Chapter 2

HARDWARE AND SOFTWARE PART OF A SMARTPHONE FOR DEVELOPMENT OF ANALYTICAL INSTRUMENTS

This chapter discusses the detail of smartphone technology that has been used for development of various sensing and imaging systems. The basic functions and the use of various embedded sensors have been extensively covered in the chapter. Two major optical sensors of a smartphone, namely, the camera and the ALS have been discussed in details. Both the sensor module of the phone have been utilised to develop several analytical platforms in the present thesis work. Furthermore, the development of Android applications is also incorporated in this chapter. At the end, the chapter concludes with some sensoristic parameters related to an analytical sensing platform.

2.1 Recent advancement in smartphone technology and its embedded sensors

The term smartphone refers to a handheld electronic device that provides connection to a cellular network, originally meant to allow individuals to communicate via voice and text massages. Today, smartphones become an intrinsic part of everyday life. Currently, the global smartphone penetration rate has reached to 80% which

Table 2.1: Embedded sensors of smartphones and their usage

SN	**Sensors**	**Does**	**Usage**
1	Accelerometer	Detect translational motion	Control screen orientation
2	Ambient light sensor	Measures ambient light intensity	Control the screen brightness according to the ambient light
3	Camera (CMOS sensor)	Record the incoming light signal	Capture images and videos
4	Gyroscope sensor	Detects rotational motion	Orientation of the phone
5	Magnetometer	Detect magnetic field lines for navigation purpose	Find the geo-graphical north pole to navigate
6	Proximity sensor	Detect infra-red signal	Automatically close the screen while talking
7	Humidity sensor	Monitoring relative humidity of the atmosphere	Evaluate the amount of water in air.
8	Temperature sensor	To monitor the temperature of the device	Control internal temperature of the phone

means 4 out of 5 people holds a smartphone [1]. This smart communication device contains a sophisticated operating system (OS) that provides a long list of features to the users such as web browsing, mailing, photography and videography. In terms of communication, smartphone technology has brought a revolution in connecting people by incorporating advanced 3rd and 4th generation (3G/4G) network connectivity that enables rapid exchange of voice, text, picture and video messages among the users. With touch screen technology smartphone provides an excellent experience to the users. Applications such as digital clock, scientific calculator and digital calendar are easily accessible on a smartphone, enabling it to do jobs of multiple gadgets on a single platform. The inbuilt Global Positioning System (GPS) enables real time navigation while travelling. Smartphones are also compatible to different custom-developed software applications which can be installed on the device according to the user's wish.

The modern-day smartphones are the most advanced handheld telephonic devices comprising of various advanced capabilities which include Artificial Intelligence (AI), cloud-based mobile applications, 5G Connectivity, applications (Apps) for small businesses, transportation and financial transactions. Along with these, various important sensors are also embedded in the smartphone which are designed and developed by utilising the latest cutting edge technology to enhance its overall performance [2, 3]. For instance, the incorporation of the temperature sensor helps in keeping an eye at the internal temperature of phone. It monitors the temperature of the central processing unit (CPU) and prevents any possible malfunctions due to overheating. Similarly, the proximity sensor automatically locks the screen while talking on the phone. It helps in preventing any unwanted touch on the phone screen and also minimises the power consumption. All these facilities allow smartphones to be used in personal or business contexts and most importantly it can be utilised in various educational purposes including Research and Development (R&D) works. In Table 2.1, some embedded sensors of a typical smartphone and their usage have been listed in a tabular format. These sensors are being used by various research groups to develop different smartphone-based sensing and imaging platforms [4–7]. The present thesis work relies on the inbuilt optical sensors of a smartphone particularly the camera and the ALS to design quite a few analytical platforms. Thus the usage of this two sensors as photo-detectors in smartphone-based sensing and their characteristics have been discussed in the subsequent sections.

2.1.1 Imaging sensor of a smartphone

The camera is one of the most used features of a smartphone followed by the voice and text message services. It is an inbuilt imaging sensor utilised either for capturing photographs or recording videos on the smartphone. A smartphone camera comprises three basic hardware components, the lens module, the semiconductors and the packaging part. Charge Couple Device (CCD) and Complementary Metal-Oxide-Semiconductor (CMOS) are two primary imaging sensors that have been widely used by smartphone manufacturers in fabricating the camera sensor. Both the sensors are capable of capturing high quality images and videos. But in the race of reducing the cost, size and power consumption, CMOS sensors has become the most reliable choice for the smartphone cameras in recent times. Currently, all the manufacturers use CMOS as smartphone's primary imaging sensor. With each generation of smartphones, the CMOS related technologies are also improving

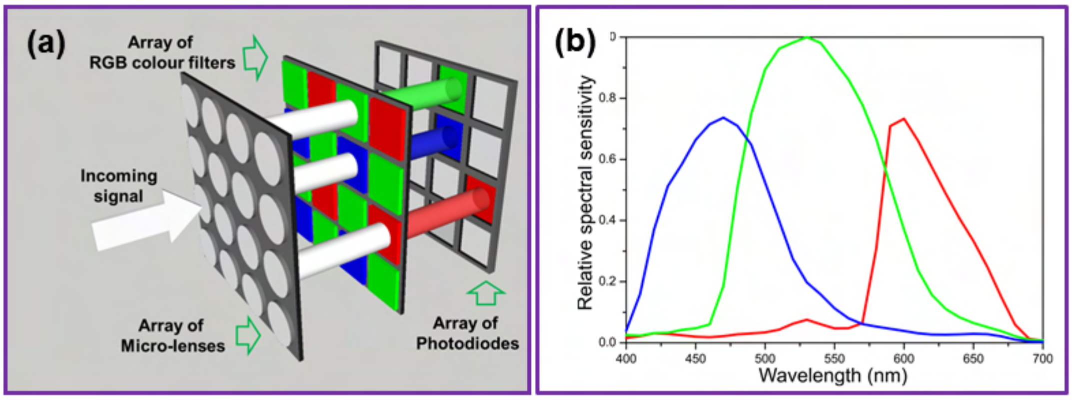

Figure 2.1: (a) Schematic representation of a conventional CMOS pixel array and (b) relative spectral sensitivity of a smartphone camera.

in parallel. With the advanced CMOS sensor, modern smartphone's camera performs very well even in the low light condition. CMOS imaging sensor is an array of pixels that have been arranged in a square matrix pattern to record the incident light signal. Figure 2.1 (a) shows the schematic representation of a conventional CMOS pixel array that comprises of different layers of micro-lenses, optical filters and semiconductors arrays. As soon as the light falls on the lenses, it guides the light towards the Bayer optical filters and focuses on the semiconducting photodiodes. Bayer filter is an optical colour filter that splits the incoming light signal into its three primary colures, namely red, green and blue. After that, the photodiodes record the colour intensities and send to the CPU of the phone to construct a digital image using the internal image processing algorithm. The inbuilt image processing software also plays an important role in enhancing the imaging quality of the camera sensor. Moreover, the physical dimension of an pixel directly influence the performance of an imaging sensor which is typically in the range of 1.2 μm. Smaller the size of a pixel, greater is the imaging quality of the CMOS sensor [8–10]. Figure 2.1 (b) depicts the spectral sensitivity of a conventional CMOS sensor embedded in a smartphone. In this thesis work, four different smartphones have been utilised for development of different analytical platforms. The characteristics of the CMOS sensors integrated with these four smartphones are listed in the Table 2.2.

Table 2.2: Characteristic parameters of four different smartphones which are used in the present thesis work

Name	**Xaiomi Redmi Note 4** [11]	**Xaiomi Redmi K20** [12]	**Samsung Galaxy C9 pro** [13]	**Motorola One power** [14]
Sensor model	Sony Exmor RS IMX258	Sony Exmor RS IMX586	Isocell	Sony IMX
Sensor matrix	13 MP	48 MP	16 MP	16 MP
Aperture	f/2.2	f/1.7	f/1.9	f/1.8
Pixel size	1.12 m	0.8 m	1.6 m	1.12 m

2.1.2 Ambient light sensor of a smartphone

The ambient light sensor (ALS) is a photo-sensitive element that is incorporated on the front panel of a smartphone [16–18]. Figure 2.2 (a) shows the actual position of an ALS on a smartphone. ALS may consist of a photo-diode, a photo-transistor or a photonic integrated circuit (PIC) which continuously measures the light intensity falling on it. A typical ALS sensor can operate properly in the intensity range from 50 to 10,000 luminance units (lux). In general, the ALS sensors are highly sensitive to the visible spectrum of the electromagnetic radiation (EMR). Some sensors are also sensitive to the near infra-red (NIR) region. The spectral sensitivity of the ALS depends on the type of photo-detector that has been used at the fabrication stage. However, Figure 2.2 (b) depicts the spectral sensitivity of a regular ALS module used in a smartphone. According to the light intensity measured by the ALS, the internal algorithm of the smartphone automatically manage the brightness of the screen. This automation helps the smartphone in minimising the power consumption and subsequently increasing the battery life. Integration of ALS significantly enhances the performance of a smartphone. Therefore, all the manufacturers incorporate this optical sensor within the smartphones. It is observed that recently ALS has been extensively used in the development of smartphone-based analytical platforms. Various ALS-based platforms have been designed that performs well for in-field material analysis. Utilisation of ALS in smartphone-based sensing has added a new aspect in analytical chemistry.

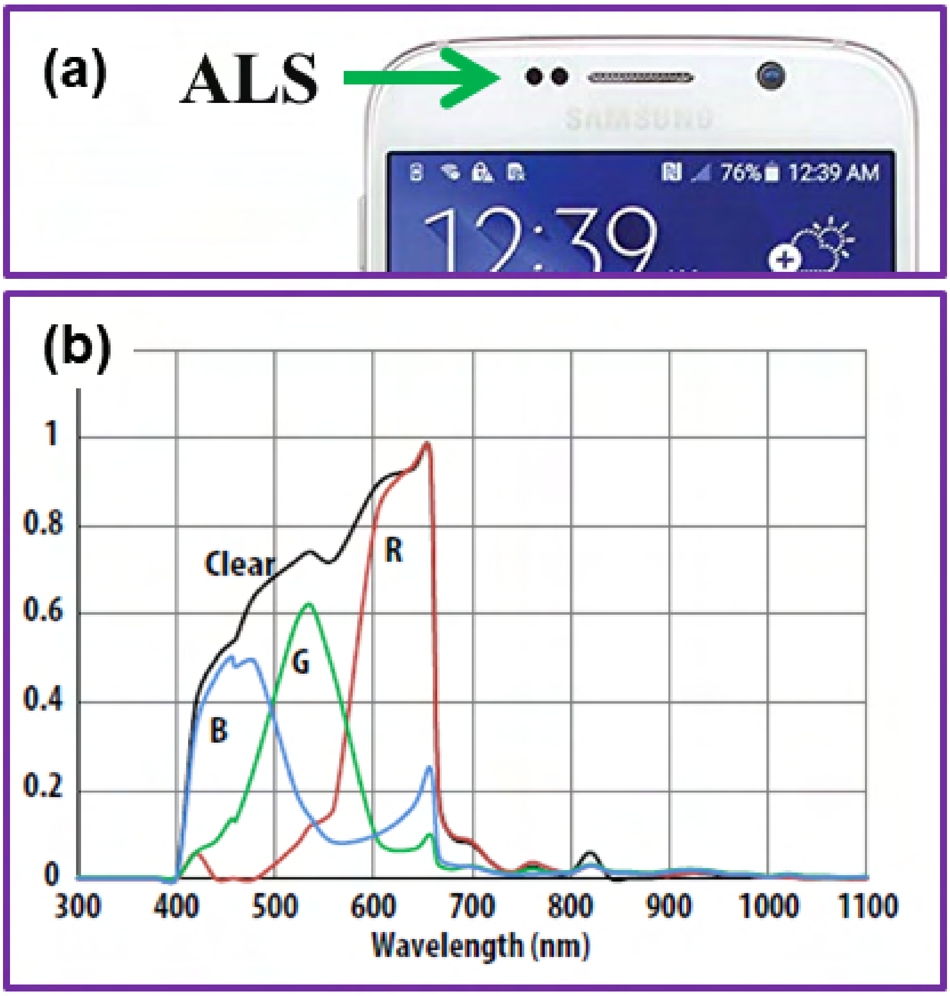

Figure 2.2: (a) Ilustrastration on the typical position of an ALS sensor embedded on a smartphone and (b) spectral sensitivity of a regular ALS, figure is reproduced from [15].

2.2 Development of an Android application

The primary objective of the present thesis work is to design and develop smartphone-based analytical platforms for assessment of different important parameters in water. Another objective of the present thesis work is to develop Android based applications for the designed platforms. The inclusion of the Android application makes the designed tools into a self-contained device. The application excludes the requirement of external computer program to analyse the signals recorded by the optical sensors of the smartphone. There are various platforms available where Android applications can be customized, and new applications can be developed. The '*Android studio*' and the '*MIT App Inventor-2*' are the two most popular open-sourced

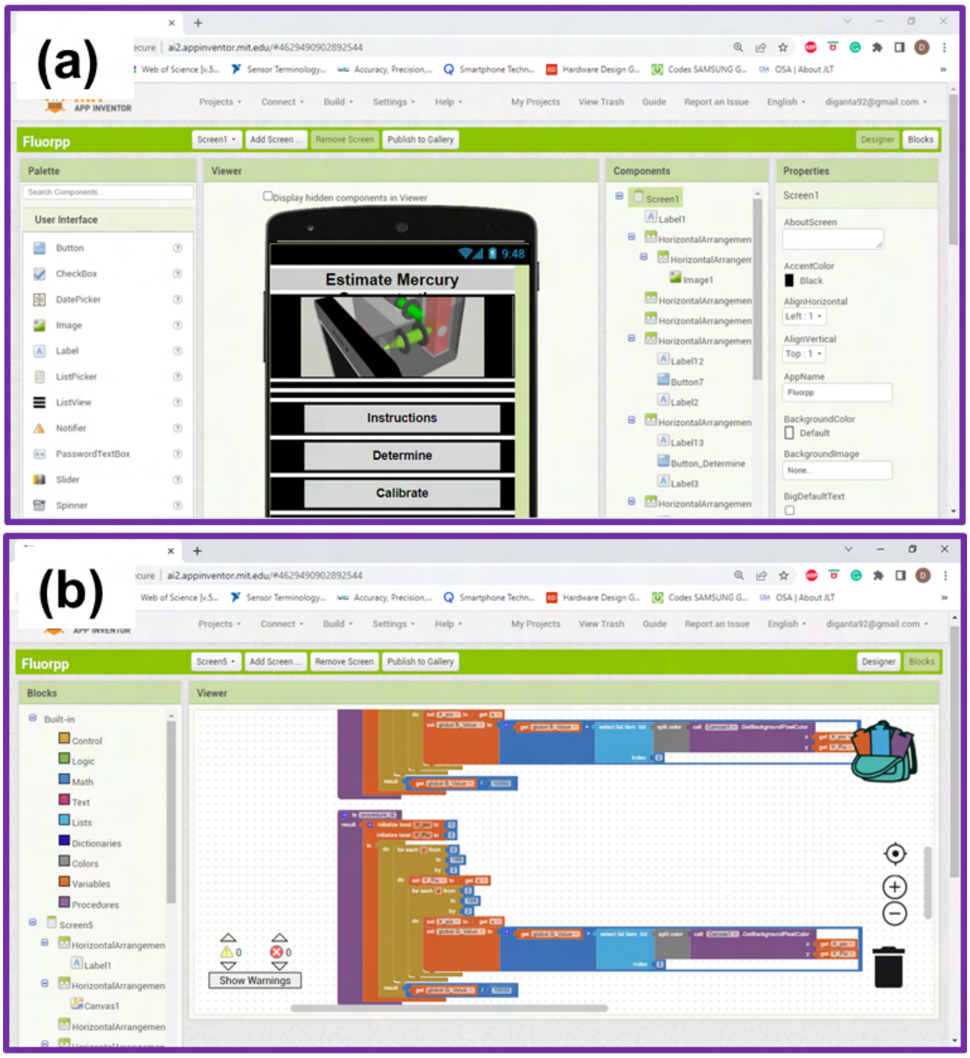

Figure 2.3: (a) '*Designer*' window and (b) '*Block*' window of the '*MIT App Inventor-2*' platform.

Android app designing platforms [19]. '*MIT App Inventor-2*' is an online platform which was developed by *Google* and presently is maintained by the *Massachusetts Institute of Technology*, USA. Recently this cloud-based platform also provides the facility to develop ISO-based applications particularly for the apple phones. Herein, the requisite Android applications have been developed on the '*MIT App Inventor-2*' platform. The platform requires a valid user account in *gmail.com* to login to the webpage which subdivided into two parts – '*Designer*' and '*Blocks*' window. Once logged in to the platform, a user can start a new project or can do necessary editing to the existing projects. Upon creating a new project, the platform redirects the user to the '*Designer*' window. The '*Designer*' window is used to design the application's interfaces where various components such as buttons, checklists, image picker, sliders

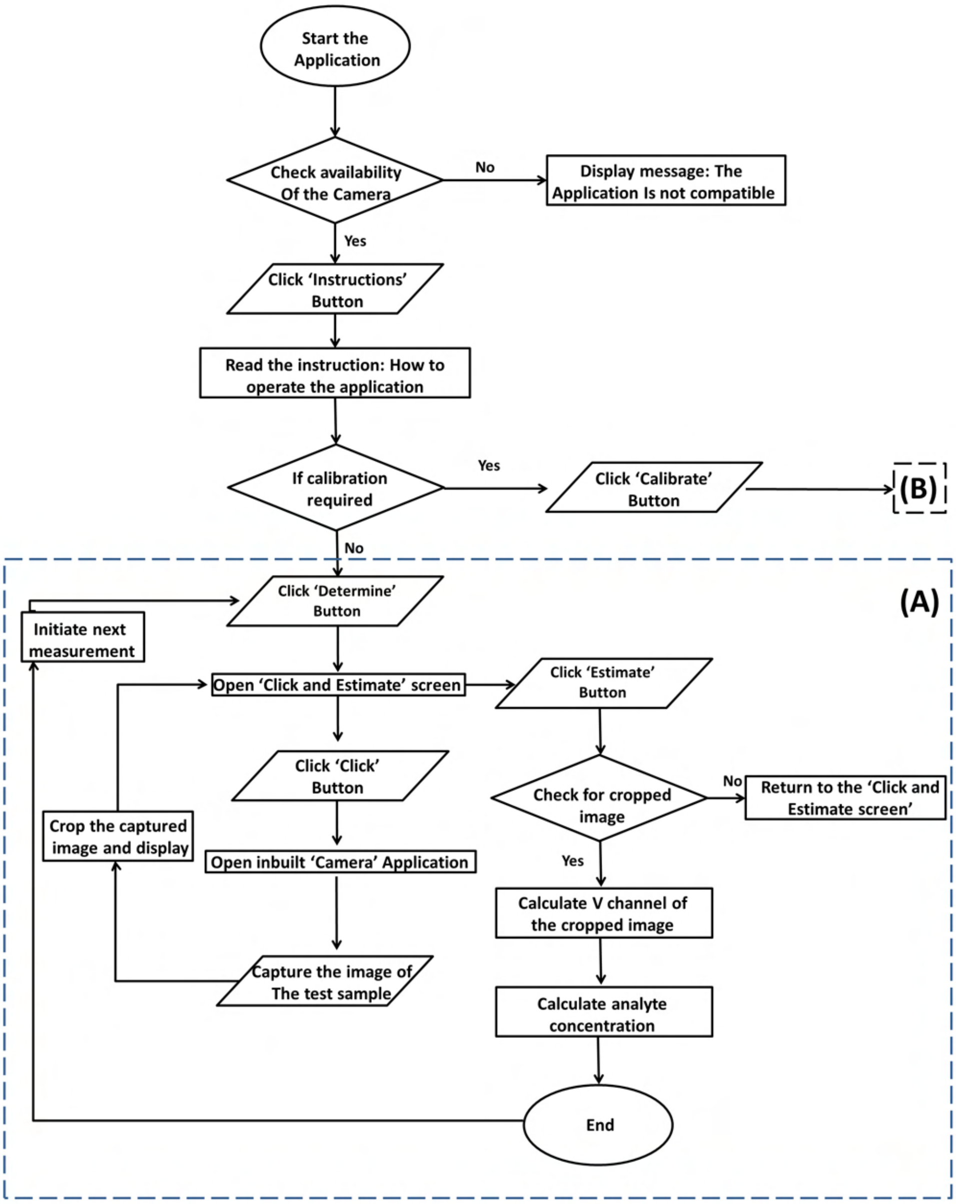

Figure 2.4: (a) Application flow chart for pre-calibrated mode of operation of a developed smartphone-based platform.

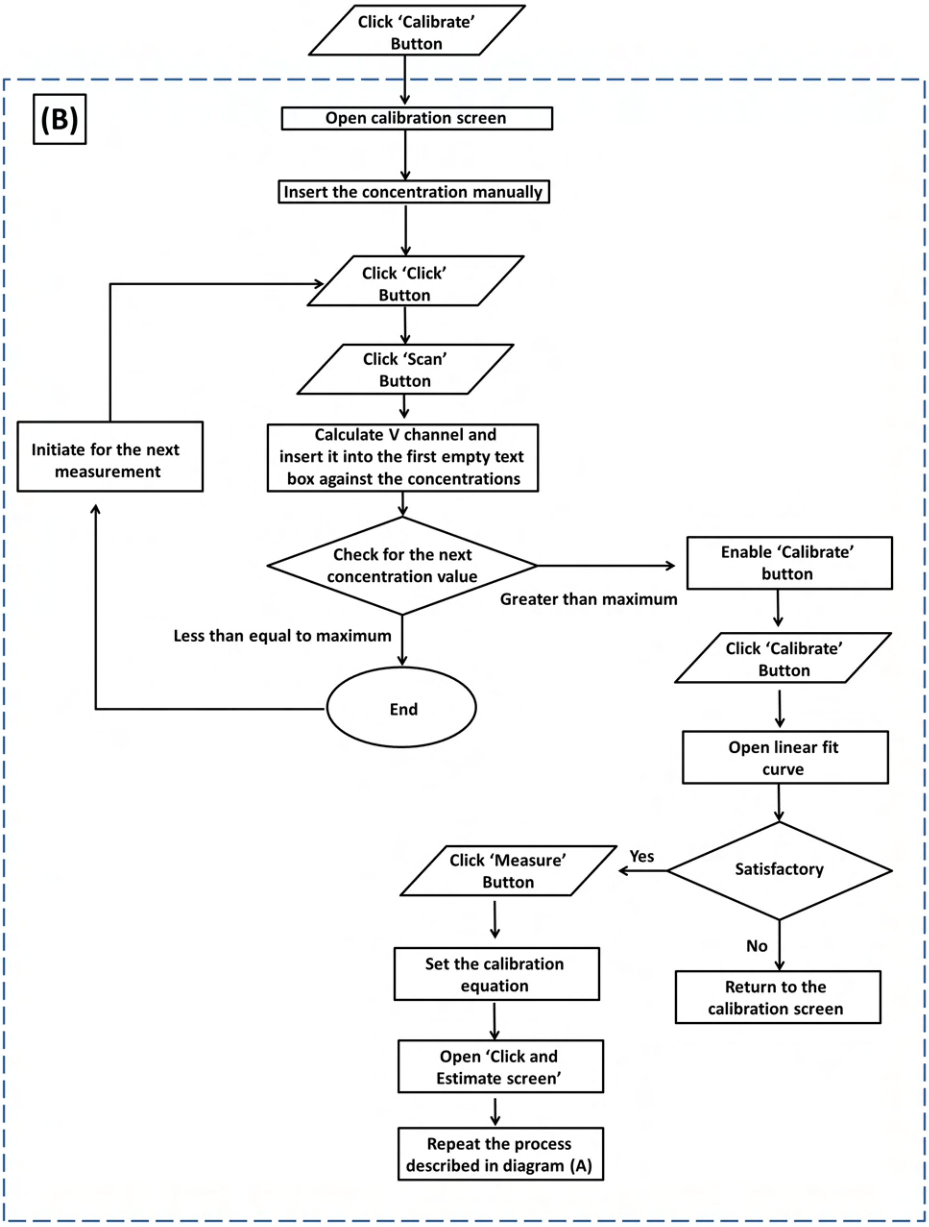

Figure 2.4: (b) Application flow chart for in-field calibration mode of operation of a developed smartphone-based platform.

and switches can be incorporated and necessary editing of these components can be carried out. Figure 2.3 (a) illustrates the '*Designer*' window of the platform. After that, user needs to go to the '*Block*' window to compile the application's program utilising the block codes shown in Figure 2.3 (b). The block code yields a unique way of software compilation where actual programming language is hidden inside some blocks. These blocks are classified into different categories such as control, logic, math, text, lists, colors, variables and more. To write the program, a user needs to drag and drop these block codes on the programming window. Finally, the completed project has to be exported from the webpage and it will be ready to install on any Android phones. Figure 2.4 (a) and (b) illustrate the architectural layout of one of the Android applications developed for the present thesis.

2.3 Analysis of accuracy and precision in instrumental methods

Measurements with instrumental methods are always associated with some unavoidable uncertainties resulting in errors in estimated results. Error in measurement can be defined as the difference between the actual value and the estimated value of a quantity. The proper evaluation of these errors is a critical aspect of realizing the reliability and reproducibility of an analytical instrument. Various statistical methods such as measurement of standard deviation (σ), percentage bias (%Bias) and percentage relative standard deviation (%RSD) have been utilised to quantify the probable uncertainties present in the measured results [20, 21]. The definitions and mathematical expression of some of these parameters are discussed below.

1. **Standard deviation(σ)**: Standard deviation measures dispersion of the data set from its mean value. The smaller numerical value of the standard deviation implies that the responses of an instrument are concentrated around the mean value. Higher value indicates a spread out data points. The mathematical expression for standard deviation can be defined as

$$\sigma = \sqrt{(\frac{1}{N})\Sigma_i(x_i - \mu)^2} \tag{2.1}$$

   where, N is the sample population, x_i is the sensor response and μ is the mean response.

2. **Percentage Bias (%Bias)**: %Bias is a measure of accuracy of the estimated

results in relation with the actual value. The %Bias with lowest magnitude indicates the highest accuracy in the obtained result. The mathematical expression for %Bias can be defined as

$$\%Bias = [(T - E)/T] \times 100 \tag{2.2}$$

where, T is the actual concentration and E is the estimated value.

3. **Percentage Relative Standard Deviation (%RSD)**: %RSD is another tool to estimate the preciseness of a data set which has been calculated on the basis of standard deviation of that data set. The mathematical expression for %RSD can be defined as

   $$\%RSD = (\sigma/\mu) \times 100 \tag{2.3}$$

   where,σ is the standard deviation of the blank sample and μ is the mean value.

2.4 Some important figure of merits of analytical instrument

1. **Sensitivity(S)**: Sensitivity is defined as the smallest distinct difference in the analyte concentrations, that a measuring instrument can distinguish and show two unique responses for both the concentrations. Within the linear range, the sensitivity of the proposed tool can be estimated as follows.

   $$S = \Delta r/\Delta P \tag{2.4}$$

   where, Δr is the change in sensor response and ΔP is the change in analyte concentration.

2. **Limit of detection (LoD)**: The LoD is the smallest analyte concentration that shows a significantly unique response compared to the response of blank sample containing no analyte. The mathematical expression for LoD can be defined as

   $$LoD = 3\sigma/S \tag{2.5}$$

   where,σ is the standard deviation of the blank sample and S is the sensitivity of the designed sensor.

3. **Limit of Quantification (LoQ)**: The LoQ is the lowest value of an analyte concentration that can be measured by an instrument with high degree of accuracy and precision. The mathematical expression for LoQ can be defined as

$$LoQ = 10\sigma/S \tag{2.6}$$

   where,σ is the standard deviation of the blank sample and S is sensitivity of the designed sensor.

4. **Percentage Recovery ($\%Recovery$)**: The %Recovery indicates the performance of an instrument on how accurately it can measure a quantity in relation with the actual value. The acceptable %Recovery is ranging from 70% to 120%. The mathematical expression for %Recovery can be defined as

$$\%Recovery = (E/T) \times 100 \tag{2.7}$$

   where, T is the actual concentration and E is the estimated value.

2.5 Summary

This chapter discusses about the recent progresses of smartphone technologies and its various features. The importance of inbuilt sensors in enhancing the performance of smartphone has also been covered in this chapter. The chapter also includes the short description of two inbuilt sensors of a smartphone, namely, the camera and the ALS which have been extensively used for development of various smartphone-based analytical devices. Finally, the chapter concludes by describing several figures of merits of an analytical instrument to test its performance and reliability while measuring the analyte concentration.

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