A low-cost multispectral camera

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Abstract: We present the results of a cost-effective multispectral camera experimental set-up. Multispectral camera set-ups are often expensive, they require special cameras with more resolution, due to the increase of spectral bands to be captured. Here we show this procedure is equivalent to solve an equations system, derived from illuminating with several light conditions a sample and capturing it with a traditional, and low-cost, RGB camera. Moreover, we achieve a back-propagation reconstructed image, thus we can get back to the original photo by mapping the corresponding reflectivity photos of the three RGB channels.

I. INTRODUCTION

Digital cameras are devices which capture information across the electromagnetic spectrum, arranged in a two-dimensional array of detectors, images of several pixels. One of the common applications of cameras is to register and reproduce scenes that a human would see, digital cameras register the spectrum in three main band: Red, Green and Blue (380 – 780 nm), roughly matching the tri-stimulus response of the human eye [1].

A multispectral camera is one that captures images within specific ranges across the electromagnetic spectrum, not only resembling the human eye response. This is useful in several cases ranging from military purposes, painting and documents datation and even knowing the state of crops and improve vegetation management.

Thus, we aim to obtain similar readings to a multispectral camera using a cost-effective set-up, we propose the use of a Raspberry Pi with its own Camera V2 (based on the SONY IMX219 sensor), an RGB bulb from Hue Light (Phillips), a low-cost spectrometer from Sparkfun (AS7265x) and an Arduino UNO. All the image acquisition and processing are handled by the Raspberry Pi, as it is a single-board computer which runs a Linux distribution equipped with a Python interpreter.

II. PHYSICAL FOUNDATIONS

The system of equations approach is derived from optics equations of reflectance of surfaces. In this experimental set-up, we have numerous different light combinations, $I_j(\lambda)$, to be used to illuminate the sample which has its unique reflectance spectrum, $R(\lambda)$, independent of the light source, and the light reflected by it will arrive to the detector of the camera, $D_K(\lambda)$. Three detectors in this case, RGB, which absorption spectrum its well documented [2]. The result is a photography taken by the camera automatically for each change in the light we programmed.

As its been stated before, we are studying twelve (12) wavelengths in the visible spectra, we have initially five independent light sources (5), and three detectors in the camera (3). We will arrange a combination of iluminants with detectors in one dimension and the wavelengths in another, ending up whit a matrix system per each photograph.

In order to solve our problem, we can reverse the system to find the reflectance knowing the other variables involved and rearranging the equations properly.

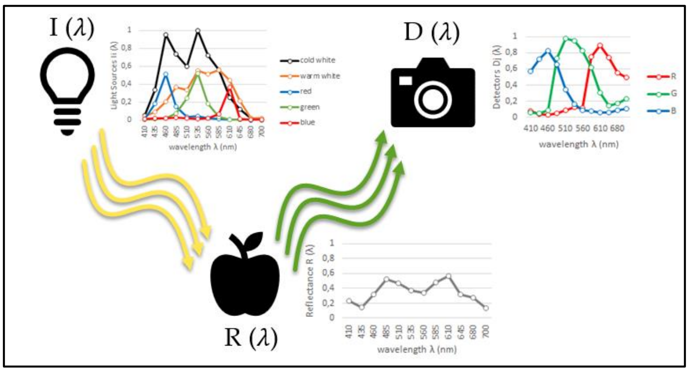

FIG. 1: Simplified schema of the physics involved in the experiment.

As it follows, the resulting signal at the detector at each wavelength S (λ):

$$S(\lambda) = I(\lambda) \cdot R(\lambda) \cdot D(\lambda)$$

The overall signal, considering all wavelengths within $[\lambda_{min}, \lambda_{max}]$ can be expressed as

$$\langle S \rangle = \frac{\int_{\lambda_{min}}^{\lambda_{max}} I(\lambda) \cdot R(\lambda) \cdot D(\lambda)\, d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} D(\lambda)\, d\lambda}$$

Which is normalized to the maximum signal of the detector in order to work within the non-saturation area. Assuming that both the intensity and the detector are normalized, the product of I = 1 per wavelength results in the maximum area the detector can possibly integrate, its white.

As we only will have discrete wavelengths to measure, we should express the previous equation as a finite sum of products for each wavelength, the sampling value of the wavelengths will depend on our instrumentation (detailed in further chapters):

$$\langle S\rangle = \frac{\sum_\lambda (I_\lambda \cdot R_\lambda \cdot D_\lambda)}{\sum_\lambda D_\lambda}$$

Now, considering the multiple light sources that will be used in the set-up, it is necessary to contemplate a few more indexes. We will use (i) for the number of discrete wavelengths we are going to study, (j) for the number of different I (λ), the same as photographs we are going to take, and (k) for the number of detectors used by the camera.

$$\langle S\rangle_j = \frac{\sum_\lambda (I_{j\lambda} \cdot R_\lambda \cdot D_\lambda)}{\sum_\lambda D_\lambda} = \frac{1}{\sum_\lambda D_\lambda} \sum_\lambda ((D_\lambda I_\lambda)_j \cdot R_\lambda) \quad \textit{with } j = 0,\dots, N$$

As the R_λ sum its constant, as it doesn't depend on the iluminants nor the detectors, we can now express the normalizing sums for the detectors as a constant (D_{max}) and the products of detectors and iluminants as a matrix, arranging the three channels of each photo per wavelength:

$$\overline{\langle S\rangle}_j = \frac{1}{D_{max}} \cdot \overline{\overline{DI}}_{ij} \cdot \overline{R}_i \quad \textit{with} \begin{cases} i = \lambda_{min}, \dots \lambda_{max} \\ j = 0, \dots N \end{cases}$$

Finally, we only need to rearrange the system using the inverse of the matrix to find using the solutions (photographs) the reflectance spectrum.

$$\overline{\langle R\rangle}_i = D_{max} \cdot \left(\overline{\overline{D_k I}}_{ij}\right)^{-1} \cdot \overline{\langle S\rangle}_j \quad \textit{with} \begin{cases} i = \lambda_{min}, \dots \lambda_{max} \\ j = 0, \dots N \\ k = R, G, B \end{cases}$$

III. EXPERIMENTAL SET-UP

For the set-up we have used a Raspberry Pi model 3B+ with its camera module coupled for convenience (V2, based on the SONY IMX219 sensor), an Arduino UNO with a SparkFun Triad Spectroscopy Sensor (AS7265x) used to get the illuminance spectrum of the lights and a White and Color ambiance Philips Hue color bulb.

The camera module RGB detectors have been calibrated, it is known the spectral response curve for the three of them and this is the first limitation we find in this work. Whilst the actual range is probably larger than that, we cannot know how it behaves beyond the limits specified (400-700 nm).

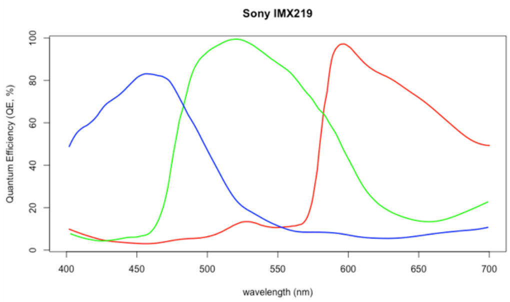

FIG. 2: Raspberry Pi Camera V2 spectral response curves.

The spectrometer it's also a low-cost type of equipment, but it's good enough for the purposes of this work. It can read eighteen spectral lines ranging between 410-940 nm, but that's beyond the response curves of the camera's detectors so we will only use up to 700 nm. We are left with twelve spectral lines, the better spectral resolution we can possibly obtain.

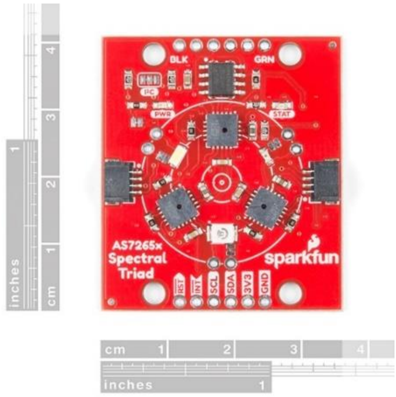

FIG. 3: A photograph of the SparkFun Triad Spectrometer.

The Hue Lights used here are the White and Color ambiance A19 4th gen. which are equipped with five independent light sources: R G B LEDs, and a cold white and a warm white LED. The Hue Light system provides an accessible cross-platform API to configure the combination of these LED. Thus, we can create lineal combinations from those five LEDs, in our set-up. The color gamut of this model is C, so we have these extremes (X, Y) representing accordingly de Red, Green and Blue independent LEDS in the CIE 1931 color space [3]:

[r = (0.692, 0.308), g = (0.170, 0.700), b = (0.153, 0.048)]

In the API we can select the color as a combination of three iluminants (X, Y) in the color space or we can choose the color as an emulation of a black body using the color temperature.

As per the programming part of the experimental set-up, we are using the well-known Least Squares method. This finds easily a solution for a linear equation like the one that we aim to solve. The solution given by this function is either the exact solution if it exists, or the best approximation it can make by the method of the least squares, as the name states.

It is interesting to use this method as we cannot access individually to the five independent LEDs in the bulb and every other iluminants used is a combination of those. For that it is convenient to use Least Squares as will find the fittest solution possible for our system by minimizing the sum of the squares of the residuals made in the results of every single equation.

IV. RESULTS

Using our set-up, we perform several experiments. Here we present a colour-full experiment and its results using an apple as the target of the multi-spectral image acquisition. The target is captured first with 5 Hue Light configurations, and then with several linear combination of them.

We can compare the 5 photos below, where we have selected both white conditions using the color temperature method within the API (2500 K for cold white, 6000 K for warm white) and the three vertices of the C gamut in CIEXY color space for the red, green and blue.

FIG. 4: Photographs of the independent light sources.

As expected, we have obtained the twelve grayscale photographs. Some of them are clearly inverted (black-white) and yet we still have five to seven nice photos, with good resolution that prove the information is still there and it has not been destroyed nor deformed by the process.

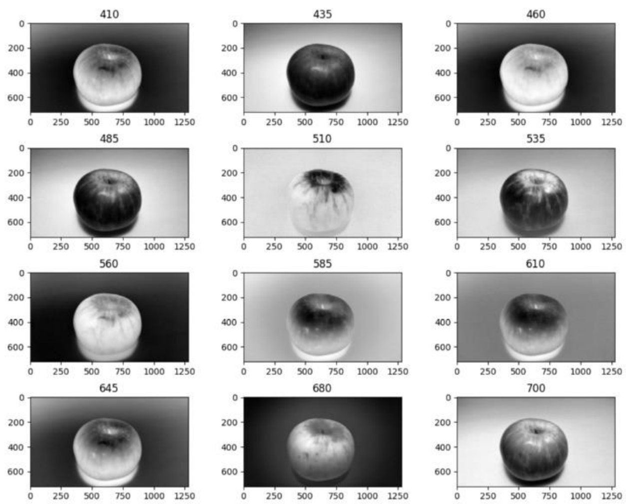

FIG. 5: Photographs of the results, each corresponding to a different wavelength (in nm).

We ought to remember that these twelve photographs are all part of the solution to our experiment, even those that are clearly not representative. As an equation system, all the pieces must fit in the solution and have some weight in it. For other photos to be OK means that the approximate solution the algorithm has found, includes those inverted photographs.

Comparing the results of three experiments, taking 5, 68 and 138 photographs of different color combinations, we have finally obtained a new band that was first inverted (the 510 nm) as shown in the comparison in the conclusions.

An exercise we can still do is to try and revert the process by assigning the most proximally photos to the detectors' spectra to its channel in a new photograph. Combining three of those like 680, 485 and 435 nm in the red, green and blue we can revert easily the problem and obtain a similar photo to that taken in white light.

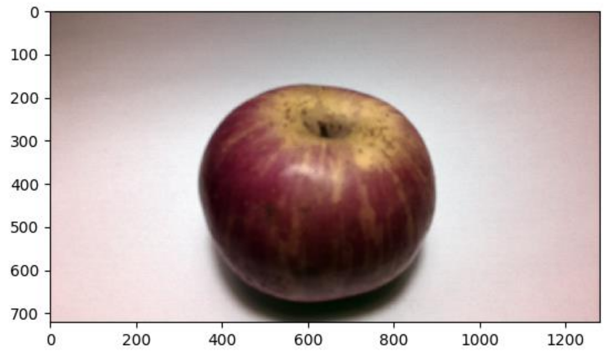

FIG. 6: Reconstruction using three of the solutions to form a RGB photograph. The most similar to the original cold white.

This reconstruction can also be tested by taking a photo corresponding to a wavelength beyond that red (like 700 nm) or a green beyond the optimal (like 585 nm). We can see in the resulting photos how they present now a redshift or a greenshift, accordingly.

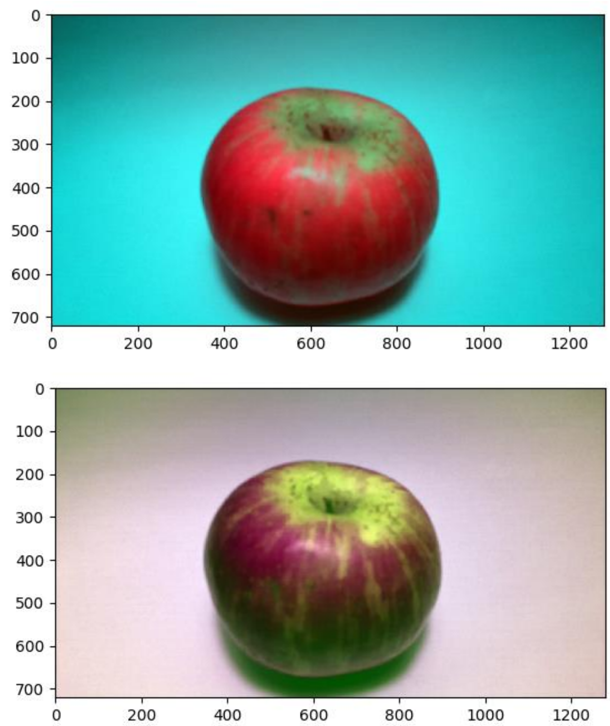

FIG. 7: Reconstructions with redshift and greenshift.

V. CONCLUSIONS

- We have obtained the 12 gray-scale photographs as initially predicted. Some of them are clearly inverted, probably due to combining those five independent lights. Then, achieving more than five good-looking results, as they are approximations to the problems' solution, proves the viability of the work.

- Still we have proved it is possible and we could arguably say we have obtained the Cian band (around the 485-510 nm) and probably also the Yellow (around the 585 nm)

- It is clear though that we lose definition in this process as the calculus it's done with more information-capable variables than those used to generate the image, low-information variable to save the photos (integer up to 255). We do not lose the image itself but the dynamic range

- Also, we can note that the more photos we use in the experiments (the more lights we use) more definition we obtain in the results.

- Furthermore, by using 138 different combinations of lights it is possible to obtain one more band (the 510 nm) than doing the experiment with only five to fifty light conditions. It would be interesting to test this to try and obtain more bands using hundreds of light combinations.

In order to improve and set-up further with this work as basis we hereby propose the following possible paths:

- Usage of other compatible cameras with the system as could be the Raspberry Pi NOIR camera which doesn't have the filter por IR (up to 1000 nm), in order to use the IR information from the spectrometer.

- Remove the usage of the Arduino by controlling the Sparkfun spectrometer directly from the Raspberry Pi.

- Usage of others and more light sources. We did use only one because of the multiple LEDs inside of it but could be interesting to test this experiment with other color light bulbs or single monochromatic lights

- Use well-known lights and samples to calibrate and measure the rate of success of the experiment

- Understand better the negative image, due to the fact the information is not erased, just inverted. An educated guess is to relate this behaviour with normalization issues in linear systems.

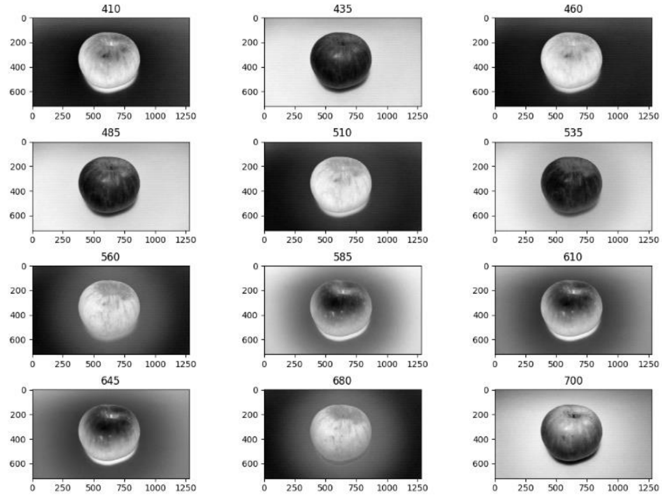

FIG. 8: Results using the five lights independent lights.

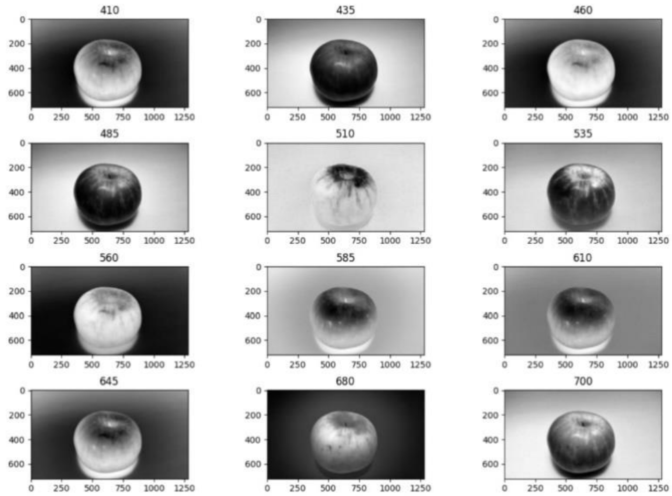

FIG. 9: Results using the five independent lights plus a hundred and thirty combination of them. Compared to using only five, it has better resolution and one more channel is not reversed (510 nm).

Acknowledgments

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[1] R. W. G. Hunt, «The Reproduction of Colour,» England: John-Wiley & Sons, 1957

[2] Koen Hufkens, «Pi-camera spectral response curves,» Ghent University, Belgium [Online resource].

Available: https://khufkens.github.io/pi-camera-response-curves/

[3] Smith, Thomas; Guild, John «The C.I.E. colorimetric standards and their use,» Cambridge (CUP), 1931