Automated Mobile pH Reader on a Camera Phone

B.Y. Loh, N.K. Vuong, S. Chan and C.T. Lau

***Abstract*—A robust classification algorithm that applies color science and image processing techniques is developed to automatically identify the pH level on a test strip. This algorithm is implemented on a camera phone that captures color images of pH test strips for healthcare or medical purpose. The pre-installed and platform independent program in the camera cell phone then processes the images captured and is able to inform visually-challenged users of the pH level of the strip. Experimental results show that this new approach is more robust and efficient in handling reflection, skewed placements, as well as different types of color reference.**

***Index Terms*—pH test, color image processing, mobile application.**

I. INTRODUCTION

pH tests are commonly used in chemical laboratories to measure the acidic or alkali levels of solutions. pH levels typically range from 1 to 14 with 7 being neutral; 1 is highly acidic and 14 is highly alkaline. In medical practice, pH tests are also used as a health indicator for human beings due to the fact that the body fluids of a healthy person should neither be too alkaline nor acidic [1]. For instance, the pH of a healthy body's blood, saliva and spinal fluid is at 7.4. Other readings from 7.0 to 7.5 indicate that the person is non-deficient and healthy while a reading from 4.5 to 6.5 indicates calcium deficiency of aging and lifestyle defects [2]. pH tests are also used for urinalysis. A highly acidic urine pH can be due to diabetes, diarrhea, dehydration and other ailments. Conversely, highly alkaline urine may be signs of chronic renal failure, urinary tract obstruction, respiratory disease and other diseases [3]. Thus, monitoring the pH level of body fluids such as saliva or urine is a simple and effective way to check for early indication of degenerative diseases which are caused by unhealthy acidic or alkaline levels in the body. An individual can then adjust his or her diet to maintain the body's pH at healthy levels, or seek medical treatment if necessary.

The equipment used to measure pH levels range from the simple litmus papers to electronic pH meters. Litmus papers are affordable, easy to use and could be easily purchased from various retail outlets. Therefore, it is widely used by medical professionals and consumers to determine the human's body pH level simply by dipping a pH test strip in the fluid. The pH level is indicated by the color change on the test strip. By visually comparing the test strip's color against a color reference, the pH level of the fluid under test is known. For example, orange is level 3, green is level 7 and blue is level 10. However, some of colors in the reference color chart are very similar to each other, which may potentially cause problem in identifying the right pH level using just the human eyes. For individuals who find it difficult or impossible to compare the colors visually, especially the elderly and color blind, we propose a convenient solution using a camera phone - a device that many people own and use in their daily life nowadays.

We have earlier developed and presented a novel assistive technology system for measuring and classifying pH levels from a digital camera phone image [4]. Various steps have since been taken to enhance the robustness of the system [5,6]. Fig. 1 shows the overall structure of the system.

An image of the pH test strip and the color reference chart is first captured by a mobile camera phone. The image processing unit (IPU) running on the J2ME enabled mobile phone that supports the MMAPI extension classifies the pH level by matching the color of the pH test strip with one of the colors on the reference chart. The result of the automatically identified pH level is displayed on the phone. At the same time, the pH result can be stored in the phone or transmitted to the doctors to seek further medical attention if necessary.

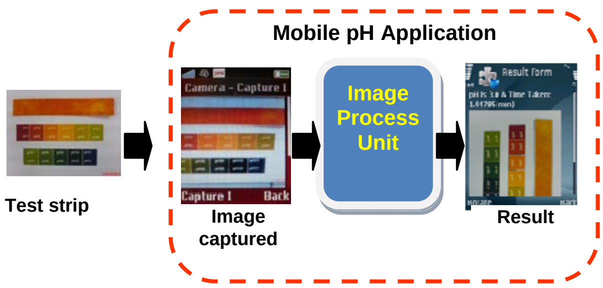

Figure 1. Structure of the proposed mobile pH application

The mobile pH application aims to provide assistance to individuals who monitor their body fluids for medical and healthcare reasons. This tool is particularly helpful for color-blind patients and elderly people with poor eye sight. It is also beneficial to those with normal eyesight but have difficulties in distinguishing colors that are similar. This automated application may also be helpful to medical professionals such as nurses or doctors who have to conduct and interpret numerous tests daily. Additionally, the proposed system has several advantages. Firstly, it does not incur much cost since it requires no special hardware other than the camera phone itself. Moreover, it is easy to use with no technical skills required. Thirdly, this software solution can be readily integrated into a comprehensive mobile healthcare system to provide holistic service which can be

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customized for individual patients. Most importantly, this software tool enables patients to monitor their health regularly in the comfort of their home thus saving time and money that would otherwise be incurred for medical consultations and laboratory visits.

II. PREVIOUS WORKS

The pH test kit comes with both rectangular and circular color reference charts (Fig. 2 and 3). Earlier works [4-6] applied color science and image processing algorithms to identify the correct pH level using rectangular charts (Fig. 2). The original approach we employed to process images of the pH test strips [4] was based on edge detection filters. First, we applied Sobel edge detection to locate those pixels on the edges of the test strip and the color reference strips. Subsequently, simple scan-line and thresholding techniques were used to determine the boundaries of the test strip and the color targets. Eventually, we classified the strip's pH level by measuring color distances between the strip color and color targets. The color patch that had minimum color distance from the one of the test strip revealed the pH level of the test strip. Experimental results produced by the edge detection based (EDB) approach were consistent with the ground truth estimation [4]. However, the EDB algorithm could not process images whose test strips were skewed more than 7 angular degrees to the horizontal axis.

Figure 2. Sample Test Image with Rectangular Color Reference Chart

We then developed an improved approach known as CQB [5] based on Wu's color quantization [7]. It comprised two steps. The first step was to quantize the entire color set in the original image to two clusters in order to remove the background as well as some noise. Next, using the prior knowledge of the number of color patches in the test image, we again quantized the colors in the residual image to 11 clusters (see Fig. 2). The cluster with the largest number of pixels was thus identified as that of the pH test strip. The computation speed of this approach was about 20 times faster than EDB. It was also able to handle test strips that were placed in skewed orientations. However, this method did not work well if parts of the image suffered from reflection. Also, CQB did not explicitly identify the numerical pH level but relied on the user to view the result from the residual image displayed.

To overcome the above limitations, we propose a new approach (Sequence Based approach or SB) that can robustly handle images in which the test strips are placed in a skewed manner or images that are partially affected by reflection. First, we use the approach similar to EDB to obtain the boundaries of the test strip and the color reference strips. Next, we use K-means clustering to separate the edge points into three clusters. Using prior knowledge of the relative lengths of the color reference and test strips, the edge points are automatically identified as three separate sets: one belonging to the test strip, one belonging to the longer color reference strip (pH1-6) and the last one belonging to the shorter color reference strip (pH7-11). This step contributes a major improvement over the previous algorithm because its function is robust even when the strips are placed in a skewed manner. Next, the color reference strips are further partitioned into 11 segments (pH1-11) using the edge points obtained earlier. With prior knowledge of the colors in the color reference strips, a color lookup table is then used to recognize the color reference segments. This is an important enhancement as it helps to recognize the color reference strips even when they are placed in arbitrary orders or orientations. Moreover, by matching against the color lookup table, even if one or two segments of the color reference strips are affected by reflection or other illumination effects, the reference strips can still be correctly identified and the color distortions of the affected segments can be rectified. This greatly improves the robustness of our algorithm. In the final step, the average color of the test strip is matched to one of the 11 color segments in the reference strip to automatically identify the test strip's pH level.

One of the advantages of the enhanced SB approach is it also can be used to process test images with circular reference charts (Fig. 3). In fact, we have applied similar processing techniques of SB approach and successfully identified the pH level of images that come with circular-shaped reference chart. The method used comprises edge detection techniques accompanied by corner detection methods to locate the positions of the color reference chart and the test strip. Thereafter, post color processing and filtering are done to the region of interest to evaluate the pH value of the test strip. The processing techniques for two categories of images (rectangular and circular reference charts) together with their experimental results will be discussed in the next sections.

Figure 3. Circular Color Reference Chart

III. IMAGE PROCESSING UNIT

The image captured by the phone camera will go through the sequence of processes as shown in Fig. 4.

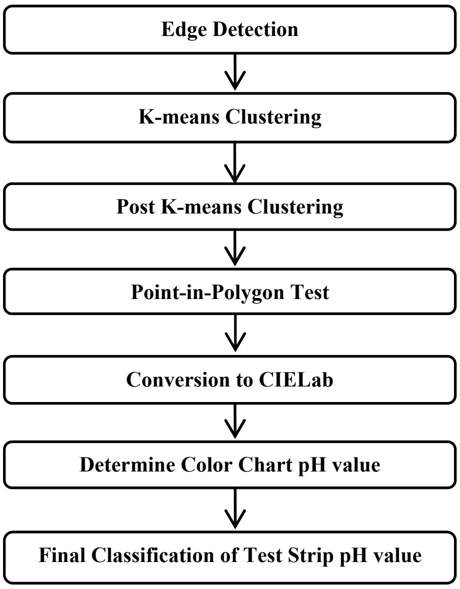

Figure 4. Sequence of operations in the IPU

A. Edge Detection

The IPU begins with Sobel Edge Detection (SED) [8] on the image captured. SED is generally used for grayscale images and modification to the algorithm is required for it to be used on color images. The modified process depicted in Algorithm 1 is obtained from J2ME-EDB approach [4].

Input: Color image, *Th* and weight w_i where $0\leq w_i\leq 1$ for each color band *i*
Output: Binary image containing edges for the input image

1. $G_x = \begin{bmatrix} G_{x1} \\ G_{x2} \\ G_{x3} \end{bmatrix} = \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix}$, $G_y = \begin{bmatrix} G_{y1} \\ G_{y2} \\ G_{y3} \end{bmatrix} = \begin{bmatrix} +1 & +2 & +1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix}$
2. **for** each 3x3 image sub-area $\begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} & z_{13} \\ z_{21} & z_{22} & z_{23} \\ z_{31} & z_{32} & z_{33} \end{bmatrix}$ of the input color image:
3. **for** each color band i:
4. compute: $\dfrac{\partial f}{\partial x_i} = G_{x1}(Z_{1i})^T + G_{x2}(Z_{2i})^T + G_{x3}(Z_{3i})^T$
5. and $\dfrac{\partial f}{\partial y_i} = G_{y1}(Z_{1i})^T + G_{y2}(Z_{2i})^T + G_{y3}(Z_{3i})^T$
6. compute: $|f| = \sqrt{\left(\Sigma w_i \left|\dfrac{\partial f}{\partial x_i}\right|\right)^2 + \left(\Sigma w_i \left|\dfrac{\partial f}{\partial y_i}\right|\right)^2}$
7. **if** $|f|\geq Th$ **then** mark the pixel z_{22} as an edge pixel
8. **else** z_{22} is a non-edge pixel
9. **return** binary image containing only edge or non-edge pixels for the input image

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Algorithm 1. Pseudo-code for SED of color images

The output of SED produces an image that outlines all the edges. A further processing returns a set of XY coordinates which identifies all the edge pixels in the image. The results of images with rectangular and circular reference charts after applying SED are shown in Fig. 5.

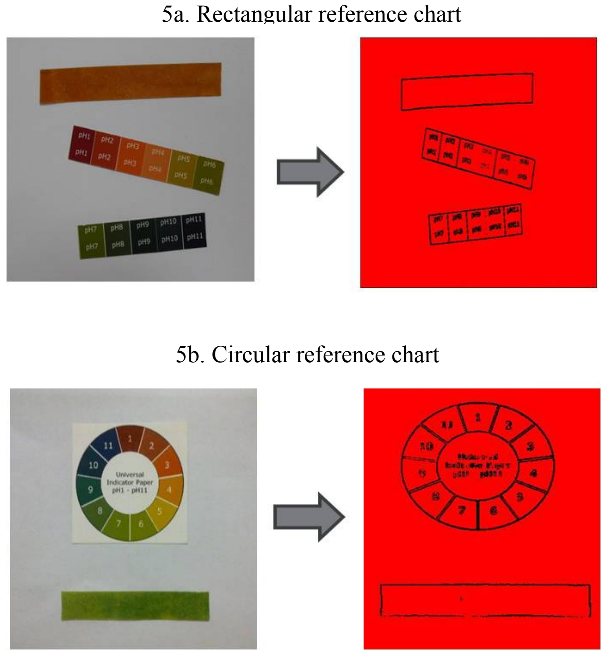

Figure 5. Results after applying SED

B. K-Means Clustering

K-means Clustering is a cluster analysis method that separates a set of points into *k* clusters or regions where each region has a centroid. An integer *k* representing the numbers of centroids is first chosen. Next, the distance of a point to a centroid is calculated. Each point has *k* distances to *k* centroids. A region consists of all the points that are nearest to the cluster's centroid. At the end of this first iteration, all the points in a region are used to calculate the new position of the centroid. The process is repeated by computing the distance of each point to the new *k* centroids. The iteration stops when there is no change to the points in each region as illustrated in Fig 6.

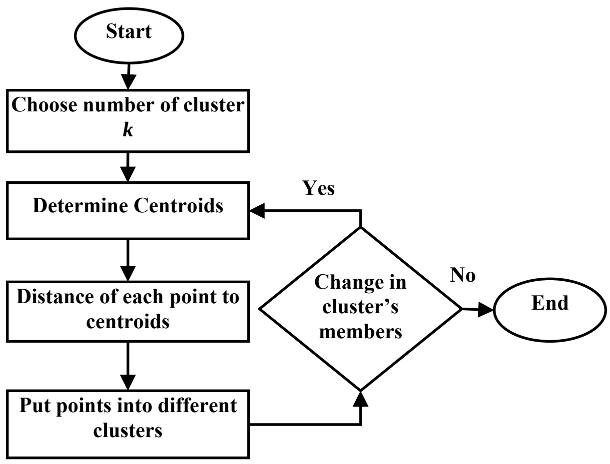

Figure 6. K-means clustering algorithm

In our application, we set k = 3 regions for images with rectangular reference chart; namely Test strip, Color reference pH 1-6, Color reference pH 7-11. Using *k*-means clustering, we are able to determine the bounding areas of each strip in 3 iterations as shown in Fig 7.

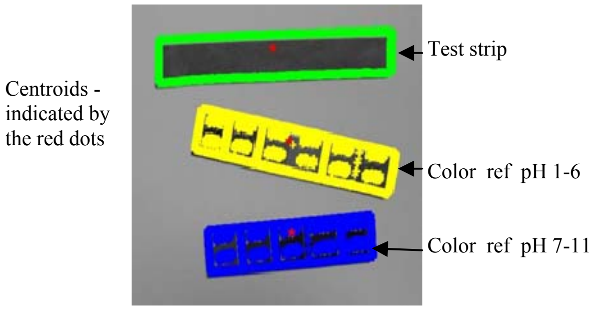

Figure 7. Complete clustering in 3 iterations

We realize that applying K-means clustering on images with circular reference chart is not necessary as such images contain only the test strip and the color chart. After using SED, we can determine the four corners of the test strip by using corner detection technique, which is presented in the next processing step. Those pixels which belong to the color chart can be deduced after separating the rectangular test strip.

C. Post K- Means Clustering

1) Images with Rectangular Reference Color Chart

After separation of all points into 3 regions, the 4 corners of each rectangular strip are determined by computing the distance of each edge point to the 4 corners of the image. The edge point nearest to the respective image corner is labeled as a corner and the bounded area of the strip is then marked out as shown in Fig. 8. The strip with the longest length is the test strip, followed by the pH 1-6 reference strip and the shortest length is the pH 7-11 reference strip.

Next, the pH 1-6 reference strip is divided into 6 regions and the pH 7-11 reference strip is divided into 5 regions to segregate each pH level into its individual region. Each pH region is bounded by its 4 corners, and their coordinates are stored for use in future steps. The 4 corner coordinates of the test strip are also stored.

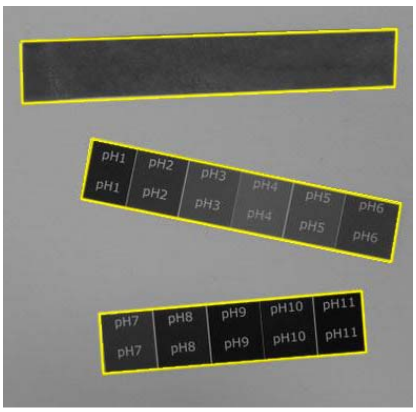

Figure 8. Bounded regions for images with rectangular reference chart

2)Images with Circular Reference Color Chart

Similarly, the 4 corners of the rectangular test strip are determined by computing the distance of each edge point to the 4 corners of the image. After separating the test strip and the circular color chart into two regions of interest, we divide the annulus region between the two concentric circles (see Fig. 5b) into 11 regions to segregate each pH level into its individual region shown in Fig. 9. Each pH region is bounded by its 4 corners of the approximate trapeziums, and their coordinates are stored for use in future steps. The 4 corner coordinates of the test strip are also stored in this case.

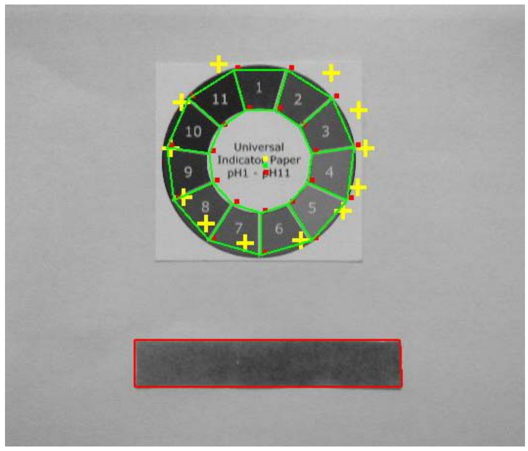

Figure 9. Bounded regions for image with circular reference chart

D. Point-in-Polygon Test and Conversion to CIELab Edge Detection

Images from most digital cameras use RGB encoding and a 3x3 linear color transformation is performed to map all the pixels in RGB color space **P** to CIELab reference values **M** using equation (1).

$$\begin{bmatrix} M_{L^*} \\ M_{a^*} \\ M_{b^*} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} P_{red} \\ P_{green} \\ P_{blue} \end{bmatrix} \quad (1)$$

This step is performed because the difference between any two colors in Lab format can be approximated by treating each color as a point in a three dimensional space (with three components: L, a, b) and taking the Euclidean distance between them [9].

Each pH region in both categories of images, rectangular and circular reference charts, consists of pixels which are bounded by the 4 corners whose coordinates have earlier been determined. A point-in-polygon check is performed to determine if the pixel is within the intended region. The application converts all pixels within each region into Lab color space. Pixels that fall outside the regions are discarded.

The entire procedure is performed for all the 12 regions and in addition, a two-pass Lab conversion procedure available in our previous version of the application [4] is used to further eliminate noise and the text in the test strip and color reference strips.

E. Determination of Color Chart pH Value

1)Images with Rectangular Reference Color Chart

It might be noted that the position of the 3 strips in this type of images can be placed in any order. However, it is required that the application has knowledge of the region type and the orientation of the color reference chart. This allows correct identification of the pH value of the respective region after the test strip has been matched to one of the pH regions.

Each pH region is matched to a pre-defined average Lab color as shown in Table 1. The average Lab values for the 11 regions are computed based on images obtained from 3 different mobile phones, each with 7 samples taken.

Table 1. Average Lab values

pH Region	L	a	b
1	63.625	46.125	15.25
2	75.125	42.875	41.5
3	91.25	25.25	78.375
4	99.625	10.75	74.0
5	95.375	-5.75	79.875
6	90.875	-15.0	75.375
7	83.125	-20.375	58.875
8	72.375	-15.375	25.25
9	61.5	-13.375	5.625
10	57	-3.875	-3.125
11	54.75	2.25	-13.5

The procedure begins by computing the root mean square (RMS) Euclidean distances between pH 1 region in the first color reference chart (pH1-6 strip) and the pre-defined average color values of pH1-6. This procedure is repeated for the other five regions in the first color reference chart. Since pH1 and pH6 have diverse color values, we are able to determine which extreme end of the first color chart belongs to pH1 or pH6 based on the RMS result. With this information, the system will also know which region belongs to pH2, pH3, pH4 and pH5. The same procedure is repeated for the second color reference chart (pH7-11) as illustrated in Algorithm 2.

In addition to determining the pH value of each region in the color reference chart, the 11 average Lab values in the color table are used to resolve wrong pH value classification when a part of the captured image has suffered reflection. If the individual pH region Lab value differs by more than 20% from the corresponding Lab value in the average color table, the individual pH region Lab value is replaced with that in the average color table. In cases when the images are affected by reflection or illumination problem, this process provides a more accurate Lab values for the final pH matching and classification.

Input: pH1-6 color ref chart coordinates ($R1_i$ where i=1 to 6), pH7-11 color ref chart coordinates ($R2_i$ where i=7 to 11), Original Lab Matrix Vector (L_i where i=1 to 11), Color Lookup Table Matrix Vector (C_j where j=1 to 11)
Output: Sorted Lab Matrix Vector

1. **for** each Lab Matrix Vector, L_i where i=1 to 6
2. **compute:** rmsCol1[i][j] = RMS of L_i to C_j where j=1 to 6
3. **set** min1 = rmsCol1[1][1] and minIndex1=1
4. **if** min of rmsCol[i][1] < min1 then min1 = rmsCol[i][1], minIndex1=i; i=1 to 6
5. **set** min2 = rmsCol1[1][1] and minIndex2=1
6. **if** min of rmsCol[i][1] < min2 then min2 = rmsCol[i][1], minIndex2=i; i=1 to 6
7. **if** minIndex2=6 or (minIndex1 >= 4 AND minIndex2 <= 3) then swop the Lab Matrix for L_i and color reference chart coordinates $R1_i$ where i=1 to 6.
8. **end for**
9. **repeat 1 to 6** where i=7 to 11
10. **if** minIndex2=11 or (minIndex1 >= 9 AND minIndex2 <= 9) then swop the Lab Matrix for L_i and color reference chart coordinates $R2_i$ where i=7 to 11.
11. **end for**
12. **return** Sorted Lab Matrix Vector L_i

Algorithm 2. Pseudo-code for computation of pH region value for images with rectangular color chart

2)Images with Circular Reference Color Chart

As the circular reference chart can be placed in any direction, it is important to determine which region belongs to the corresponding pH level after segregating the reference chart into 11 regions of interest. Similarly, we also use the pre-defined lookup table of the average Lab colors in order to determine the pH level of each region.

In the previous step, each region's average Lab values are stored in sequential order in an array. For each unknown region in the pH chart, the average Lab value is used to match against the most similar pH in the lookup table, based on the closest Euclidean distance calculated. For each match, the difference between the position in the pH array and the position of the matched pH in the lookup table is then calculated. The difference that has the highest frequency will determine the number of rotation shift the pH array has to be re-arranged. The procedure is illustrated in Algorithm 3.

Input: pH1-11 color ref chart coordinates (R_i where i=1 to 11), Original Lab Matrix Vector (L_i where i=1 to 11), Color Lookup Table Matrix Vector (C_j where j=1 to 11)
Output: Sorted Lab Matrix Vector

1. **for** each position in the $pHArray_i$, where i= 1 to 11
2. **compute** the DistanceLAB[i][j]to all the pH in the $LookUpTable_j$, where j=1 to 11
3. **for** each position in DistanceLAB[i], find the minimum DistanceLAB[i][j]
4. **set** CorrespondingpH[i]=j
5. **for** each CorrespondingpH[i], $difference_x$= (i-j) where x=1 to 11
6. **if** $difference_x$<0, $difference_x$ = $difference_x$+11 (clockwise shift)
7. **for** each unique value $difference_x$, find the frequency that it occurs
8. **set** $difference_x$ that as the highest fequency to be an interger K
9. **for** Count=1 to 11 and $newArray_z$ where z=1 to 11
10. shift=count+K
11. **if** shift<11, shift=shift -11
12. newArray[z]=ImageArray[shift]

Algorithm 3. Pseudo-code for computation of pH region value for images with circular color chart

F. Final pH Classification

With the enhanced Lab values of the 11 pH color chart regions and the knowledge of each region pH value and its coordinates, the final step is to compare the test strip with the 11 pH regions. The RMS Euclidean distances between the test strip Lab values and the 11 pH regions Lab values are compared. The region with the smallest RMS indicates that it is the best match to the test strip and is considered as the final pH classification. Fig. 10 and 11 show the results with Lab values in yellow. The classifications indicate that the test strips have pH level of 3 and 7 respectively.

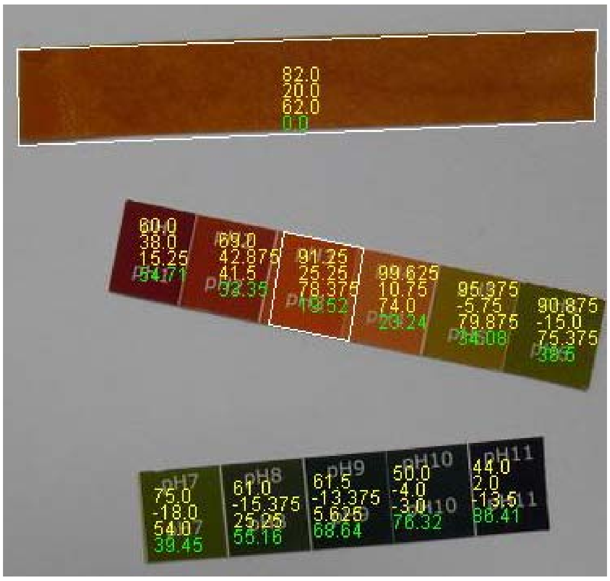

Figure 10. Final classification of pH=3

Figure 11. Final classification of pH = 7

IV. RESULTS AND DISCUSSION

A series of experiments were conducted to evaluate the effectiveness of the application.

A. Images with rectangular reference color chart

Eight test solutions were individually tested with 5 different pH test strips [10] and 5 respondents were tasked to visually match the test strip to the pH value on the color reference chart. Each respondent viewed a different test strip tested on each of the 8 solutions and their responses are collated in Table 2.

The same pH strips viewed by the respondents were captured by the phone camera and classified using the application. Each solution has 5 sample images for evaluation. For evaluation of our pH classification application, we compare the results against those obtained visually by the respondents in Table 2. The pH classification results achieved by our application are consistent with those indicated by the respondents.

Table 2. Experimental results of images with rectangular reference chart

Solution Index	1	2	3	4	5	6	7	8
Respondent 1	7	3	3	4	7	9	10	11
Respondent 2	7	3	3	4	7	9	11	11
Respondent 3	7	3	4	4	7	9	10	11
Respondent 4	7	3	4	3	6	9	11	11
Respondent 5	7	4	4	4	6	9	11	11
Application Classification	7	3	3	4	7	9	11	11

Images with reflection and slanted strip placements as shown in Fig. 12 have been tested and the results indicate that the pH values of the test strips are correctly classified by our application.

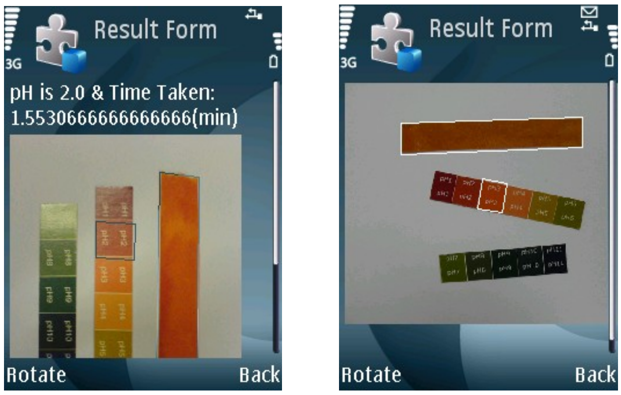

Figure 12. Images with reflection (left) and slanted strip placements

B. Images with circular reference color chart

Seven test solutions were tested each using 3 different pH strips [10]. Table 3 shows the list of solutions used in the experiment.

Table 3. List of solutions used in the experiment

Index	Solution
1	OPTI-FREE® Contact Lens Solution
2	Domestic Bleach
3	Multi-Purpose Cleaner
4	Vinegar
5	Nail Polish Remover
6	Persil Washing Detergent
7	Freshly Squeezed Lime

The pH classification was performed on 2 smart phones. 3 respondents were invited to visually identify the pH of the solution on the test strip. The results are shown in Table 4.

Table 4. Experiment results for images with circular reference chart

Solution Index	1	2	3	4	5	6	7
Respondent A	6	10	10	3	5	8	3
Respondent B	7	11	10	3	5	9	3
Respondent C	7	11	11	4	5	9	3
Application Classification by iPhone 3GS	7	10	9	3	5	9	3
Application Classification by Nokia 6700	6	10	10	3	5	9	3

As we can see from the values in Table 4, the results yielded from the predicted pH by the application are close to the results visible to the human eyes, with a deviation of 1 pH value. Certain colors, especially those in the pH range 6-7, can be rather difficult to classify even by the human eyes. Also, environmental conditions such as humidity may contribute to the change in colors of the test strip and make it drop or increase by one pH level after a short period of time. In general, we conclude that the application predicts an accurate and reliable pH.

V. CONCLUSION

This paper has presented a robust solution to the problem of mobile pH classification. We have overcome the major limitations in two earlier approaches. This new algorithm is able to handle test strips or color reference strips that are placed in a skewed manner or arbitrary order. It can also automatically identify the correct pH level even when a part of the image is affected by reflection. Additionally, the application is also integrated and customized to operate on different types of pH test color reference charts and produce results accurate and consistent with the ground truth estimation. This is one major step closer to accomplishing an efficient, robust, low cost, accurate, and intelligent mobile pH reader that is of great use to the elderly or color-blind people.

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