SMARTPHONE BASED FOCUS-FREE MACROSCOPY USING AN ADAPTIVE DROPLET LENS

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ABSTRACT

Smartphones have been extensively used for macroscopic imaging by both professional and amateur photographers. Current macroscopic lenses for smartphones often have a fixed focusing power and a narrow depth of field. One has to move the smartphone to keep the image in focus. This is challenging for imaging small and moving objects. This paper reports a smartphone based microscope that allows for focusing-free image acquisition. A tunable droplet lens is placed in front of the smartphone camera and driven dynamically by a dielectric elastomer actuator to scan the entire field. The desired object planes can be extracted by after-the-fact “focusing”. The adaptive focusing capability of the device thus enables macroscopic imaging in an easier and faster way.

INTRODUCTION

Optical macroscopy has been widely used for various applications including healthcare, agriculture, education, and biomedical fields [1-4]. Current microscopes are often laboratory-based and have high cost and bulky volume, which considerably limit their applications in low-resource settings. During the last few years, smartphone technology has been rapidly growing. The built-in illumination, high-resolution cameras and display, advanced smartphone apps and high-speed networks of modern smartphones strongly promotes the next generation of miniature, portable, and cost-effective macroscopy. The smartphone-based macroscopy thus expects extensive applications in photography, machine vision, and other imaging applications in the field.

The methodologies that are used in the pioneer studies of smartphone-based macroscopic/microscopic imaging can be divided into two categories [5-8]: lens-free technologies and add-on lens(es). The lens-free imaging devices utilize the holographic imaging principle and reconstruct images from the captured fringe patterns. This approach often requires the removal of the camera lens [9, 10]. The add-on lenses approach is implemented by attaching one or multiple solid refractive optical components to the camera [1, 11, 12]. These solid optical components often have a fixed optical power and a small depth of field. The operator has to change the distance between the smartphone and the object to keep the image in focus. Such operation is challenging for imaging small and moving objects. Although it is possible to adjust the focus by displacing one or more lens components along the optical axis, the operation associates with increased system/operation complexity and requires larger overall device size. The miniaturization advantage of smartphone devices is largely compromised.

Tunable lenses with adjustable focusing capability make it possible to achieve miniature varifocal imaging without any moving any optical components [13-19]. Among various actuation mechanisms, dielectric elastomer actuator (DEA) is attracting considerable interests due to its simple configuration, fast response and low cost [20-22].

In this study, we report a smartphone based microscope using a tunable droplet lens. The droplet lens is driven by a DEA and has a large focusing power range and fast response. This allows the device to scan a large depth of field within a short time. The driven voltage is reduced using a high voltage converter. By working in conjunction with the video mode of the smartphone camera, the fast

scanning of an extended depth of field was implemented. The desired object planes of the objects of interest can be extracted from the video using after-the-fact “focusing”.

MATERIAL AND METHOD

Principle and Design

The device consists of a dielectric elastomer membrane, carbon black nanoparticles, a super-hydrophobic coating, a droplet lens, a high voltage converter, and an acrylic frame (**Figure 1a**). The dielectric membrane was made of VHB 4910 (3M) and stretched equibiaxially by 350%. The thickness of the stretched membrane was 80 μm . The dielectric membrane was self-bonded to an annular acrylic frame which has the inner diameter of 10 mm. Carbon black nanoparticles were coated into an annular area of both sides of the membrane using patterned pad printing. The annular area has the inner diameter of 6 mm and the outer diameter of 10 mm. Copper tapes were applied to the two sides of the membrane and were connected to the carbon black. The copper tape on the top surface of the actuation membrane was connected to a high voltage converter, and that on the bottom surface was grounded. The high-voltage converter was used to amplify the DC voltage by 1000 times. The super-hydrophobic coating was applied to the top surface of the dielectric membrane except for a circular area of 3 mm in inner diameter at the center. The droplet fluid was 40% wt/wt glycerol-DI water mixture. The droplet was positioned at the center of the dielectric membrane and was confined within the area not covered by the super-hydrophobic coating. The overall dimensions of the device were $\Phi 14\text{mm} \times 1\text{mm}$. Once a DC voltage was applied, the pre-stretched dielectric membrane exhibited an in-plane expansion, which compresses the center areas that are not covered by the carbon black coating. This changes the contact radius of the droplet, and in turn changes the curvature and the focal length of the droplet lens (**Figure 1b**). The optical path for smartphone-based macroscopic imaging is illustrated in **Figure 1c**. The object is located at the focal plane of the droplet lens. Collimated light forms once the light from the object passes through droplet lens, which is subsequently focused on the image sensor by the camera lens. By changing the focal length of the droplet lens, the objects from different working distances can be focused.

The focal length of the droplet lens (f) is determined by the refractive index (n), the droplet volume (V), and the radius of its contact area with the dielectric membrane (r). By assuming the droplet as a spherical cap, the radius of curvature R of the droplet can be derived from the equation:

$$V = \frac{1}{3}\pi(2R + \sqrt{R^2 - r^2})(2R^2 - r^2 - 2R\sqrt{R^2 - r^2}) \quad (1).$$

The focal length f of the droplet lens can be calculated using the Gaussian thin lens equation:

$$f = \frac{R}{n-1} \quad (2).$$

The change of the focal length of the droplet lens (f) with the droplet volume (V) and the contact radius (r) is plotted in **Figure 2**. In this study, the refractive index of the liquid (n) is a constant, *i.e.*, 1.38. When the contact radius r is constant, the focal length decreases with the increasing droplet volume. This indicates that in order to examine an object with a very short distance from the lens, a relatively large droplet volume should be used. On the contrary, a

small droplet volume should be used for viewing the objects placed distant from the lens. **Figure 2** also shows that with a given droplet volume V , the focal length increases with the increasing contact radius r . The changing range of the focal length can thus be estimated from the droplet volume and the contact radius. When the contact radius changes from 1.5 mm to 1.2 mm, the focal length of a 2.9 μL droplet changes from 4.51 mm to 2.12 mm. For a 0.5 μL droplet, the focal length changes from 24.18 mm to 9.98 mm. This shows that a smaller droplet volume can lead to a wider range of the focal length under the same change of the contact radius.

Figure 1. Schematic of the droplet lens. (a) The cross-section view of the droplet lens; (b) The curvature of droplet lens changes upon a voltage bias of 6V; and (c) The optical path for smartphone-based macroscopic imaging.

Figure 2. The change of focal length with the contact radius and the droplet volume.

RESULT AND DISCUSSION

Droplet Lens Characterization

The focal lengths of the droplet lenses were experimentally measured with systematically varied droplet volumes and applied voltages. The results showed that when the applied voltage increased from 0 to 6V, the contact radius that was defined by the area not covered by the superhydrophobic coating exhibited about

17% change (from 1509 μm to 1259 μm) (**Figure 3a**). The focal length change of the droplet lenses with 0.5 μL and 3 μL volumes is shown in **Figure 3b**. The focal length of the 0.5 μL droplet changed from 23.58 mm at 0V to 10.76 mm at 6V. The focal length of the 3.0 μL droplet changed from 4.38 mm at 0V to 2.05 mm at 6V. These results agree with the previous estimation, indicating that Equations 1&2 can be used to predict the initial focal length of the droplet lens and the changing range of the droplet lens upon actuation.

Figure 3. The experimentally measured contact radius change and the focal length change upon actuation. (a) The change of contact radius, and (b) The change of focal length.

Response and Recovery Time

Fast response is needed for acquiring the images at different object planes for the “after-the-fact” focusing. Here, the response and recovery time of the droplet lens were measured by passing a collimated laser beam through the droplet lens and examining the size change of the laser beam on a screen placed on the other side of the droplet lens. In this measurement, the collimated laser beam was 3 mm in diameter. The volume of the droplet lens was 0.5 μL . The screen was placed 25 mm away from the lens. The actuation voltage was increased from 0V to a positive bias, held for an extended period, and returned to 0V. The size of the laser beam on the screen during

Figure 4. Response and recovery time under different voltage changes during the actuation and recovery processes.

the entire procedure was monitored and recorded at the frame rate of 300 *fps* using the high-speed camera. The response time refers to the response of the droplet shape change upon a voltage increase, while the recovery time refers to the response of the droplet shape change upon a voltage decrease. The response and recovery time were approximated as the moment when the change of the spot size reached 90% of the design value. **Figure 4** shows the measured response and recovery time of the droplet lens upon different voltage changes. As expected, the response and recovery time both increased with the increasing voltage change. The response time for the voltage change from 0V to 1V (corresponding to the working distance from 23.58 mm to 21.03 mm) was 83 ms. The value became 646 ms for the voltage change from 0V to 6V (corresponding to the working distance from 23.58mm to 10.76 mm). The recovery time was slightly longer than the response time for the same voltage change, e.g. the recovery time was 117 ms for the voltage change from 1V to 0V and 708 ms for the voltage change from 6V to 0V.

Gravity Effect

When the dielectric membrane where the droplet sits is placed vertically, the droplet becomes asymmetric due to the gravity and the imaging performance may be impaired. The imaging resolutions of the droplet lens under the horizontal and the vertical arrangements were quantified by imaging a USAF 1951 resolution target with iPhone SE (**Figure 5a**). The droplet lens was attached to the smartphone and aligned with the camera. The droplet volume was 3 μ l. The applied voltage was 6V. Under the horizontal arrangement (when the droplet was placed on a horizontal surface), the minimal resolvable line bar was group 6 element 6, which corresponds to the spatial frequency of 114 line pairs per mm. Under the vertical arrangement, however, the minimal resolvable line bar was group 5 element 5 which corresponds to the spatial frequency of 50.8 line pairs per mm. It shows that the gravity deteriorates the imaging performance. The horizontal arrangement of the lens is thus preferable for high resolution imaging.

The deteriorated optical resolution under the vertical arrangement is caused by the asymmetric droplet shape. The contact angle difference between the top and bottom edges of the droplet lens at different applied voltages was measured (**Figure 5b**). A 3 μ l droplet was placed on the dielectric membrane and the membrane was positioned vertically. The result showed that the contact angle difference increased with the increasing voltage. The initial contact angle difference between the top and the bottom edges of the droplet was 13.8°. The contact angle difference increased to 18.3° when the applied voltage increased to 6V. This indicated that the droplet shape asymmetry increased with the applied voltage, which may further impair the image performance. Future study is deserved to reduce the contact angle difference between the top and bottom edge of the droplet for enhancing the optical resolution.

Focus-free Macroscopic Imaging

A proof-of-concept experiment was performed to demonstrate the efficacy of the tunable droplet lens for focus-free macroscopic imaging. In this study, the distance of the objects from the lens was estimated. Appropriate droplet volume and applied voltage were determined based on the object distance range. The high-speed video was recorded while increasing the voltage across the dielectric membrane from 0V to a positive value. The individual image frames that represent different object planes were extracted from the video, where the objects at different distances were brought in focus. **Figure 6a** shows the “after-the-fact” focusing of three objects that were placed at different distances from the lens. The picture of a castle was 100 mm away, the rule was 40 mm away, and the tweezer was 20 mm away from the lens, respectively. A droplet lens with the

Figure 5. Gravity effect examination. (a) The optical resolution measurement using a USAF 1951 resolution target when the droplet was placed horizontally and vertically. (b) The contact angle difference between the top and bottom edges of the droplet at different voltages.

volume of 0.3 μ l was used. It took about 800 ms to change the voltage from 0V to 6V. After the scanning, the in-focus images of the castle picture, the ruler, and the tweezer were extracted from the video. Similarly, “after-the-fact” imaging was demonstrated by placing a piece of paper at an angle with the dielectric membrane, where the four letters on the paper have different distances from the lens (**Figure 6b**). The first letter ‘E’ was 10 mm away, and the last letter ‘E’ was 20 mm away from the lens. A droplet lens with the volume of 0.5 μ l was used. The “in-focus” images of the four letters can be extracted from the video. **Figure 6c** shows the imaging of a multi-layered microfluidic device that was placed 2mm away from the lens. The microfluidic device had three channels of the same width (200 μ m) that were placed into three layers. Each layer was 500 μ m thick. The lateral displacement between the neighboring channels was 300 μ m. To differentiate the channels at different distances, the top channel (that was closest to the lens) was filled with blue ink, the middle channel was filled with red ink, and the bottom channel was filled with green ink. Since the microfluidic channel was very close to the lens, a small droplet volume was needed. According to the experimental measurement shown in **Figure 3**, the droplet lens with the volume of 3 μ l was used. By increasing the voltage to 6V, the minimum working distance of 2 mm can be reached. The three microfluidic channels can be brought into focus sequentially. In all above measurements, it took less than one second to scan through the field. Manual focusing is not needed.

CONCLUSION

In this paper, a smartphone based microscope that allows for

fast and focus-free image acquisition is proposed. The macroscope utilizes a tunable droplet lens to scan the entire depth of field. The droplet lens is actuated by a miniature DEA, with a 120% focal length variance with the response and the recovery time less than 800 ms. The focusing range can be adjusted by changing the droplet volume, providing flexibility for extensive imaging applications.

Figure 6: Demonstration of focus-free macroscopic imaging. The extracted “after-the-fact” focused images of (a) three objects, (b) four letters on a piece of paper and (c) multi-layered microfluidic channels placed at different working distances from the high-speed videos. The focused areas are indicated by the red dashed lines.

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