# CHAPTER 2

# HARDWARE AND SOFTWARE OF A SMARTPHONE FOR THE DEVELOPMENT OF OPTICAL IMAGING DEVICES

*This chapter gives a brief overview of the usability of the different sensors and other functional components embedded in a smartphone for the realization of cost-effective and robust optical imaging and sensing devices. The usability of the CMOS imaging sensor of the phone along with other functional components that have been used to develop different optical imaging platforms has been thoroughly discussed. Furthermore, the chapter discusses the introduction of the software platform that has been implemented to convert the smartphone imaging system into a standalone tool for data analysis.*

## 2.1 Background

With the easy availability and accessibility of various consumer electronic devices such as smartphones, Arduino microcontroller board (with the camera module), small single-board computers, e.g., Raspberry Pi with the camera module, CCTV, miniature display modules and low-cost optics module, bring new possibilities to develop alternative, inexpensive, field-portable various imaging and sensing platforms [1, 2]. Specifically, the smartphone has been exploited extensively for this purpose because of its many superior features, such as portability and accessibility, even in low-income countries [1]. Since the introduction of the first handheld mobile phone in the early 1980s, modern smartphones are one of the rapidly developing innovations of the 21st century. It is estimated that there are approximately 6.05 billion users by the end of

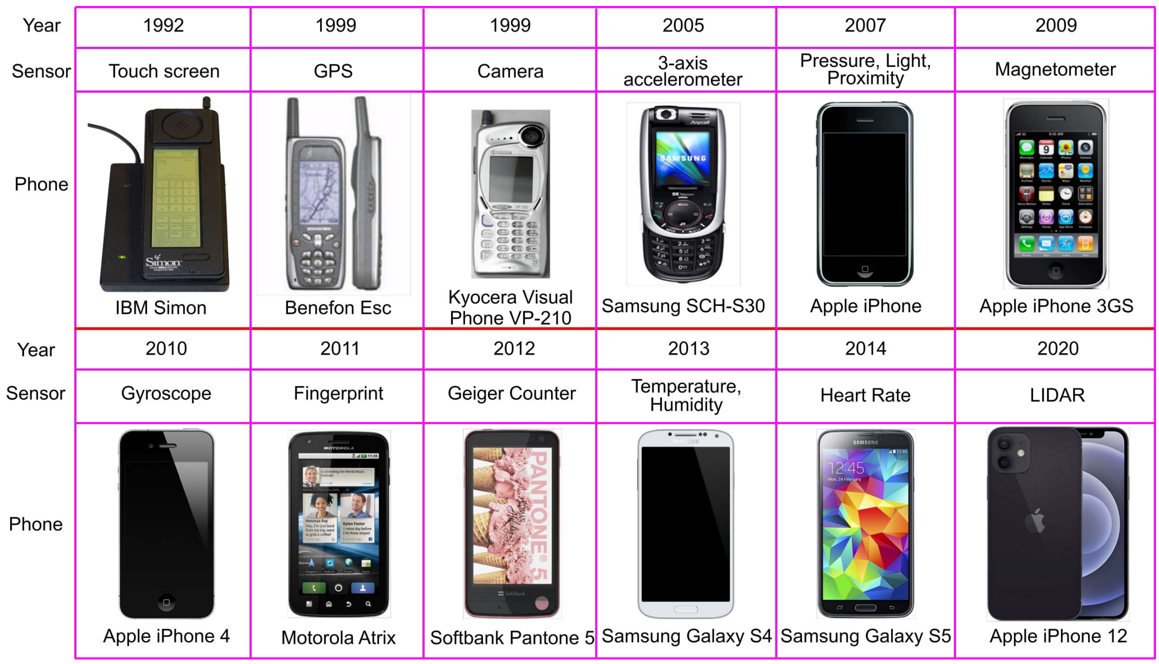


Figure 2.1: Evolution of smartphone sensors from 1992 to 2020

2020 and more importantly, 70% of those are in developing countries [3]. This is the outcome of a continuously developing process where different cutting-edge technologies available on a large scale are being integrated on a small footprint. The integrated sensors have the capability to provide different parameters such as location, motion, tilt, ambient illumination, temperature, pressure, humidity etc., with precise accuracy [4]. To attract the customer's interest, smartphone manufacturers are always being forced to make technological refinements in terms of better hardware, computational performance and user experience. Currently, only a few manufacturers share the global smartphone market with an estimated sales of $409.1 billion annually in 2020, which relies on two major software ecosystems known as the operating system (OS); the Android from Google Inc. and iOS from Apple [5]. Till now, smartphones with the Android OS holds the largest share of the global market and have become the most popular platform with an 88% market share [6]. Open-source application development framework ensures the superiority of the Android platform by promoting the development of numerous convenient and user-friendly applications.

## 2.2 Sensors and functional components integrated in a smartphone

Modern day smartphones are integrated with various important sensors. These can be either hardware-based physical sensors, where data of the physical parameters can be interpreted directly or software-based virtual sensors, where more than one physi-

Table 2.1: Most commonly used sensors in different variant smartphones.

| **Sensors** | **Sensor Type** | **Illustration** |
|---|---|---|
| Camera (CMOS) | Hardware | Photography and videography |
| Ambient light sensor (ALS) | Hardware | Measuring the ambient light controls the brightness level of the display screen |
| Accelerometer | Hardware | Motion detection by measuring acceleration along x, y, and z-direction |
| Gyroscope | Hardware | Rotation detection due to spinning and turning by measuring the rate of rotation of the device along x, y, and z-direction |
| Magnetometer | Hardware | Works as a compass by measuring geomagnetic field along x, y, and z-axes |
| Proximity sensor | Hardware | Detects object at the close proximity of the display screen of the phone |
| Gravity | Software/Hardware | Detects motion due to shaking or tilting of the phone |
| Orientation | Software | Determines the phone position utilizing the gravity sensor and magnetometer to obtain the inclination matrix and rotation matrix of the phone |

cal sensor is required to interpret sensoristics data. Combining them along with data processors and their connectivity, a whole new functions and processes can be realized that no other small devices had managed to do so before [7]. Figure 2.1 illustrates the evolution of different smartphone sensors from 1992 to 2020. The latest variant smartphones not only can sense the physical nature of activities and their manifestation in digital format but also helps to discover hidden patterns and structures in the data. The most frequently used sensors in almost all variants smartphones are illustrated in table 2.1, along with their uses. Apart from all of those sensors, other useful functional components such as the USB port, LED Flash lamp, Wi-Fi connectivity, gyroscope are also embedded in all smartphones.

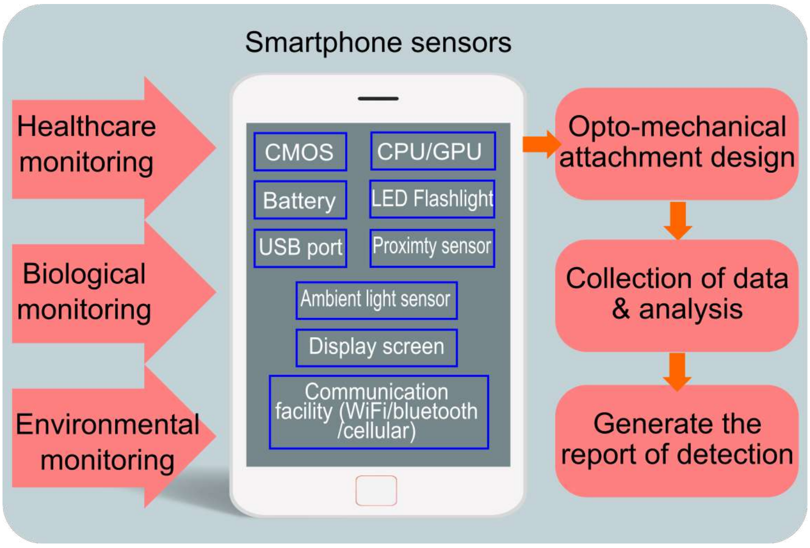


Figure 2.2: Typical illustration of the development of the smartphone based optical imaging and sensing platforms.

## 2.3 Smartphone-based optical imaging and sensing platforms

Over the past two decades, the development of alternative and field-portable imaging and sensing platforms that are very cost-effective compared to the gold standard laboratory instruments have been extensively studied [8–10]. In this regard, smartphone has emerged as an ideal platform for this motive as they are embedded with various useful sensors such as the CMOS imaging sensor, ALS, gyroscopic sensor etc., along with powerful computational units and various user-friendly applications [1]. Figure 2.2 illustrates the typical realization of different optical imaging and sensing platforms using smartphone hardware. By using rapid fabrication techniques such as 3D-printing technology, a compact optical setup can be designed to couple it to the phone, thus transforming it into a convenient and cost-effective solution for sensing and imaging applications. Again, by developing custom-designed applications, it is possible to convert the designed smartphone platform tool into a standalone system that converts the results into a readable format, thus enabling a common citizen to operate the system without having technical knowledge.

Optical imaging is the most important technique in the development of medical devices for application at the PoC. It can provide high-resolution microscopic and macroscopic information of biological specimens in real-time [11]. It is the basic foundation of scientific imaging and analysis that allows the visualization of cellular and sub-cellular structures and their dynamics. This thesis work discusses the realization of affordable and portable microscopic imaging systems by exploiting the smartphone platform for in-field applications with reference to the resource-poor regions. Due to the wide availability and open-source application development platform, Android-based smartphones have been considered to develop different optical imaging tools. Three different phones namely Moto G5 Plus, Samsung Galaxy C9 Pro, and Redmi k20 have been considered to develop the proposed imaging platforms. The CMOS sensor specifications of the considered phones are given in table 2.2. Detail illustrations of the CMOS imaging sensor and other functional components of the phone, along with the applications that have been used to develop an optical imaging device, are discussed in the section 2.4.

Table 2.2: Imaging sensor specifications comparison of three different smartphones.

| **Technical specs** | **Moto G5 Plus** | **Samsung Galaxy C9 Pro** | **Redmi K20 (Main camera)** |
|---|---|---|---|
| Sensor type | CMOS (Sony Exmor RS IMX362 Sensor) | CMOS | CMOS (Sony Exmor RS IMX586 Sensor) |
| Basic resolution | 12 MP (4032 x 3024) | 16 MP (4616 x 3464 ) | 48 MP (8000 x 6000) |
| Sensor size | 7.06 mm (1/2.55") | ——- | 8.0 mm (1/2.25") |
| Pixel size | 1.4 $\mu$m | 1.6 $\mu$m | 0.80 $\mu$m |
| Aperture | $f/1.7$ | $f/1.9$ | $f/1.7$ |

## 2.4 CMOS imaging sensor and functional components of a smartphone for development of an imaging device

One of the fierce competitions among of the smartphone manufacturers is the camera technology, because of which phone cameras are being rapidly improving with time. Now a day, smartphones are with multiple camera features are available that have additional lenses for ultrawide, macro and telephoto acquisition. These camera modules are optoelectronic systems in a small form factor typically consisting of multielement lenses, optical filters, apertures, sensors, and motors for optical image stabilization. Simply, it can be visualized as shown in figure 2.3. Smartphone cameras are, in general, designed for consumer applications such as videography and photography. Their spectral response is limited within the visible region from 400 nm to 700 nm by introducing an infrared (IF) filter in front of the sensor array. Since the sensor array itself cannot differentiate colors, a color filter array (CFA) known

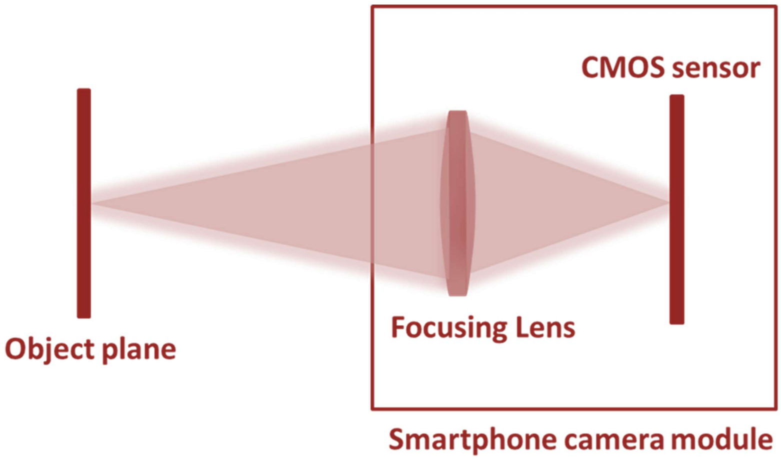


Figure 2.3: Schematic optics design of the smartphone camera.

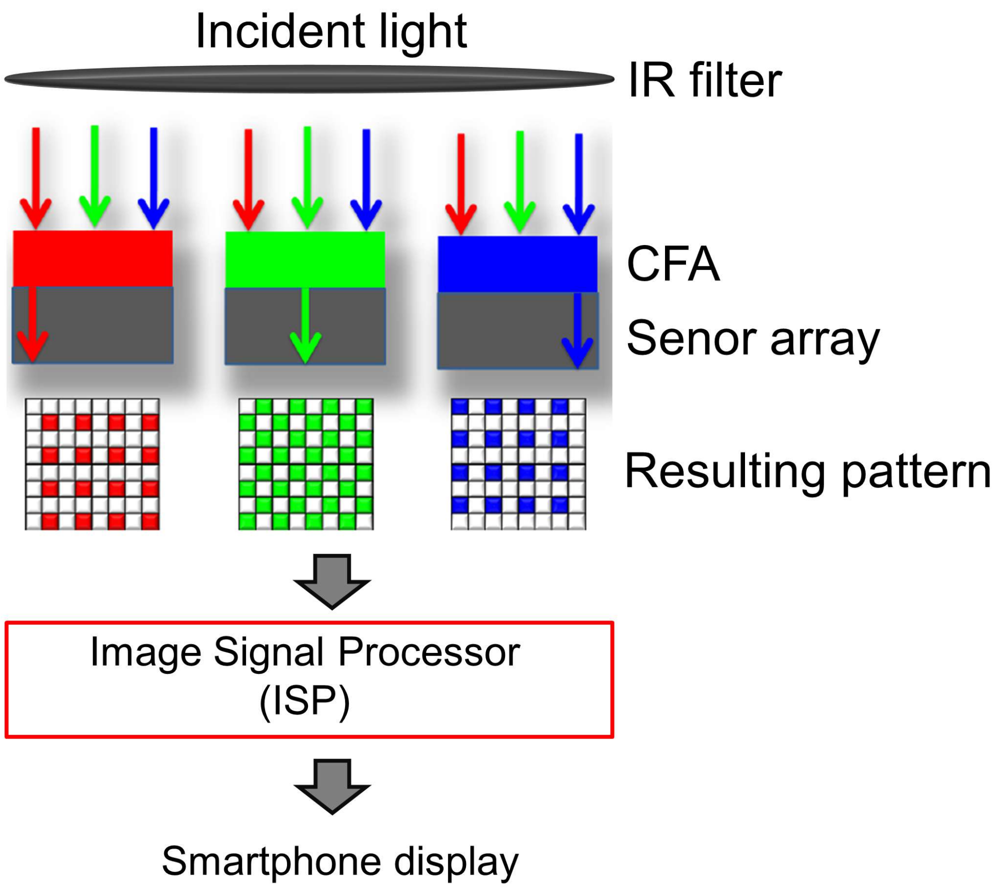


Figure 2.4: Schematic representation of the Bayer pattern formation and digital color image recognition by the CMOS sensor of a smartphone.

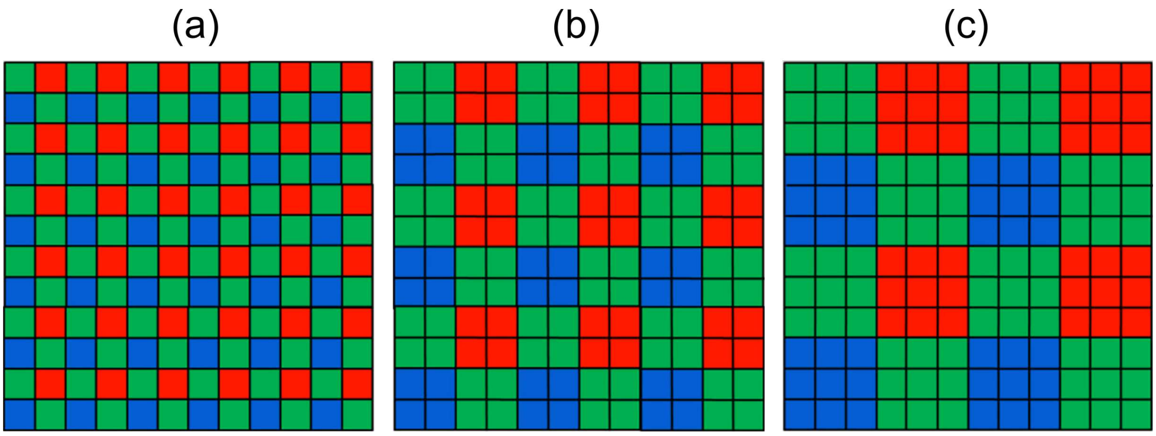


Figure 2.5: Different sensor architectures of modern smartphone camera. (a) Standard Bayer Pattern, (b) 4-cell configuration, and (c) 9-cell configuration.

as Bayer pattern after Bryce Edward Bayer (1929-2012) is introduced on top of the pixel array of the sensor. It is an RGB color matrix pattern arranged in square grid of photosensors which is half green, one-quarter red and one-quarter blue. Figure 2.4 shows the schematic of the digital color image formation process by the CMOS sensor of the phone. Each pixel of the sensor cannot fully specify the values of each of the three colors on its own, thus various demosaicing algorithms have been utilized to interpolate the missing color information. These algorithms utilize the neighbourhood pixels of the corresponding colors to estimate the values of a particular pixel. The photodiodes of the CMOS sensor record the intensity values in shades of grey in terms of 8-bit format (0-255 levels). These numbers can be manipulated by the internal image processing algorithm of the phone to reconstruct the color image and visualize it on the display screen [12].

Most smartphones use a 1/3" format CMOS sensor with 5-12 MP resolution that has pixels with dimensions of 1.1-1.8 $\mu$m. Newer variant phones have ultrahigh-resolution sensors with 48 MP, 64 MP, or even 108 MP to attract consumers. Most of these are 'multicell sensors', different from the standard Bayer sensors. These are named by different manufacturers as 'Quad-Bayer' (from Sony), 'Tetracell technology' (from Samsung), and '4-cell' (from OmniVision). The schematic representations of these sensors are shown in figure 2.5, which are arranged in clusters of pixels or in other word 'macro-pixels' of 4 or 9 pixels. Thus, the number of pixels in the final image is typically 12 MP which is a standard benchmark. The number of pixels greater than this are not useful due to practically unused resolution and the optical performance of the lens is also limited within this value [4]. That's why some manufacturers focus only on handling a reasonable amount of pixels, better image noise, and better dynamic range. However, macro-pixels do have some advantages over a single pixel such as enhanced light sensitivity, which could only be achieved by using a larger pixel. Other advantages include the flexibility, an increase of dynamic

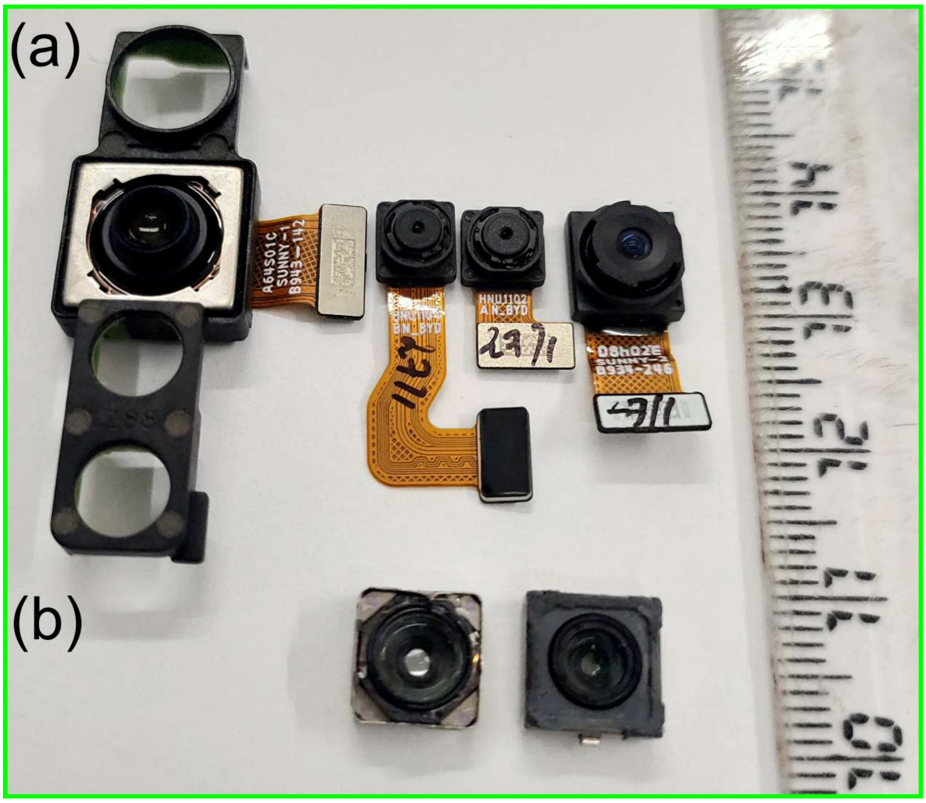


Figure 2.6: Smartphone camera module. (a) Imaging sensors integrated into a phone in different size format, and (b) aspheric compound lens module detach from the phone camera module.

range by selecting different exposure times of the pixels, noise reduction through pixel binning, or acquisition of a very high-resolution image. Figure 2.6(a) shows the images of different sizes of sensors integrated into the smartphone's camera technology. Figure 2.6(b) represents the optics modules detached from the camera modules of the smartphone. These are highly specialized modules of different aspheric lenses stacked together to eliminate image degrading parameters such as aberrations and distortions.

Here, the RGB spectral response of the mentioned three different smartphone cameras- Moto G5 Plus, Samsung Galaxy C9 Pro, and Redmi K20 have been estimated, and compared the spectral response with the scientific color camera (Axiocam 105 color camera) that is used in a laboratory microscope. Figure 2.7 shows the simple experimental setup to record the spectral response of the cameras. The outputs from the smartphone cameras, generally, are in JPEG (Joint Photographic Experts Group) format, where RGB color information is significantly compressed and cannot be recovered later on. Thus, it is important to read the RGB values in RAW format that contains the uncompressed and unprocessed pixel values [12]. New variant high-end and some low-end smartphones also provide direct access to the RAW images in "Pro Mode" in the default camera application. In our case, all the three variant

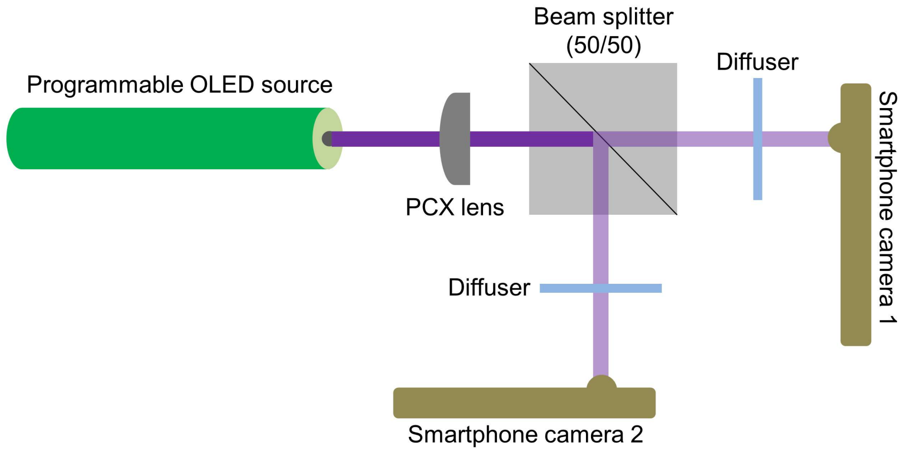


Figure 2.7: Experimental setup to measure the RGB spectral response of the smartphone cameras.

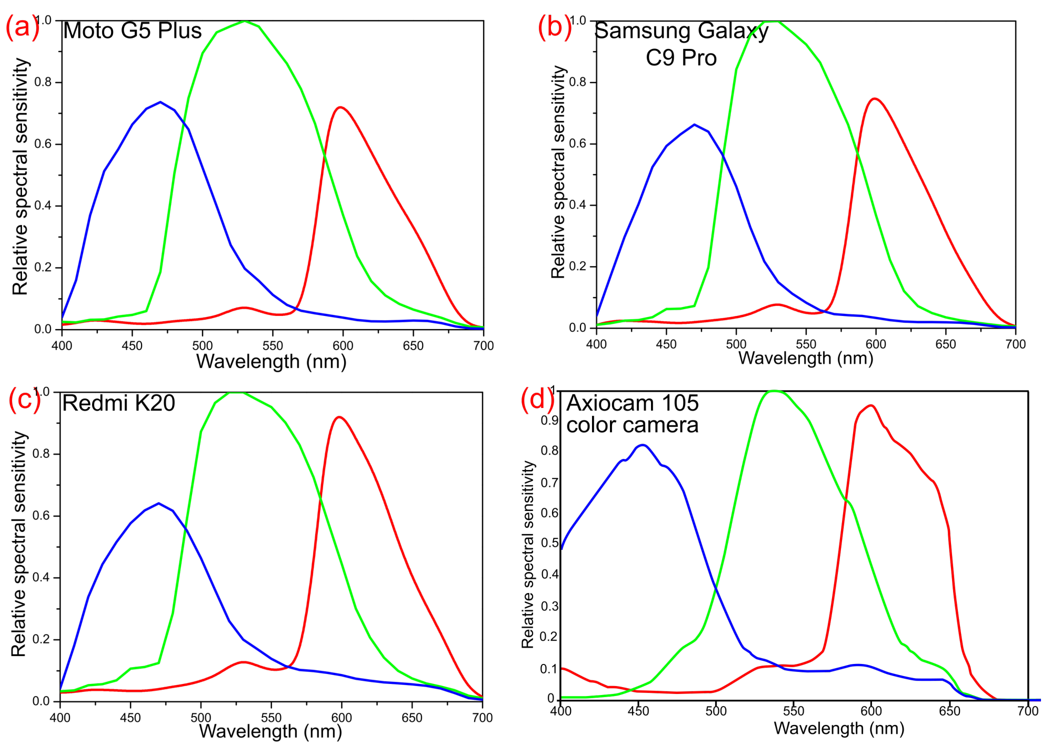


Figure 2.8: RGB spectral response measurement of (a) Moto G5 Plus, (b) Samsung Galaxy C9 Pro, and (c) Axiocam 105 color camera used in laboratory microscope, respectively.

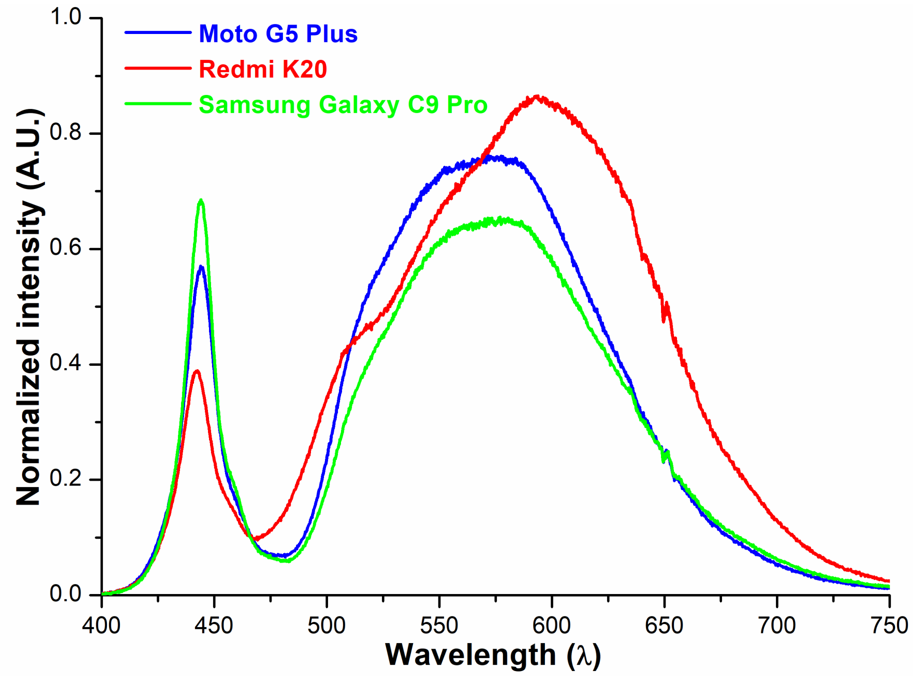


Figure 2.9: Emission spectra of the LED flash of three different variant smartphones used in this thesis work.

phones do not have that facility. However, using openly available third party camera applications such as Open Camera by Mark Harman [13], we were able to retrieve the RAW image files. These are then used to measure the spectral response of the respected cameras. Figure 2.8(a), 2.8(b), and 2.8(c) represents the spectral response of the phone cameras, respectively. The spectral response of the phone camera sensors are not available in public domain since the manufacturers do not provide these specifications in detail. The comparison of the spectral response of the phone cameras with that of a laboratory microscope Axiocam color camera [14] has been studied and the results are shown in figure 2.8(d). Here, it can be seen that the performances of the phone cameras are comparable to those of scientific cameras. Detail spectral response comparisons of different smartphone cameras are available in the literature [15, 16].

**The LED flash lamp** embedded in a modern smartphone, which is useful for photography in the absence of ambient light condition, is a super bright white LED with an emission wavelength ranging from 400-750 nm. With proper optical components, it can be reconfigured as an optical illumination source for different microscopic imaging techniques. Figure 2.9 shows the emission spectra of the LED flash of three different variant smartphones recorded by an optical spectrometer (Thorlabs compact spectrometer-CCS175/M).

**The USB port** of the smartphone is generally used to charge the device and communicate with a memory device through the USB On-The-Go (OTG) protocol which establishes a communication link between the devices to switch them back and

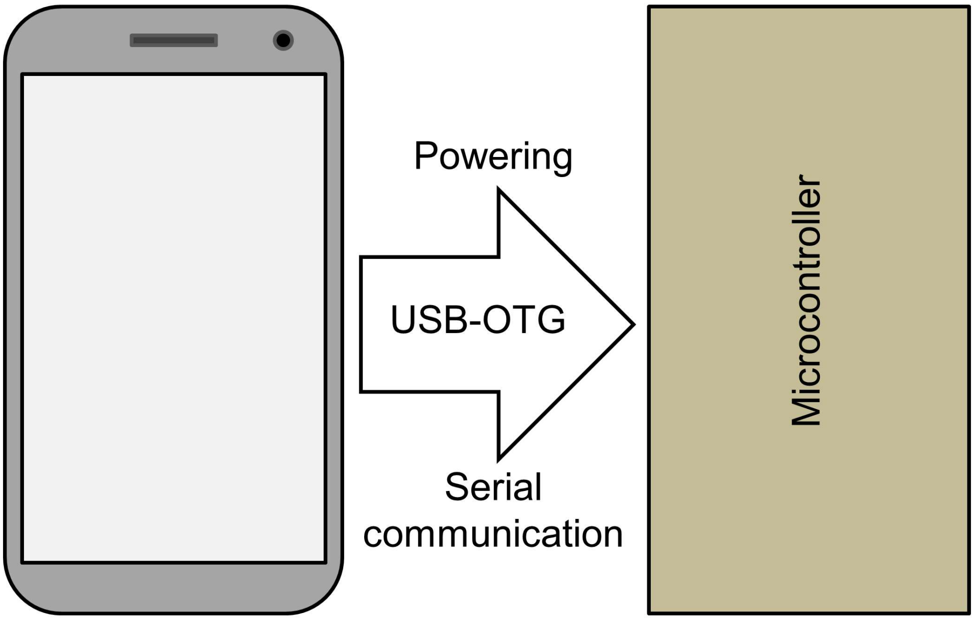


Figure 2.10: Powering and establishing serial communication with peripheral electronic device using USB-OTG protocol.

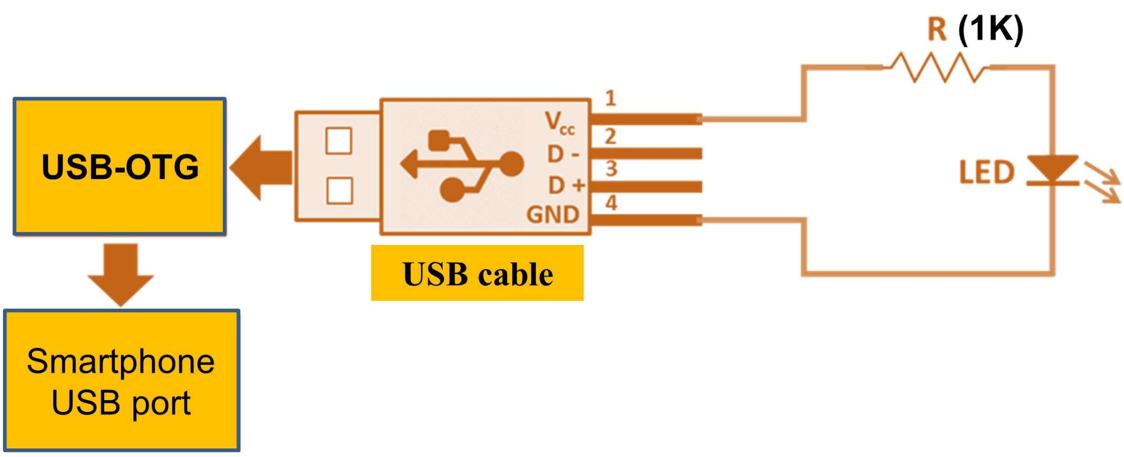


Figure 2.11: Powering an external LED directly using the phone battery through the USB port.

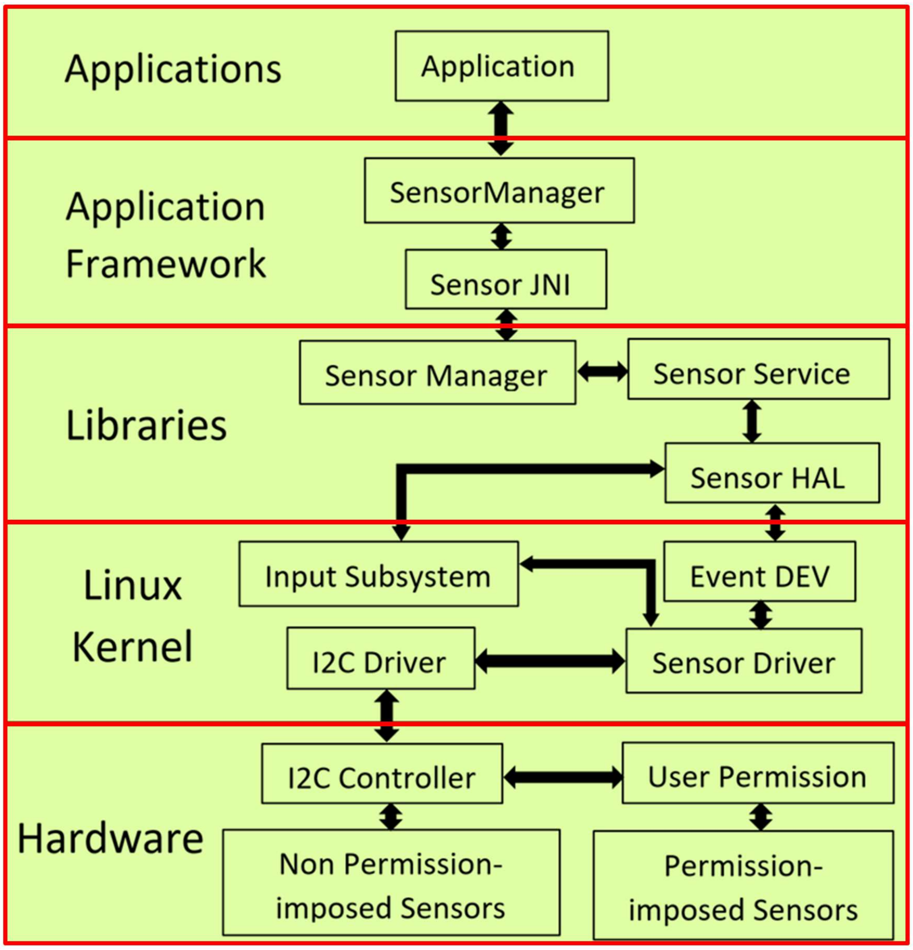


Figure 2.12: Android sensor hub system

forth as host and peripheral devices. The smartphone USB port can deliver a power of 5V at 500mA. Hence, it can be used simultaneously to power and control electronic devices such as microcontrollers using serial communication, as shown in figure 2.10. Similarly, an external LED for illumination can also be powered directly using the smartphone battery through the USB port. This is shown in figure 2.11.

## 2.5 Software platform for phone-based application development

The Application development part is vital in designing a truly user-friendly, standalone and handheld imaging system. Modern smartphones have the tremendous processing power to support onboard computation of complex algorithms such as digital image processing etc. In the present thesis work, the phone-based application has been developed in the Android OS platform. The Android platform is based on an open-source application development framework. "Android Studio" is the common and official Integrated Development Environment (IDE) for application development

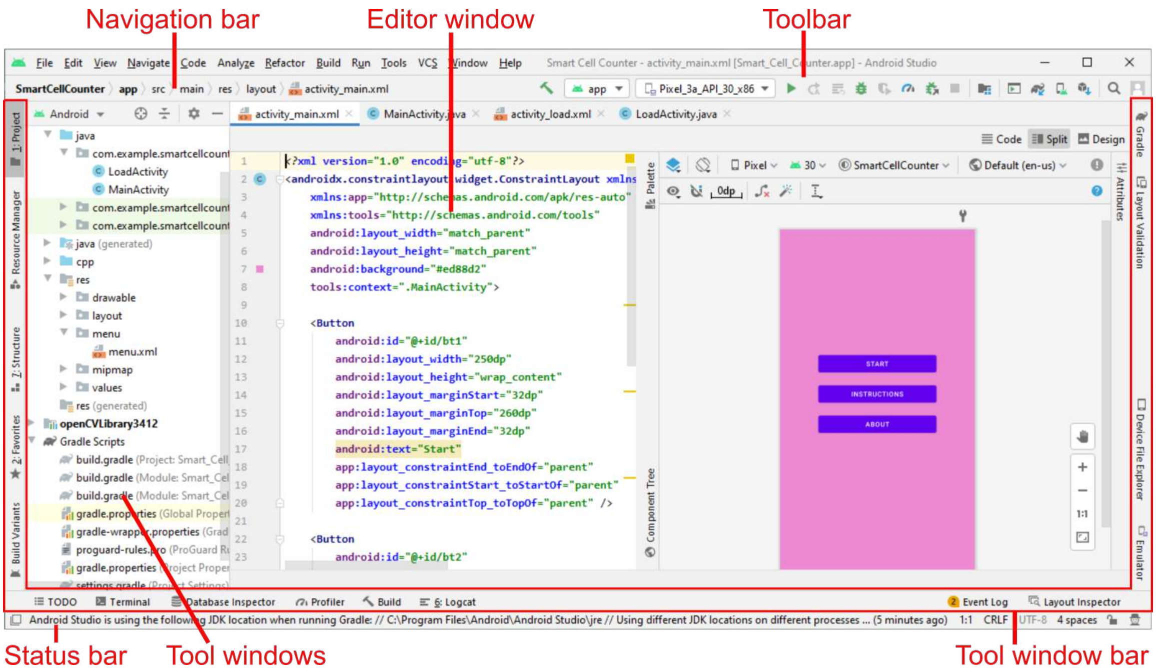


Figure 2.13: User interface (UI) of the Android Studio platform with essential components.

which is based on JetBrains IntelliJ IDEA environment [17]. Besides this, "MIT App Inventor", which is a cloud-based open-source app development platform maintained by the Massachusetts Institute of Technology (MIT), can be used [18]. However, using this platform, complex image reconstruction algorithms is not possible. In this thesis work, only Android Studio has been used to develop analytical applications. The raw data from the embedded sensors of the phone can be directly accessed from the Android sensor manager module by developing custom applications. Figure 2.12 displays the Android sensor hub system [19]. To develop an analytical application for android smartphones, we have imported the OpenCV (Open Source Computer Vision) library, which is specially optimized for the Android platform, also known as OpenCV4Android [20]. It is an open-source library optimized for real-time image processing applications on Android operated mobile devices. The user interface (UI) of the Android Studio IDE with the essential components are shown in figure 2.13.

## 2.6 Summary

The usability of various sensors and other functional components integrated on a modern smartphone has been discussed in this chapter. The usability and characteristics of the CMOS imaging sensors integrated in three different phones have been discussed. The spectral responses of three different smartphones- Moto G5 Plus, Samsung Galaxy C9 Pro, and Redmi K20 have been evaluated and compared with the responses of a laboratory grade camera. Besides, the effectiveness of other functional components such as the LED flash of the phone as an illumination source, and the use of the USB port of the phone to power and control external peripheral electronic components such as microcontroller, LED etc. have also been discussed. The development of analytical applications using open-source software development platforms such as Android Studio and MIT App Inventor have also been incorporated at the end of this chapter.

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