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Original Research

Smartphone microscopy: Design and implementation of a dual magnification system

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Abstract

This paper presents a dual magnification smartphone microscope designed for versatile imaging, enabling low magnification for wide-field viewing and high magnification for detailed biological sample analysis and automatic control of the working distance. It offers a cost-effective alternative to traditional lab microscopes, particularly in low-resource settings. Simulated, optimized, and designed using Ansys Zemax OpticStudio, the microscope was fabricated with 3D printing technology. Dual magnification (150x and 1000x) was achieved with two optical paths, improving resolution to 1 µm at higher and 1.5 µm at lower magnifications. The design provides clear and accurate images. The smartphone integration enhances usability, allowing easy magnification switching, image capture, and potential use of diagnostic applications.

Keywords: Smartphone microscope, Zemax simulation, High-resolution imaging, Low-cost microscopy, High magnification, Biomedical applications

1. Introduction

Smartphone microscopes are revolutionizing the way microscopy is conducted by combining the power of digital imaging with the convenience of mobile technology, offering a versatile, low-cost, and portable alternative to traditional laboratory microscopes [1, 2]. The popularization of smartphones and cellular networks worldwide has made the operation of smartphone microscopes uncomplicated. As a result, average users can test and upload microscope images to the Internet without requiring a complicated training process [3, 4]. This displays a remarkable advantage in terms of efficiency and accessibility in resource-limited situations.

Numerous research groups are working on improving smartphone optical microscope design; Agbana et al. (2018) developed a two-magnification cellphone microscope 4.5x and 8.5x by using two switchable ball lenses with different diameters (1 and 0.5mm) and oil immersion [5]. Rabha et al. revealed a portable smartphone optical microscope using a pair of ball lenses with a diameter of 1mm and a plano-convex lens with a focal length of 11mm as magnifying optics. They achieved 520x optical magnification with an optical resolution of ~2µm [6]. Wan et al. proposed a smartphone microscope with adjustable magnification (0.8-11.5x) by combining three cellphone camera lenses and digital zoom. The microscope attains high-quality images with an utmost resolution of 575 lp/mm [7]. In recent years, smartphone microscopy has gained widespread interest. However, practical applications remain

limited due to inherent limitations, such as inferior imaging performance and invariable magnification [8, 9]. Challenges include precise control of the working distance and complex adjustment mechanisms, which reduce portability and ease-of-use [10].

This manuscript proposes a smartphone microscope with a dual magnification system that addresses the challenges of existing models. It offers high-quality imaging with micrometer-level resolution, a field of view up to the millimeter level, and autonomous control of the working distance. The manuscript's organization is as follows: Section 2 introduces the design process and discusses the simulation techniques used; Section 3 elucidates the result, discussion, and performance evaluation; Section 4 concludes the work.

2. Method

2.1. Simulation of the proposed design

The simulation design of a smartphone microscope was done using Ansys Zemax OpticStudio software (2024 R1). Figure 1 exemplifies the configuration of the proposed smartphone microscope's optical systems (system_1 and system_2).

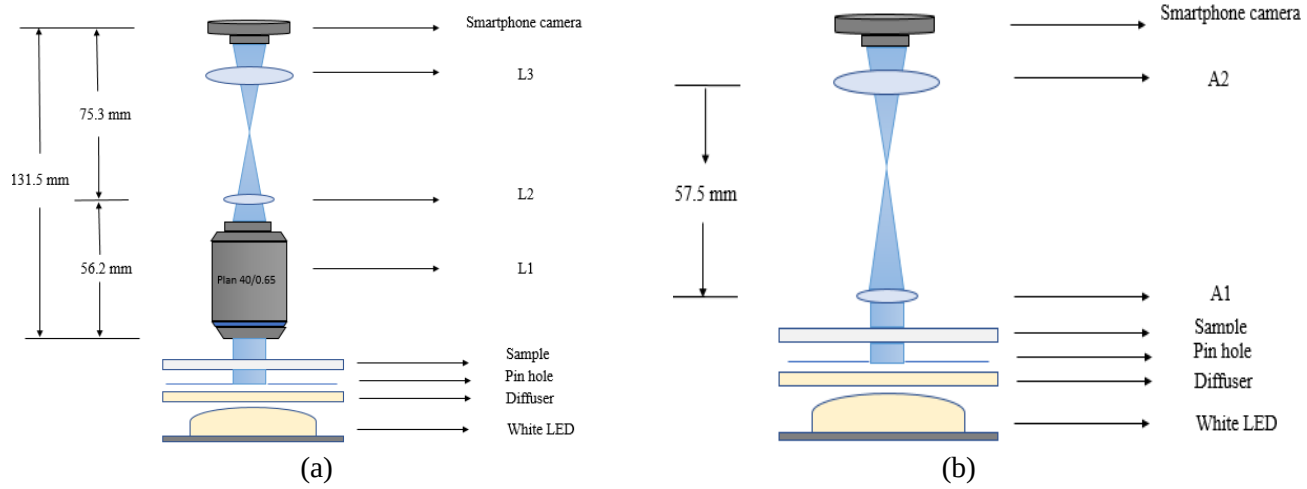


Figure 1. The block diagram represents the optical configuration of (a) system_1 and (b) system_2 for the proposed smartphone microscope

As illustrated in this figure, system_1's optical components include a 40x plan achromatic objective lens (L1) with NA 0.65, a tube lens (L2) with a 2.8mm focal length and 3mm diameter, an eyepiece lens (L3) with 12.5x magnification, and a smartphone camera. System_2 features an objective lens (A1) with a 4.464mm focal length and 1.6mm diameter, an eyepiece lens (A2) with 12.5x magnification, and a smartphone camera.

Table 1. Specification of L_2 and A_1

Properties	L_2	A_1
Material type	Polycarbonate	High quality glass (BK7)
Refractive index	1.597	1.514
Lens type	biconvex lens	biconvex lens
Diameter	3mm	1.6mm
Focal length (f)	2.8mm	4.464mm
The radius of the curvature (R)	3.343mm	4
F-number	1.8	2.79

The lenses are aligned sequentially, and light rays pass through each lens to focus on the smartphone's camera sensor.

2.2. Fabrication and assembly of the proposed design

The optomechanical system, designed using CAD software (Solid Works) and 3D printed with an FDM printer (ANYCUBIC Mega-S), houses all optical components and ensures precise alignment between lenses and the smartphone camera. A 4-lead Nema 17 stepper motor and DRV8825 motor driver, controlled by an Arduino Nano, move the lens holders via a precision lead screw. The system includes a 128x64 blue OLED display for messages, a voltage divider for the illumination source, and screw shafts for manual specimen movement.

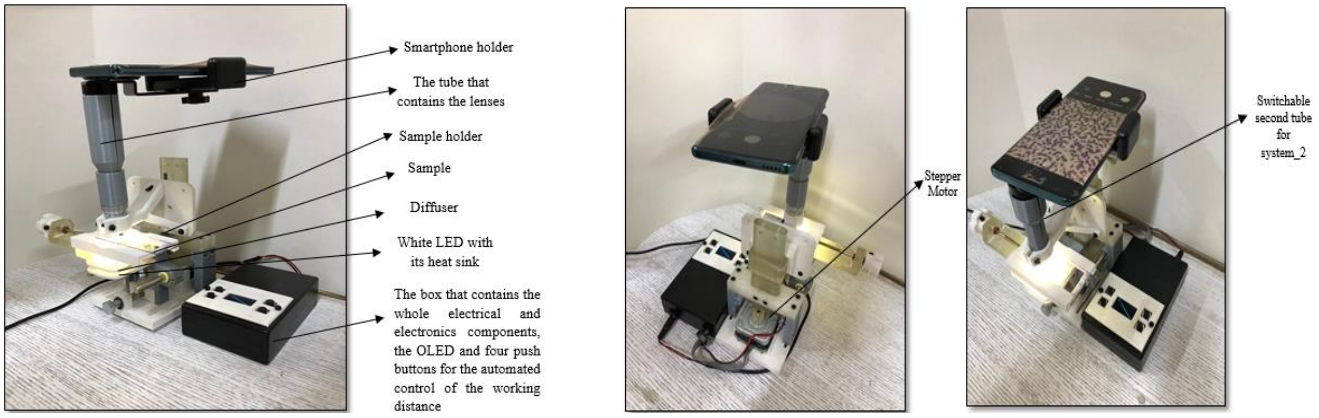


Figure 2. Assembly of the final model, (a) system_1, (b) other view of system_1, (c) system_2

3. Results and discussion

3.1. Optical simulation results

The optical simulation results from Ansys Zemax OpticStudio provide a detailed performance analysis of the proposed dual-magnification smartphone microscope, including ray tracing, spot diagram, MTF analysis, Huygens PSF cross-section, and aberration control. These metrics are crucial for assessing the optical quality and effectiveness of the design.

3.1.1. Ray tracing analysis

Figure 3 illustrates the ray tracing of systems_1 and 2. These setups ensure that the light rays are properly focused and magnified at each stage, leading to a clear and detailed image captured by the proposed smartphone camera.

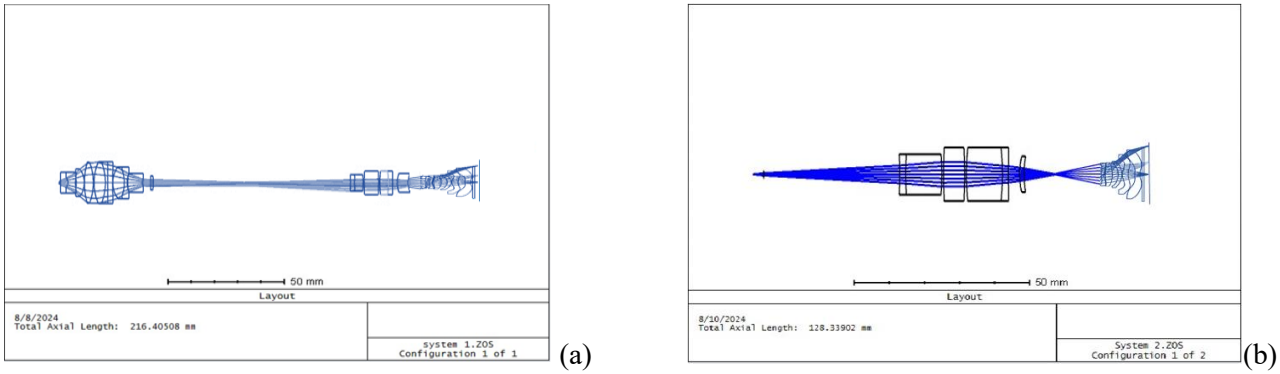
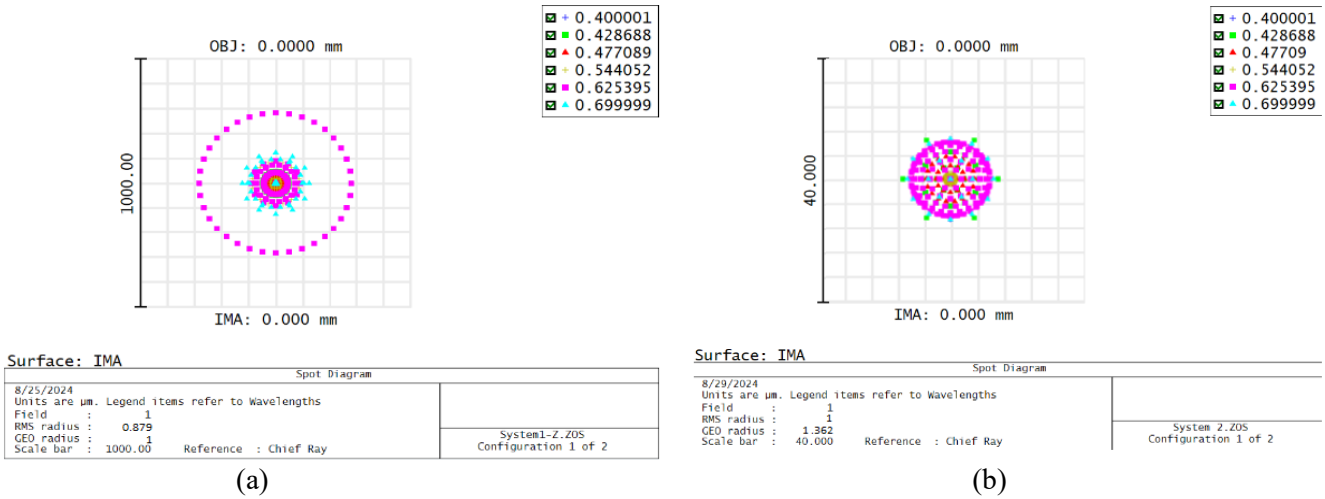


Figure 3. The ray tracing of (a) system_1 and (b) system_2

3.1.2. Spot diagram analysis

The spot diagram illustrates how different wavelengths focus through the smartphone microscope's optical system.



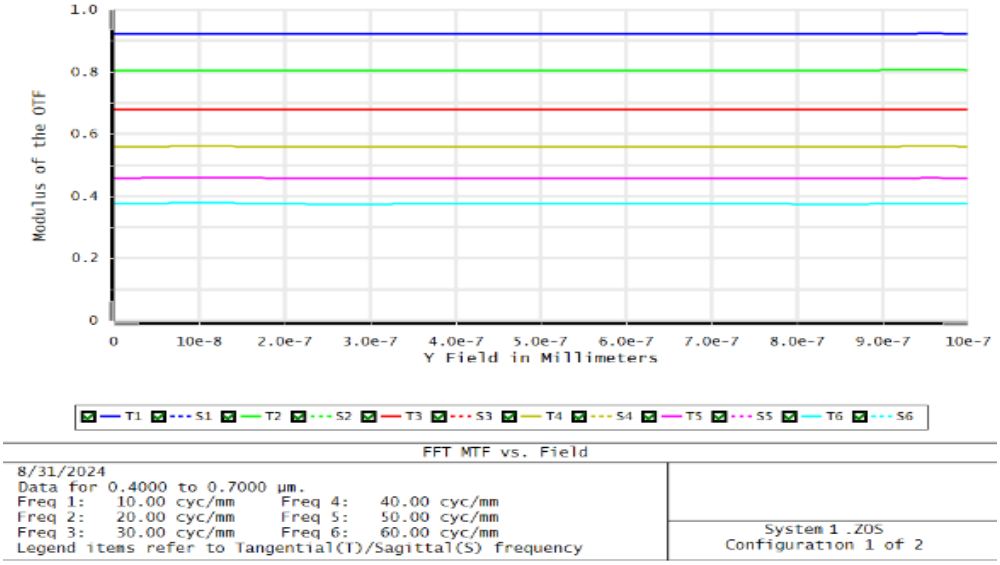
(a) (b)

Figure 4. Standard spot diagram distribution for (a) system_1 and (b) system_2

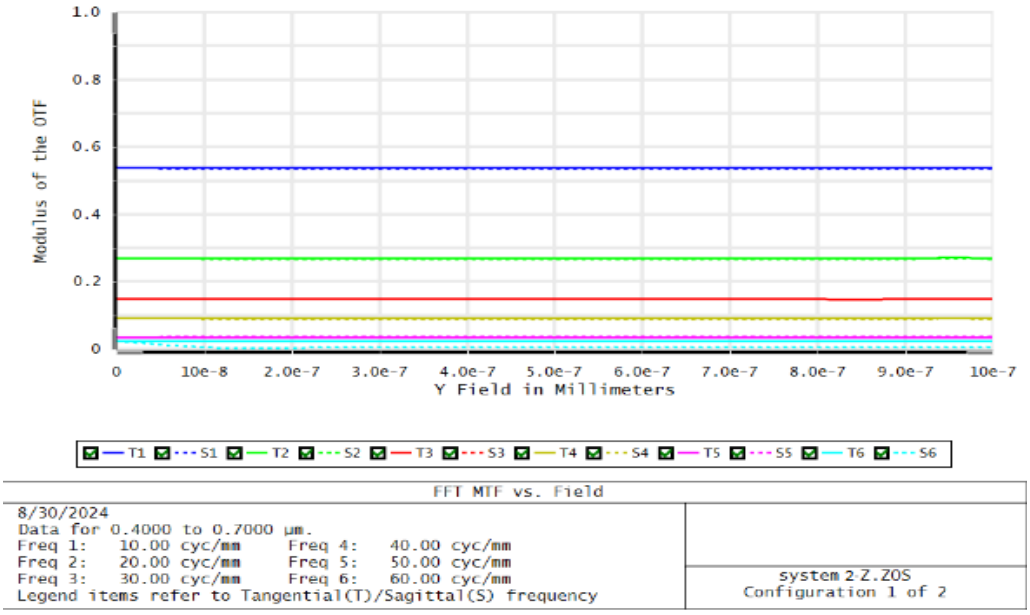
In system_1, Figure 4a, most wavelengths are centered around the origin with slight aberration at 0.6253 and 0.6999 µm. The root mean square (RMS) and geometric (GEO) radii are 0.879 µm and 1 µm, respectively. In system_2 (Figure 4b), these values are 1 µm and 1.362 µm. Lower RMS and GEO radii indicate better focus and image sharpness, making system_1 superior for precise imaging applications. Despite system_2's more spread-out spot pattern, it still provides good optical performance for overall sample scanning.

3.1.3 Modulation transfer function (MTF)

MTF analysis evaluates the system's ability to reproduce image details by measuring contrast at various spatial frequencies. Figure 5 depicts MTF versus field for system_1 and system_2. System_1 has high MTF values at lower frequencies, indicating excellent contrast and resolution for low-frequency details. A slight decrease at higher frequencies still ensures good contrast for fine details. System_2 shows a natural decrease in MTF at higher frequencies, limiting fine detail resolution but producing high-contrast images at lower spatial frequencies.



(a)

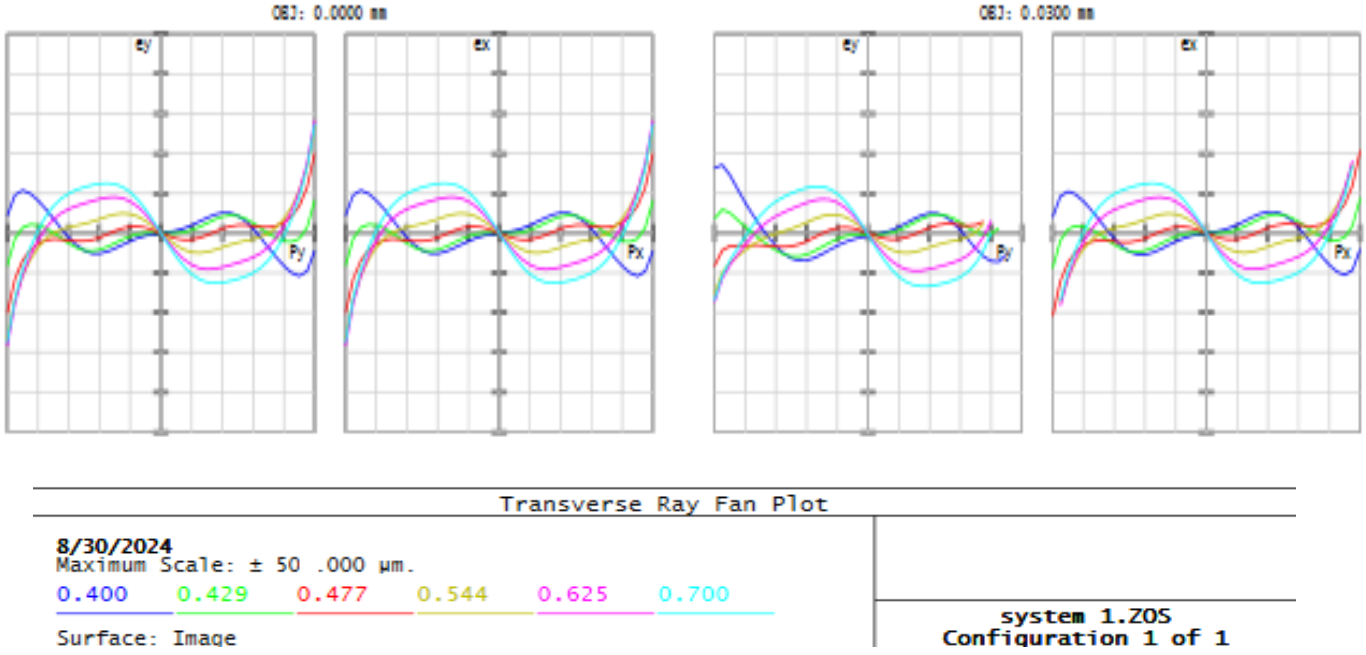


(b)

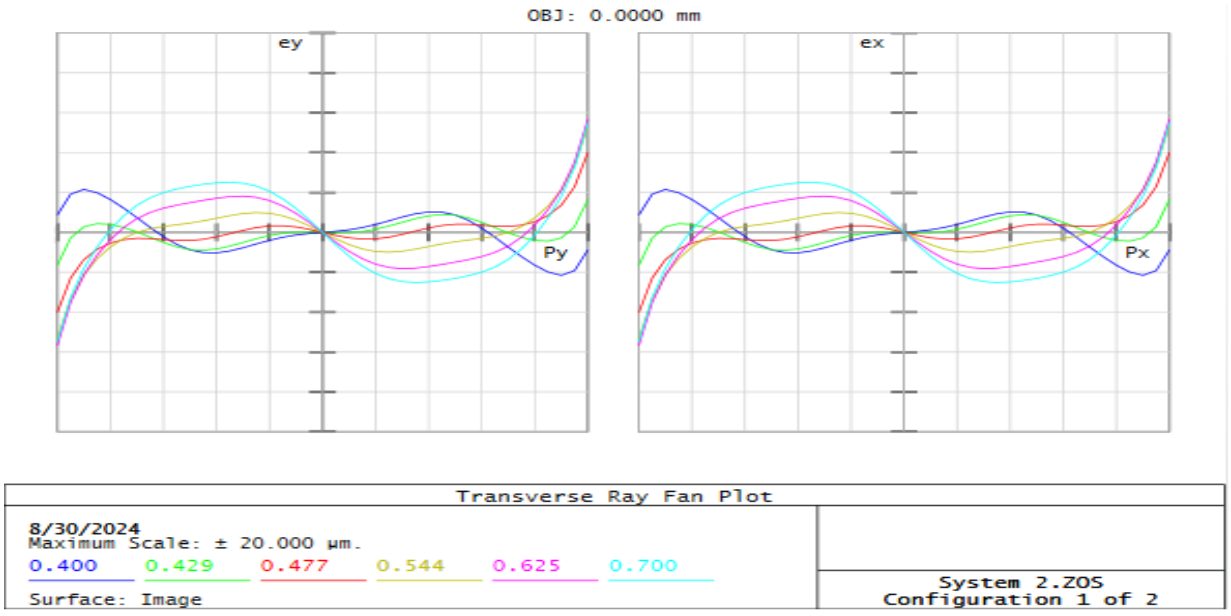
Figure 5. MTF versus field of the proposed smartphone microscope (a) system_1 and (b) system_2

3.1.4 Aberration analysis

The transverse ray fan plot analyzes lens system aberrations by examining light ray deviations from the ideal focus. Figure 6 represents MTF versus field for system_1 and system_2. In system_1, wavy lines indicate aberrations, with curvature showing primary spherical aberration and non-overlapping colored lines indicating slight chromatic aberration. System_2 (Figure 6b) performs better in controlling aberrations, with fewer deviations and smaller scale measurements revealing some spherical and chromatic aberrations.



(a)

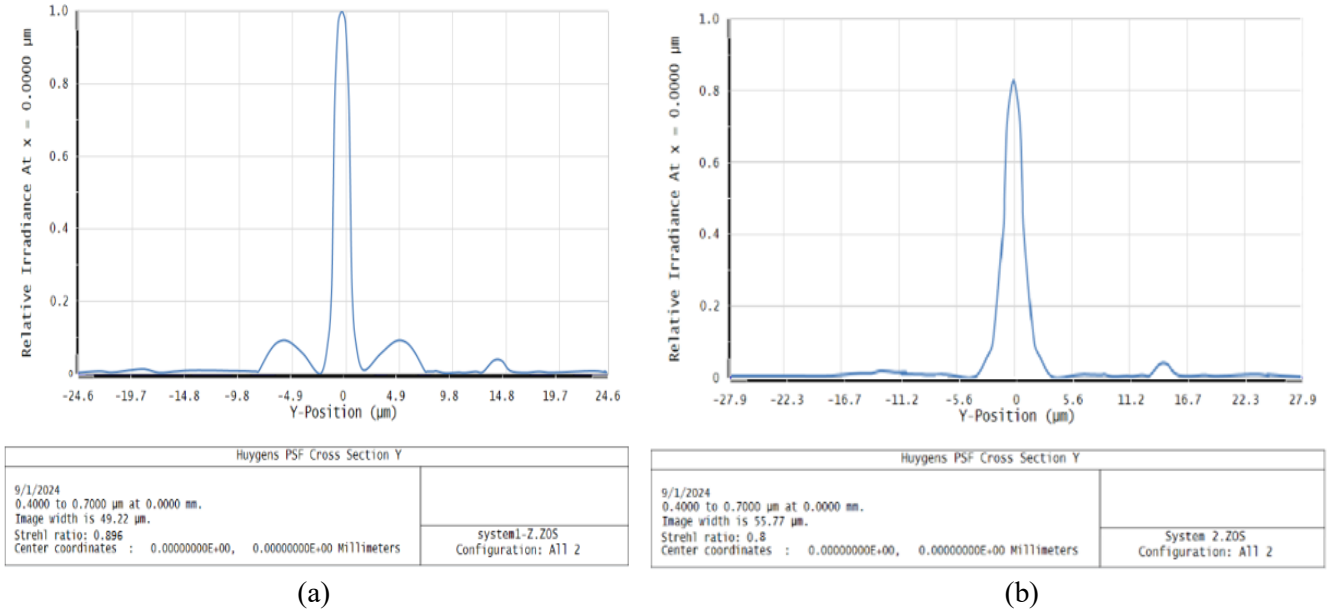


(b)

Figure 6. Transverse Ray Fan Plot for the proposed smartphone microscope (a) system_1 and (b) system_2

3.1.5. Huygens PSF cross section

In Zemax, the point spread function (PSF) is crucial for evaluating optical system image quality. Figure 7 reveals the Huygens PSF cross-section for the proposed smartphone microscope. For system_1, the central peak at 0 µm indicates high light intensity and focal accuracy, with minimal diffraction and a Strehl ratio of 0.896. The resolution is approximately 1 µm. In system_2, the broader central peak at 0 µm has a maximum intensity of 0.83, with less diffraction and a Strehl ratio of 0.8. The resolution is approximately 1.6 µm.



(a) (b)

Figure 7. The Huygens PSF cross section for the proposed smartphone microscope (a) system_1 and (b) system_2

4. Performance evaluation

The performance of smartphone microscopes can be assessed based on several key factors:

4.1. Smartphone microscope imaging performance

4.1.1. Image quality (resolution)

The proposed smartphone microscope's imaging performance is evaluated using the USAF 1951 resolution test target. Figure 8 shows the captured image by system_2, revealing group 9 and element 3, according to the resolution equation [6]:

$$Resolution\left(\frac{lp}{mm}\right)= 2^{(Group\ number+\frac{Element\ number\ -1}{6})} \quad (1)$$

The group and element number refer to the resolvable white and black bars on the target element acquired by the proposed smartphone microscope. Therefore, the system's resolution is 645 lp/mm, equivalent to 1.5 μm, which aligns with the PSF Huygens cross-section results.

4.1.2. Field of view (FOV)

The field of view (FOV) is estimated using a stage micrometer. For system_1 at 1000x magnification, the FOV is 0.5mm, while for system_2 at 150x magnification, it is 1mm. The FOV decreases with increasing magnification.

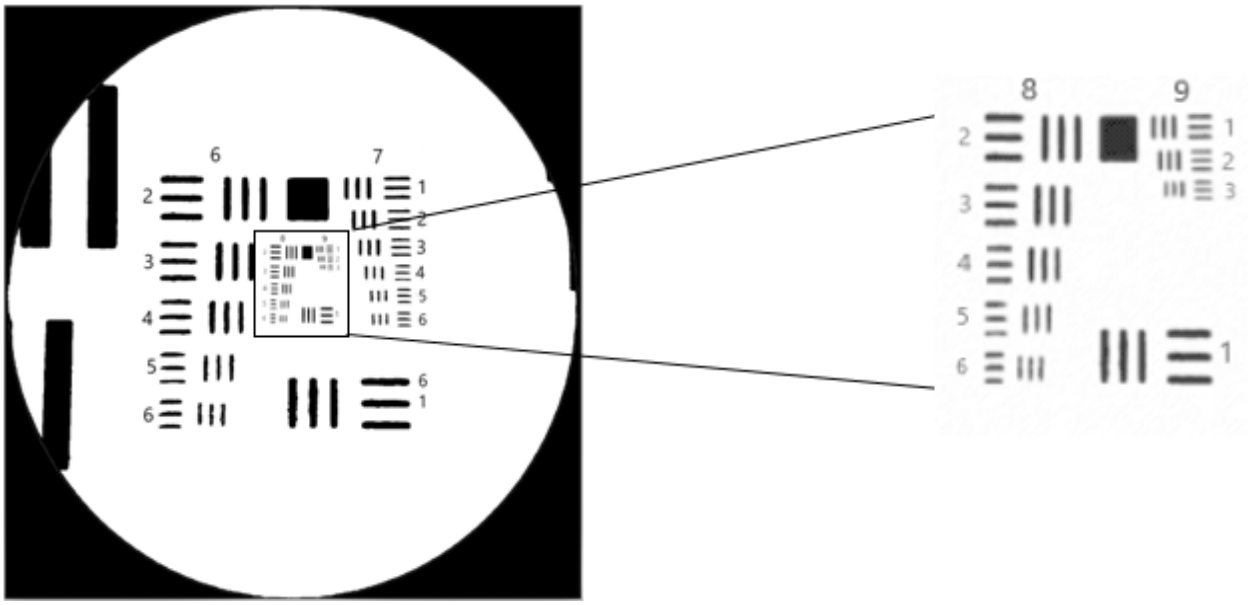


Figure 8. Image of USAF resolution test target for system_2

4.2. Real sample imaging performance

The proposed smartphone microscope was evaluated by imaging biological tissues and plant tissues, as well as prepared slides. Figure 9 depicts that at 150x magnification, the device effectively resolved onion cells, leaf tissues, and vascular lesions of a Cavernous Hemangioma sample with visible cell walls and nuclei. While detail was slightly lower than traditional lab microscopes, red and white blood cells in a stained blood smear were discernible. For finer details, system_1 at 1000x magnification provided micro-level resolution. The figure also compares images of the identical specimens captured with a conventional optical microscope at 400x and 600x magnification.

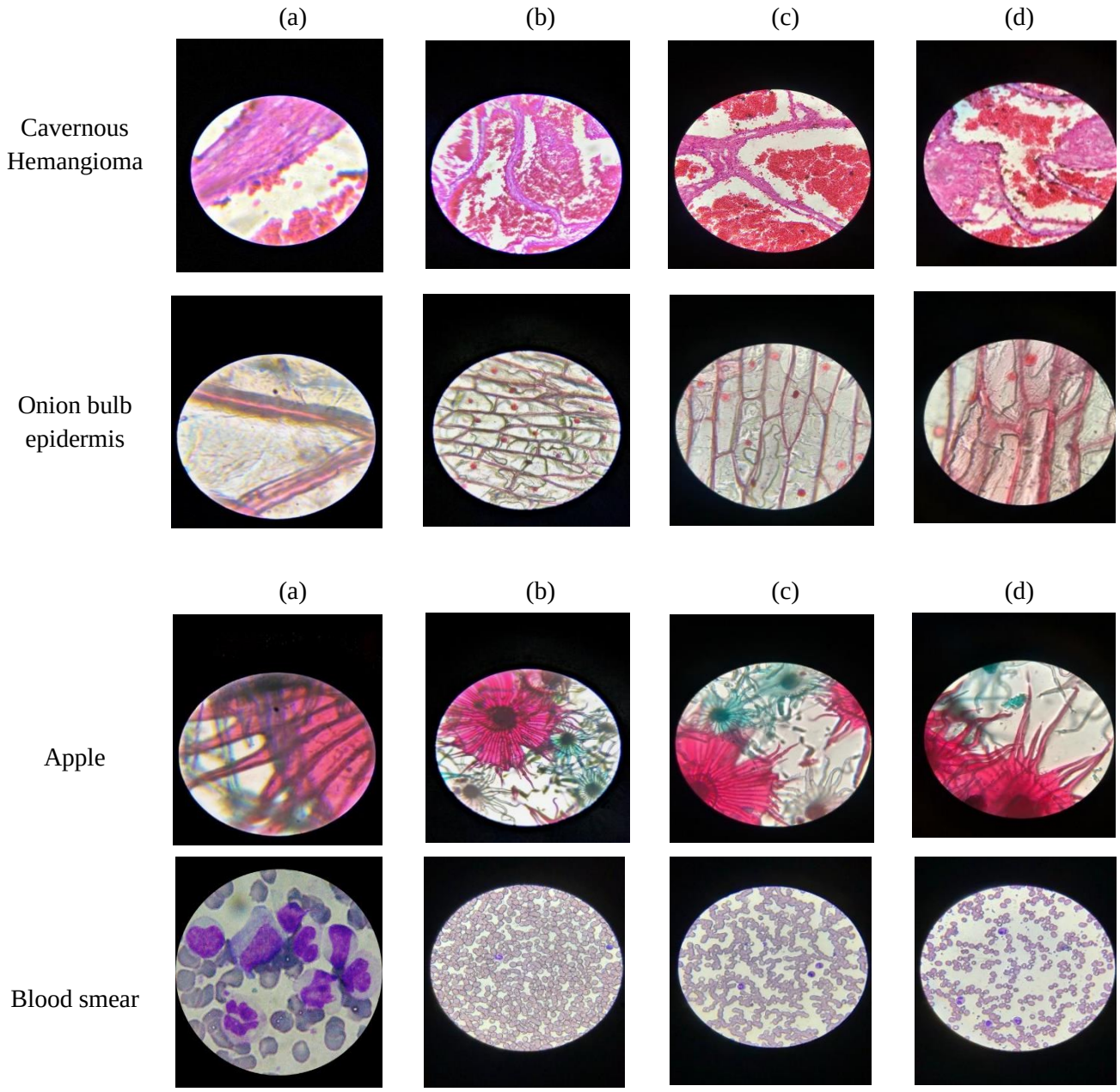


Figure 9. Images of various actual samples (Cavernous Hemangioma), Apple, Onion bulb epidermis, and stained blood smear) acquired by the proposed smartphone microscope (a) system1, (b) system2, and by conventional optical microscope as shown in (c) magnification 400x, and (d) magnification 600x

Table 2. Compares the merits of the proposed smartphone microscope with the number of similar present systems.

Authors	Magnification	Resolution (µm)	FOV	Portability	Complexity	Automated control for
S. Kheireddine et al. [11]	2x	2	3.6×2.7mm	Yes	Medium	No

X. Wan et al. [7]	0.8x, 11.5x	4.9,1.7	(1749×1320)μm, (505×381)μm	Yes	Low	No
D. Rabha, et al [12]	1.16x	2	5130 × 4100 μm^2	Yes	Medium	No
D. Rabha et al. [13]	1.16×, 2.86× and 37.33×	1.21	4530 μm (diameter)	Yes	Medium	No
C. Yu et al. [14]	164x	5	840μm×630μm (0.5292mm^2)	Yes	Medium	No
G. Cheng [15]	350x	-	1.5×1.5mm	Yes	Low	No
Proposed smartphone microscope	150x and 1000x	1.5, 1	1mm and 0.5 (diameter)	Yes	Low	Yes

6. Conclusion

Smartphone microscopes have limitations like low image quality, permanent magnification, and inconvenient operation. This paper presents a dual magnification system (150x and 1000x) for smartphone microscopy to enhance versatility and imaging performance. Designed and optimized using Ansys Zemax OpticStudio, the system improves image quality, minimizes aberrations, and maximizes resolution. Simulation results show significant advantages over single-magnification microscopes, with high-quality images at both magnification levels. The system achieves a maximum resolution of 1 μm for system_1 and 1.5 μm for system_2. Future work may focus on further miniaturization and integrating machine learning for automated sample analysis.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

Lubna A. Alkareem: Conceptualization, Methodology, Writing-review & editing, Formal analysis, and investigation, Writing, and editing.
Anwaar A. Al-Dergazly, Review and supervision.

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