Chapter 7

DESIGN OF A UNIVERSAL 3D PRINTED HOLDER FOR SENSING AND IMAGING STUDIES IN ALL VARIANT SMARTPHONES

This chapter discusses the design of a universal smartphone holder that can be used for both sensing and imaging studies in all variant smartphones. The usability of the holder has been demonstrated by attaching it with a dual mode sensing and a microscopic imaging platform separately. The holder can be coupled in all smartphones regardless the camera positions and dimensions of the phones. It also comprises an XYZ translational stage, which enables the attached sensing and imaging platforms to align properly with the inbuilt sensors of the phones. Three smartphones of different physical dimensions and different camera positions have been utilised to test the compatibility of the designed holder.

7.1 Introduction

Recent times, scientific Instruments are widely used in the field of material characterisation. Although these instruments are sensitive and reliable yet they have some disadvantages in terms of their size, cost and the involvement of complex analytical protocols. These factors make the instrumental method completely laboratory con-

fined, less user-friendly and less suitable for resource poor regions. Scientists and engineers all over the world are continuously working towards the development of simple yet highly sensitive devices which will overcome the drawbacks of the existing conventional instruments. Current technological advancements in the instrumental method for material analysis are gradually evolving in the development of compact devices which are reliable, accurate and sensitive. Over the past decade, numerous research groups across the globe have demonstrated various analytical sensing and imaging platforms which are compact, hand-held, low-cost and relatively easier to handle [1–5]. These compact platforms are easy to use and one can handle them without the presence of an expert operator. Also, the recent development of user-friendly data analysing softwares have contributed equally to the handling and smooth functioning of these analytical tools. The compactness of these analytical setups significantly increases the applicability of these tools in different directions such as on-site analysis, real-time monitoring and regular assessment of materials. Thus, by observing the history of evolution of the analytical instrument, it can be assessed that the future of material analysis will dependent on the development of easily available, low-cost components that will possess a high degree of accuracy and precision.

In this regard, smartphone-based analytical tools is also growing at a good pace and is able to find applicability in the field of chemical sensing, bio-sensing, safety measures and many more [6–13]. Smartphones have been used extensively in various on-site investigations related to the environmental monitoring, clinical trials, food quality assessment and more. This new kind of analytical tool is completely standalone, handheld and user-friendly. The reliability of the smartphone-based platforms is found to be at par with commercially available instruments. For a resource-poor region, the smartphone-based sensing and imaging platform can be used as an alternative tool in place of the conventional analytical tools. The smartphone-based analytical platforms are based on the development of custom-designed attachments that can be easily coupled to the embedded sensors of the smartphone. Most of these attachments are usually designed for a particular variant of smartphone model [14–18]. This implies the designed attachments are not compatible with other smartphones whose sensor position and physical dimensions are not identical. As a result, a user will need a specific phone complementing the particular attachment to perform sample analysis with the designed sensing system. Although it is a primary requirement to develop a robust system for obtaining consistent results, yet it appears to be a limiting factor for smartphone-based analysis

[19, 20]. In this regard, the smartphone-based sensing and imaging platforms that use the phone's inbuilt optical sensors as photo-detector encounters the same problem. The primary optical sensors of a smartphone, namely the camera and the ALS are positioned differently in different smartphones. Moreover, the inconsistency in the phone's dimension is another major motivation for many researchers to design some universally compatible platforms which can be attached to multiple smartphones to avoid the requirement of a particular smartphone for sensing or imaging studies.

Present study demonstrates the working of a universally compatible smartphone holder that can be used for various sensing and imaging purposes. Currently, a dual mode sensing platform and a microscopic imaging platform have been designed and incorporated with the universal holder. The holder can be attached to any variant of smartphones regardless of their physical dimensions. Furthermore, an XYZ translational stage has been incorporated within the holder to perfectly couple the sensing platform with the phone's inbuilt sensor. The usability of the designed holder has been realised by attaching it to three different smartphones of different dimensions and rear camera positions. The dual sensing platform has been utilised for the colorimetric and the fluorescence based analysis. The proposed sensing setup successfully measures the transmitted and fluorescence signals of rhodmine 6g (R6G) solutions of varying concentration. On the other hand, a microscopic platform has been developed to capture high-quality images of micro-particles in bright field illumination. As a proof-of-concept, imaging of red blood cells has been captured by attaching the imaging system with the universal holder. It is envisioned that the platforms which are discussed in chapters 3, 4, 5 and 6 can be customised for the designed universal holder and a common water quality monitoring platform can be built. Users can check the responses of the sensing and imaging platforms by attaching them with different phones and pick the phone with best results for further analysis.

7.2 Hardware design

7.2.1 Design of the universal smartphone holder

Figures 7.1 (a) and (b) show the schematic of the designed universal holder. The holder has two expandable arms for holding the smartphones of varying dimensions. The arms can be extended up to 30 mm and can hold phones of widths ranging from

65 mm to 95 mm. The M6 screws have been used to lock the arms once the setup is attached to a smartphone. The universal holder consists of an XYZ translational stage that enables an user to align the analytical platforms with the inbuilt sensor of a smartphone. The stage can move in all the three dimensions to attain a perfect alignment between the phone's sensor and the custom designed sensing and imaging setups. The travel distances of the stage are 85 mm, 10 mm and 20 mm along X, Y and Z direction respectively. The stage can be secured in position with the help of M6 screws attached to the holder. The overall dimension of the universal smartphone holder is 120×70×25 mm. In the present study, a dual mode sensing platform and a microscopic imaging system have been attached separately with the universal holder to test its performance. The designing of the dual mode sensing and microscopic imaging systems are discussed in the subsequent sections 7.2.2 and 7.2.3.

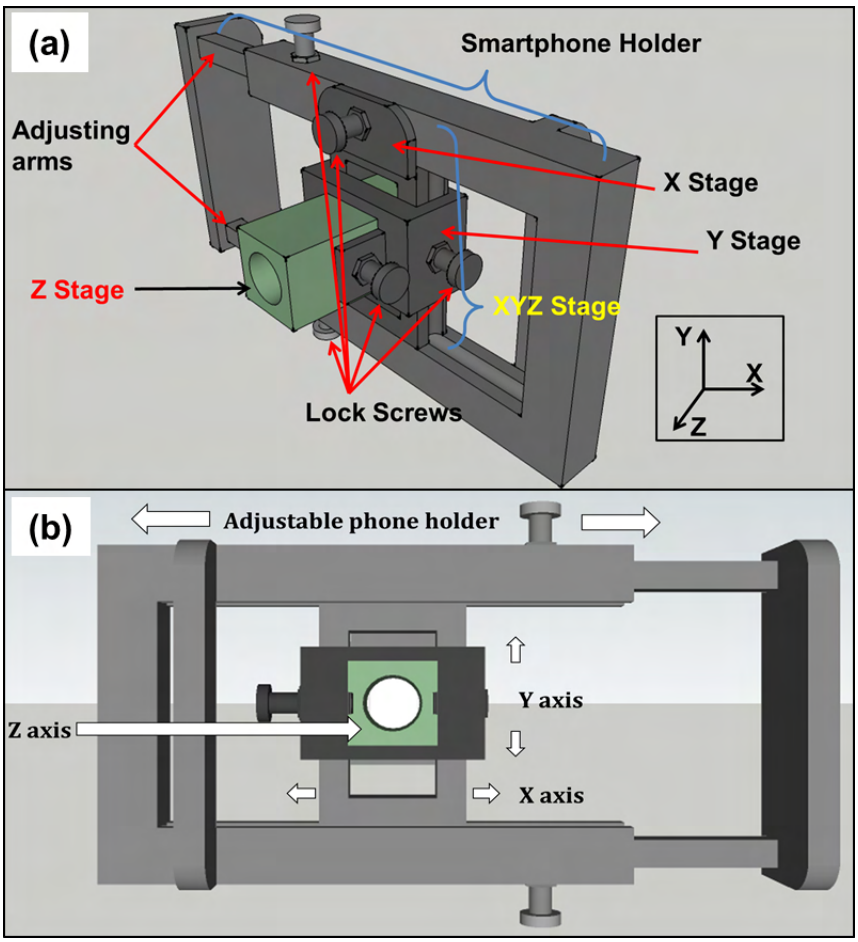

Figure 7.1: Illustration of the 3D drawing of the universal smartphone holder from the (a) isometric and (b) front view perspective.

7.2.2 Design of the dual mode colorimetric and fluorescence based sensing system

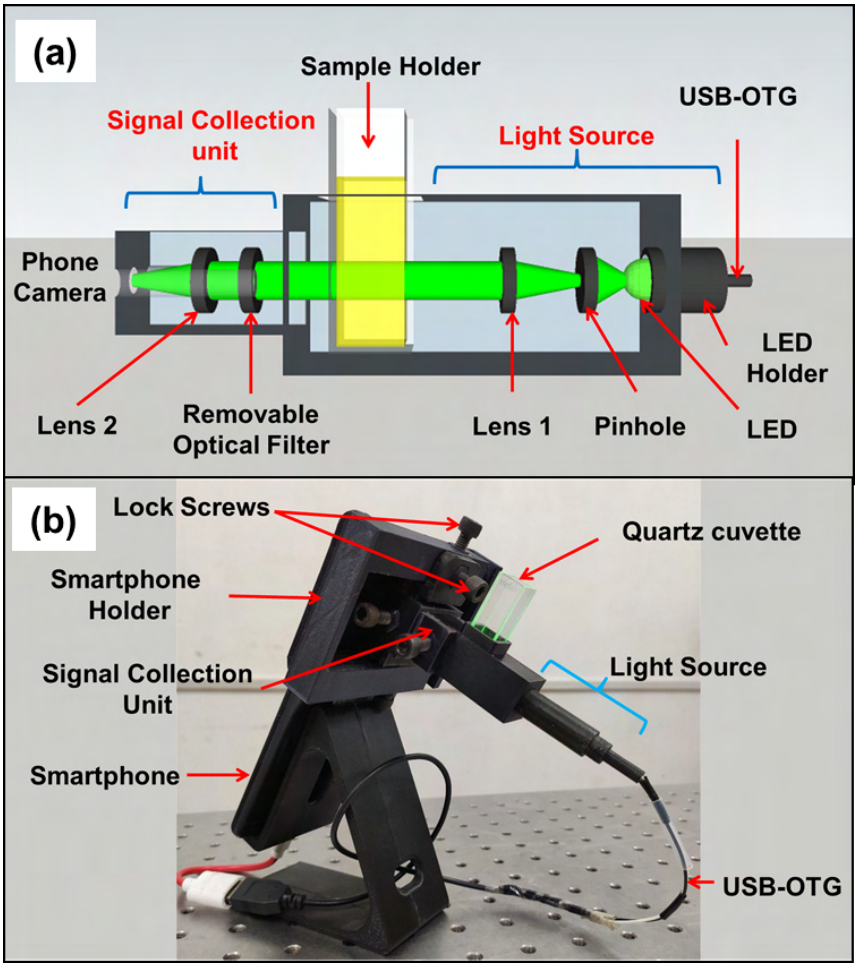

Figure 7.2: (a) Schematic of the optical layout design and (b) the 3D printed prototype of the dual mode colorimetric and fluorescence platform coupled to the smartphone using the universal phone holder.

Figure 7.2 (a) shows the optical layout design of the developed dual mode sensing system which can be used as a colorimeter as well as a fluorometer. Mainly, the system consists of a light source, sample holder and a signal collection unit. The photo image of the working prototype of the setup is shown in Figure 7.2 (b). For colorimetric sensing, a light emitting diode (LED) has been used as an optical source for the proposed setup. The LED is powered from the phone's internal battery through a USB-OTG cable. A plano-convex lens of focal length 10 mm and diameter 6 mm (Lens 1, *Edmund Optics*, Product id: 37-775) is used to obtain the collimated light signal to illuminate the analyte solution. The sample solution

is poured into a quartz cuvette (10×10 mm) and placed inside the sample holder compartment. The collimated incident signal that transmits through the samples is guided towards the phone's rear camera using a plano-convex lens (Lens 2) of similar specifications. The camera captures the incoming light signal and converts into a digital image. Later the captured images have been analysed to estimate the transmitted light signal and subsequently evaluates the sample's optical density. To convert the present sensing platform into the fluorescence mode, an additional optical filter has been incorporated in the setup as a plug and play component. The filter can be easily removed for employing the designed setup as colorimetric sensor. As a proof-of-concept, the transmitted and fluorescence signals of R6G solutions have been measured with the proposed platform. From the literature it is found that the R6G shows optimal absorbance and emission at 530 nm. Hence, a green LED with peak emission wavelength of 530 nm (*RS components India*, Product id: 769-3621), has been used as an incident light source to measure both the transmitted and emitted signal from the considered solution. An optical long-pass filter of cut-off wavelength 550 nm (*Edmund Optics*, Product id: 49-027) has been incorporated in the optical path of the setup for measurement of fluorescence intensity. The dimension of the setup is measured to be 100×25×20 mm.

7.2.3 Design of the microscopic imaging system

Figure 7.3 (a) illustrates the optical layout design of the smartphone-based microscopic imaging system. The system consists of a magnifying unit, a sample unit and an illumination unit. The illumination unit comprises of an LED, a collimating lens (Lens 1) and an optical diffuser. Here, a white LED (*RS Components India*, 818-4452) has been used as an optical source for the microscopic setup. The combination of a plano-convex lens and a diffuser is used to obtain a uniform illumination pattern over the sample slide. The sample unit consists of a slide holder and a translational stage. The slide holder holds the sample slide in place for capturing the microscopic images by the rear camera of the phone. The slide holder is attached to a translational stage which has been used to bring the sample under the focal point of the magnifying unit. This will help to capture resolved and focused images on the designed imaging system. The magnifying unit of the microscopic system is designed with the combination of a ball lens (lens 2) and a plano-convex lens (lens 3). The plano-convex lens is placed near the rear camera lens, followed by a ball lens. In the present demonstration, a ball lens of 3 mm diameter (*Edmund Optics*,

Product id: 43-711) and a plano-convex lens of 6 mm diameter and 10 mm focal length (*Edmund Optics*, Product id: 37-775) have been incorporated as magnifying unit for the proposed imaging setup. The overall dimension of the microscopic setup is measured to be 100×55×45 mm. Figure 7.3 (b) shows the photo image of the compact microscopic setup which has been coupled to a smartphone's camera by utilising the universal holder. As a proof-of-concept, the human red blood cells have been imaged utilising the designed smartphone-based imaging system.

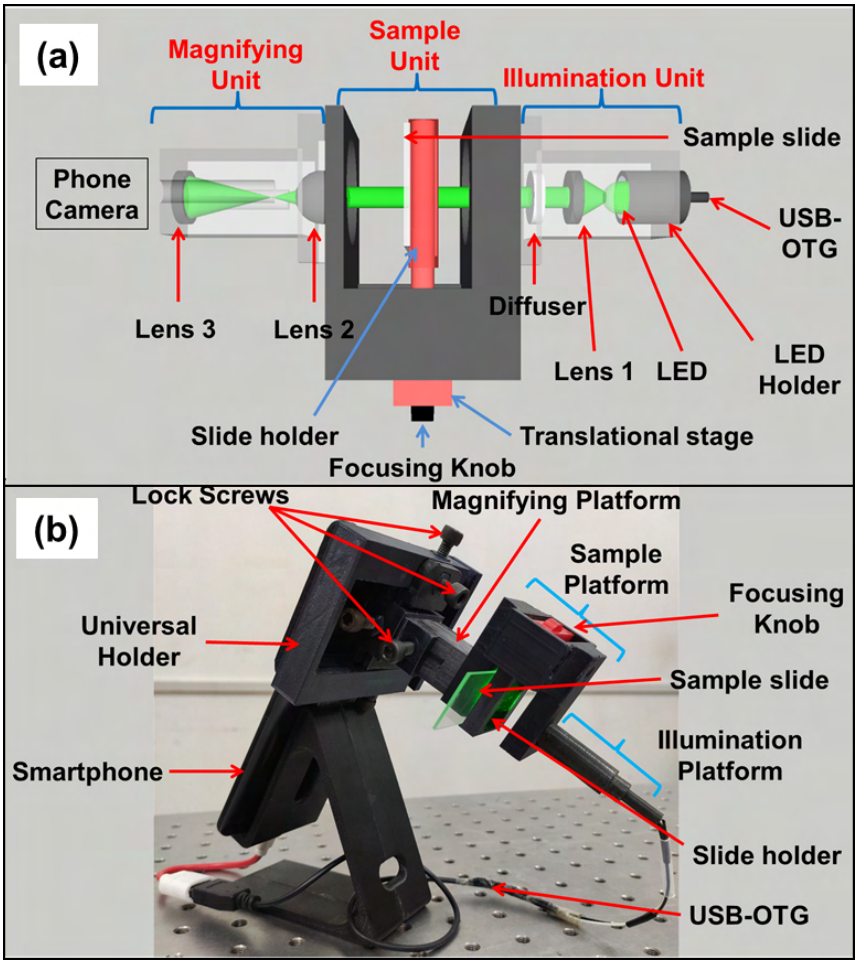

Figure 7.3: (a) Schematic of the optical layout design and (b) the 3D printed prototype of the microscopic imaging system coupled to the smartphone using the universal phone holder.

Universal compatibility of the designed smartphone holder

The universal compatibility of the designed platform has been realised by using smartphones of different brands. Three different smartphones, namely, Samsung

Galaxy C9 Pro, Xiaomi Redmi K20 and Motorola One Power, have been used for both the sensing and imaging studies. The physical dimensions of the phones and the camera positions are different for the considered smartphones as shown in Figure 7.4. Absorbance and fluorescence emission of R6G and imaging of red blood cells have been investigated successfully using the designed universal holder and the respective analytical platforms.

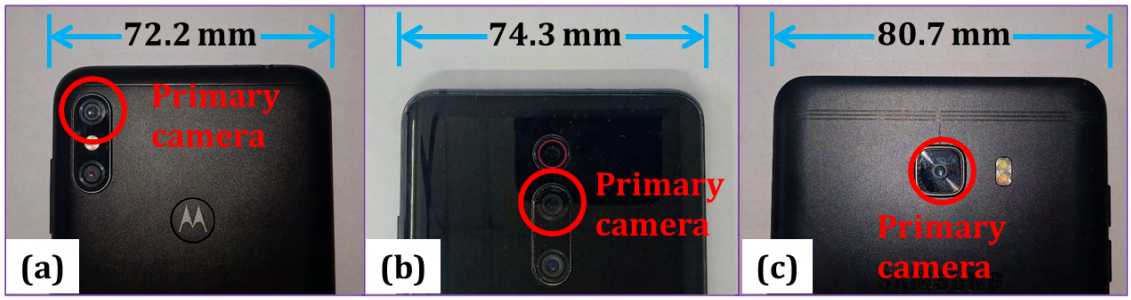

Figure 7.4: Illustrations of size and camera position of three different company-make smartphones, namely (a) Motorola One power, (b) Xiaomi Redmi K20 and (c) Samsung Galaxy C9 Pro.

7.3 Software

For the colorimetric and fluorescence based sensing, the designed tool captures images of transmitted and emitted light signals from the R6G solutions. Upon capturing the images, a freely available image processing software, namely, '*ImageJ*' has been utilised for further analysis [21]. In the present investigation, a green LED source with peak emission wavelength of 530 nm has been used for both the modes of sensing to evaluate the transmitted and emitted light signals of R6G solutions. For colorimetric based sensing, the green channel (G Channel) values of the captured images have been extracted to evaluate the transmitted intensity. On the other hand, for fluorescence based sensing, the red channel (R Channel) values of the captured images have been extracted for emitted intensity measurement. The values of colour channels have been evaluated for an area of 500×500 pixels that was cropped from the central region of the original images. The images were captured under identical camera settings for all three phones. The ISO of the inbuilt camera application has been maintained at 100 while the exposure time was set to be 0.1 sec. The microscopic images of blood samples are shown as captured by the different phone's camera without further processing.

7.4 Materials and methods

All necessary chemicals were acquired from certified suppliers and used as received without further purification. Laboratory grade rhodamine 6G (R6G) was procured from *Merck*, India. The stock of R6G solution (1mM) was prepared by dissolving 0.479 g of R6G reagent in 1000 ml of distilled water. The stock solution was diluted to desired levels using distilled water for the investigations. Leishman stained blood smear slides have been acquired from the *Tezpur University Health Centre* to examine under the designed microscopic platform. The sample has been prepared under the supervision of the clinical technician of the *Tezpur University Health Centre*.

7.5 Utilisation of the dual-mode sensing platform

7.5.1 Colorimetric mode of sensing

For colorimetric mode of sensing, the designed platform measures the transmitted light signal passes through the analyte solutions. R6G solutions of different molar concentrations have been examined with the proposed platform. The prepared R6G solutions fall in the concentration range of 0.01 mM to 0.1 mM. The platform shows a linear trend in sensor responses within the considered concentration range. Five consecutive images have been taken under identical camera settings for each sample. The mean G channel values of the captured RGB images were plotted against the varying concentration of R6G, shown in Figure 7.5. The calibration equations obtained for three different phones are shown in equations 7.1, 7.2 and 7.3. The standard deviation, regression coefficient (R^2), sensitivity and limit of detection obtained for the considered smartphones are summarized in Table 7.1.

Motorola,

$$C = 1.69 - (0.006 \times G) \tag{7.1}$$

Xiaomi,

$$C = 0.93 - (0.003 \times G) \tag{7.2}$$

Samsung

$$C = 1.11 - (0.008 \times G) \tag{7.3}$$

where, C is the concentration of the sample and G is the green channel value of the captured image.

Table 7.1: Characteristic sensor parameters obtained for the colorimetric mode of the designed colorimeter.

SN	Company/Model	SD	R^2	Sensitivity	LoD
1	Motorola/ One Power	0.065	0.96	0.15 AU/M	0.4 µM
2	Xiaomi/Redmi K20	0.085	0.98	0.30 AU/M	0.3 µM
3	Samsung/Galaxy C9 pro	0.061	0.98	0.11 AU/M	0.5 µM

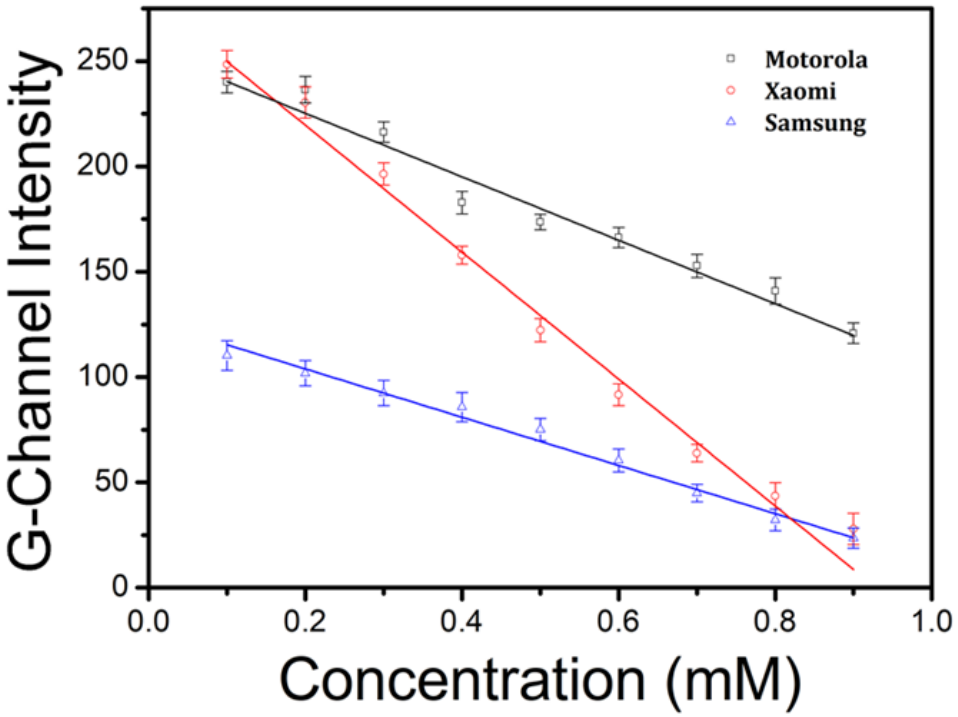

Figure 7.5: Transmitted intensity of rhodmine 6g with varying concentration as measured in the designed system using three different smartphones.

7.5.2 Fluorescence mode of sensing

The fluorescence emission signal of R6G has also been estimated using the designed sensing tool. An optical filter with a cut off wavelength of 550 nm has been incorporated into the setup for fluorescence study. Upon excitation of the sample with an LED source of 530 nm, the fluorescence signals emitted from R6G solutions have been captured by the rear camera of the phone. The quantification of the emitted light signal has been carried out by extracting the R channel values of the captured images. The plot between the R channel values and analyte concentrations is shown

in Figure 7.6. Like the colorimetric mode of sensing, five consecutive images of fluorescence signal have been captured for the regression analysis. The characteristic parameters are summarized in Table 7.2. Three calibration equations have been obtained for three variants of phones for the fluorescence-based study are given by equations 7.4, 7.5 and 7.6.

Motorola,

$$C = (0.0026 \times R) - 0.42 \tag{7.4}$$

Xiaomi,

$$C = (0.0042 \times R) - 0.62 \tag{7.5}$$

Samsung,

$$C = (0.0081 \times R) - 1.20 \tag{7.6}$$

where, C is the concentration of the sample and R is the red channel value of the captured image.

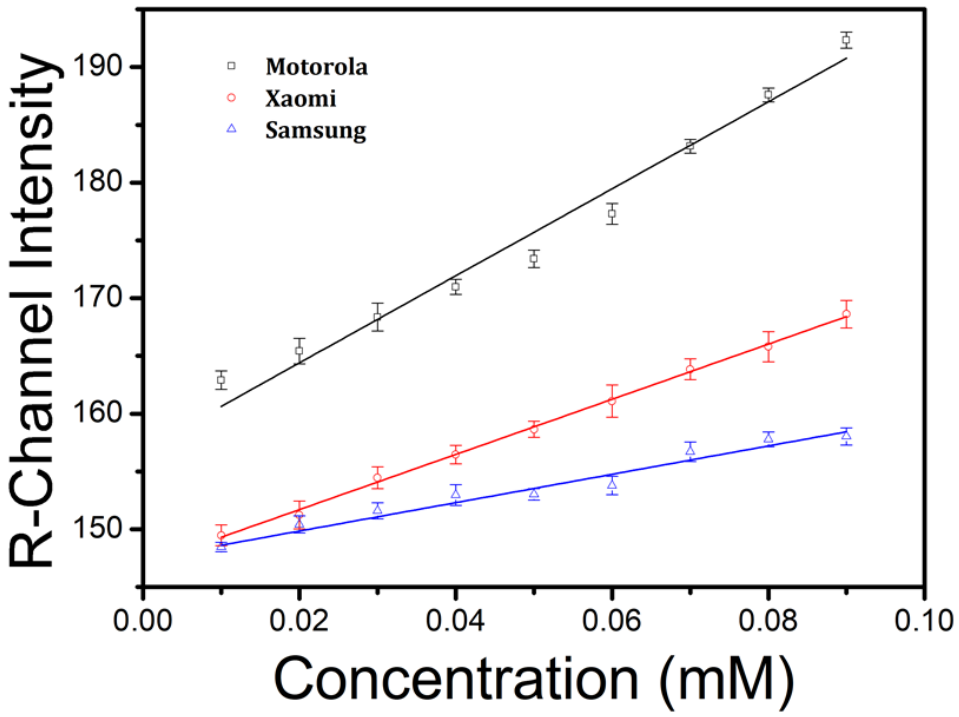

Figure 7.6: Fluorescence intensity of rhodmine6g with varying concentration as measured in the designed colorimeter using three different smartphones.

Table 7.2: Characteristic parameters obtained for the fluorescence mode sensing of the designed system.

SN	Company/Model	SD	R^2	Sensitivity	LoD
1	Motorola/ One Power	0.08	0.97	0.37 AU/M	0.6 µM
2	Xiaomi/Redmi K20	0.06	0.99	0.24 AU/M	0.8 µM
3	Samsung/Galaxy C9 pro	0.05	0.97	0.12 AU/M	1.2 µM

Discussion

For both the considered sensing approach, the responses of the designed smartphone platform show a good degree of correlation between the analyte concentrations and sensor responses. The characteristic curves for the considered analyte within the specific range of concentrations are found to be unique for each smartphone. Among the three variant smartphones, Xiaomi phones show the highest sensitivity and the lowest detection limit in colorimetric mode while for fluorescence mode of sensing, the Motorola phone shows the highest sensitivity for the considered samples. These variations in sensor responses are attributed to different CMOS sensors configurations in different phones. Again, every phone has its unique image processing algorithm of converting the signals recorded by the CMOS into the RGB images. So, the RGB values may differ for different phones, though the optical path, the light condition and camera setting are kept identical for all the phones.

7.6 Microscopic setup for imaging study

The custom designed microscopic imaging platform has been attached with the universal smartphone holder and utilised it to capture images of red blood cells. The designed microscopic platform performs under the bright field configuration and utilises a white LED to illuminate the sample. The magnification of the designed imaging tool has been obtained by using a combination of a ball lens (3 mm diameter) and a plano-convex lens (11 mm focal length, 6 mm diameter). The resultant magnification of the optical configuration is calculated to be 175× using the following equations.

$$M_{Total} = M_{BL} \times M_{PCX} \tag{7.7}$$

where, M_{Total} is the effective magnification of the two lens system, M_{BL} is the magnification of the ball lens and M_{PCX} is the magnification of the PCX lens.

$$M_{BL} = \frac{1000 \times (\eta - 1)}{\eta \times D} \tag{7.8}$$

where, η and D are the refractive index (1.517) and the diameter (3 mm) of the ball lens.

$$M_{PCX} = 1 + \frac{d}{f} \tag{7.9}$$

where, d and f are the outer diameter (6 mm) and the focal length (11 mm) of the PCX lens.

The resolution of the designed microscopic system has been evaluated by imaging the 1951 USAF resolution test target. It is often used as a standard test device to validate the imagining ability of a microscopic platform on the micro-scale. The standard equation to evaluate the resolution of a microscopic system using a test target is given by -

$$Resolution(lp/mm) = 2^{GN+(EN-1)/6} \tag{7.10}$$

where, the GN and EN indicates the clearly resolvable group and its smallest element in the test chart that can be imaged by the imaging system. Figure 7.7 (a) shows the images of the resolution target captured by the designed microscopic platform on three different smartphones. The designed imaging platform can easily resolve the element number 6 in group 7 of the target element, suggesting that the resolution of the microscopic platform is as good as 2.1 µm. Figure 7.7 (b) depicts the intensity profile of three distinct white lines of the smallest element of the test target. All three smartphones are capable of capturing the smallest line element present on the 1951 USAF test target with the aid of the universal holder that couple the microscopic setup in all the phones. Finally, the designed microscopic platform has been utilised to image the blood cells, shown in Figure 7.7 (c). All the images captured by the smartphone microscope are compared with a standard optical microscope. It is observed that the magnified image of blood cells captured by the smartphone microscope is good enough for diagnostic applications. It is envisioned that the proposed microscopic platform can be utilised for various other useful purposes such as the monitoring the micro-organisms or particles present in water samples.

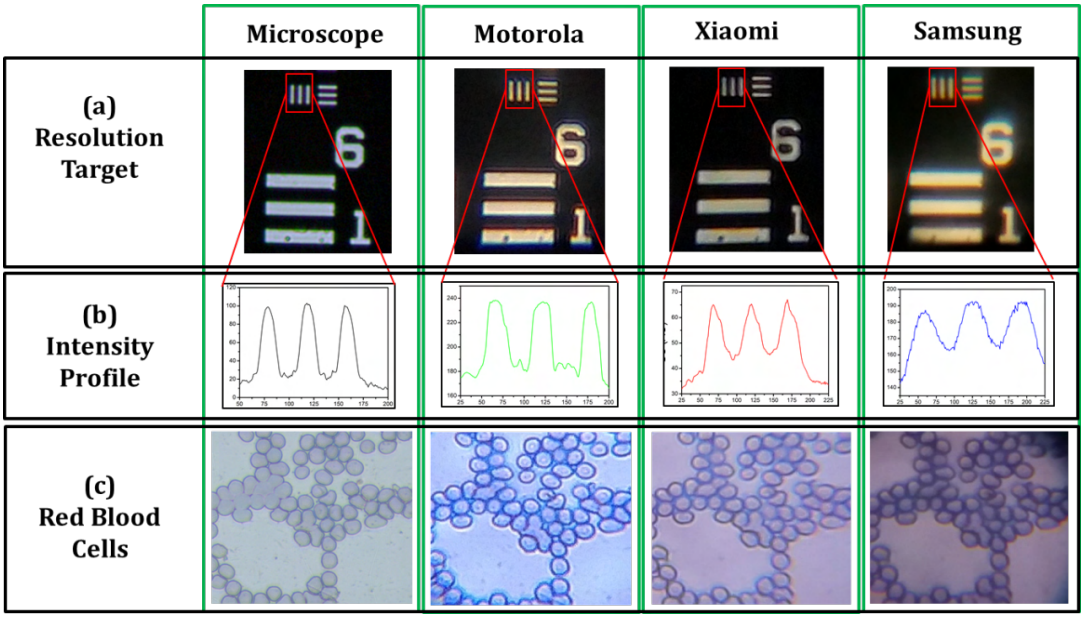

Figure 7.7: Images of the (a) resolution target (b) intensity profile and (c) blood cells captured by a standard optical microscope and the smartphone microscope attached with three different smartphones such as Motorola, Xiaomi and Samsung respectively.

7.7 Summary

The working of a universal phone holder that can be used for multi-purpose analyses has been discussed in this chapter. The holder can be attached to any smartphones regardless of the dimension and position of the rear camera. Smartphones of varying width ranging from 65 mm to 95 mm can easily be coupled to the designed universal holder. By utilising the holder; colorimetric, fluorescence and microscopic based studies have been performed using a custom developed dual mode sensing and a microscopic imaging platform. The designed holder will be developed as a universal analytical platform where different kinds of analytical investigations can be carried out using a smartphone. It is further envisioned that the designed holder can also be used to couple optical sensing setups to the front camera and the ambient light sensor (ALS) of the phone for scattering and photometric based sensing studies.

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