Low Cost Spectrometer Accessory for Cell Phone Based Optical Sensor

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***Abstract*—Point-of-care (POC) diagnostics integrated with smartphone platform has gained increasing attention in recent years due to its portability, cost-effectiveness and user-friendly setting. In this paper, we present an optical sensor based on a smartphone platform with extremely low-cost spectrometer accessary, which can be applied for colorimetric sensing. The spectrometer accessory enables separation and quantification of color information from various samples, which are essential in many colorimetric and fluorescence-based detections. The proposed smartphone based optical sensor consists of LED as excitation light source, assembled spectrometer structure and transparent fluidic sensing chamber for liquid analyte. The functionality of this smartphone based optical sensor is proved by applying it for pH sensing, realized by injecting standard pH buffer solution into the fluidic sensing chamber prefilled with pH indicator dye. The color change of pH indicator in the sensing chamber can be distinguished by the imbedded spectrometer and the spectrum image can be captured using external smartphone camera without the need for expensive camera. Image-processing software is employed to obtain quantitative pH sensing result. In general, this smartphone based optical sensor can be used for any colorimetric sensors in food, agriculture and medicine. Furthermore, the cost of the sensor can be further reduced by replacing the sensing chamber with test strips, such as the ones made from paper, making it a highly practical sensing device for resource-limited settings.**

I. Introduction

Since 2007, thousands of smartphones with integrated cameras, access to Internet, and user-friendly interface have come into the market and gained wide popularity in several years [1]. This rapid acceptance can be attributed to the technological innovations, which reduced the production cost and improved the functionalities of smartphones. Meanwhile, Point of care (POC) diagnostics has gained more and more attention in health care industry by eliminating the use of expensive instrumentation compared with traditional laboratory based diagnostics. POC diagnostics can be used to test various body fluids, including urine, blood, saliva and even human cells, which is very helpful in disease screening and health monitoring [2]. POC diagnostics is rapid, handy and cost-effective, and is especially needed in resource-limited areas, where expensive medical test instruments and well-trained technical staff are not available. Considering the popularity of smartphone and the need to have quick data acquisition and analysis, it is promising to use smartphone as the readout device for POC test. Recent examples include accessories that enable smartphones to serve as stethoscopes [2], ultrasound probes [3], microscopes [4], fluorescent microscopes [5], ELISA measuring spectrometer [6], label-free biosensor detection instruments [7], and colorimetric detection [8]. When applying smartphone platform for colorimetric sensing, it is crucial to allow separation of colors from the illuminated sample and quantifies them. Direct imaging using a camera does not provide the resolution and accuracy to perform such measurements, and one typically uses bulky and highly engineered optical accessories such as beam splitters, filters, lenses etc.

In this paper, we present a smartphone platform with very low-cost spectrometer accessary as an optical sensor. This optical sensor contains LED illumination, an embedded spectrometer, and a sensing chamber for holding solvent based sensing elements and analytes, as well as the smartphone for signal capturing. The embedded spectrometer uses a diffraction grating to separate the colors from the sample and quantifies them using a smartphone camera. To prove its functionality, the optical sensor is used for pH sensing considering the importance of pH measurement in various engineering fields, including biology, chemistry, medicine industry, food science and environmental science [9]. What Is the Best Method to Evaluate Urine pH. The pH indicator dye (Methyl red) is prefilled in the sensing chamber. With embedded spectrometer, the color change of pH indicator dye upon adding different pH buffers can be sensed by observing the whole visible spectrum image captured by smartphone camera. The captured image of visible spectrum is imported in MATLAB for quantitative analysis. This device is low-cost and user-friendly while achieving satisfied accuracy.

II. Material and Methods

A. Sensor Fabrication

Fig. 1 shows all the single components and the integrated structure of spectrometer based optical sensor. The sensor is consisted of three main parts, which are spectrometer structure, sensing chamber and smartphone cradle. The spectrometer structure contains illumination circuit, diffraction grating and a slit. The role of the spectrometer is to separate the colors using the diffraction grating and capture the intensity using the smartphone camera. The illumination circuit includes a white LED bulb, a 9V battery and a resistor (1000 Ohm).

The grating used for the device is a linear grating with 1000 lines per millimeter (purcahsed from *Rainbow Symphony* on *Amazon.com*). The slit is made using two pieces of plastic blades merged together, with a spacing of 100 μm in between. The sensing chamber is fabricated using 3D printer with VeroClear RGD810 material. The as-printed chamber has a round reservoir of 10 mm in diameter and 2 mm in depth with a 10 mm long cuboid of the same depth extending from the top of the reservoir. It is attached to a thin glass slide in order to hold solvent based pH indicator dye and pH buffer later. The spectrometer structure and the sensing chamber are packaged in a wood-base dark box to eliminate the effect of surrounding light. The smartphone cradle is fabricated with wood material and can be attached to the dark box to allow smartphone camera capturing the spectrum image. The complete structure is shown in Fig. 1(a), the size of which is 55 mm in width and height and 155 mm in length. The real image of the as-fabricated device is shown in Fig. 1(b).

B. Preparation of Sensing Elements and Analytes for Testing

A commonly used pH indicator dye, methyl red (Sigma Aldrich), is used as sensing element for pH detection, the color of which is red below pH 4.4 and yellow above pH 6.2. Methyl red solution is made by dissolving 22.5 mg methyl red powder into 5 mL of ethanol, and stirring the mixture on the magnetic stirrer for 2 hours followed by 2 hours of sonication to make uniform dye solution [17]. Then 10 mL of this as-fabricated dye solution is injected into the sensing chamber using a syringe (1-10 mL). The pH buffer solutions (pH 5 to pH 12) were purchased from Fisher Scientific and used directly as analytes during experiment.

C. Experimental Procedure

The experiment started by powering the LED in front of the grating for illumination and by placing the smartphone in the smartphone cradle to capture spectrum image. The smartphone used in this experiment is iPhone 5s with iSight Camera (8 megapixels with 1.5 pixels, CMOS sensor with f/2.2, 5 element lens). The sensing chamber with methyl red solution was then placed between the illumination LED and the slit to ensure that white light passing through the dye-contained transparent chamber get diffracted by the grating and the spectrum get imaged in the smartphone. After that, different pH buffer (pH 5 to pH 12) was injected into the sensing chamber subsequently and different images of spectrum were captured by smartphone successively. Between two pH measurements, the sensing chamber was completely cleaned with de-ionized water to make sure no residue from the previous experiment.

D. Image Processing

Spectrum images were collected and imported in MATLAB for quantitative analysis. First of all, original spectrum was extracted from smartphone-captured image, which was represented by a 250 by 150 pixel block. For color separation and quantification, the spectrum image was further divided into six equally distanced parts, and along the center of the

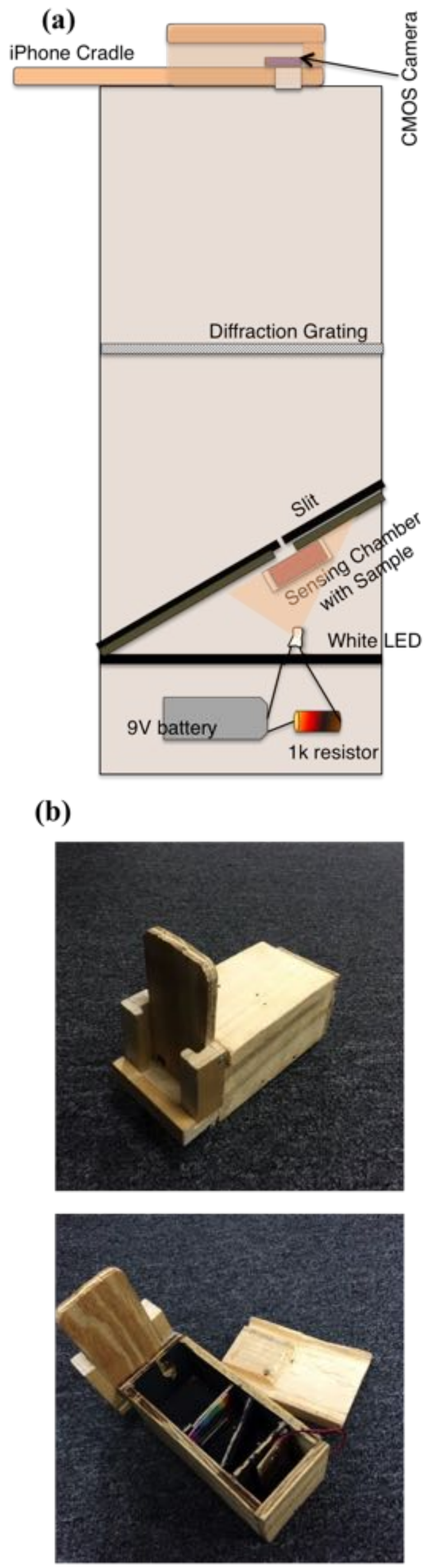
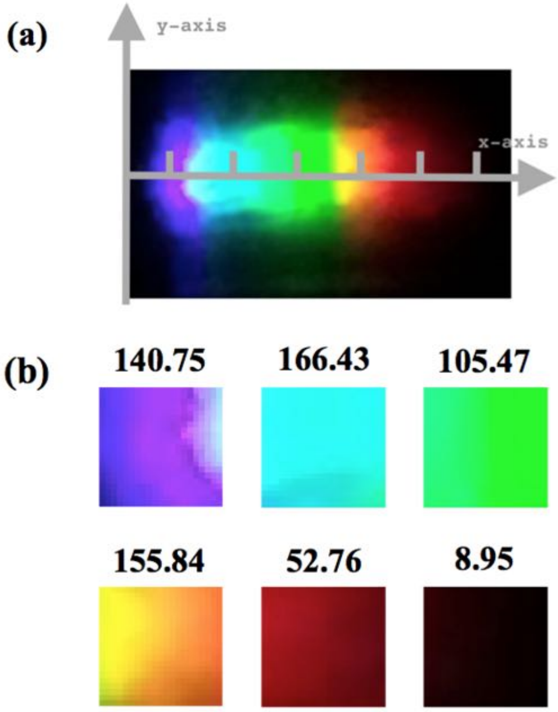


Fig. 1. (a) overview of as-assembled sensor; (b) top view of sensor schematic.



(c)
$$I = \frac{1}{400}\sum_{x=1}^{20}\sum_{y=1}^{20}(R+G+B)_{(x,y)}$$

Fig. 2. Principles of image processing: (a) data block selection rules: six blocks of 20 by 20 pixels are cropped from six marked points along the x-axis; (b) the average intensity of six blocks, which is calculated by taking the average of RGB sum of each pixel of four hundred selected pixels; (c) the formula for calculating the intensity from the corresponding R, G, B ($0 <=$ R,G,B $<= 255$) of each block in the RGB color space.

spectrum, six color blocks, each of 20*20 pixel were extracted from the six parts (Fig. 2a). The average intensity of each color block was then calculated by averaging the RGB values of the specific color block through calculating the average intensity of 400 hundred pixels. In this way, the complexity of calculation is greatly simplified since one-dimension vector instead of three-dimension, was used. The as-calculated color intensity of extracted six color blocks and the formula for calculation were shown in Fig. 2 (b) and (c).

III. Results and Discussion

In the following experiments, the smartphone platform based optical sensor is used for pH sensing from pH 5 to pH 12 as a proof of functionality of this optical sensor. Fig. 3 shows the original spectrum images of pure methyl red solution (Fig. 3a) and methyl red solution added with same amount of different pH buffer (pH 5 to pH 12) captured directly by smartphone. In Fig. 3 (a), 20 mL of methyl red solution was injected into the sensing chamber and the corresponding spectrum was recorded. Same process was repeated eight times for comparison and the resulting spectrum images were displayed. It is observed that in eight testing, the spectrums of all the dye samples are highly consistent, which indicates that the color of sensing dye was uniform, which can serves as a reliable reference for the following pH measurement. In Fig. 3(b), different pH buffers (pH 5 to pH 12) were added into the sensing chamber containing pH indicator dye methyl red. The corresponding spectrum under different pH was recorded and aligned together for comparison, from which the evolution of spectral changes with incremental pH can be observed. In this set of experiment, same amount (10 mL) of methyl red solution and pH buffer were added into the sensing chamber. The difference in the spectrums can be seen from naked eyes: for example, the left tail of pH 5 and pH 6 spectrums showed very little green color, and from pH 8 onwards, the intensity of the shorter-wavelength part (yellow and green) started to increase. Such increment experienced a dramatic jump from pH 8 to pH 9. The difference from one spectrum to another is the important indicator of different pH values.

The next step is to extract the colormap from the spectrum obtained from smartphone through MATLAB. Fig. 4 shows the colormaps for spectrums obtained in Fig. 3. Each color block is 20 by 20 pixels in size and evenly spaced on the vertical center with highest intensity of the spectrum as indicated in Fig. 2 (a). Block1 from x = 20 to 40, block 2 from x = 60 to 80, so on so forth until the last block from x = 220 to 240. It is observed in Fig. 3 (a) that the spectrum of methyl red concentrated on the longer wavelength range, thus in the corresponding colormap in Fig. 4 (a), block 1 to block 3 on the y-axis are predominantly black while block 4 to block 6 reflect the combined RGB color at the higher wavelength part. Fig. 4 (b) plotted the color map based on the spectrums in Fig. 3 (b), from which the change of pH is more visible in different blocks. For example, block 2 and 3 (color green 495–570nm) showed dramatic increase in their intensity from pH 7 to 9 and stayed relatively constant at higher pH values, whereas block 4 (color yellow 570–590 nm) becomes brighter as pH increased. By translating the raw spectrum images to the block intensity representation, it is shown that the recognizable hue and shades in the 6 blocks of the colormap vary significantly from spectrum to spectrum depending on the pH of the buffer solutions. The combination of color information in 6 blocks can provide a unique signature for specific pH, which indicate the potential effectiveness of this sensor in discriminating different pH values in complicated environment.

To distinguish different pH, it is crucial not only to visualize the change, but also quantify the amount of change. In Fig. 5, the block color intensity in the colormaps (Fig. 4) of all the samples, with or without adding pH buffers, was plotted. Fig. 5 (a) is the histogram representation of intensities at different color blocks for consistency test, which quantitatively proves the reproducibility of the dye spectrum from one test to another. Similar to Fig. 5 (a), Fig. 5 (b) is a numerical representation of the color map in Fig. 4 (b) for pH measurement. Each pH measurement is repeated for three times for the consideration of accuracy. There is small variation in the color block intensity values from time to time, which

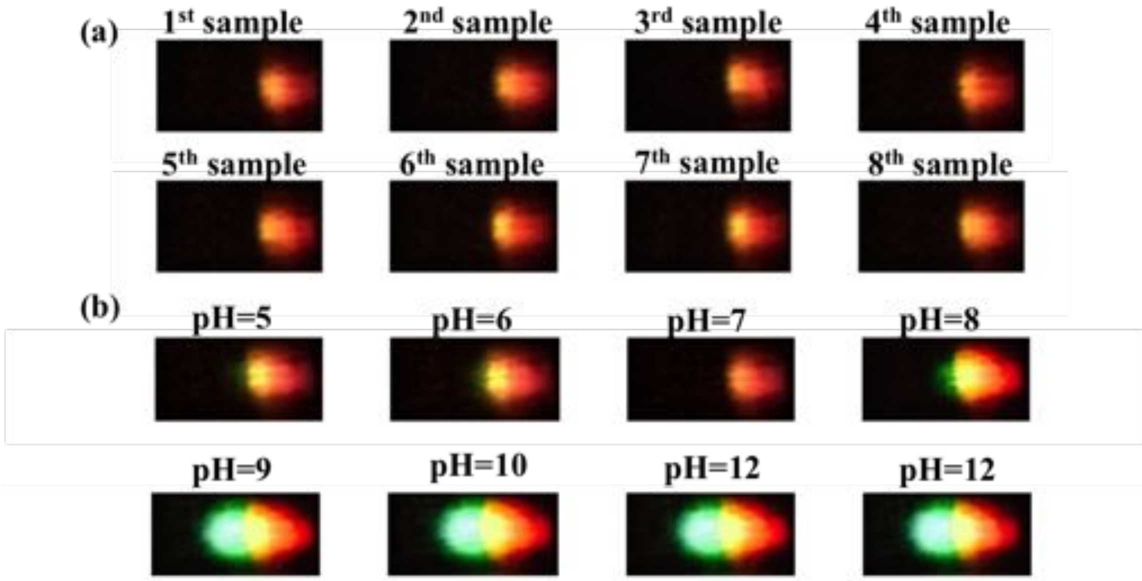


Fig. 3. Original spectrum obtain in smartphone: (a) dye spectrums resulted from 8 separate dye solution tests; no clear difference can be observed with bare eyes; (b) pH spectrums of optical dyes with added pH (from 5 to 12) solutions. Note: all the spectrums are 250 pixels by 150 pixels and are cropped with same coded program at the same position.

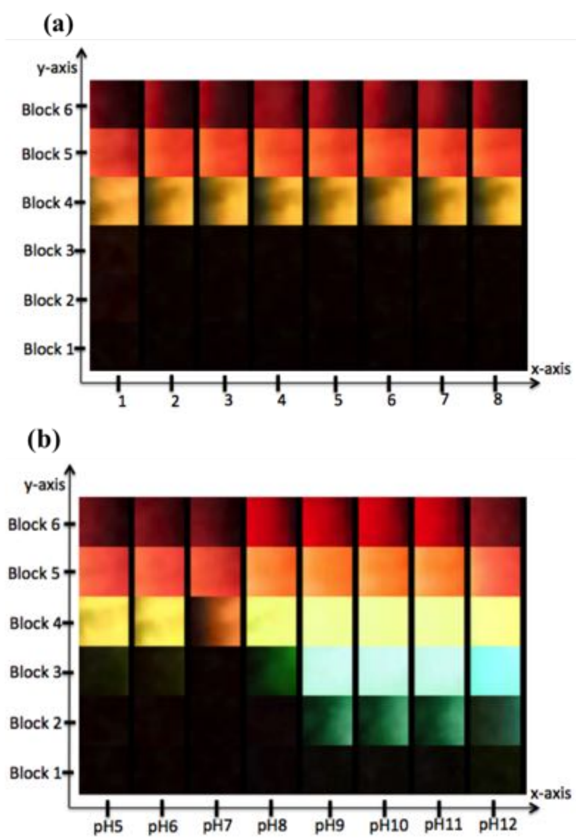


Fig. 4. (a) the colormap derived from the spectrums in Fig. 3(a); the colormap derived from the spectrums in Fig. 3(b), showing the result of pH measurement.

is mainly due to relatively large amount of analyte (in the mL range) and the difficulty to precisely control the amount of analyte by hand from time to time. The relatively small variation among three repeated tests for one pH indicates the stability and reproducibility of the sensor performance.

IV. Conclusion

A flexible, low-cost smartphone based optical sensor with spectrometer accessary has been developed for colorimetric sensing, with great potential to be more accurate and publicly accessible than existing sensing methods. Applying it for pH sensing proves the functionality of this sensor. This sensor can potentially surpass the computational limitation of the smartphone by utilizing cloud-sync for pictorial data and converting raw images to spectrum and then into values that reflects the actual sample information. All components of the sensor can be readily obtained from the lab, which ensure that the system is inexpensive, compact, and easy to build.

Future improvement on this smartphone sensor can focus on enhancing the resolution of the measurement, further reducing the production cost, and better feasibility. For example, new pH indicators can be made to accommodate the need for more acidic solution measurement. Production cost can be reduced by replacing the 3D-printed fluidic platform with cellulose-paper platform. Better feasibility of this device can be achieved by building a dynamic website to cloud-source the computational need instead of manually using MATLAB and amplifying the data-sharing capability of the smartphone for users in various locations.

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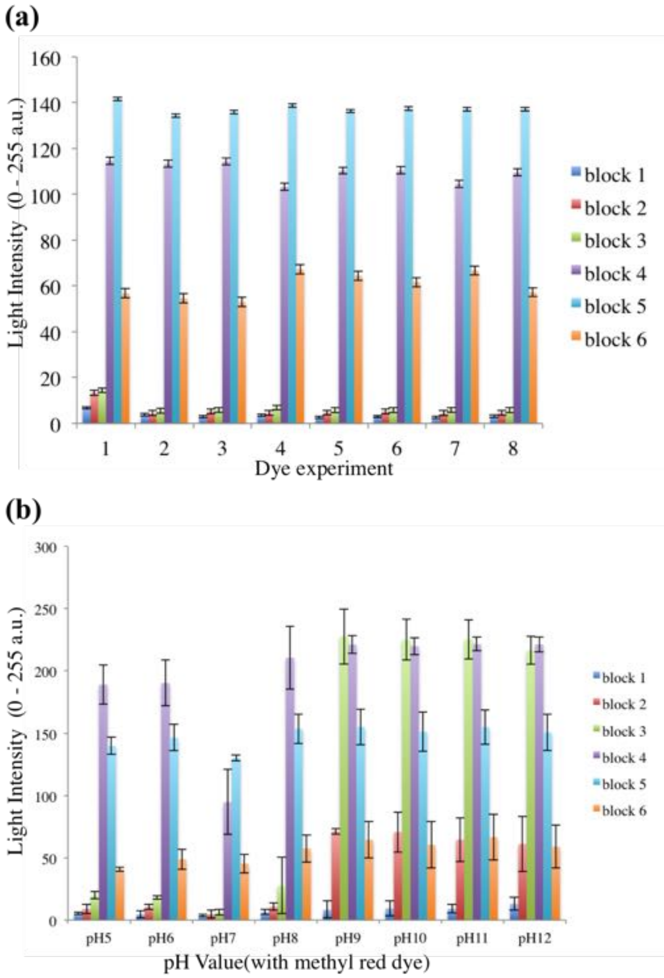

Fig. 5. (a) Consistency Test for only dyes: it plots the intensity (0-255, according to 8 bit unsigned representation of RGB color model) of each pixel block with respect to the corresponding dye experiment; (b) Trend Test for pH added dyes: the level of each column corresponds to the intensity level of the spectra block in Fig. 4b. The error bar is calculated by taking the standard deviation of three repetitions.

research work.

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Appendix: Software Source Code:

I. MATLAB code for generating figures and analytical results

1) MATLAB Command Lines

%Code for generating Figure 2(b)

```
pH9 = imread('raw pic with pH 9'); %read in the raw picture

            %crop the area with spectrum from the raw picture
pH9crp = imcrop(pH9, [1651, 1243,250,150]);
DisplayBlockProcessing(pH9crp); %generating figure 2(b)
```

%Code for generating Figure 3(a)/(b)

```
%read in the raw pictures
dye1 = imread('dye1.jpg');
dye2 = imread('dye2.jpg');
dye3 = imread('dye3.jpg');
dye4 = imread('dye4.jpg');
dye5 = imread('dye5.jpg');
dye6 = imread('dye6.jpg');
dye7 = imread('dye7.jpg');
dye8 = imread('dye8.jpg');

%crop out the spectra portion of the picture
dye1crp = imcrop(dye1, [1651, 1243,250,150]);
dye2crp = imcrop(dye2, [1651, 1243,250,150]);
dye3crp = imcrop(dye3, [1651, 1243,250,150]);
dye4crp = imcrop(dye4, [1651, 1243,250,150]);
dye5crp = imcrop(dye5, [1651, 1243,250,150]);
dye6crp = imcrop(dye6, [1651, 1243,250,150]);
dye7crp = imcrop(dye7, [1651, 1243,250,150]);
dye8crp = imcrop(dye8, [1651, 1243,250,150]);

%plot the 8 spectrum graph of all dye samples
subplot(2,4,1), imshow(dye1crp), title('1st sample');
subplot(2,4,2), imshow(dye2crp), title('2nd sample');
subplot(2,4,3), imshow(dye3crp), title('3rd sample');
subplot(2,4,4), imshow(dye4crp), title('4th sample');
subplot(2,4,5), imshow(dye5crp), title('5th sample');
subplot(2,4,6), imshow(dye6crp), title('6th sample');
subplot(2,4,7), imshow(dye7crp), title('7th sample');
subplot(2,4,8), imshow(dye8crp), title('8th sample');
```

%Code for generating the data for Figure 5(a)/(b), graph is created using excel

```
DataPipingProcessing(dye1crp);
DataPipingProcessing(dye2crp);
DataPipingProcessing(dye3crp);
DataPipingProcessing(dye4crp);
DataPipingProcessing(dye5crp);
DataPipingProcessing(dye6crp);
DataPipingProcessing(dye7crp);
DataPipingProcessing(dye8crp);
```

2) <u>DisplayBlockProcessing.m</u>

```
%Contains all routines to handle subplots for one spectrum

function []= DisplayBlockProcessing(spectrum)

%stores 6 data blocks (evenly spread across spectrum) into a cell array
for i = 1:6
   x = (-20+i*40);
   datablocks{i} = imcrop(spectrum, [x 70 20 20]);
   % y value, 70, sets the cropping area, to y =90,
   % which is close to the middle of the spectrum
end

%iterate through each data block and calculate the values
for i = 1:6
   buffer = 0;
   for x = 1:20
      for y = 1:20
          buffer = buffer + impixel(datablocks{i},x,y);
      end
   end
   buffer2 = sum(buffer(:)); %add up all the R, G, B values for every pixel
   avgP{i} = buffer2 / 3 /400; % calculate average intensity of each pixel

   subplot(2,3,i);
   imshow(datablocks{i});
   title(avgP{i});
end
```

3) <u>DataPipingProcessing.m</u>

```
%contains code to output spectra numerical data for excel modeling

function []= DataPipingProcessing(spectrum1)

%stores 6 data blocks (evenly spread across spectrum) into a cell array
for i = 1:6
   x = (-20+i*40);
   datablocks1{i} = imcrop(spectrum1, [x 70 20 20]);
   % y value, 70, sets the cropping area, to y =90,
   % which is close to the middle of the spectrum
end

fileID = fopen('data.txt','A')

%iterate through each data block and calculate the values
for i = 1:6
   buffer = 0;
   for x = 1:20
      for y = 1:20
          buffer = buffer + impixel(datablocks1{i},x,y);
      end
   end
   buffer2 = sum(buffer(:)); %add up all the R, G, B values for every pixel
   avgP{i} = buffer2 / 3 /400; % calculate average intensity of each pixel

   fprintf(fileID, '%6.2f\n',avgP{i});

end
fprintf(fileID, '\n');
fclose(fileID);
```

II. Python code for rearranging spectra blocks

1) Terminal Command Lines

#Code for generating Figure 4(a)
Command line: python image.py

2) image.py

```
#contains code to handle image cropping and rearranging

from PIL import Image

dyes = []

dye1 = Image.open("1 dye only.jpg")
dye1crp = dye1.crop((1651, 1243,250,150)).convert('RGB')
dyes.append(dye1crp)

dye2 = Image.open("2 dye only.jpg")
dye2crp = dye2.crop((1651, 1243,250,150)).convert('RGB')
dyes.append(dye2crp)

dye3 = Image.open("3 dye only.jpg")
dye3crp = dye3.crop((1651, 1243,250,150)).convert('RGB')
dyes.append(dye3crp)


dye4 = Image.open("4 dye only.jpg")
dye4crp = dye4.crop((1651, 1243,250,150)).convert('RGB')
dyes.append(dye4crp)

dye5 = Image.open("5 dye only.jpg")
dye5crp = dye5.crop((1651, 1243,250,150)).convert('RGB')
dyes.append(dye5crp)

dye6 = Image.open("6 dye only.jpg")
dye6crp = dye6.crop((1651, 1243,250,150)).convert('RGB')
dyes.append(dye6crp)


dye7 = Image.open("7 dye only.jpg")
dye7crp = dye7.crop((1651, 1243,250,150)).convert('RGB')
dyes.append(dye7crp)

dye8 = Image.open("8 dye only.jpg")
dye8crp = dye8.crop((1651, 1243,250,150)).convert('RGB')
```

```
dyes.append(dye8crp)

new_im = Image.new('RGB', (720, 480))   #a canvas to hold all the pastes


dyecrps = []
dye_count = 0

for j in range(0,8):
    datablocks = []
    # print "about to print datablocks%i" %j
    for i in range(0,6):
        x = 20 + i * 40;
        datablocks.append(dyes[j].crop((x, 70, x+20, 90)))
    # print len(datablocks)
    dyecrps.append(datablocks)


for i in xrange(0,720,90):
    data_count =0
    for j in xrange(0,480,80):
        #paste the image at location i,j:
        new_im.paste(dyecrps[dye_count][data_count].resize((80,80)), (i, 400-j))
        data_count +=1
        # print count
    dye_count +=1
# new_im.show()
new_im.save( "uniformity colormap for sensing chamber.png”)
```