Can QR Codes be used to readout Colorimetric Gas Sensors? A Back-Compatible Color QR Code with an Embedded CO2 Sensor Dye

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***Abstract*—Colorimetric dye readout devices have been explored extensively, with many approaches relying on complex hardware setups that stabilize the illuminant and capture conditions, typically involving attachments to smartphones or other digital cameras. In this work, we introduce a cost-effective sensor fabrication pipeline to embed a colorimetric dye in a QR Code, enabling readout by any standard smartphone without the need for specialized equipment. QR Codes, as established machine-readable patterns, offer a robust platform for integrating gasometric active dyes. Our approach ensures the preservation of QR Code data integrity by employing a novel method for maintaining back-compatibility throughout the pattern creation process, avoiding the limitations of dye placement solely in the center or outside the QR Code. We demonstrate this concept by embedding a CO2 sensor dye in a QR Code, while the QR Code presents a link to our website and a traceability ID. The dye is based on a pH-sensitive dye that changes color in the presence of CO2, focused on Modified Atmosphere Packaging (MAP) applications.**

***Index Terms*—colorimetric dyes, gas sensors, QR Codes, CO2 Sensors, machine-readable patterns**

I. Introduction

Food packaging industry has been developing solutions for food quality over the last decades. Most of the solutions consists of improving how to know the quality of the food contained in the packages. There exists two gold-standard methods to preserve food: modified atmosphere packages (MAP) and skin packaging. MAP works by replacing the air inside the package with a mixture of gases that will preserve the food for longer periods of time. While skin packaging, a vacuum sealing is performed to the food with a plastic film that will be in contact with the food. Despite this, there is an increasing need to assess the quality of the food inside the packages, and this is where atmospheric sensors come into play [1].

In parallel, the industry has also grown a consciousness about the environmental impact of the packaging, and wants to keep track of the food supply chain. This is where QR Codes came into play. As of today, there exists several proposals on how to use QR Codes to track the food supply chain, i. e. Dey et a. have proposed using QR Codes and blockchain [2]. Often, such traceability methods rely on the digital information of QR Codes to track the food supply chain, this is why the data inside these QR Codes is important. Here we propose a back-compatible Color QR Code which does not break the QR Code standard and preserves the data within the codes [3].

We present an improvement over other similar machine-readable patterns, i.e.: we presented a previous version of these codes without any digital data at all [4]; or, Escobedo et al. presented a similar approach with digital data, despite that tinkered with the digital data and computer vision patterns of the QR Code, which can be seen as non-back-compatible for some smartphone decoders [5]. Our new Color QR Code can embed colorimetric dyes; such as a CO2 sensor dye [6]. Moreover, the Code QR Code embeds a hundred color modules to act as color references to be able to perform colorimetric readouts from the QR Code using advanced color correction techniques [7].

In order to demonstrate our approach, we fabricated our sensors combining ink-jet –QR Code patterns and reference colors– and screen-printing –gasometric sensor–. Later, we submitted the sensors to different environmental conditions resembling those from Modified Atmosphere Packaging (MAP) and captured the images with a digital camera sensor, within a controlled variable light setup [8]. All in all, we demonstrated the use of this technique, reducing the relative error from random illumination capture conditions from 440% to 14%.

II. Experimental design

A. Color QR Code specification

We designed a back-compatible Color QR Code [3] (see Fig. 1) following the subsequent specifications:

- A version 3 QR Code, this is the QR Code contains up to 29 $\times$ 29 modules;
- with an embedded URL: c-s.is/#38RmtGVV6RQSf, which contains a unique ID, which can be used to track the QR Code;
- with an error correction level H (30% error correction);
- with a colorimetric dye printed above the lower finder pattern –represented here as seven purple modules–;
- and, 125 color references placed in the rest of the QR Code, but specially in the data zone in a back-compatible fashion.

The machine-readable pattern was printed using a common ink-jet printing machine, on top of polypropylene-coated white card stock. The printed pattern measured 1 $\times$ 1 inches (see Fig. 2).

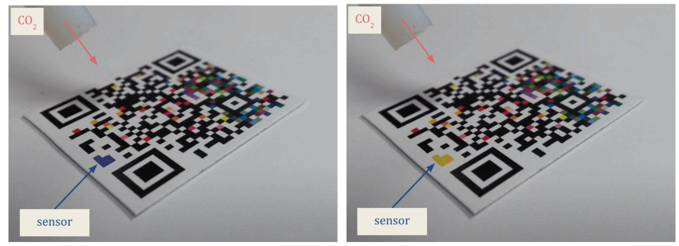
Fig. 1: A back-compatible Color QR Code for the evaluation of colorimetric indicators. This QR Code is read by commercial scanners and should display the URL: c-s.is/#38RmtGVV6RQSf, includes up to 125 reference colors and the colorimetric dye is printed above the lower finder pattern, represented here as seven purple modules.

Later, colorimetric dye was formulated following Zhang et al., mainly based on a combination of *mCP* (meta-Cresol Purple) and *PR* (Phenol Red) [6], which was printed using a screen-printing method. Figure 2 shows the final result of printing the device with both layers. Active modules of the Color QR Code turned from purple to yellow in presence of CO_2 (see Fig. 2).

B. Environmental conditions

We exposed the sensor to different environmental conditions, resembling those from Modified Atmosphere Packaging (MAP), where CO_2 is present in higher ranges than in the atmosphere, i.e. 20% - 50% [9]. We used a chamber with controlled CO_2 concentration, and a variable light setup to simulate the light conditions of a smartphone camera.

The station incorporated a *mass-flow control* system that provided modified atmospheres to a chamber with an optical port where the gas sensors were placed. The colorimetric indicator was exposed to a series of pulses of different controlled atmospheres. The sensors were exposed to 15 gas pulses, each lasting 100 minutes. One pulse consisted of exposing the measurement chamber with the target gas CO_2, for 30 minutes, followed by a 70-minute exposure to synthetic air (21% oxygen, 79% nitrogen) to return to a CO_2 free atmosphere state, both states exposed to a relative humidity of 40% (see Fig. 3).



(a) (b)

Fig. 2: The sensor is exposed to concentrated CO_2, like a Modified Atmosphere Packaging (MAP) environment. The dye changes from purple to yellow when exposed to CO_2, while common ink remains the same. (a) Sensor without exposure to CO_2. (b) Sensor after exposure to CO_2.

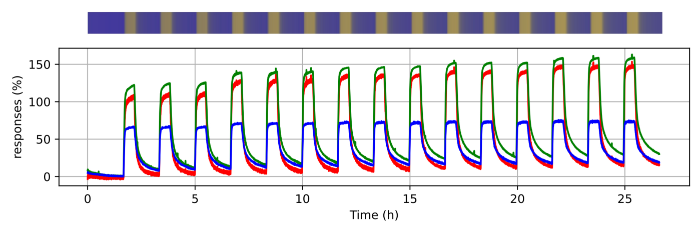


Fig. 3: The response of the sensor to a series of CO2 concentrations.

As for the light conditions, we used a controlled variable light setup, with a 5000K LED light source, and an 8M pixel digital camera sensor, similar to those used in smartphones [8]. We captured the images of the sensors in the chamber with the controlled light setup (see Fig. 4).

(a) (b) (c)

Fig. 4: A printed machine-readable pattern featuring a Color QR Code and a colorimetric indicator inside the sensor chamber. The image shows the Color QR Code before exposure to the target gas under three different light conditions: 2500 K (a), 4500 K (b), and 6500 K (c).

C. Color calibration and sensor measurement

In this work, we expected the sensor to behave following a linear model with the logarithm of the concentration, similar to other pH-sensitive dyes, i.e. NH_3 [4]. Before submitting the measures to a model, we proposed two different baseline corrections to check the quality of the color correction. First, a *raw* baseline, which consisted in fitting the model colorimetric model without performing any color correction. Then, we performed a *white-balance* correction, which is the simplest affine color correction, to obtain a second baseline. Finally, we performed a general affine color correction as our candidate method to correct the colorimetric readout [7].

III. Results

Results showed the green channel of the colorimetric sensor increased its signal with the increase of gas presence. The sensor responded linearly with the logarithm of the concentration, as expected. This is true for each of the 9 different light conditions tested. As it can be seen in Fig. 5.a. Changing the illuminant conditions on the sensor proved to be critical damage to the sensor readout, as the model fitted really poorly, with a R^2 metric of 0.04. Reproducing here the main problem of using colorimetric sensors with digital cameras in the wild. This marked the first *raw* baseline of results.

After applying the second baseline method, *white-balance*, we found this baseline to easily broke through *raw* results. The model fitted better, with a R^2 metric of 0.56. Despite this, the relative error of the model was still too high to consider this a functional sensor. The relative error of the sensor was 90% and 102% for the 20% and 50% concentration levels, respectively (see Table I).

Finally, we applied our general color correction consisting in an *affine model* to the sensor readout. The model fitted better, reducing the relative error to 14% and 16% for the 20% and 50% concentration levels, respectively. The model fitted with a R^2 metric of 0.98, which is a good result for a colorimetric sensor. This marked the third baseline of results, and the best one. The relative error of the sensor was 3% and 8% for the 20% and 50% concentration levels, respectively (see Table I).

TABLE I: This table summarizes the metrics for fitted gasometric models for the two baselines (raw data and white-balance) and for our color correction method (a general affine color correction). The model parameters are as follows: m, n and r^2 –from linear model fitting–, Δc_{20}, Δc_{50}, ϵ_{20}, ϵ_{50} –resolution and relative error at specific concentration levels.

Metrics	***Raw model***	***White-balance model***	***Affine model***
m [%/%]	90 ± 80	101 ± 19	100 ± 3
n [%]	200 ± 130	-17 ± 31	-19 ± 5
r^2 [-]	0.04	0.56	0.98
Δc_{20} [%]	88	18	3
Δc_{50} [%]	249	51	8
ϵ_{20} [%]	440	90	14
ϵ_{50} [%]	497	102	16

IV. Conclusions

Our study tackled one of the major challenges to implementation of colorimetric sensors in modern-day digital cameras. We demonstrated how a simple color correction method, like a generic affine color correction, can solve the color consistency problem. But, we focused also in demonstrating that only correcting with one color reference (white) is not enough (approx. 100% relative error) [5].

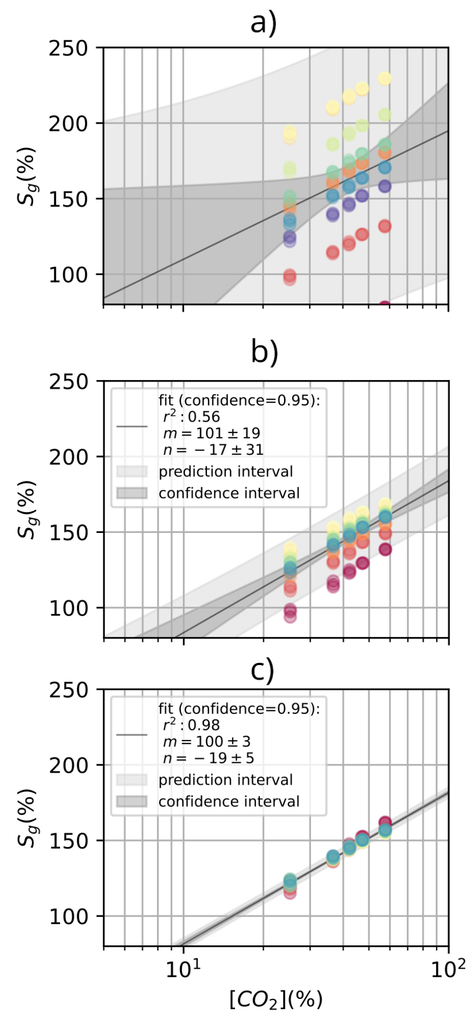


Fig. 5: Linear fitting of the logarithm of the concentration against the response of the green channel of the sensor. a) Raw model, b) White-balance model, c) Affine model.

Moreover, we presented a miniaturized sensor based on a back-compatible Color QR Code, which can be printed in the size of a thumb (one inch per one inch) [3]. This kind of pattern can be further applied to other colorimetric dyes, such as NH_3 or CH_2O [4, 10]. Taking advantage of QR Codes can enable these kinds of sensors to be attached to challenging surfaces as well, such as bottles or food packaging [11].

Following up this work, color correction could be improved upon more complex color correction methods: such as polynomial [12] or spline color corrections [13]. But, we found that a generic affine color correction was sufficient to solve the color consistency problem for this work.

All in all, our method presented a systematic way of embedding color references alongside with colorimetric dyes in a machine-readable pattern, which can be used to readout colorimetric sensors. This is a good solution to solve the color consistency problem, and can be applied to other colorimetric sensors in the future.

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