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Smartphone Modulated Colorimetric Reader with Color Subtraction

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Abstract— Color analysis has been essential for the interpretation of optical readouts, e.g. colorimetry, fluorescence, spectroscopy, and scanometry. However, existing colorimetric readers can hardly eliminate the color interference of colored solutions, e.g., interpreting pH test strips to assess the pH value of red wine. This paper introduces a smartphone modulated colorimetric reader that is compatible with most smartphone models and a novel color subtraction algorithm that eliminates color interferences due to colored solutions. Experiments were conducted to validate the effectiveness of the developed reader and algorithm on evaluating pH test strips produced from transparent and colored solutions using multiple smartphone models. Applicability of the developed reader was demonstrated through its interpretation of pH test strips measuring pH values of colored and non-transparent food samples including red wine and milk.

Keywords—*smartphone; colorimetry; color subtraction; versatile; low-cost; portable*

I. INTRODUCTION

Thanks to the rapid development of smartphone platforms in recent years, a rapidly increasing number of smartphone colorimetric readers have been developed to enable and popularize practical food analysis [1], point-of-care [2], and environment monitoring [3] by novice end-users in everyday scenarios. However, most smartphone optical readers reported in the literature can only be attached to one specific smartphone model, limiting their versatility and generating a gap between research and practicality [4][5]. Also, most of the developed readers can only work with transparent buffer solutions despite the fact that colored solutions are very common in real-life and need to be considered [6][7]. Giving red wine as an instance, monitoring the pH of red wine is essential during wine making. However, by far measuring the pH of red wine is only possible by using an electrochemical pH meter since the red color of red wine will greatly interfere with the interpretation of the pH test strip. Even worse, the pH of the colored solution would be impossible to be measured by a novice end-user if the sample volume is too limited to immerse the sensing probe of an electrochemical pH meter.

To enable an interpretation of pH test strips produced from red wine, the color of red wine needs to be subtracted from the color of the absorption pad on the pH test strip. Color perception is originated with light-material interactions under the spectral domain. However, color intensity of the image taken by a smartphone is usually nonlinearly related to scene

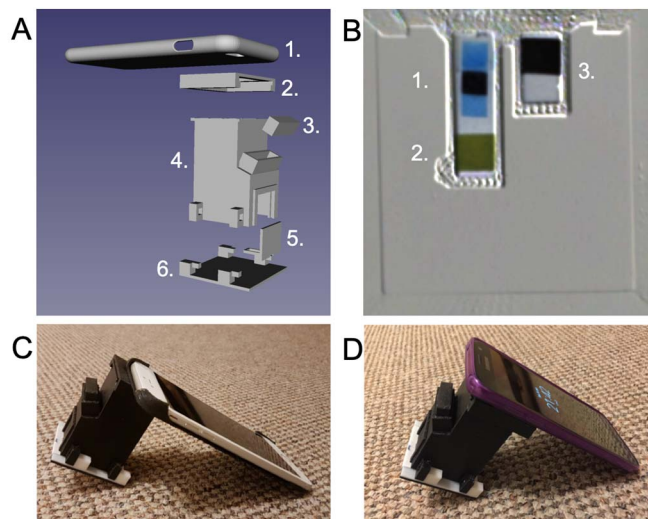


Fig. 1. A) Components of the modulated smartphone apparatus including a (1) smartphone case, (2) light-box connector, (3) external light-source, (4) light-box, (5) assay platform adaptor, and (6) bottom panel. B) An illumination corrected image taken by our reader with a (1) solution color catcher on (2) a pH test strip and (3) dark/light references for color intensity matching. C) and D) demonstrate our reader being installed on an iPhone and Android smartphone.

radiance in the spectral domain after applying the Camera Response Function (CRF) [8]. Therefore, color intensity of image needs to be linearized by a reverse CRF before it can be used for color subtraction.

A correlation between the original color of the absorbing pad and color of the pad after absorbing colored solution was observed yet not considered by the current color subtraction method [9]. Color subtraction performance will be improved by an interpretation of such correlation.

In this paper, we demonstrate a smartphone modulated colorimetric reader (SMCR). The reader consists of two parts: a 3D-printed smartphone apparatus for light normalization and a smartphone App for providing user interfaces and data handling. The modulated smartphone apparatus is compatible with most smartphone models and is capable of supporting various light sources (e.g. visible and UV LEDs) and assay platforms (e.g. test strip, lateral flow, and microfluidics devices). For the first time, the developed reader is able to interpret pH values of colored solutions (e.g. red wine) by using improved pH test strips and applying a novel linear interpreted color subtraction algorithm.

II. PROPOSED METHOD

A. Fabrication of Special pH Test Strip

Small pieces of paper named solution color catcher (SCC) were prepared and installed on traditional pH test strips. They were cut from filter papers (Fisherbrand, France), half black-drawn by a permanent marker (Staedtler, Germany), and attached to the pH test strips above their absorption pads. The SCC were dipped into a solution together with the absorption pad of the pH test strip, collecting the color of the solution through both empty and black-drawn parts of the SCC. An example of SCC is shown in Fig. 1B.

B. Smartphone Apparatus and Application

The smartphone apparatus was modulated into four major parts: a commercial smartphone case attached with a light-box connector that robustly secures the reader-to-smartphone bonding and also enables compatibility for different smartphone models, a light-box that normalizes light condition, a light source adapter that supports various light sources (e.g., UV LED for fluorescence excitation and visible light LED for colorimetry), and an adapter to accommodate different assay platforms (e.g., dip strip, lateral flow device, and microfluidics). A CR-10 fused-deposition modelling (FDM)-based 3D-printer (Crealty3D, China) was used to manufacture the apparatus using polylactide (PLA) material. LED diffuser was printed using clear methacrylate-based photopolymer resin with a stereolithographic-based 3D printer, Form 2 (Formlabs, USA). Different parts of the prototype can be easily assembled together by a simple clicking mechanism. Breakdown of the overall design is visualized in Fig. 1A.

Smartphone applications (Apps) running on both Android and iOS operating systems [10] were developed to provide user interfaces (e.g. taking photos, handling user interactions, and displaying results). Data processing (e.g. image analysis, signal processing, and database related operations) was handled by a backend service [11] deployed on a local or cloud server that interacts with the Apps through RESTful APIs [12].

To interpret color accurately and quantitatively, the data processing pipeline consists of procedures including camera radiometric calibration, illumination correction, color subtraction, and parametric color regression.

C. Camera Radiometric Calibration

Several techniques are available to estimate the reverse CRF from a single image. They work by analyzing histograms [13], geometry invariants [14], color blending in edge regions [15], probabilistic intensity similarity [16], or noise distribution [17].

The camera radiometric calibration technique proposed by Lin et al. [15] was used to measure the reverse CRF using only a single image. This technique measures the color intensity nonlinearity at the edge of imaged objects where color blending takes place. The nonlinearity was estimated by maximizing the response function g :

$$g = \arg \max p(g|\Omega) = \arg \max p(\Omega|g)p(g)$$

where $p(\Omega|g) = \frac{1}{Z} \exp(-\lambda D(g; \Omega))$ is the likelihood function exponentially composing distances between the nonlinear and linear CRFs, and $p(g)$ is the Gaussian mixture model.

The Empirical Model of Response (EMoR) generated by applying Principle Component Analysis (PCA) on a large real-world CRF dataset [8] was selected to model the nonlinearity of color intensity as it outperformed the other compared models described previously [14].

D. Illumination Correction

To tackle imaging defects due to illumination (e.g. nonuniform distributed illumination and illumination color inconsistency [18]), camera lens (e.g. vignette [19]), image sensor (e.g. color shading [20]), and dust on the camera, color of a test image was illumination corrected by a background image using the Spectral Nonuniform Illumination Correction (SNIC) algorithm proposed in [18]:

$$R_T = R_B \cdot \frac{\mathcal{F}^{-1}(D_T)}{\mathcal{F}^{-1}(D_B)}$$

where \mathcal{F}^{-1} is the reverse CRF, R_T and R_B are albedo of the materials in test and background images respectively, and D represents pixel value.

E. Color Subtraction Algorithm

Since color intensity of an image has been linearized with scene radiance, color in this spectral domain will follow the law of subtractive color mixture as for scene radiances [9] as summarized by Algorithm 1.

Algorithm 1 Color subtraction algorithm

Input: Sensor correction ratio r . RGB color value of the absorption pad \mathbf{t} , empty part of SCC \mathbf{x} , and original color of the empty part of SCC \mathbf{y} .

1. $\mathbf{t} \leftarrow \mathbf{t} \cdot r \cdot \mathbf{y} / \mathbf{x}$

Output: Color \mathbf{t} after color subtraction.

An improved algorithm was proposed based on Algorithm 1. The color of the solution on the absorption pad was predicted by linearly interpolating the two colors collected by the SCC. The corrected color was calculated by subtracting the color of absorption pad with the interpolated color of colored solution:

Algorithm 2 Linear interpolated color subtraction algorithm

Input: Sensor correction ratio r . RGB color value of the absorption pad \mathbf{t} , empty part of SCC \mathbf{x} , dark part of the SCC \mathbf{m} , and original colors of the empty and dark parts of SCC \mathbf{y} and \mathbf{n} .

1: $s, i \leftarrow$ linear regression on $\{(y, x/y), (n, m/n)\}$

2. $st \leftarrow \mathbf{t}$

3. **for** $j = 1$ **to** N **do**

4. $st \leftarrow \mathbf{t} \cdot r / (s \cdot st + i)$

Output: Color st after color subtraction.

A loop was included in Algorithm 2 to iteratively converge the result to its optimal value. $N = 3$ was empirically selected in this work.

F. Regression Model

Firstly, colors of the image were converted from RGB to LAB color space. For training and predicting, the three-dimensional fourth-order (3D-4O) polynomial was empirically selected as the regression model. Its hypothesis is:

$$h_\theta(\mathbf{x}) = \sum_{i=0}^N \sum_{j=0}^{N-i} \sum_{k=0}^{N-i-j} \theta_{ijk} x_1^i x_2^j x_3^k$$

where θ is the parameter vector, $N = 4$ is the order number, and \mathbf{x} is the three-dimensional color vector. Adam optimizer [21] was used to minimize the following cost function and calculate the optimal parameters:

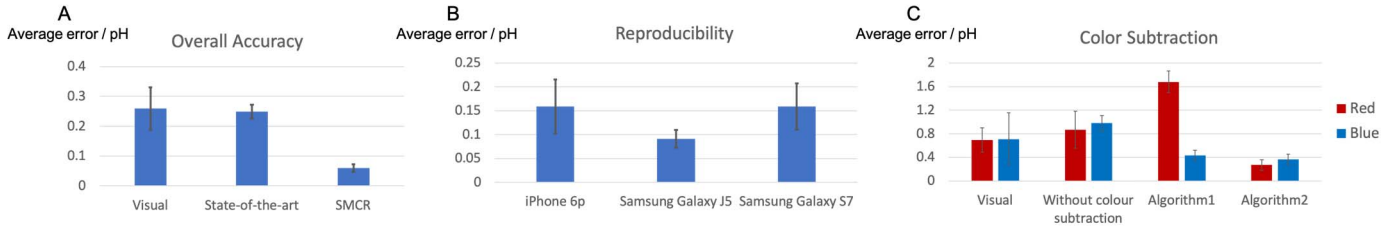


Fig. 2. A) Accuracy of pH test strip interpretation using transparent buffer solutions. B) pH test strip interpretation using three different smartphones at different times and locations. C) Performance of color subtraction with red and blue colored solutions.

$$\mathcal{J}(\theta) = \frac{1}{2m} \left[\sum_{i=1}^m (h_{\theta}(x^i) - y^i)^2 + \lambda \sum_{j=1}^n \theta_j^2 \right]$$

where m is the number of training data and λ is the regularization parameter. The optimal regularization parameter was chosen through a k -fold cross-validation using $k = 3$ [22].

III. EXPERIMENT

pH test strips were widely used for the validation of portable colorimetric devices [23][24][25]. Five experiments ($n = 3$) were designed and conducted to validate the developed SMCR using pH test strip. pH test strips (Home Health, UK) with a pH range of 5.0 to 8.5 were selected to validate the reader except for Experiment 5. pH test strip (Precision Laboratories, USA) with a pH range of 2.8 to 4.4 was selected for Experiment 5. They were dipped into solutions, dried for 1 minute and 10 seconds respectively for two different types of pH test strips, placed into the reader, and photographed. pH values measured by a lab-based 3510 pH meter (Jenway, UK) were used as the true values. Human visual interpretation ($n = 3$) was measured by people with normal color discrimination ability.

The first experiment validates the accuracy of the reader using an iPhone 6 Plus, its flashlight, and transparent buffer solutions (pH 5.0 to 8.3 with a step of 0.3). The second experiment validates reproducibility of the developed reader using three different smartphones, external white LEDs, and the same transparent buffer solutions as in Experiment 1. The third experiment examines the performance of the proposed Algorithm 2 on removing color interference caused by colored solutions. Red and blue colored buffer solutions (pH 5.0 to 8.3 with a step of 0.3) were used for this experiment. Experiment 4 demonstrates applicability of the reader by interpreting the pH test strips measuring the pH values of six milk samples exposed at room temperature for different days whilst Experiment 5 validates that by measuring the pH of three different types of red wines using Algorithm 2.

As shown in Fig. 2A, the result of Experiment 1 indicates that our reader has achieved an approximately 4-fold better

accuracy compared to both human visual interpretation and that of a state-of-the-art smartphone pH test strip reader [23] in terms of average error in pH values.

Fig. 2B shows the result of the reproducibility test using three different smartphones performed at different times and locations. Two high-end smartphones (iPhone 6 Plus and Samsung Galaxy S7) produced a lower accuracy probably due to the more sophisticated image post-processing operations integrated in the imaging pipeline designed to improve visual quality. However, these operations downgrade the accuracy of the colorimetric analysis.

The effectiveness of the proposed color subtraction algorithm is demonstrated in Fig. 2C. Algorithm 1 showed instability across colors while prediction accuracies of pH test strips produced from both red and blue colored solutions were tremendously improved by applying the proposed Algorithm 2.

In Fig. 3A, it has shown that the pH change of milk across six different days can be roughly monitored using the developed device. Also, the experimental results in Fig. 3B indicates that the pH of red wine can be much more accurately tested by applying the proposed color subtraction algorithm.

IV. CONCLUSION

In this paper, a smartphone modulated colorimetric reader is reported enabling colorimetric analysis by most smartphone models, different external light sources, and multiple assay platforms. A color subtraction algorithm was proposed to remove color interferences due to colored solutions. Performances of the developed reader such as accuracy, reproducibility, and applicability were demonstrated through five experiments. For the first time, the smartphone reader was used to interpret pH test strips produced from red wine.

The results have indicated that the developed smartphone colorimetric reader is a versatile, accurate, and applicable device to be used by novice end-users. Also, there is great potential for this device to be used for the optical interpretation of biosensors (e.g. lateral flow and microfluidic devices) with real food matrices.

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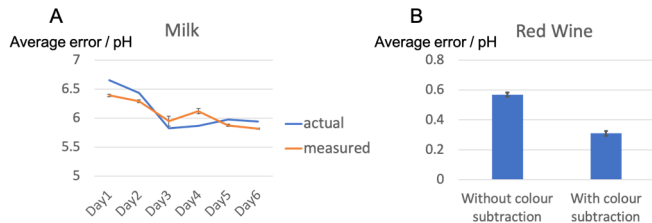


Fig. 3. A) pH monitoring of six milk samples exposed at room temperature for different days. B) Interpretation accuracy of pH test strips produced from red wine with or without applying color subtraction.

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