CHAPTER 7

CONCLUSIONS AND FUTURE PROSPECT OF THE PRESENT THESIS WORK

This chapter summarizes the comprehensive findings of the present thesis work. The limitations of the different microscopic imaging platforms developed on a smartphone are being pointed out here. At the end of the chapter, the future implications of the current thesis work for finding of its new different imaging applications in different areas and their potential advancement have been highlighted.

7.1 Conclusions

Several implementations of miniaturized microscopes based on the smartphone platform have been covered in this thesis work, with the aim of accomplishing compact and budget-oriented imaging for various biomedical and biological applications in resource-constrained settings. The imaging systems are based on the so-called $3f$ and $4f$ optical configurations and provide the imaging of biological specimens in different multi-contrast modes as per the requirements in a single optical platform. The CMOS imaging sensor and other functional components of the smartphone have been exploited in leveraging the functionality of these microscopic imaging systems for economical realization. The use of rapid manufacturing technology (3D-printing) and easily available off-the-shelf optical and electronic components ensure the cost-effectiveness and versatility of the fabricated imaging devices. Along with the imaging systems, the development of the computational platforms has also been discussed for onboard data analysis purposes within the phone itself. Some of the salient points of this thesis work are summarized below:

1. In chapter 3, a high resolution and wide-field multimodal finite-conjugate (also $3f$ configuration) microscopic system offering three dynamically adaptable imaging modes, namely transmission BF, OIDF and TIRDF on the smartphone, has been proposed and demonstrated. It utilizes the integrated camera module to record the microscopic images, and the LED flash of the phone illuminates the specimen. The tool provides an optical resolution below 2 μm with an FoV of $\sim$5130 $\times$ 4100 μm^2. It can reliably image all kinds of specimens, from histopathology to microorganisms, which is comparable to the 10$\times$ objective lens of a laboratory microscope. The TIRDF imaging mode of the microscopic system is even capable of imaging plasmonic nanoparticles beyond the diffraction limit, which is, otherwise, not possible with conventional DF illumination technique.

2. The finite-conjugate imaging system is easy to implement, however, one of the major drawbacks of this system is that the spatial resolution depends on the pixel pitch of the CMOS sensor due to low optical magnification. To tackle this, in chapter 4, a low-cost 3D-printed $4f$ smartphone microscopic system with a very high optical magnification has been proposed and developed. It allows the utilization of the numerical aperture of the objective lens at its full potential delivering an enhanced resolution of the imaging system. An image processing algorithm has also been developed by using cloud-based services, which can be accessed anytime through a mobile broadband network. Using this facility, the quality of the captured images can be further enhanced, thus obviating the need for dedicated computational tools for post-processing of the images. Further, the optimization in the optical design of the platform has been performed and modified to operate in high-throughput BF and fluorescence modes at three different optical magnification levels that perform at par with that of a laboratory-grade microscope. The versatility of the device has been demonstrated through imaging of standard microbeads and human blood samples both in BF and fluorescence modes of imaging. The three different optical magnifications of the system are 1.16$\times$, 2.86$\times$ and 37.33$\times$ with a spatial resolution of $\sim$1.21 μm, and the FoV is measured to be $\sim$4530 μm, 400 μm and 200 μm in diameter, respectively. In addition, the platform is equipped with an on-board cell recognition feature which has been obtained through developing a smartphone application for automatic cell counting with high precision.

3. Chapter 5 presents an affordable, versatile and robust programmable illumination smartphone microscopy-PISM as a flexible multimodal imaging platform for contrast enhancement of various specimens using different low-cost consumer optoelectronics parts. Herein, a miniature programmable OLED display

works both as an optical source and SLM, which eliminates the requirements of expensive and bulky spatially modulated illumination systems to obtain multimodal imaging in a single platform. By displaying different color and binary patterns on the OLED panel, seven well-established imaging modes, namely BF, DF, OI, FI, RI, DPC and polarized imaging, have been demonstrated on a single optical setup. The microscopic system is capable of imaging all kinds of specimens, even the translucent ones, with a spatial resolution of $\sim$1.7 μm and FoV of 3118 $\times$ 2452 μm^2.

4. In chapter 6 of the thesis, a low-cost and flexible one-shot BF, DF and DPC imaging solution, adapted both in smartphone-based $3f$ (cmSM) and laboratory-based $4f$ microscope (cmLM) imaging systems using the off-the-shelf optical and electronic components has been demonstrated. The basis for economical and versatile multi-contrast microscopic imaging in resource-constrained regions is the cost-effective engineering of the illumination component. This chapter details the design and development of a one-shot multi-contrast microscopic imaging by generating a multiplexed color pattern on an OLED display panel used as an optical source in the proposed microscopic systems. The color channel of the final RGB image has been decomposed into individual R, G and B color channels and subsequently computed to obtain the different contrast enhancing imaging modes.

7.2 Limitations

In spite of the ample advantages in terms of affordability and cost-effectiveness, the developed smartphone platform microscopic imaging systems have several issues that limit their efficacy as an alternative tools for various applications in PoC settings. It is important to address these constraints to realize the proposed tools as a universal add-on to the smartphone. The smartphone business is very dynamic, where the manufacturers are under tremendous pressure to innovate and implement the latest features that customers want in just a few months. Thus, the dimension of all the phone models varies along with their design, even within the same manufacturer. This makes to change frequently the positions of the embedded sensors and other functional components such as camera module, ALS, LED flash etc. As a consequence of this, the proposed imaging systems are not adaptable to all variant smartphone models due to the fixed design and dimension of the systems. Therefore, the design of optomechanical parts that are compatible to all variant smartphones remains a challenge. In all the proposed microscopic imaging systems, the phone battery has been used as a power source for the illumination section. This may introduce overheating

issues and reduce the investigation period for long term use due to the continuous drawing of power from the battery to the optical setup of the designed microscopic system.

7.3 Future prospects

In this thesis, various affordable and versatile microscopic imaging techniques have been proposed and demonstrated using the embedded CMOS imaging sensor and other functional components of the smartphone. These tools can be made useful for imaging biological and biomedical applications in regions where access to imaging tools is very limited. In the future course of work, the developed multi-contrast imaging platforms will be explored for the real-world practical applications such as diagnosis of sickle cell disease, urinalysis etc. With the increasing computational power of smartphones, deep learning-based smart applications are trending. With the aid of these powerful smart applications, the proposed imaging platforms can be converted even more for the automated onboard diagnosis within the phone itself. This might reduce the possible errors due to many factors, such as the handling issue irrespective of any user. Further, in the above section, it has been discussed that there is a limitation of the developed imaging platforms for their universal adaptability due to the frequent variation in the phone models. In future, this matter would be taken care of by introducing a novel design approach to fit with any smartphone irrespective of the brand and sensors positions in the phone. Thus, the developed imaging platforms would be advanced accordingly and find their applicability beyond the areas that were not covered in the present thesis work.