dot-, or matrix-codes are better suited due to their higher storage capacity and their automatic error correction in production and logistics. In addition to basic data to identify a product, more and more quantitative and individual product information can be of interest to producers, suppliers, retailers and consumers. Three-dimensional codes can extend the functionality of the codes, to indicate information about external influences or conditions during a transport, such as time-temperature indicators. As a result, in addition to its use as an advertising medium, the packaging also has another function as a carrier for individual product information. Smart packages are using electronic components or different smart materials (indicators) to communicate directly about the current state of the packaged product. For example, an interrupted cold chain, moisture or bacterial contamination can affect the packaged product, with negative effects on the health of consumers. In comparison, active packaging supports the stability of the product through barrier layers, protective atmospheres and functional materials. - Exemplary a pad of absorbent material, absorbs any liquids, is used for fresh meat packaging. Active packaging cannot be used for reliable evaluation of the product state. The advantage of smart materials can help to reduce the problem of food waste and control the state of a product.

Smart Materials such as photochromic compounds have a light detecting behavior – light with a specific wavelength, such as UV-A light. Halochromic compounds respond to pH (acid - base) variances. They change their color after an induced stimulus from one color gradually to another color. These color gradations can be defined as specific limitation – in form of an inactive [0] to an active state [1], to indicate different environmental influences. Sensors are essential in the Internet of Things. They continuously measure changes, detect deviations and can report on external conditions such as temperature, humidity, light, gases, mechanical pressure or pH. The field of application covers various corporate fields (pharmaceutical sector, food sector, health sector and applications in areas with physical limits for electrical components). Smart materials work without any external power supply, printed circuit boards, microcontrollers and other electronic components. They are autonomous, collect data in real time and monitor themselves. Integrated into a smart code, not only static data (2D), but also dynamic sensor data (3D) can be stored and transmitted. By a connectivity with the Internet of Things (IoT) an autonomous exchange of information can take place (Ashton, 2009).

Methods

Instruments

A piezoelectric inkjet printer (Epson WorkForce WF-3620) was used to print samples with the described photosensitive ink. Technical parameters: Print Head: PrecisionCore; Thin Film Piezo element: 1/1000mm; Droplet Size: 2.8 pl (range of 1.5 – 32.5 picoliters); Nozzle Configuration: 800 Nozzles Black (K), 256 Nozzles per Colour (CMY); Printing Resolution: 4,800 x 2,400 DPI.

The colour changing functionality of the photochromic compound were measured through a spectral-densitometer (TECHKON SpektroDens). In order to determine reference values (RGB and CIEL*a*b) for the comparison of the color change. Technical parameters: polarizing filter: off; type of light: D50, 2° standard observer; diameter of measuring orifice: 3 mm.

The prototyped codes were image captured through a 2.07 MP camera (ELP-USBFHD01M-BFV-D) with a CMOS image sensor, manually variable 2.8-12mm objective and 1080P (1920 × 1080) image resolution.

Substrates	Inapa tecno, oxygen pure high-white recycled paper, Format: 210 x 297 mm (A4), Grammage: 80 g/m²
Dye	Photosensitive Prussian blue, CAS Number: 14038-43-8, Chemical formula: $C_{18}Fe_7N_{18}$, Molar mass: 859.24 g·mol−1
Water-based base ink	E24, Octopus Fluids GmbH & Co KG, Colour: colourless, pH: 7,86, Conductivity: (mS/cm): <5, Viscosity (mPa·s): 3,00

Materials

Types of Codes

Different barcode types are currently in use. The focus here is on the 2D codes and their finder pattern. They will used to identify the position, the content and the orientation of the code. The data content of a code bases on encoded data, format information and error correcting. By measurement the geometric properties such as size, shape and orientation of the components, every sector within the code can be determined. When a recognition algorithm is developed, the reliability and robustness of code reading is important. Especially for the real-time detection of a moving target, these quality features are relevant. The most popular code is the QR code (Quick Response Code; Patent No. JP 2938338). The QR Code was invented in 1994 from Denso Corporation, with its subsidiary Denso Wave, a subsidiary of Toyota. The QR Code was approved as an AIM standard in 1997 (Denso Wave, 2018). The code was used to scan the components of a car for a quick assembly.

The smallest code (Version 1, low) measures 21 x 21 modules, with character capacity of 19 data code words and 7 error correction words, whereby the size grows by four modules per side and the maximum size (Version 40, high) measures 177 x 177 modules, with a character capacity of 1276 data code words and 2430 error correction words.

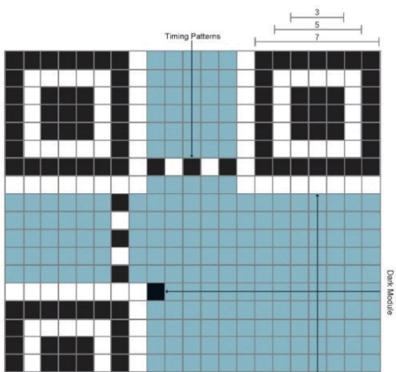

Fig. 1. *Finder pattern of a QR code*

The QR code in Figure 1 is prominent through its squares in the top left, top right and bottom left corner, where its finder pattern are located. The finder pattern base on 7 x 7 outer black modules, 5 x 5 inner white modules and 3 x 3 black modules inside (solid black square). The separator whitespace areas beside the finder patterns, separate the finder pattern and the data region. The timing patterns (horizontal and vertical), connect the finder patterns to each other and provide information about the version.

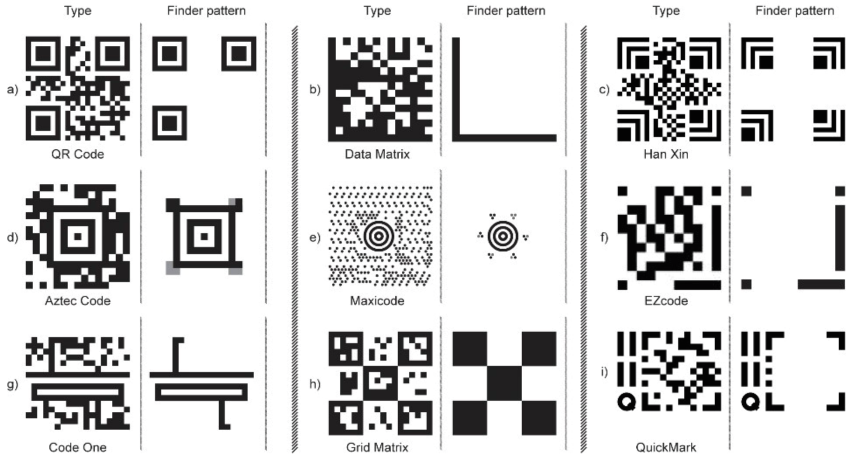

Fig. 2. *Finder pattern of codes*

In Figure 2 shows nine different types of codes, which base on various finder pattern. The clarification of the functionality of the components within the code will help in the development process of a smart code. It is necessary to understand the differences and relationships of the existing 2D-codes (Lenk, 2014). In particular, the finder pattern are important to begin the first step of code recognition. The finder pattern have a function to locate the area of data.

a) The QR code has already been described previously. b) The Data Matrix code uses a vertical and horizontal boundary line in form of an "L", which is used to identify, align, and correct the code. c) The Han Xin Code bases on chevron shaped square pattern and reminds to the QR Code. d) The finder pattern of the Aztec code bases on concentric square frames with a single black module in the middle and four squares black and grey marked for orientation. e) The finder pattern of the Maxicode base on gradually growing alternating rings (bull's-eye pattern). Six different orientation pattern are located to enable the orientation of the Maxicode. f) The EZcode bases of three black module squares in the top left, top right and in the bottom left corner. - Besides two different lengths of lines. g) The finder pattern of the Code One base on parallel lines and a rectangle line in the middle. h) An integrated variant of a finder pattern is the Grid Matrix Code, which looks like a checkerboard pattern due to the alternating black-and-white contrast, which has a finder pattern functionality. i) The QuickMark can clearly identified by the two double vertical lines above the letter "Q" and the chevron shaped pattern in each corner "viewfinder". This was a small selection of common codes. The following codes were not discussed: Color Ultra Code, Array Tag, Beetagg, Blotcode, CoolDataMatrix, Dandelion Code, Data Glyphs, Dot Code, High Capacity Color Barcode (HCCB), JagTag, etc. (Lenk, 2007).

Process of Code reading

The focus here is on the code capturing by means of a CCD camera. The process of decode will be concreted on classical methods, without the usage of Computer Vision. Many code reader applications use a viewfinder field to restrict the data set of the image information already before the capturing. The relevance is to increase the processing speed and reduce the data quantity. By converting the captured image into a grayscale image, the image data can be manipulated by a thresholding method, such as Otsu's method. Hereby a binarisation of each pixel can be realized that provides a basis for the following steps of programming. Before the counting process of the modules inside the code, it is useful to scale the matrix to the smallest size possible and find the ratio of the image to its one pixel per black pixel equivalent.

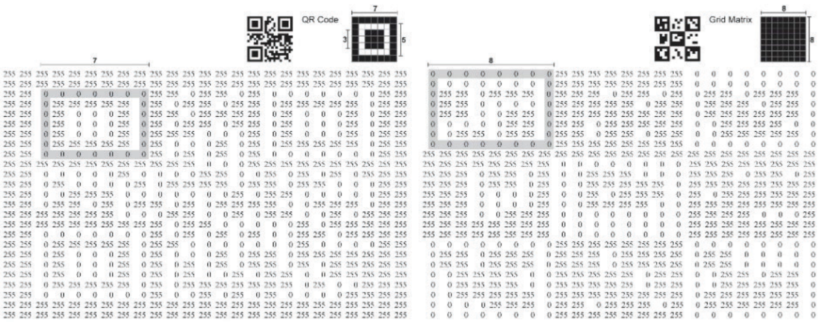

Fig. 3. *Transformation of image information*

In addition, Figure 3 shows the transformation of the image information of a QR and Grid Matrix code into binary information. The 25 x 25 digits represent the space of code information. The black modules are defined with the digit 0 and white modules with the digit 255. - The properties of each finder pattern are defined in the specification of the particular code. - The figure shows 7 x 7 outer black modules inside the QR and 8 x 8 outer black modules inside the Grid Matrix. By counting the particular black and white modules (gray marked), the finder pattern and specific components of the code can be identified.

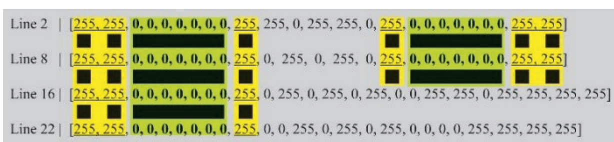

Fig. 4. *output of the position of finder pattern*

Furthermore, the output of the position pattern in form of a list type will shown in Figure 4. The yellow marked and underlined fields are the white spaces of the finder pattern. The green marked bold zeros are the finder pattern with the sequence of 7 digits. Through a system in the order of digits (black squares and black lines), it is possible to identify the patterns. Particular attention is given to the lines two and eight, because here are two search patterns next to each other. In this context, the sequence of digits are mirrored.

Identification process of the finder pattern: By writing, a programming routine in python. It is possible to seek and find (Figure 5) relevant sequences inside the code. In this example, a search variable - which represents the exemplary of a pattern sequence - was defined to find matches in the dataset. The output shows the similarities (green squares = True) and differences (red squares = False) of the both sequences. Another variant to find a sequence is the knowledge of the position of each row and column, where the finder pattern are located. Required positions can be outputted easily.

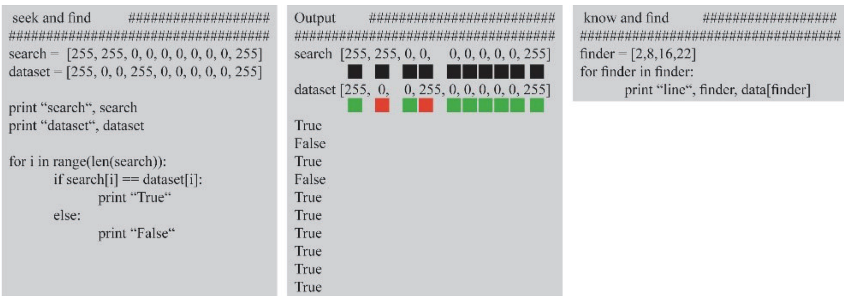

Fig. 5. *programming routines*

When developing finder pattern, it is important that the markers stand out from the entire data set. Otherwise, they make the identification more difficult. The examples of finder pattern (Figure 6) represent some common codes and individual designs. Position, rhythm, order and form of the symbols (in this example squares) are important for the design, since its characteristic sequence for writing the algorithm are important to identify the finder pattern.

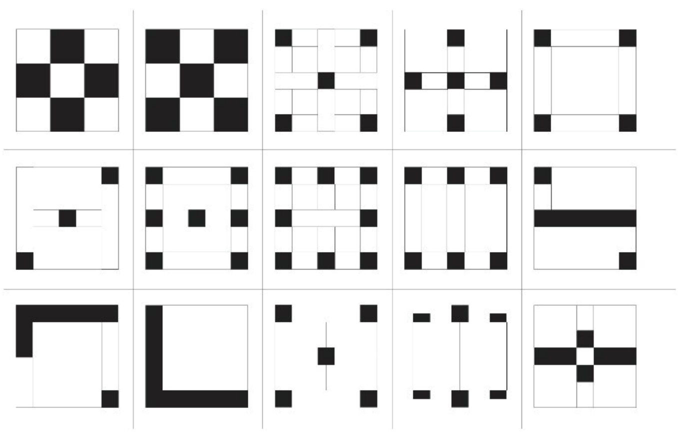

Fig. 6. *examples of finder pattern*

Especially the identifiability of geometric forms, have an effect at the read-ability. Inaccuracies make the readability more difficult. Therefore, a minimum size of the code itself, especially of the finder pattern is necessary. Square shapes are more resilient and even with small sizes and reduced resolutions produce better results than rectangular or circular shapes (Figure 7).

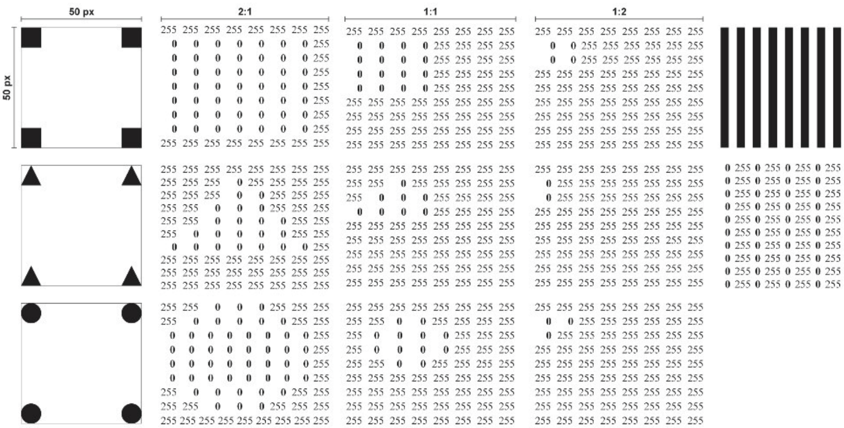

Fig. 7. *geometric forms and its identifiability*

The size of the modules (black and white) depends on the reliability of the code scan. The module size depends on the number of dots (dpi) in the printer head. "DENSO WAVE recommends for stable operations that each module is made up of four or more dots." – The number of dots increases the printing quality (Denso Wave, 2018). Another factor, which has an influence of the readability of the code, is the scanning distance and the pixel resolution.

Encode and Decode

First of all: What should be the functionality of my smart code?
There are many ways to encode information and implement them inside a fixed location. There are many encoding schemes (morse code, nautical signal flags, semaphore, binary, numbers to letter conversion and more). The focus here is on the 8-dot Braille characters (International Standard ISO/IEC 10646 - Unicode), which is used by people who are visually impaired.

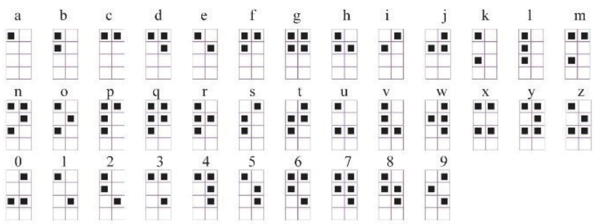

Fig. 8. *8-dot Braille characters*

For visually impaired people, the static content should also be readable manually. The static data should also be machine-readable for people who do not know the braille writing system. The dynamic part of the code is also machine-readable. An error correction is omitted in this paper, as this would go beyond the scope.

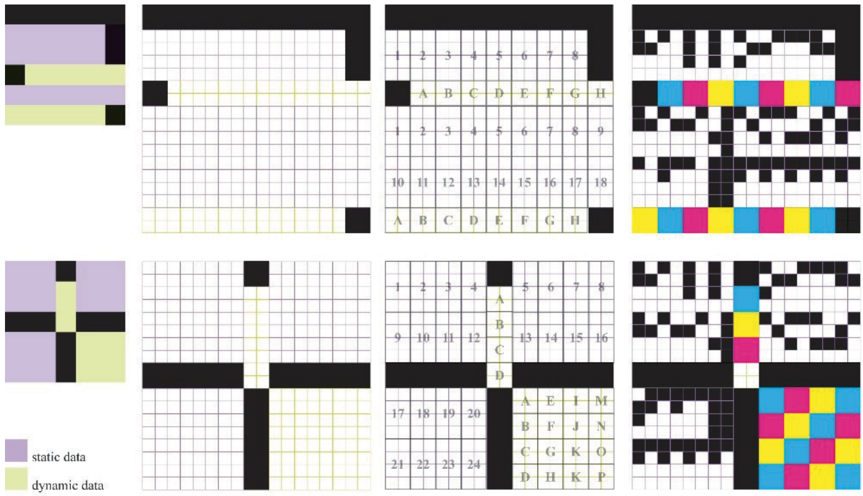

Fig. 9. *allocation of static and dynamic data*

The assignment of static (purple) and dynamic (green) data is shown in Figure 9. Here are two different prototypes of codes visualized. The finder pattern of both codes base on different systems. The upper code is bases on a horizontal black line (two black modules one below the other). Six black modules from the upper right corner continue this black line horizontally. This delimits the first static subarea in the code (segments: 1 - 8). - One segment bases on 8 bits. - A four black module square starts the dynamic section (A - H). This is followed by a large subarea for static data (1 - 18). Which also finds its end by the second dynamic section based on a four black module square (A - H). The finder pattern of the lower code divided by a black horizontal and vertical line, which is interrupted by the segment D (whitespace) in the middle. The code starts in the upper middle of the code, with four black modules, which form a solid black square. Below this square are four segments for dynamic data (A - D). The center of the code is divided by a black horizontal line, which is interrupted by the segment D, which is a quiet zone.

Color changing behavior of photochromic squares

Smart Materials such as the irreversible photochromic Prussian blue have a light detecting behavior – sensitive to light with a specific wavelength, such as UV-A light. The photochromic Prussian blue bases on a light-induced redox reaction. UV light activates a redox reaction at exposed areas, oxidize the citrate anion, and turns the trivalent (ferric) iron into divalent (ferrous) iron. It is compounded by adding ammonium ferric citrate and potassium ferrocyanide and dissolving the mixture in an aqueous solution. The resulting yellow-green solution is photosensitive (Roesky & Möckel, 1994).

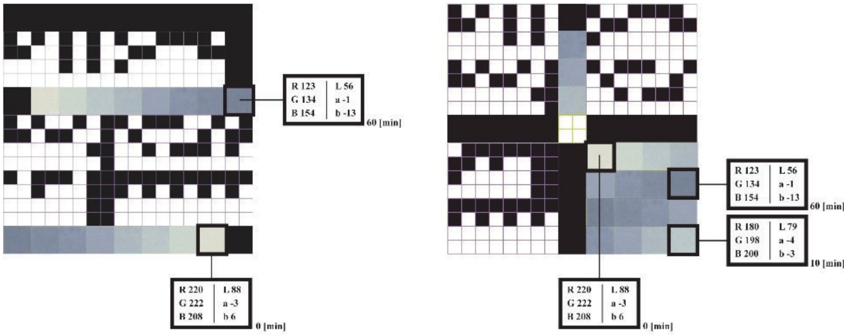

Fig. 10. *Color changing of photochromic squares*

Figure 10 shows the color changing process of the dynamic data of both prototyped codes. In the last experiments, the color changing behavior of the Prussian photochromic ink was already examined (Bilgin & Backhaus, 2018). Additionally, the influence of three different types of light sources were analyzed. The prototyped smart codes in Figure 10 where exposed every 5 minutes in a range of maximum 60 minutes by UV-light. Every colour-changing phase was measured through a spectral-densitometer (TECHKON SpektroDens) and a 2 MP camera (CMOS).

Inactive squares are yellow (0 min / L 88) and active squares are blue (60 min / L 56). The colour values were measured according to RGB (Adobe RGB, 1998) and CIEL*a*b. By focusing the L* values and RGB greyscale values, it is possible to store information about critical influences in a range from 0 (black) to 100 (white) in L* and in a range from 0 (white) to 255 (black). Therefore a smart device could identify the L*or RGB greyscale intensities of the different colour squares and compare them with the L* or RGB greyscale reference values and set the colour difference (ΔE) into correlation with duration and intensity of exposition by UV light.

	[min]	0	5	10	15	20	25	30	35	40	45	50	55	60
UV	R	220	207	189	174	163	156	149	140	137	131	128	126	121
	G	221	214	197	182	172	163	157	148	145	139	136	133	129
	B	208	205	199	188	183	181	176	168	166	157	155	150	150
	L*	88	85	79	74	70	68	65	61	60	58	57	55	54
	a*	-2	-5	-4	-3	-2	-1	-2	-1	-1	-1	-1	-1	-1
	b*	7	4	-2	-5	-8	-11	-12	-13	-11	-12	-12	-11	-13

Table 2. *Measurement of the photochromic Prussian blue: CIEL*a*b, RGB (Adobe RGB, 1998)*

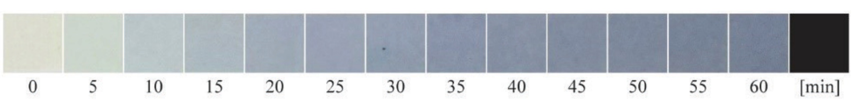

Fig. 11. *UV light exposed squares*

The respective color values in Figure 10 can be transformed into information about the intensity of a contamination. In the first example and upper and lower limitation of two conditions can be determined: $L^* < 79$ could be defined as a lower limit and $L^* > 79$ could be defined as an upper limit. A photosensitive switch could be realized, which displays a single on / off functionality after an exposure duration of 10 minutes. It is also possible to divide the data values into four equal groups (quartiles), to display different exposure durations such as 5, 15, 30 and 60 minutes exposure.

Conclusions

This paper was focusing on the developing process of a smart code. Individual barcode types, which are currently in use, were analyzed. The similarities and differences of the 2D codes and their various finder pattern were examined. Here, the characteristics of the geometric properties such as size shape and orientation was discussed to show how to identify the prototyped smart codes. The functionality of the components inside the codes were clarified, to understand the development process of a smart code. Hereinafter the attention was directed to the transformation of an image information of a QR and Grid Matrix code into binary information. When developing finder pattern, it is important that the markers stand out from the entire data set. Criteria have been set to define the properties of the codes. The detection of the position markers, static (information) and dynamic (smart materials) section was shown. Additionally, the color switching behavior of different photochromic squares inside two prototyped smart codes were analyzed. Color changings between its states (inactive to active states) were examined under the exposure of UV light. The respective color values were transformed into information about the intensity of a contamination. In form of an array with multiple printed smart materials in smart codes, the printable sensors can detect critical deviations. They can be visualized and transmitted via a common smart device.

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