Chapter 7

Conclusions and future prospect of the thesis work

The overall findings of the present thesis work have been summarized in this chapter. Limitations of the developed smartphone sensing systems are discussed here. At the end of this chapter, future prospect of the current thesis work for finding of its new applications in different areas and its further possible evolution has been discussed.

7.1 Conclusions

The thesis work has demonstrated the design of various affordable, compact and easy to use smartphone platform optical sensing systems and related computational platforms developed for water quality monitoring and interferometric sensing applications. The ALS of the smartphone has been extensively used as a light signal detector and its usability has been demonstrated in leveraging the usability of the smartphone for different sensing investigations in the VIS-NIR spectral regime. Moreover, rigorous computational facilities or smart apps have been developed for detection, data analysis and data transfer of the experiential readings by the phone itself. The salient points of the present thesis work are summarized as follows:

1. A smartphone platform photometric sensing system has been designed by considering the embedded ALS as a detector which is sensitive both in visible and NIR spectral regime. To demonstrate the system as a standalone device, the LED flash of the phone has been utilized as a light source using proper optical filter configuration. Using this configuration, fluoride level concentration in water has been reliably estimated [1]. Since, the resolution of the

embedded ALS is as low as 0.01 Lux, the developed sensing system provides an excellent platform for sensitive investigations. The emission wavelength range of the embedded LED flash is within the visible spectral domain (400 nm to 700 nm), for NIR absorption based sensing studies an external LED has been used to demonstrate the applicability of the ALS for NIR absorption based sensing applications. Using the USB-OTG protocol, the external LED has been powered from the internal battery of the smartphone which eventually promotes the designed platform as a self-powering device. Using the external LED, the designed sensing system has been demonstrated as a single platform for both VIS-NIR light absorption based sensing investigations [2,3]. The proposed work provides new opportunities for different sensing applications which was not possible previously with the smartphone camera based sensors.

2. The NIR detection capability of the ALS has been further utilized to develop the smartphone based nephelometric platform using simple and inexpensive laboratory optical components[3]. The ISO:7027 protocols for developing the turbidimeter has been followed by setting the device parameters as mentioned in the method [4]. An NIR LED has been used as a light source and allowed to scatter by the turbid medium. The experimental results obtained from the proposed smartphone turbidimeter were found to be at par with that of standard laboratory grade nephelometer generally used for such purpose.

3. The usability of the smartphone based sensing has system has been further demonstrated for non-colorimetric sensing applications such as detection of salinity level in water. Since, fiber optic evanescent wave based sensing systems have been extensively demonstrated as an excellent optical platform for sensing applications, therefore the present thesis work also demonstrates an inexpensive and field portable smartphone integrated fiber optic sensing system which has been designed exclusively to determine salinity level in water samples. To enhance the sensitivity ,a U-bent configuration has been considered for development of the sensor by using a plastic optical fiber. The designed smartphone sensor is found to be highly sensitive and yields

reliable data in measuring salinity variation of liquid samples.

4. Beyond demonstrating the smartphone based sensing system for analytical investigation, the usability of the smartphone has been further explored for optical metrological applications using the embedded CMOS camera. An interferometric system has been developed to demonstrate the smartphone camera as an alternative detector over its sophisticated counterpart such as CCD. The developed system has been used to monitor change in optical phase difference in an interferometer which is occurring due to the reflections from top and bottom surface of a reflecting glass. With the 3D printing technology, a compact optical set up can be obtained easily which can be attached to the camera of the phone. An application has been developed for onboard fringe preprocessing. The developed system has been used to determine small angular rotations of the glass slide. Angular rotations as small as $0.02°$ can be measured accurately with the proposed system. With necessary modifications the same system can be used as an affordable and field portable interferometric system for other metrological sensing applications.

5. Besides developing the hardware platforms, the present thesis demonstrates the development of smartphone apps which promotes the onboard computation within the smartphone. The developed apps provides an integrated and unique platform for detection, data analysis, data transfer and data calibration within the smartphone itself. This computational facility is essential for remote water quality monitoring applications. In a nutshell, with the development of both hardware and computational platform a fully automated and functional sensing system which would be useful for decentralized monitoring of water quality in resource limited regions.

7.2 Limitations

Although the developed smartphone sensing systems provides ample advantages in terms of affordable alternatives for various in-field sensing application still there remains some limitations to visualize the developed tools as a universal add-on the smartphone. The design and dimension of the smartphone varies from model to model even within the same manufactures which consequently changes the position of the ALS, LED flash and the rear camera in the smartphone. Due to the fixed design and dimension of the developed sensing systems, they can not be modified to work with other phone models. Thus, there remains a challenge for a universal opto-mechanical design that can be attached to any phone model. For ALS based sensing systems it has been observed that the sensing data fluctuates with the increase in light intensity. These intensity fluctuations leads to the greater measurement errors in the developed tools and limits the sensing range of the platform. In many cases, the smartphone battery has been used as a power source for external LEDs. Continuous drawing of battery power in long term investigations may reduce the overall performance of the smartphone sensor. Moreover, self-heating of the smartphone is a point of concern because this can significantly affect the response characteristic of the embedded ALS in the phone.

7.3 Future prospects

In the present thesis, the usability of smartphone ALS has been demonstrated for various studies and computation the developed platform can be used for many different medical diagnostic applications. Due to the responsivity of the ALS in the NIR spectral regime, the ALS based photometric sensing system can be developed for non-invasive detection of hemoglobin level [1]. Nephelometry has been extensively used for determination total protein in urine; and thus the applicability of the designed smartphone nephelometric platform can be further explored for urinalysis applications [2,3].With the required modifications, the developed sensing systems can contribute to the basic healthcare needs in resource limited settings. As discussed in the above section, frequent variation in the phone model may become a limitation of the currently developed sensing systems for their universal applicability. In future, this limitation can be surpassed with proper design approach and 3D printing technology. Due to the complex fringe processing capability and high-end configuration of the CMOS camera of the smartphone, in future the designed smartphone based interferometric system will be explored further for development of affordable, sophisticated and field portable optical interferometric based instrumentations [4]. The usability of the optical interferometry has been demonstrated in many bio-chemical sensing application [5-7]. Thus, there is a huge scope for smartphone based interferometric sensing application for real field applications which can also be explored in future endeavor. Going side by side with the technological advancement of smartphone, the developed sensing systems would be evolved accordingly which may find its usability beyond the areas discussed in this thesis.

References

[1] Horecker, B.L. The absorption spectra of hemoglobin and its derivatives in the visible and near infra-red regions. *Journal of Biological Chemistry*, 148(1):173-183, 1943.

[2] Strzelak, K. and Koncki, R. Nephelometry and turbidimetry with paired emitter detector diodes and their application for determination of total urinary protein. *Analytica chimica acta*, 788:68-73, 2013.

[3] Shephard, M.D. and Whiting, M.J. Nephelometric determination of total protein in cerebrospinal fluid and urine using benzalkonium chloride as precipitation reagent. *Annals of clinical biochemistry*, 29(4):411-417, 1992.

[4] Hariharan, P. *Optical Interferometry*, Elsevier, Netherlands,2002.

[5] Gauglitz, G., Brecht, A., Kraus, G. and Mahm, W. Chemical and biochemical sensors based on interferometry at thin (multi-) layers. *Sensors and Actuators B: Chemical*, 11(1-3):21-27, 1993.

[6] Mariani, S., Strambini, L.M. and Barillaro, G. Femtomole detection of proteins using a label-free nanostructured porous silicon interferometer for perspective ultrasensitive biosensing. Analytical chemistry, 88(17):8502-8509, 2016.

[7] Hu, P., Dong, X., Ni, K., Chen, L.H., Wong, W.C. and Chan, C.C. Sensitivity-enhanced Michelson interferometric humidity sensor with waist-enlarged fiber bitaper. *Sensors and Actuators B: Chemical*, 194:180-184, 2014.