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Optical zoom imaging systems using adaptive liquid lenses

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Keywords: optical zoom, adaptive liquid lenses, liquid crystal, polymer elastic membrane, electrowetting effect

Abstract

An optical zoom imaging system that can vary the magnification factor without displacing the object and the image plane has been widely used. Nonetheless, conventional optical zoom imaging systems suffer from slow response, complicated configuration, vulnerability to misalignment during zoom operation, and are incompatible with miniaturized applications. This review article focuses on state-of-the-art research on novel optical zoom imaging systems that use adaptive liquid lenses. From the aspect of the configuration, according to the number of adaptive liquid lenses, we broadly divide the current optical zoom imaging systems using adaptive liquid lenses into two configurations: multiple adaptive liquid lenses, and a single adaptive liquid lens. The principles and configurations of these optical zoom imaging systems are introduced and represented. Three different working principles of the adaptive liquid lens (liquid crystal, polymer elastic membrane, and electrowetting effect) adopted in the optical zoom imaging systems are reviewed. Some representative applications of optical zoom imaging systems using adaptive liquid lenses are introduced. The opportunities and challenges of the optical zoom imaging systems using adaptive liquid lenses are also discussed. This review aims to provide a snapshot of the current state of this research field with the aim to attract more attention to put forward the development of the next-generation optical zoom imaging systems.

1. Introduction

Optical zoom imaging systems refer to the configurations that can implement various magnification factors without changing the working distance and the image plane [1, 2]. Such systems have found widespread applications in consumer electronics [3–5], telescopy [6–8], laparoendoscopy [9–11], microscopy [12–14], clinical ophthalmic correction [15–17], dynamic spectral imaging systems [18, 19], interferometers [20, 21], and military weapons [22, 23]. Two basic conditions should be satisfied simultaneously in optical zoom imaging systems: an adjustable focal length, and a fixed image plane [24, 25]. To satisfy these two conditions, at least two lens groups are often included in optical zoom imaging systems in general: one zooming group serves as a variator taking charge of the zooming function, and one focusing group serves as a compensator taking charge of the focusing function [26, 27]. The zooming group adjusts the magnification factor by changing the focal length of the optical zoom imaging system. The focusing group keeps the image plane stationary and maintains the image refocus to compensate for the focal shift defocus introduced by the zooming group. A conventional optical zoom imaging system often consists of multiple solid refractive optical elements (figure 1(a)). Each optical element usually has a fixed curvilinear surface and a fixed refractive index. The varied magnification is usually accomplished by dislocating certain optical elements along the longitudinal axis over specific distances using different mechanical driving mechanisms [28–33]. When an optical element serving as the variator (lens 2 in figure 1) moves along the longitudinal axis to vary the focal length of the system, another optical element serving as the compensator (lens 3 in figure 1) should also move to compensate for the shift of the focal point. The range of the magnification factor associates with the maximally allowable displacement of the optical elements. To achieve a wider range of optical magnification, a

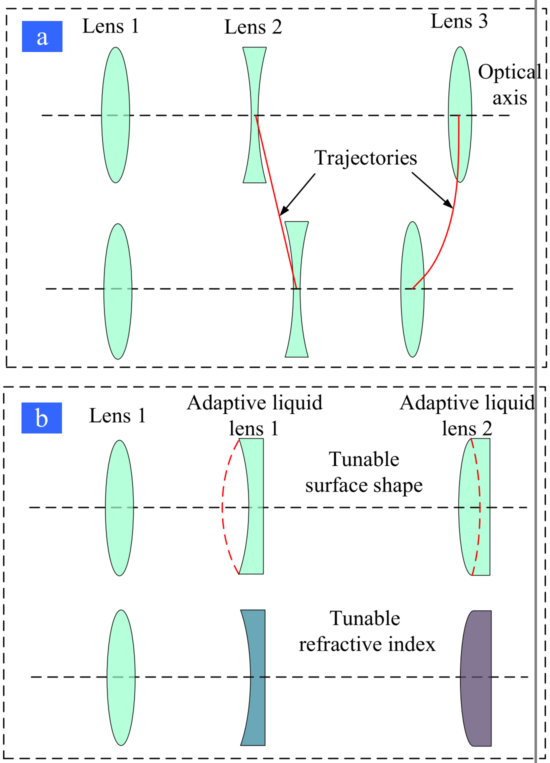

Figure 1. Comparison of optical zoom imaging systems comprising conventional solid lenses and adaptive liquid lenses. (a) A conventional optical zoom imaging system that consists of three solid lenses, where lens 2 serves as the variator and lens 3 serves as the compensator. (b) An optical zoom imaging system consisting of one solid lens and two adaptive lenses. All the lenses are stationary. In the upper panel, the refractive powers of the two adaptive liquid lenses are varied by changing the curvatures of the surface shape. In the lower panel, the refractive powers of the two adaptive liquid lenses are altered by changing the refractive indexes of the adaptive liquid lenses.

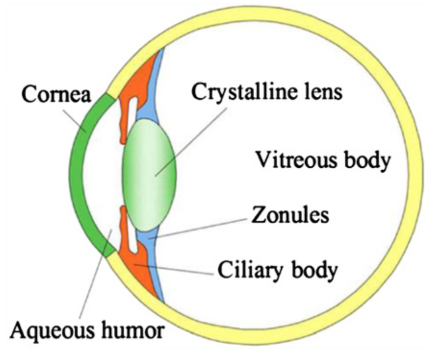

Figure 2. A diagram of the structure of the human eye. Reproduced from [36].

larger displacement of the movable optical element is expected. The approach that relies on mechanically moving groups of solid lenses in conventional optical zoom imaging systems inevitably increases the footprint and the weight of the system. Moreover, each movable optical element should be independently driven by an individual actuator, which complicates the system configuration. It is thus challenging to miniaturize an optical zoom imaging system [34, 35]. Furthermore, the need to displace the optical elements makes the system vulnerable to mechanical vibration and misalignment. Also, the response time increases with the displacement making fast switching between different magnifications difficult.

Biomimetics is the extraction of good design from nature. Having evolved from the human eye, the adaptive liquid lens has achieved adaptive focusing ability without any moving components [36, 37]. Its working principle is functionally analogous to the accommodation process that takes place in the human eye [38, 39]. A diagram of the structure of the human eye is shown in figure 2. The crystalline lens is made of elastic tissues and is surrounded by the ciliary body and connected to the ciliary body by the annular zonule. The focal length of the crystalline lens can be adjusted without any mechanically moving groups. The crystalline lens is stretched or relaxed by the ciliary body to adjust the focal length. When the ciliary body contracts inward, the crystalline lens is compressed by the zonules, thus changing the surface curvature and the focal length of the crystalline lens. Inspired by the optical structure and focusing mechanism of the human eye, the adaptive liquid lens is capable of providing a tunable focal length without moving parts and yet is compact and robust.

The adaptive liquid lens with tunable optical powers was a good option to address the aforementioned limitations of conventional optical zoom imaging systems [40–44]. Unlike solid lens counterparts, adaptive liquid lenses can implement tunable optical power without displacing the lens bodies. The mechanical motion of the lens can be removed and the misalignment during displacement is thus eliminated [45]. As shown in figure 1(b), the optical powers of the adaptive liquid lenses can be changed by either varying the curvatures of the surface shape (upper panel), or the refractive indices of the lenses (lower panel). The optical zoom imaging systems using adaptive liquid lenses can thus be more compact without compromising the magnification capacity, making them conducive to miniaturized designs in applications with space constraints.

As the core optical component of novel optical zoom imaging systems, adaptive liquid lenses have recently attracted extraordinary research attention and have the potential to be the next-generation optical elements [46–49]. According to working principles, adaptive liquid lenses can be generally categorized into three categories: liquid crystal lenses, elastomer–liquid lenses, and electrowetting lenses [50–53]. Liquid crystal lenses use liquid crystals as the lens material, whose refraction indexes can be changed upon an electric voltage bias, resulting in the alteration of its focal length [53–55]. Elastomer–liquid lenses change the refractive power by changing the pressure of the optical fluid encapsulated within the elastomer capsule [56–58]. Electrowetting lenses alter the focal length by changing the contact angle of two liquids using a simple voltage application [59–61]. Besides these three working principles, other working principles are also proposed for the adaptive liquid lens, including, but not limited to, mechanical-wetting [62, 63], dielectric elastomers [39, 64], stimuli-responsive hydrogels [65, 66], and the dielectrophoresis effect [67, 68].

The structure of this review paper is described as follows. From the aspect of the configuration (section 2), according to the number of adaptive liquid lenses, we broadly divide the current optical zoom imaging systems using adaptive liquid lenses into two categories: multiple adaptive liquid lenses, and single adaptive liquid lenses. In section 3, from the perspective of the working principles of the adaptive liquid lenses, we review and discuss the optical zoom imaging system using adaptive liquid lenses based on the working principle of the liquid crystal, polymer elastic membrane, and electrowetting effect, respectively. Section 4 reviews some representative applications of the optical zoom imaging system using adaptive liquid lenses, including, but not limited to, consumer electronics, biomedical imaging, telescopes, and projectors. The opportunities for and the potential challenges of optical zoom imaging systems using adaptive liquid lenses are discussed in section 5.

2. Configurations

2.1. Optical zoom imaging systems using multiple adaptive liquid lenses

Although a single adaptive liquid lens has the capability of tunable focal length, it needs multiple adaptive liquid lenses to simultaneously realize the zooming function and focusing function for optical zoom imaging. Among the multiple adaptive liquid lenses, some of them served as variators and others served as compensators. Many studies have been devoted to the development of optical zoom imaging systems using multiple adaptive lenses. Benefiting from the ability to provide tunable focal length of the adaptive liquid lenses, the locations of these adaptive liquid lenses and solid lenses are fixed. Moreover, compared to the configuration of the traditional optical zoom imaging system, this configuration can save at least two mechanical driving actuators because it eliminates the translational movements required in conventional optical zoom imaging systems.

To develop an optical zoom imaging system using multiple adaptive liquid lenses, it is necessary to establish its mathematical model first. Miks *et al* described a paraxial parameter calculation method and analyzed the third-order aberrations of an optical zoom imaging system using two adaptive liquid lenses. The equations and values of the focal lengths of individual optical elements concerning the transverse magnification were derived [69]. A paraxial and aberration analysis of an optical zoom imaging system consisting of three-element lens systems based on two adaptive liquid lenses (Optotune OL1024) and one classic solid glass lens made of N-ZK7 glass material was also studied by Miks *et al*. The general formulas for calculating basic optical variables and structure parameters of the adaptive liquid lenses and the solid lens were derived [70–73]. They also conducted a theoretical analysis of the paraxial optical properties of the optical zoom lens system using three adaptive liquid lenses [74, 75]. Cheng *et al* presented a first-order design procedure for an optical zoom imaging system based on two variable focal power lenses. The equations relating to the zoom performance were established through the use of matrix optics [76]. Peng *et al* proposed a 1×–2× optical zoom imaging system employing two electrowetting liquid lenses. A detailed calculation for two adaptive liquid lenses to meet the basic requirement of the desired zoom ratio was presented [77, 78].

Because the technology of the traditional optical zoom imaging system using several solid lenses is relatively mature, it appears to be a good approach to substitute some solid lenses with adaptive lenses to realize optical zoom imaging without moving parts. Park *et al* proposed an 8× optical zoom imaging system including two adaptive liquid lenses. The optical zoom imaging system was constructed from four fixed groups, as shown in figure 3(a). Several solid lenses constituted the first and third groups. The solid lenses had aspheric surfaces to reduce aberrations. The distortion aberration was balanced to less than 5%. The second group was used to realize the zooming function by one adaptive liquid lens working as a variator. The fourth group was regarded as a compensator to realize the focusing function to compensate for the image plane shift by another adaptive liquid lens. The focal length of the optical zoom imaging system varied from 4 mm to 31 mm. The aperture was F/3 at a wide position and F/4.5 at a tele position [79]. Similarly, an optical zoom imaging module with 1×, 2×, 4× zoom ratio was developed by Lee *et al.* The optics system consisted of six glass lenses, one polymer lens, one iris with a diffraction optical element, and two adaptive liquid lenses, as shown in figure 3(b). Two adaptive liquid lenses worked together to adjust the zoom ratio. The effective focal lengths under wide-angle zoom (66°), medium-angle zoom (32°), and zoom-in modes (13.8°) were 3.24 mm, 6.4 mm, and 12.94 mm, respectively. The overall length of the system was 23.26 mm. Benefitting from the miniaturized size, the optical zoom imaging module can be used as a laparoscope. The diffraction optical element was used to reduce chromatic aberration. The optical distortions under wide-angle zoom, medium-angle zoom, and zoom-in modes were 16%, 5.16%, and 2.98%, respectively. The modulation transfer functions (MTF) were 35%, 45%, and 30% at a frequency of 140 lp/mm [80]. Besides designing the specific surfaces of the solid lenses, the

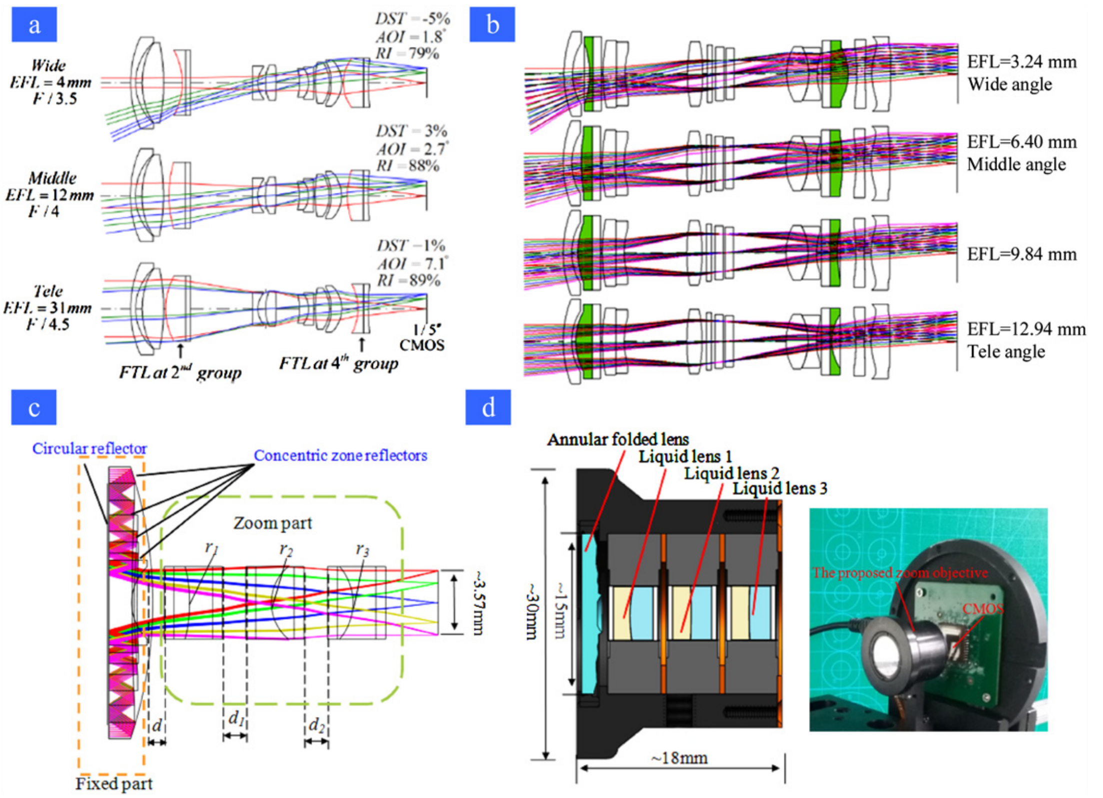

Figure 3. (a) The layout of an 8× four-group zoom imaging system with two adaptive liquid lenses placed in the second and fourth groups, respectively, at the wide, middle, and tele positions. (DST: distortion, AOI: angle of incidence, RI: relative illumination.) Reproduced from [79]. CC BY 4.0. (b) Ray tracing of an optical zoom imaging system at a wide angle, middle angle, and tele angle, respectively. Reproduced with permission from [80]. (c) The Zemax layout of the telescopic objective was composed of an annular folded lens and three electrowetting adaptive liquid lenses. (d) The schematic cross-sectional structure of the ultrathin zoom telescopic objective. Reproduced with permission from [85].

parameters of the adaptive liquid lenses can also be optimized to reduce the aberrations. An adaptive liquid lens with one or two changeable surfaces is not good enough for aberration correction. The aberrations in optical zoom imaging using adaptive liquid lenses were analyzed by Wang *et al* based on the three-order aberration theory. The results showed the two-group adaptive liquid lens system is the simplest one that contains no moving mechanical parts and has sufficient parameters for aberration correction [81]. Li *et al* reported an optical zoom imaging system, which exhibited a continuous optical power range (18–27 mm). The system was composed of a fixed solid lens and four adaptive liquid lenses. Each adaptive liquid lens was operated to change its focal length to realize the whole optical zoom. Moreover, the four adaptive liquid lenses were filled with different optical fluid mediums. By selecting a proper liquid medium, achromatic and spherical aberrations can be corrected by these four adaptive liquid lenses [82]. Zhang *et al* designed and optimized a 1.8× micro-optical zoom system without moving elements using two adaptive liquid lenses, which were based on the electrowetting effect. An adaptive liquid lens was used to change the focal length, while another adaptive liquid lens compensated the imaging shift. Three groups of classical solid lenses were adopted to eliminate the aberration. The overlength of the optical zoom imaging system was as small as 10 mm [83].

Employing two adaptive liquid lenses to form a variable-power Keplerian telescope structure can also realize optical zoom imaging. An optical zoom imaging system possessing a variable magnification ratio (from 0.1× to 10×) was developed by Savidis *et al*. The proposed system was composed of two single-chamber plano-convex adaptive liquid lenses and a conventional fixed solid lens. The solid lens was used to focus the collimated light emerging from the second adaptive liquid lens onto a charge-coupled device (CCD). Each adaptive liquid lens can change its focal length independently by controlling fluid pressure in the single-chamber. The focal lengths of the two adaptive liquid lenses were changed synchronously to realize the optical zoom. The focal length of the first adaptive liquid lens varied from 60 mm to 300 mm, and that of the second adaptive liquid lens varied from 40 D to 1 D [84].

Although one of the main advantages of optical zoom imaging systems using adaptive liquid lenses is the reduction in the system size, the current optical zoom imaging systems based on adaptive liquid lenses show little advantages in system length compared with conventional optical zoom imaging systems. The main reason is that the optical power of one liquid lens

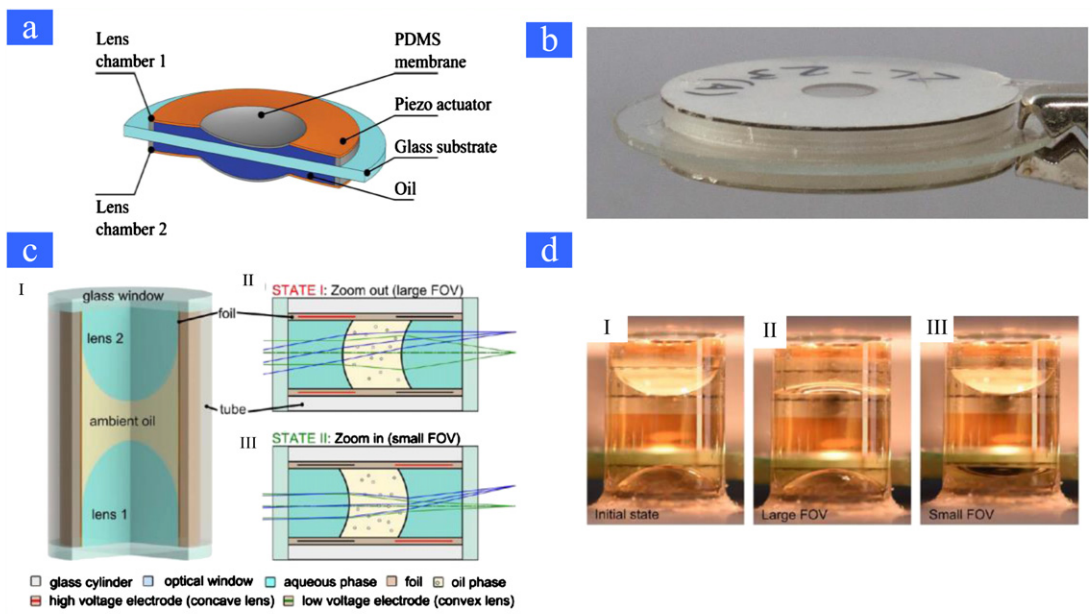

Figure 4. (a) and (b) The schematic structure and a photograph of the optical zoom imaging system using two adaptive liquid lenses on both sides of a glass substrate. © (2011) IEEE. Reprinted, with permission, from [86]. (c) A schematic cross-section through the adaptive zoom system showing two adaptive liquid lenses. (I) Configuration of the two primary operating states. (II) Wide-angle state, and (III) telephoto state. The two liquid phases are aqueous and oil. (d) Side views of the lens cylinder showing independent lens tuning. (I) initial state. (II) Wide-angle configuration, and (III) telephoto configuration. Reproduced with permission from [87].

is still small. Therefore, multiple adaptive liquid lenses are needed to obtain the same optical power as that of a solid lens, which increases the total system length. To solve this issue, an annular folded lens was used to undertake the majority of the focal power and fold the optical path to reduce the overall length of the optical zoom imaging system dramatically. Three electrowetting adaptive liquid lenses were placed behind the annular folded lens and their positions were fixed, as depicted in figures 3(c) and (d). The three electrowetting adaptive liquid lenses not only served as a zooming part but were also used to correct the aberrations by adjusting the three liquid–liquid interfaces. The aperture and the total length of the optical zoom lens were ∼15 mm and ∼18 mm, respectively [85].

In the above optical zoom imaging systems (shown in figure 3), the focal power of the optical zoom imaging systems was mainly determined by solid lenses. However, the existence of the solid lenses may complicate the structure of the system and increase the overall dimensions, which is not beneficial to miniaturization. To develop optical zoom imaging systems with a more compact structure, many efforts have been made to realize an optical zoom imaging system free from solid lenses. It is worth noting that when the surfaces of two adaptive liquid lenses form a meniscus, the solid lenses can be removed, meanwhile realizing the optical zoom imaging. For example, when the first adaptive liquid lens is a concave lens and the second one is a convex lens, the first adaptive liquid lens diverges rays and the second one converges rays. Therefore, it is possible to keep the summation of conjugate distances of the two adaptive liquid lenses unchanged by changing the focal lengths of two adaptive liquid lenses properly. In other words, the image plane of the system remains fixed. Hence, an optical zoom imaging system using multiple adaptive liquid lenses free from solid lenses can be developed. A thin (overall thickness was 4.4 mm) 1.42× optical zoom imaging system consisting of two adaptive liquid lenses was proposed by Draheim *et al*. As depicted in figure 4(a), two adaptive liquid lenses were aligned and placed on the two sides of a glass substrate. Each adaptive liquid lens consisted of a liquid chamber made of a polydimethylsiloxane (PDMS) elastic membrane in the center and a ring-shaped piezoelectric actuator (Ekulit GmbH). The liquid chamber (the diameter was 20 mm) was filled with silicone (RTV 615 with a refractive index of 1.33). When a voltage was applied to the ring-shaped piezoelectric actuator, it bent downwards. Therefore, the PDMS elastic membrane bulged upward, and then the adaptive liquid lens was convex. In contrast, when the polarity of the driving voltage was changed, the adaptive liquid lens was a concave lens. The fabricated two adaptive liquid lenses on both sides of a glass substrate are shown in figure 4(b) [86]. A higher zoom ratio can be obtained by filling the liquid chamber with the optical fluid of a higher refractive index. Similarly, a 1.5× optical zoom imaging system consisting of two adaptive liquid lenses was demonstrated by Kopp *et al*. As shown in figure 4(c), in contrast to the work carried out by Draheim *et al*, the shapes of

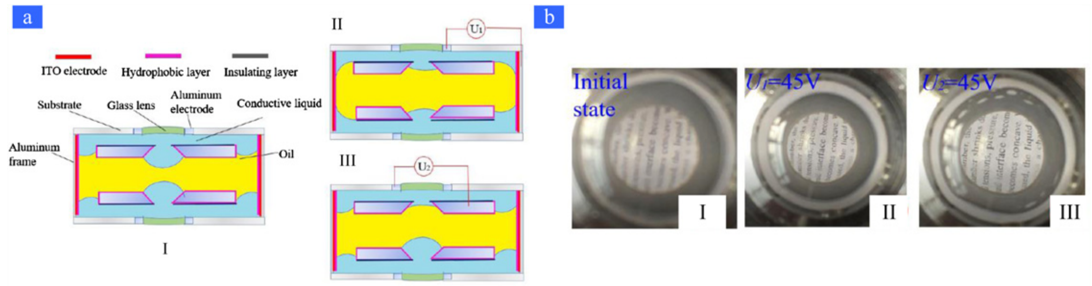

Figure 5. (a) The schematic cross-sectional structure and operating mechanism of the optical zoom imaging system using two movable electrowetting adaptive liquid lenses: (I) cross-sectional structure, (II) moving actuation, (III) deforming actuation. (b) An optical zoom imaging experiment: (I) initial state, (II) moving state, (III) focal length change state. [88] John Wiley & Sons. © 2019 The Society for Information Display.

the two adaptive liquid lenses were tuned by applying a voltage to the buried electrode based on the electrowetting effect. To image an object with a large field of view, a 62.72 V voltage was applied to the bottom adaptive liquid lens and a voltage with 205.93 V amplitude was applied to the top adaptive liquid lens. Similarly, to image an object with a small field of view, a voltage with 193.17 V amplitude was applied to the bottom adaptive liquid lens, and one of 59.62 V amplitude was applied to the top adaptive liquid lens, as shown in figure 4(d). The imaging resolution of the proposed optical zoom imaging system was better than 5 line pairs/mm (lp/mm) [87].

In an optical zoom imaging system using adaptive liquid lenses, the focusing function was realized by changing the focal length of the adaptive liquid lenses. As an alternative, moving the primary plane of the adaptive liquid lens can be used to realize the focusing function to keep the image plane stationary. Two movable electrowetting liquid lenses were used to realize optical zoom imaging by Li *et al.* As shown in figure 5(a), the two adaptive liquid lenses were controlled by two actuators, i.e. moving actuation and deforming actuation. The silicone oil layer was sandwiched between the two conductive liquid layers to form two liquid–liquid interfaces. The two liquid–liquid interfaces not only change their shapes to achieve different focal lengths of the zooming function but also its position was moved for the focusing function. As shown in figure 5(b), in the initial state, the image was a little blurred because of the defocusing. In the moving state, when an external voltage (U_1 = 45 V) was applied, the two liquid–liquid interfaces moved downwards due to the electrowetting effect that happens on the frame. In the deformation state, when another external voltage (U_2 = 45 V) was applied on the aluminum frames, the two liquid–liquid interfaces deformed to vary the focal length. Because both the curvature radius and the position of the two liquid–liquid interfaces were changed, the image was magnified and clear [88, 89].

The optical zoom imaging system includes a zooming group and a focusing group. Adaptive liquid lenses can only act as a zooming group or a focusing group and the other group is composed of solid lenses for optical zoom imaging. An adaptive optical zoom imaging system with a large zoom range (from ~45 mm to ~70 mm) was proposed by Li *et al.* The system can vary the focal length by both variable curvature of the lens surface and variable refractive index of the optical material, whose principle was different from the existing methods. The system consisted of two solid glass lenses, three adaptive liquid lenses, a liquid optical path switcher, and a complementary metal oxide semiconductor (CMOS) image sensor, as shown in figure 6(a). Three electrowetting adaptive liquid lenses were used to increase the optical power and to realize the zooming function. The optical medium in the optical path switcher varied from the air phase to the liquid phase, aiming to change the refractive index of the optical path. The liquid optical path switcher acted as a compensation part to shift the back focal plane to realize the focusing function. The size of the whole zoom objective lens was 25 mm × 24 mm (diameter × length), and that of the liquid optical path switchers part was 48 mm × 31 mm × 31 mm, as shown in figure 6(b) [90]. Moreover, Fang *et al* proposed an optical zoom imaging system consisting of four groups, including two adaptive liquid lenses (RCTIC 416, Varioptic), as shown in figure 6(c). Two adaptive liquid lenses controlled the major optical power of the optical zoom imaging system. A modified genetic algorithm was proposed, which was not only used to eliminate the chromatic aberration and field curvature but could also find the best solution for a discrete zoom set. The system had a 0.125×–2× variable zoom ratio and the overall length was under 20 mm [91]. Due to the assistance from adaptive liquid lenses, the number of moving groups can be significantly reduced to design an optical zoom imaging system. A 2.5× zoom noncoaxial optical imaging system including one prism, some solid lenses, and two adaptive liquid lenses was proposed by Sun *et al.* The two adaptive liquid lenses were mainly responsible for the zooming function, and two moving groups consisting of several solid lenses acted

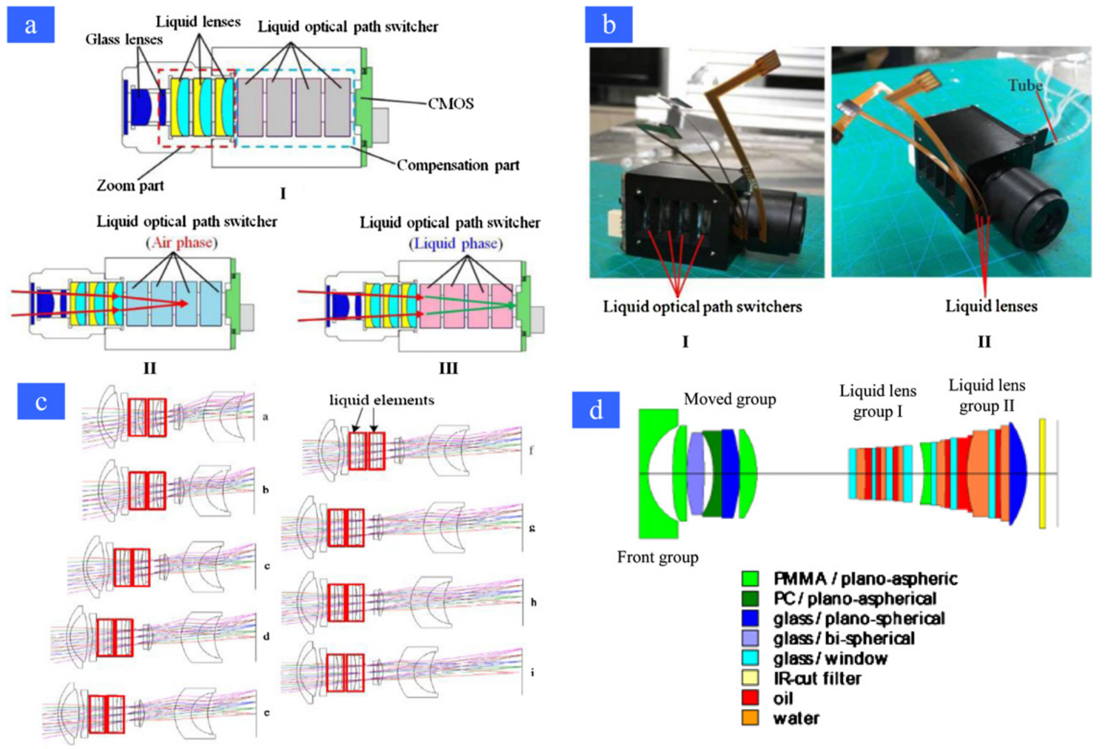

Figure 6. (a) (I) The schematic cross-sectional structure of the optical zoom imaging system consisting of two solid glass lenses and three commercialized electrowetting adaptive liquid lenses: (II) the air phase mode of the liquid optical path switchers, (III) the liquid phase mode of the liquid optical path switchers. (b) The fabricated optical zoom imaging system: (I) top view, (II) side view. © (2018) IEEE. Reprinted, with permission, from [90]. (c) The optimized layout of an optical zoom imaging system under different zoom ratios. Two adaptive liquid lenses mostly control the optical power of the system. Reproduced with permission from [91]. (d) A hybrid zoom lens with solid lenses and two liquid lens groups. The moved group provided the required change in power to achieve the different focal lengths. The two liquid lens groups were used to realize the focusing function and to minimize the field curvature to an acceptable level. Reproduced with permission from [93].

as compensators [92]. Besides acting as the zooming group, the adaptive liquid lenses can solely work as the focusing group. Because of the large mechanical stroke of mechanical actuators, the movable solid lenses can act as a zooming group to provide a wide zoom range. Considering the limited change in optical power of state-of-the-art commercially available adaptive liquid lenses, Wippermann *et al* used two adaptive liquid lenses for image shift compensation to realize the focusing function and minimize optical aberrations (such as field curvature) to an acceptable level. As shown in figure 6(d), the front group was fixed and followed by a movable solid lens group with a travel range up to 5.3 mm. The moved group provided the required change in power to achieve the different focal lengths. The system had a 2.5× zoom ratio and the optical power range was 108 dioptries [93, 94]. Yen *et al* proposed a 9× zoom imaging system by cascading two subsystem zoom groups. The front zoom group and the back zoom group both had a 3× zoom ratio. The adaptive liquid lens was placed at the final position in the second subsystem group. The adaptive liquid lens not only worked as a focusing group to reduce the error of the effective focal length but also mitigated some optical aberrations [95]. An optical imaging system consisting of an original lens and a scanning lens (two adaptive liquid lenses) was proposed by Song *et al.* An image with local variable magnification (1×–2×) was obtained by moving the two adaptive liquid lenses synchronously along the optic axis [96].

For this configuration, the optical zoom imaging is realized by multiple adaptive liquid lenses. Compared with that of the traditional optical zoom imaging systems, this configuration provides several advantages in terms of compact size, light weight, and low energy consumption. It saves at least two mechanical driving actuators and significantly reduces the number of moving groups. However, because multiple adaptive lenses are still required for optical zoom imaging, these systems are often still costly and bulky in size. To further reduce the cost and system size, some optical zoom imaging systems using a single adaptive lens were proposed.

2.2. Optical zoom imaging systems using a single adaptive liquid lens

In the above optical zoom imaging systems, multiple adaptive liquid lenses worked together to realize optical zoom imaging. Recent progress and continued efforts have been devoted to developing optical zoom imaging systems using only a single adaptive liquid lens. Thus, this configuration provides a more compact structure for optical zoom imaging. In contrast

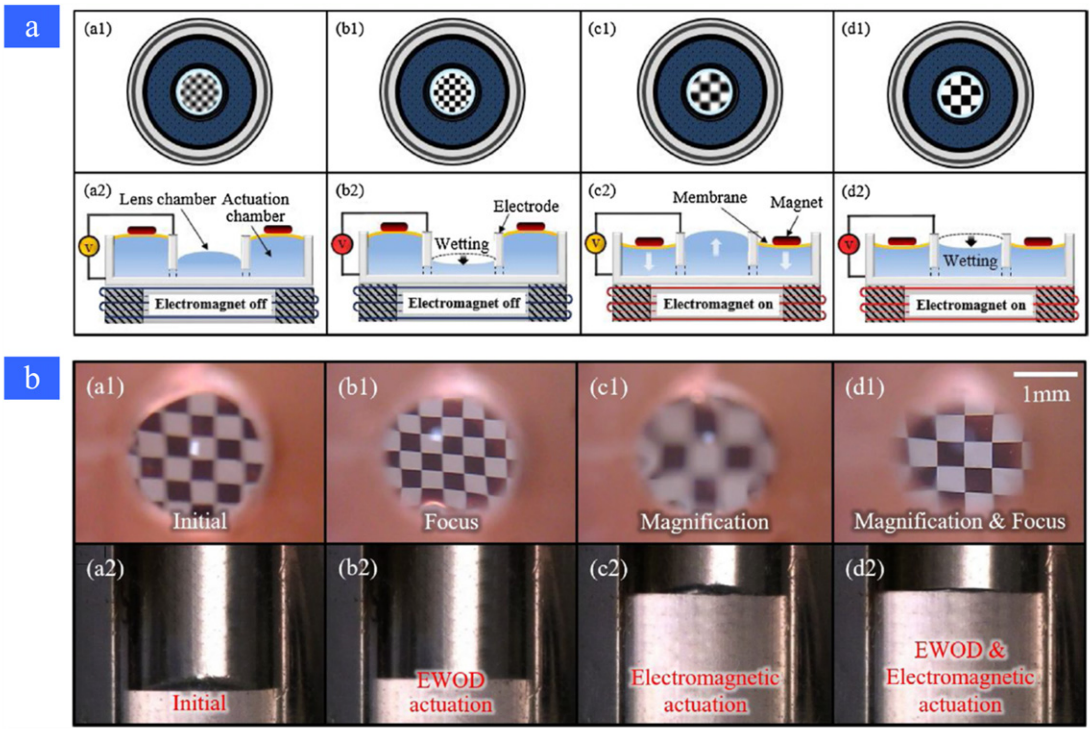

Figure 7. (a) A schematic diagram of a multifunction adaptive liquid lens. (b) An optical zoom imaging test: snapshots of sequential focusing and zooming functions using EWOD and electromagnetic actuation. Reprinted from [97], Copyright (2018), with permission from Elsevier.

to the typical adaptive lenses that are driven by one actuator to obtain a tunable focal length, the single adaptive liquid lens used in optical zoom imaging systems is always regulated by two or more driving actuators. With the help of multi-actuators, it is possible to realize optical zoom imaging by changing both the surface shape and primary lens plane simultaneously. An adaptive liquid lens controlled by two different actuation methods simultaneously was designed by Park *et al* for optical zoom imaging. The two actuation methods were electrowetting-on-dielectric (EWOD) actuation and electromagnetic actuation, as shown in figure 7(a). The EWOD actuation was used to control the curvature radius of the liquid interface by applying voltages to an electrode, resulting in the focal length change in the adaptive liquid lens. The electromagnetic actuation was used to control the height of the liquid column, i.e. the position of the primary lens plane by applying an electrical voltage to an electromagnetic system. As shown in figure 7(b), firstly, a voltage (70 V) was applied to the EWOD electrode to make an initially blurred check-patterned image well focused. Secondly, when another electrical voltage (50 V) was applied to the electromagnetic system, the magnification factor of the image changed, and the image was blurred again. Lastly, the magnified but blurred image became clear again by applying another voltage (50 V) to the EWOD electrode. When the applied electrical voltage varied from 0 V to 50 V, the initial image was magnified about 1.5 times [97].

Besides employing EWOD actuation and electromagnetic actuation, two EWOD actuation methods can also be employed to drive the single adaptive liquid lens for optical zoom imaging. An 8× optical zoom imaging system consisting of eight solid lenses and one adaptive liquid lens was proposed by Zhao *et al*. The adaptive liquid lens was an electrowetting-based triple liquid lens, which had more variable parameters compared with the double adaptive liquid lens. The zoom range varied from 2.7 mm to 20.3 mm. The total length of the optical zoom imaging system was 22 mm and the MTF was more than 0.4 at 180 lp/mm [98]. A displaceable and tunable electrowetting liquid lens was designed by Li *et al*. It can be employed to realize optical zoom imaging with ∼1.31× magnification ratio. As shown in figure 8(a), there were two actuation electrodes in the single adaptive liquid lens. When a voltage (U_1) was applied to the upper cylindrical tube electrode, the contact angle of the liquid–liquid interface was changed due to the electrowetting effect. Therefore, the conductive liquid pulled upward and pushed the silicone oil down, with the result that the liquid–liquid interface descended in the inner tube. When a voltage (U_2) was applied to the inner tube electrode, the contact angle of the liquid–liquid interface was changed, resulting in a tunable focal length. Hence, the translational motion and focal length of the single adaptive liquid lens were controlled by applying voltages to the two electrodes, respectively. As shown in figure 8(b), firstly,

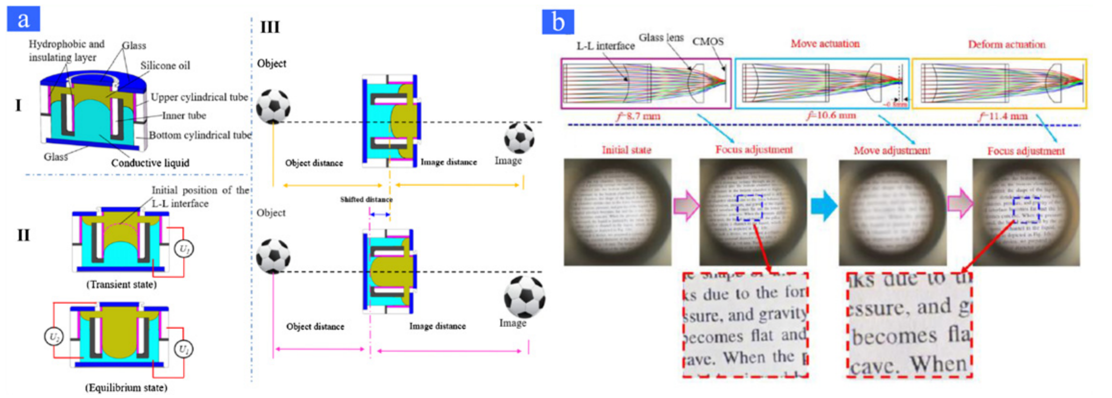

Figure 8. (c) The schematic cross-sectional structure and operating mechanism of the displaceable and focus-tunable electrowetting adaptive liquid lens for optical zoom imaging: (I) cross-sectional structure; (II) moving actuation and deforming actuation; (III) working principle. (b) The Zemax model of the zoom lens system and experimental results of zoom-in and zoom-out. Firstly, the liquid–liquid interface remained in the initial position and deformed the shape to focus the image on the CMOS. Then, the position was shifted forward. Finally, the shape of the liquid–liquid interface was deformed to refocus the image on the CMOS. Reproduced with permission from [99].

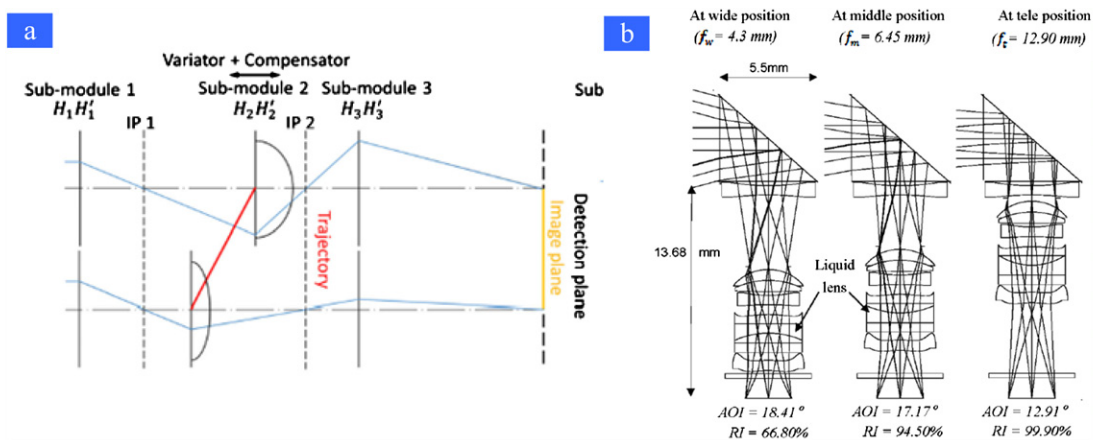

Figure 9. (a) The structure layout of the hybrid optical zoom imaging system consisting of several sub-modules. The second sub-module was an adaptive liquid lens. The adaptive liquid lens can not only be moved to realize the zooming function as a variator but can also change its focal length simultaneously to realize the focusing function as a compensator to keep the image plane stationary. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Journal of the European Optical Society-Rapid Publications [100] Zoom systems with tuneable lenses and linear lens movements, Lenk L, Mitschunas B and Sinzinger S, (c) 2019. (b) An optical zoom imaging system with an adaptive liquid lens and a right-angle prism. An adaptive liquid lens was inserted into the second group and it can be moved to the first group to obtain a longer focal length. Moreover, the focal length of the adaptive liquid lens was changed to maintain the image plane at different magnifications. Reproduced with permission from [101]. © The Korean Physical Society.

a blurred image was obtained because of defocusing initially. Secondly, when a voltage ($U_2 = {\sim}56$ V) was applied to the inner tube electrode, the image became clear because the focal length of the adaptive liquid lens was changed. Then, when a voltage ($U_1 = {\sim}100$ V) was applied to the upper cylindrical tube electrode, the image magnification was changed significantly because of the position movement of the liquid–liquid interface and the image was blurred again. To make the magnified image clear again, a voltage ($U_1 = {\sim}62$ V) was applied to the inner tube electrode [99].

Generally, the optical power range of a single adaptive liquid lens is narrow. Therefore, when the position of the single adaptive liquid lens in the optical zoom imaging system is fixed, the zoom ratio is small. Benefiting from the large mechanical stroke of mechanical actuators, the single adaptive liquid lens can be mechanically moved to develop an optical zoom imaging system with a high zoom ratio. A hybrid 3× optical zoom lens consisting of two solid sub-modules and a liquid lens was investigated by Lenk *et al*. As shown in figure 9(a), the second sub-module was an adaptive liquid lens (APL™-1050, Holochip Corp). The adaptive liquid lens can not only be mechanically moved to realize the zooming function as a variator but it can also change its focal length simultaneously to realize the focusing function as a compensator to keep the image plane stationary [100]. Similarly, a 3× zoom system (the focal length range was 4.3 mm to 12.90 mm) consisting of a prism and two lens groups was proposed by

Park *et al*. As shown in figure 9(b), the second group was moved to the first group to obtain a long focal length to realize the zooming function. An adaptive liquid lens was inserted in the second group to change the focal power of the system to realize the focusing function, i.e. maintaining the image plane at different magnifications [101].

Compared with that of an optical zoom imaging system using multiple adaptive liquid lenses, this configuration that uses a single adaptive liquid lens has a more compact structure because only one adaptive lens is needed. Whereas, because at least two actuators should be introduced to manipulate the adaptive liquid lens, the main disadvantages of this configuration are that the control process of the single adaptive liquid lens is complicated and it is difficult to achieve a high zoom ratio since there is only one adaptive liquid lens, which is as a result of a narrow tunable optical power range. Although the single adaptive lens can be moved mechanically to develop an optical zoom imaging system with a high zoom ratio, a mechanical movement unit is still needed, which inevitably increases the size of the footprint and the weight of the optical zoom imaging system.

2.3. Performance comparison

The above two configurations can be used to construct a compact optical zoom imaging system. However, different configurations have different impacts on the performance of the optical zoom imaging systems. Table 1 lists the influence of different configurations on the performance of the optical zoom imaging systems. From table 1, we find that the configuration using multiple adaptive liquid lenses always has a larger zoom ratio than that using a single adaptive lens. The solid lenses used in the optical zoom system using multiple adaptive liquid lenses relay the light ray and can provide a large focus power range. Moreover, some surfaces of the solid lenses can be designed to optimize aspheric shapes to balance some optical aberrations. Therefore, compared with the configuration that uses a single adaptive lens, that which uses multiple adaptive liquid lenses offers a higher MTF, which indicates a better imaging performance. Benefiting from these advantages, this configuration may be the most widely used method to realize optical zoom imaging. However, the existence of multiple adaptive liquid lenses always complicates the structure of the optical zoom imaging system and increases the overall dimensions, which is not beneficial for miniaturization. The configuration that uses a single adaptive liquid lens has a more compact size. But the zoom ratio of this configuration is smaller because of the limited tunable focal length range of the adaptive liquid lenses. Additionally, the MTF is also smaller than that of the configuration that uses multiple adaptive liquid lenses. This is mostly because the adaptive liquid lenses with optimized aspheric surface shapes are hard to obtain. Moreover, the number of known liquids with suitable properties such as refractive index, Abbe number, transparency, and viscosity, is very limited.

3. Working principles of the adaptive liquid lenses

Different actuation mechanisms can be employed to operate adaptive liquid lenses to obtain a variable focal length. To the best of our knowledge, the adaptive liquid lenses can be broadly grouped into three categories: liquid crystal lenses, elastomer–liquid lenses, and electrowetting lenses. Liquid crystal lenses vary their focal length by changing the refractive index of the optical material. The elastomer–liquid lenses and electrowetting lenses adjust their focal length by changing liquid–air or liquid–liquid surface shapes. In this section, we review the three working principles (liquid crystal, polymer elastic membrane, and electrowetting effect) adopted in the optical zoom imaging systems in detail.

3.1. Liquid crystal

The concept of the liquid crystal lens was first proposed in 1977 [102]. A classic liquid crystal lens often consists of two glass substrates with transparent indium tin oxide (ITO) electrodes [103, 104]. When a voltage was applied to the ITO electrodes, the director orientation of the liquid crystal changed from being parallel to the surfaces to being perpendicular to the surfaces, the result of which was that the refractive index was changed and then the focal length of the liquid crystal lenses was varied.

Although one liquid crystal lens can change its focal length electrically, two or more liquid crystal lenses were needed to realize optical zoom imaging. The first theoretical analysis of an electrically controlled zoom system using liquid crystal lenses (spatial light modulator) was conducted in 1992 [105]. In 2009, Ye *et al* realized 1.5× zoom imaging using two liquid crystal lenses as a variator and a compensator, respectively. Two liquid crystal lenses with identical structures labeled focal lengths f_1 and f_2 were placed symmetrically before and after a glass lens. The liquid crystal lens with focal length f_1 was regarded as a variator to change the image magnification and the liquid crystal lens with focal length f_2 was regarded as a compensator to keep the image stationary on the CCD [106]. Hirai *et al* also employed two liquid crystal lenses to realize a non-mechanical optical zoom imaging system (maximum and minimum magnifications were 2.0× and 0.5×, respectively). With a different structure from that of the optical zoom imaging system proposed by Ye *et al*, two liquid crystal lenses were constructed in the Galilean structure in the system proposed by Hirai *et al*. The focal length of the system can be varied by applying different voltages to two liquid crystal lenses. Three factors, i.e. the range of magnification change, the response time, and

Table 1. The influence of different configurations on the performance of the optical zoom imaging systems.

Configurations	Reference	Year	Number of lenses	Tunable focal length range	f-number	Zoom ratio	Dimensions	MTF
Multiple adaptive liquid lenses	[79]	2018	Nine solid lenses and two adaptive liquid lenses	4–31 mm	F/3.5–F/4.5	8×	The overall length was about 35.5 mm and the maximum diameter of the lenses was 11.28 mm.	>0.3 @180 cycles/mm
	[80]	2013	Seven solid lenses and two adaptive liquid lenses	3.241–12.945 mm	F/4.9–F/6.04	1×, 2×, 4×	The overall length was 23.26 mm and the diameter was 4.1 mm.	1×: 0.35 @140lp/mm; 4×: 0.30 @140 lp/mm
	[95]	2015	About 13 solid lenses and one adaptive liquid lens	7.068–63.204 mm	F/3.2–F/5.6	9×	The overall length was about 140 mm.	Compared with a standard 9× zoom lens, MTF increases by nearly 3988%@ 40 lp/mm.
	[77, 78]	2007, 2008	One solid lens and two adaptive liquid lenses	10–20 mm	—	1×–2×	The overall length was 7 mm.	—
	[82]	2012	One solid lens and four adaptive liquid lenses	18–27 mm	—	1.5×	—	1×: 0.3 @298 cycles/mm; 1.5×: 0.3 @193 cycles/mm
	[83]	2013	Three group solid lenses and two adaptive liquid lenses	4.8–8.6 mm	F/3.2–F/5.4	1.8×	The overall length was 10 mm.	MTF: 0.27–0.41 @ 40 lp/mm
	[85]	2016	One reflector and three adaptive liquid lenses	48–65 mm	F/3.14–F/4.10	1.35×	The overall length was 18 mm.	103 cycles/mm
	[90]	2018	Two solid lenses and three adaptive liquid lenses	45–70 mm	—	1.55×	Φ25 mm × 24 mm	—
	[84]	2013	One solid lens and two adaptive liquid lenses	35–342 mm	F/97.14–F/1.03	0.1×–10×	—	—
	[93, 94]	2006, 2007	Two solid lens groups (one is movable) and two adaptive liquid lenses	4.8–12 mm	F/3.5	2.5×	Φ8 mm × 24 mm	—
	[92]	2009	About ten solid lenses and two adaptive liquid lenses	—	—	2.5×	The length was 10 mm in the x direction, and was 23.7 mm in the y direction	>0.4 @100 lp/mm
	[96]	2019	About eight solid lenses and two adaptive liquid lenses	10–20 mm	—	1×–2×	—	1.0×: 0.3@ 100 cycles/mm; 1.5×: 0.3@60 cycles/mm; 2.0×: 0.3@30 cycles/mm

Table 1. continued

	[86]	2011	Two adaptive liquid lenses	36–51 mm	—	1.42×	The overall thickness was 4.4 mm	1.0×: 43.5 lp/mm
	[87]	2017	Two adaptive liquid lenses	FOV: 2.66°–1.93°	—	1.5×	Φ5 mm × 9.88 mm	>5 lp/mm
	[100]	2019	Two solid sub-modules and a moved adaptive liquid lens	50–150 mm	F/9.24–F/17.99	3×	—	—
A single adaptive liquid lens	[101]	2009	About ten solid lenses and one adaptive liquid lens	4.3–12.9 mm	F/3–F/5	3×	—	>0.3@ 200 lp/mm at all zoom ratios
	[98]	2017	Eight solid lenses and one adaptive liquid lens	2.7–20.3 mm	—	8×	The overall thickness was 22 mm	>0.4@ 180 lp/mm
	[97]	2018	One adaptive liquid lens	—		1.5×	Φ22 mm × 15 mm	—
	[99]	2018	One adaptive liquid lens	—	—	∼1.31×	Φ22 mm × 14.5 mm	—
	[88]	2019	One adaptive liquid lens	15 mm ∼ unknown	—	—	Φ5 mm	—

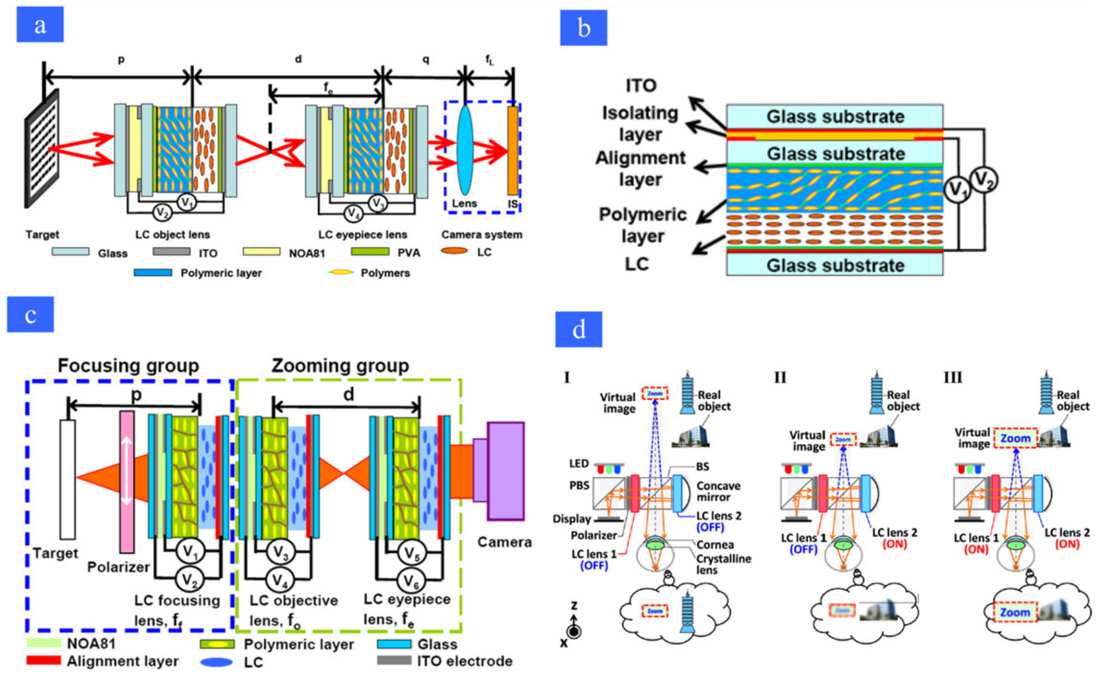

Figure 10. (a) The structure of the optical zoom imaging system using two liquid crystal lenses. Reproduced with permission from [108]. (b) The structure of the composite liquid crystal lenses. Reproduced with permission from [109]. (c) The structure of the optical zoom imaging system using three liquid crystal lenses. Reproduced with permission from [110]. (d) The working principle of the optical zoom AR system via two liquid crystal lenses. Reproduced with permission from [112].

the brightness, were discussed to estimate the performance of the optical liquid crystal zoom imaging system [107].

Lin *et al* proposed an electrically adaptive optical zoom imaging system (zoom ratio up to ∼7.9×) using two composite liquid crystal lenses. The optical zoom imaging system was constructed from a target, a liquid crystal object lens, a liquid crystal eyepiece lens, and a camera, as shown in figure 10(a). The composite liquid crystal lens (as shown in figure 10(b)) included three ITO glass substrates, an isolating layer, mechanically buffered alignment layers, a polymeric layer, and a liquid crystal layer. The composite liquid crystal lens can be operated by two voltages (V_1 and V_2) to change its focal length and shape. When $V_1 > V_2$, the composite liquid crystal lens acted as a convex lens, and it acted as a concave lens when $V_1 < V_2$. By adjusting the voltages of two composite liquid crystal lenses, the images with different continuous magnifications can be obtained at the objective distance that varies from infinity to 10 cm [108, 109]. However, in this optical zoom imaging system, the optical zoom ratio decreased as the object distance increased because one of the liquid crystal lenses took charge of both focusing and zooming functions. Therefore, Lin *et al* further demonstrated an electrically continuous tunable optical zooming system (0.3×–2.2× magnification) based on three tunable composite liquid crystal lenses, as shown in figure 10(c). The focusing function and zooming function were separated: (1) one liquid crystal lens worked as a focusing group and took charge of the focusing function to maintain the formed image in the same position; (2) two other liquid crystal lenses worked as a zooming group taking charge of the zooming function to form an image with a continuously tunable magnification of image size on the camera. The magnifications of the images can be switched continuously for the target in a range between 10 cm and 100 cm. The optical zoom ratio of this system maintained a constant ∼6.5:1 at different object distances [110, 111]. An augmented reality (AR) system with optical zoom function via two liquid crystal lenses was also proposed by Lin *et al.* As shown in figure 10(d), one liquid crystal lens (LC lens 1) was placed between a polarizing beam splitter and a beam splitter, and another liquid crystal lens (LC lens 2) was located between the beam splitter and a concave mirror. The image was reflected by the concave mirror and arrived at the retina of an eye through LC lens 2, a beam splitter, a cornea, and a crystalline lens of the eye. Firstly, when there were no voltages applied to LC lens 1 and LC lens 2, the eye saw the distant real object and the virtual image, as shown in figure 10(d)-I. Secondly, a voltage was applied to LC lens 2 and no voltage was applied to LC lens 1; both the virtual image and the real object were blurred due to presbyopia, as shown in figure 10(d)-II. Lastly, when LC lens 1 and LC lens 2 were both subjected to voltages, the project virtual was magnified and the magnified virtual image in the retina became clearer, as shown in figure 10(d)-III. By changing the optical powers of two liquid crystal lenses, the AR system indeed exhibited the optical zoom function [112].

3.2. Polymer elastic membrane

Adaptive liquid lenses based on polymer elastic membranes are usually constructed by encapsulating an optical fluid in a cavity with the assistance of an elastic membrane. Usually, polymer PDMS is a preferred elastic membrane material because it is highly transparent in the visible spectrum range and offers large deformation as well as good biocompatibility [113, 114]. By pumping optical fluid in or out of the cavity to change the liquid pressure, the shape of the polymer elastic membrane becomes a convex or concave profile; then the focal length of the adaptive liquid lens is tunable [115–118].

Compared with the liquid crystal lens, the elastomer–liquid lens is polarization independent and often exhibits a larger optical aperture and wider tunable optical power range. To the best of our knowledge, an integrated adaptive liquid zoom lens was first demonstrated by Zhang *et al*. The liquid zoom lens consisted of two adaptive liquid lenses made of PDMS and a glass substrate. The two PDMS chambers were bonded to a glass substrate to form a sandwich structure using an oxygen-plasma-activated bonding approach. By pumping an appropriate volume of the liquid (a 63% sodium chromate solution with a refractive index of 1.5) into the two PDMS chambers, a zoom ratio range of 1.62×–2.14× could be obtained when the object distance was 250–1000 mm and the image distance was 50–30 mm [119]. Zhang *et al* also built a mathematical model of a zoom lens consisting of two adaptive liquid lenses. Optical zoom imaging with 4.0× zoom ratio was achieved at 30 mm image distance and 1000 mm object distance without any moving parts [120].

Our research group proposed a four-group optical zoom imaging system with a 5.06× zoom ratio using two polymer elastomer–liquid lenses (Optotune, Switzerland) and two solid lens groups, as shown in figure 11. The response time of the optical zoom imaging system was less than 2.5 ms. The effective focal length ranged from 6.93 mm to 35.06 mm and the field of view varied from 8° to 40°. Optimization of optical parameters was realized by mathematically solving an extreme value and a maximum gradient of the function. The ranges of the optical power of two adaptive liquid lenses were 0.008–0.022 mm^{-1} and -0.0142–0.022 mm^{-1}. The adaptive liquid lens 2 was used as an active element to change the focal length, and the adaptive liquid lens 1 was used as a compensator [121]. A four-group stabilized zoom lens with 2× and 5× zoom ratios using two focal-length-variable elements was also proposed and the zoom equations were established through the use of the Gaussian brackets method [122].

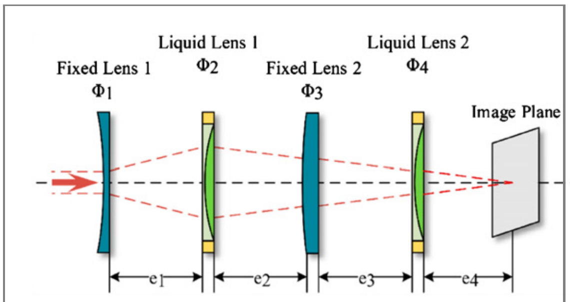

Figure 11. The structure of the optical zoom imaging system using four-groups (two fixed solid lenses and two elastomer–liquid lenses). Liquid lens 2 was employed to realize the zooming function, and liquid lens 1 was used to realize the focusing function. Reproduced from [121]. CC BY 4.0.

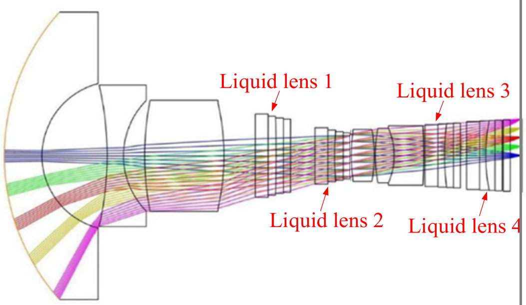

Figure 12. The layout of an optical zoom imaging system using several solid lenses and four electrowetting lenses. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Microsystem Technologies [123] The vehicle zoom ultra wide angle lens design by using liquid lens technology, Chih-Ta Yen *et al*, (c) 2020.

3.3. Electrowetting effect

The electrowetting effect was studied in detail by Berge *et al* in the early 1990s [129, 130]. Optical fluids and an electrode are often separated by a thin dielectric layer. These two optical fluids, which are immiscible with each other and have different refractive indexes, are sealed within a rigid chamber. One optical fluid is conductive and another one is non-conductive. When a voltage is applied across the conducting liquid and the electrode, the contact angle can be tuned electrostatically. Then the focal length of the adaptive liquid lens can be varied accordingly.

An optical zoom imaging system (as shown in figure 12) consisting of four electrowetting adaptive liquid lenses (ARCTC-416, Varioptic Company) and solid lenses for wide-angle vehicle imaging was proposed by Yen *et al*. The zoom ratio was changed with the variation of the surface curvature and thickness of the four adaptive liquid lenses. Three different fields of view, i.e. 170°, 160°, and 150° with 6%, 30%, and 27% spatial frequency of 180 lp/mm were realized without any moving elements. The total length of the proposed system was 21.9642 mm [123].

In [90], the liquid optical path switcher acted as a compensation part to shift the back focal plane to

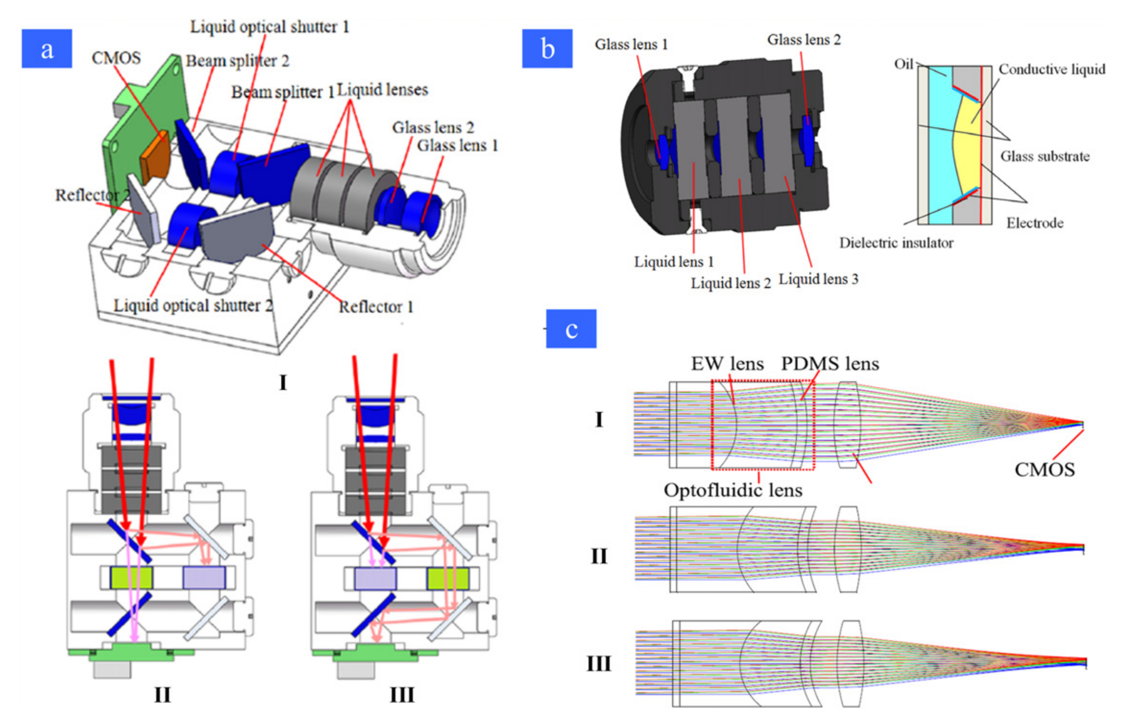

Figure 13. (a) I. A schematic structure of the optical zoom imaging system with a zoom objective lens (three electrowetting adaptive liquid lenses and two glass solid lenses) and a switchable light path. II. Short focal length mode. III. Long focal length mode. Reproduced with permission from [124]. (b) A schematic structure of the zoom objective consisting of three electrowetting adaptive liquid lenses and two glass solid lenses. Reproduced with permission from [125]. (c) An optical zoom imaging system using the hybrid driving variable-focus liquid lens. The optofluidic lens took charge of the zooming and focusing function at the time. (I) The focal length was 14 mm. (II) The focal length was 20 mm. (III) The focal length was 30 mm. Reproduced with permission from [126].

realize the focusing function. By replacing the liquid optical path switcher with the liquid optical shutter as the compensator, Li *et al* developed an electrically tunable adaptive zoom imaging system with continuous zoom ability from 36 mm to 92 mm. As shown in figure 13(a)-I, the system included three electrowetting adaptive liquid lenses (Arctic 39N0, Varioptics) and two glass solid lenses. The switchable light path was composed of two beam splitters, two reflectors, and two liquid optical shutters. When the system worked at a short focal length, the three adaptive liquid lenses changed their surface shape by applying appropriate driving voltages. Meanwhile, the short light path turned on while closing the long light path by applying voltages to the liquid optical shutter 2, as shown in figure 13(a)-II. Similarly, when the system worked at a long focal length, the focal lengths of the three adaptive liquid lenses varied and the long light path was turned on. Meanwhile, the short light path was closed by applying voltages to the liquid optical shutter 1, as shown in figure 13(a)-III [124]. A continuous zoom microscope objective lens (zoom ratio ranged from ∼7.8× to ∼13.2×) consisting of three adaptive liquid lenses and two solid glass lenses was reported by Li *et al.* The schematic structure of the proposed objective lens is shown in figure 13(b). The three adaptive liquid lenses can not only change the zoom ratio without any moving parts by applying appropriate driving voltages but can also correct some aberrations, especially chromatic aberration, by filling with different optical mediums, which had different refractive indexes and Abbe numbers [125].

Multiple driving mechanisms can also be employed to a single adaptive liquid lens to realize optical zoom imaging. Wang *et al* proposed a hybrid driving liquid lens and combined an adaptive liquid lens with a solid lens to realize optical zoom imaging (2.1× zoom ratio). The adaptive liquid lens was driven by two different actuation approaches, i.e. the electrowetting effect and an electromagnetic actuator. The position of the water–oil interface of the electrowetting adaptive liquid lens was shifted by an electrowetting actuator and one elastomer–liquid lens was deformed by pumping liquid in or out of the cavity by means of the electromagnetic actuator. The focal length of the adaptive liquid lens varied from ∼6.02 mm to ∼−11.15 mm. As shown in figure 13(c), the electrowetting (EW) lens was employed to change the focal length to realize the zooming function and the PDMS played a role in refocusing the image on the CMOS. The glass solid lens was used to provide high focal power and correct some optical aberrations [126].

3.4. Performance comparison

The above three actuation mechanisms of the adaptive liquid lenses can be used to develop optical zoom imaging systems. Different actuation mechanisms of the adaptive liquid lenses have different effects on the performance of the optical zoom imaging systems. Liquid crystal lenses are easy to fabricate and have good long-term stability as well as low driving voltages. For those optical zoom imaging systems where a small aperture (less than 5 mm) is needed, liquid crystal lenses may be a preferable option to develop the optical zoom imaging system. However, because the liquid crystal lenses are based on the gradient refractive index change, its phase difference between the center and edge is relatively small (of the order of a few tens of micrometers). Therefore, it often suffers from a limited tunable focal length range (of the order of a few diopters). The variable range of the magnification of the optical zoom imaging system depends on the potential maximum optical power of the liquid crystal lenses. The higher optical power of the liquid crystal lens provides a wider magnification range. Although a thicker liquid crystal layer can obtain a wider focal length range, it inevitably leads to slow response speed. The response time increases in proportion to the square of the thickness of the liquid crystal layer. Therefore, a trade-off exists between the focal length range and the response speed for this actuation mechanism. It often takes a few seconds for liquid crystal lenses to achieve the desired focal length in the optical zoom imaging systems.

Unlike liquid crystal lenses, the elastomer–liquid lenses and the electrowetting lenses are polarization independent. Moreover, they can often provide a larger aperture while preserving a wider tunable focal length range (of the order of millimeters). (1) For the elastomer–liquid lenses, hydraulic and pneumatic actuation may be the simplest approaches for the development of adaptive liquid lenses. However, bulky size and fluid leakage may be two challenges for this working principle of the adaptive liquid lenses employed in optical zoom imaging systems. The gravity effect for a liquid lens with a small aperture can often be negligible for such an actuation mechanism. However, as the aperture increases, the influence of the gravity effect increases drastically [127]. (2) For the electrowetting effect, the adaptive liquid lens with a fast response speed can be obtained. Moreover, the gravity effect can be weakened by using two optical fluids with similar densities. However, the driving voltage should be further reduced in the optical zoom imaging systems [103].

Table 2 lists the influence of different working principles of adaptive liquid lenses on the performance of optical zoom imaging systems. The response time of the adaptive liquid lenses directly influences the imaging speed of the optical zoom imaging systems. An adaptive liquid lens with fast response speed is needed for those optical zoom imaging systems such as digital cameras and dynamic spectral imaging systems. The driving voltage of the adaptive lenses is another important performance parameter in optical zoom imaging systems. A low driving voltage is expected for optical zoom imaging systems, especially for those applications related to human safety, such as laparoscopes, endoscopes, and so on. Zoom range and zoom ratio are also important performance parameters in optical zoom imaging systems. A wide zoom range and a high zoom ratio are supposed. The size of the optical zoom imaging systems is desired to be as small as possible for those space-constrained applications. Optical zoom imaging systems with high MTF are also expected to obtain a high-quality image.

4. Applications

The ability to provide a tunable focal length of the adaptive liquid lenses allows optical zoom imaging without any moving elements. Such a remarkable feature makes it possible to significantly reduce the number of moving groups and the operational complexity of the optical zoom imaging system. The unique advantages of adaptive liquid lenses exhibit distinguished benefits in many fields. A non-exclusive review of some representative applications of optical zoom imaging systems using adaptive lenses is elaborated below.

4.1. Consumer electronics

Cameras in consumer electronics have changed our lives by giving people a way to capture images and preserve specific memories at any time and place. Miniaturization of the camera is of great interest to many portable electronic devices [117, 128]. However, traditional zoom cameras are often realized by mechanically displacing one or more components and are much harder to downscale because of the difficulties in fabrication and assembly of the tiny components, the increases in surface-to-volume ratio, and the significance of friction [5, 129]. The advent of adaptive liquid lenses provides a new approach for designing a miniaturized camera. A 1.7× VGA optical zoom imaging system based on two adaptive liquid lenses and three plastic fixed lenses was developed by Kuiper *et al*. As shown in figure 14(a), an adaptive liquid lens with a diameter of 4.8 mm faced the front of the system to collect as many light rays as possible. Behind the first adaptive liquid lens, two plastic solid lenses followed and were placed between an aperture stop. The stop was placed between two plastic lenses. Another adaptive liquid lens with a diameter of 3.45 mm followed the last plastic lens. The last plastic lens projected the object image onto an image sensor. These two adaptive liquid lenses were actuated by the electrowetting effect principle. One adaptive liquid lens was employed for the focusing function and the other one worked as the zooming function. The complete assembled camera module is shown in figure 14(b) [130]. A miniaturized optical zoom imaging camera consisting of a mirror, two adaptive liquid lenses, and three spherical fixed glass lenses was proposed and manufactured by Zhao *et al*.

Table 2. The influence of different working principles of adaptive liquid lenses on the performance of optical zoom imaging systems.

Working principle	Reference	Year	Diameter of adaptive liquid lens	Focal length or focus power of adaptive liquid lens	Objective distance	Zoom ratio	Zoom range	Driving voltage or pressure	Response time	Dimensions	MTF
Liquid crystal	[105]	1992	0.73 mm	40 cm	Infinity ~ 30 cm	1.53×	9.8–14.8 cm	—	—	Length was 20 cm	—
	[106]	2009	3 mm (MLC-6080 from Merck)	-8.7 m^{-1} ~ 0 (lens 1); 0–8.7 m^{-1} (lens 2)	—	~1.5×	—	15–60 V	—	Length was ~108 mm	—
	[107]	2019	2 mm	−13–13 dpt	—	0.5×–2.0×	—	3–50 V	—	—	—
	[108]	2011	1.28 mm	−5.3–21.8 m^{-1}	Infinity ~ 10 mm	~7.9×	—	0–80 V	~4 s	—	—
	[109]	2012	1.28 mm	−13.5–21.8 m^{-1}	Infinity ~ 10 mm	7.9×–1.86×	—	0–80 V	3.8 s	Length was less than 10 cm	—
	[110]	2014	1 mm	−11.3–24.9 m^{-1}	10–100 cm	~6.5×	—	0–90 V	—	—	—
	[111]	2013	—	17.9–179.9 m^{-1}	Infinity ~ 10 cm	5×	—	—	—	Length was 10 cm	—
	[112]	2019	2.5 mm	−14.1 ~ +17.5 D for lens 1; −3 ~ +4.8 D for lens 2	0–300 cm	~1.2×	—	0–75 V	A few seconds	—	—
Polymer elastic membrane	[80]	2013	2.08 mm	3–13 mm	110 mm	1×, 2×, 4×	3.24 mm, 6.4 mm, 12.94 mm	—	—	Length was	0.3@140 lp/mm 23.26 mm
	[82]	2012	2.5 mm	—	Infinity	—	18–28 mm	—	—	—	—
	[86]	2011	4 mm	0–45 dpt	Infinity	1.42×	—	0–40 V for piezo actuator	—	Thickness was 4.4 mm	43.5 lp/mm
	[119]	2004	20 mm	—	250–1000 mm	2.0×	22–64 mm	−2 kPa–10 kPa	—	Length was less than 43 mm	—
	[120]	2005	20 mm	15.8 mm ~ infinity; −11.7 mm ~ infinity	250–1000 mm	4.0×	26–140 mm	−1 kPa–7 kPa	—	—	—
	[121]	2016	10 mm	0.0087–0.0192 m^{-1} for lens 1; −0.01 –0.0185 m^{-1} for lens 2	265 mm	5.06×	6.93–35.06 mm	0–300 mA for lens 1; 0–100 mA	Less than 2.5 ms	—	0.4 @20 lp/mm for lens 2
Electrowetting effect	[77]	2007	—	—	—	2.0×	6–14 mm	~78 V	—	—	—
	[78]	2008	2 mm	—	~500 mm	0.85×–1.05×	—	~40 V	—	—	—
	[85]	2016	3.9 mm (Arctic 39N0, Varioptics)	−5–15 dpt	~15 m	~1.35×	48–65 mm	—	—	Length was ~18 mm	103 cycles/mm
	[90]	2018	3.9 mm (Arctic 39N0, Varioptics)	−5–15 dpt	~6 m	—	45–70 mm	—	—	Φ25 mm × 24 mm	
	[87]	2017	5 mm	—	200 mm	1.5×	—	~205.93 V	Below 1 s	Diameter 5 mm, length 9.88 mm	5 lp/mm

Table 2. continued

[97]	2018	3 mm	8.94–30 mm when voltage is 0–90 V; −45–−13.42 mm when voltage is 100–130 V	—	1.5×	—	0–70 V	∼900 ms	—	—
[99]	2018	6 mm	−66.7–29.5 mm	∼100 mm	1.31×	8.7–11.4 mm	100 V	5 s	20 mm (diameter) × 14.5 mm (height)	—
[88]	2019	5 mm								
[123]	2019	3 mm	∼15–115 mm	∼10 mm	—	—	45 V	—	—	—
		(ARCTC-416)	−200–67 mm	—	—	1.20–1.31 mm	0–60 V	—	Length was ∼22 mm	0.27@180 lp/mm
[124]	2017	3.9 mm (Arctic 39N0, Varioptics)	−5–15 dpt	5 m	2.6×	36–92 mm	23–70 V	2 s to open the liquid optical shutter	Φ25 mm × 24 mm	Over 0.2@ 82 cycles.mm
[125]	2016	3.9 mm (Arctic 39N0, Varioptics)	−5–15 dpt	—	7.8×–13.2×	12–19 mm	23–70 V	—	—	Reaches diffraction limited resolution
[126]	2019	—	−11.15–6.02 mm	∼1000 mm	∼2.14×	14–30 mm	75 V	—	Φ12 mm × 10.5 mm	Angular resolution is 23″

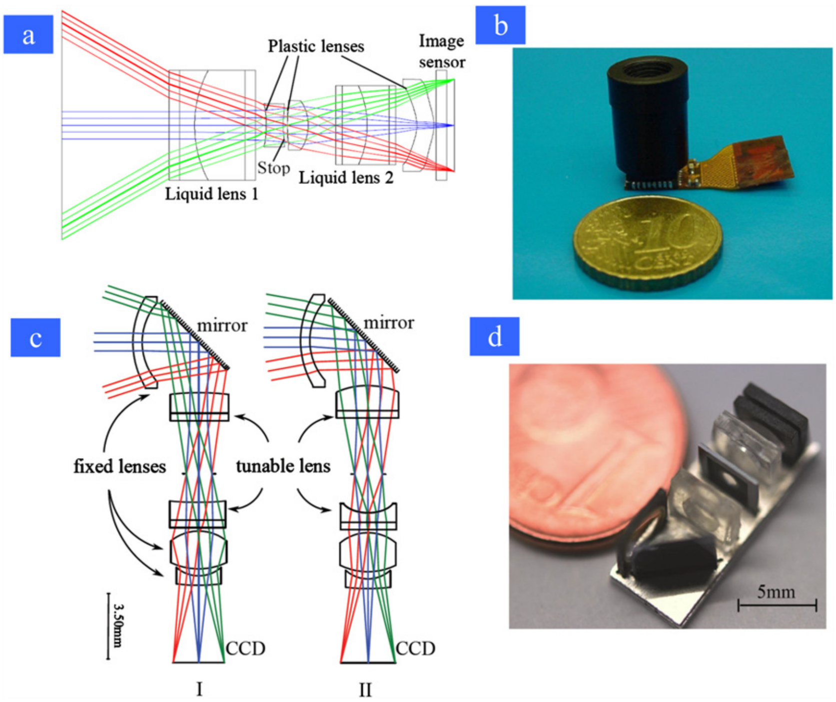

Figure 14. (a) The layout of a zoom camera consisting of two adaptive liquid lenses and three solid lenses. (b) The assembled camera. Reproduced with permission from [130]. (c) Ray tracing simulation results of an optical zoom imaging camera consisting of a mirror, two adaptive liquid lenses, and three spherical fixed glass lenses: (I) short effective focal length; (II) long effective focal length. (d) The zoom imaging camera was integrated with all the optical components on the optical platform. Reproduced with permission from [131].

As depicted in figure 14(c), one solid fixed lens was placed facing the object to collect as many light rays as possible. One adaptive liquid lens was used to change the focal length of the system to realize the zooming function through an external pressure controller. Another adaptive liquid lens was employed to realize the focusing function to maintain the image plane position and was also used to minimize the optical aberrations through another external pressure controller. The last focusing group consisting of two fixed glass lenses was employed to bend the light rays onto the CCD. The diameter of the adaptive liquid lens was 3 mm. The effective focal length of the zoom camera changed from 4.5 mm to 9 mm and the field of view varied from 40° to 20°. The overall size of the proposed zoom camera was 5 mm × 6.5 mm × 17 mm, as shown in figure 14(d) [131].

4.2. Biomedical imaging

The traditional laparoscope suffers from a long mechanical length and a rigid field of view because it is usually made of several fixed solid lenses [132–134]. To address this issue, Tsai *et al* proposed a miniaturized 4× optical zoom laparoscope consisting of two bioinspired adaptive liquid lenses, as shown in figure 15. The bioinspired adaptive liquid lens based on an elastomer membrane had a focal power of over 100 diopters and was convertible between a convex and a concave shape. The optical zoom laparoscope had a 4 mm clear aperture and was less than 17 mm in thickness. By changing the curvature and focal length of the two adaptive liquid lenses, the zooming and focusing functions can be realized. The proposed laparoscope had 100 times higher sensitivity than traditional laparoscopy, and it allowed one to work under illumination as low as 300 lux. The proposed laparoscope was inserted into the abdominal cavity of a pig. When zoomed out, the entire surgical field was within the field of view and the whole organ could be seen. When zoomed in, the details of blood vessels were visible to facilitate precise surgical operation [135] (figure 16).

A continuous 2×–3× optical zoom imaging system for a high-magnification medical probe was proposed by Qin *et al*. The proposed system consisted of two electrically controlled adaptive liquid lens groups and an imaging solid lens, as shown in figure 17(a). The image magnification can be varied without changing the object distance and imaging distance by appropriately adjusting the focal lengths of the two adaptive liquid lens groups. The two adaptive liquid lenses in the two adaptive liquid lens groups were Optotune EL-10-30-LD, whose focal lengths varied from 40 mm to 120 mm. To improve the imaging quality, several solid lenses were added to the optical zoom imaging system to reduce optical aberrations. (1) In the first adaptive liquid lens group, a plano-convex lens placed between the tunable lens and the beam splitter was used to provide adequate optical power and correct the spherical aberration to some extent. (2) In the second adaptive liquid lens

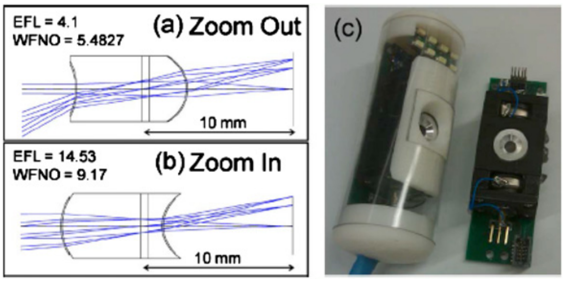

Figure 15. (a) Ray tracing of fluidic zoom lens zoom out. (b) Zoom in. (c) The fabricated zoom laparoscope. Reproduced from [135]. CC BY 4.0.

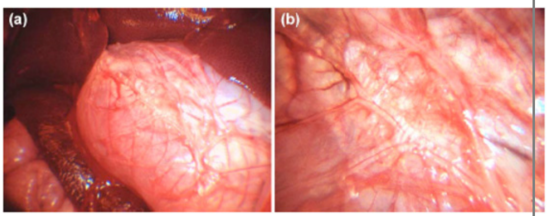

Figure 16. Images of the organ of a live pig taken from the optical zoom laparoscope. (a) The zoomed-out view and the entire stomach can be observed. (b) The zoomed-in view showing detailed information. Reproduced from [135]. CC BY 4.0.

group, a doublet was used to correct the chromatic aberration and sphere-chromatism. A plano-concave lens and a plano-convex lens were used to correct the field curvature and astigmatism in the imaging lens. The proposed optical zoom imaging system had an up to 3× zoom ratio with an 8.98 lp/mm resolution at a 120 mm working distance. The images of a bladder model at different zoom ratios are shown in figure 17(b) [136].

4.3. Telescope

The optical zoom of the traditional telescope is often realized by moving solid lens groups controlled by a cam. A pair of Alvarez lenses were used to design a telescope to reduce the large mechanical motions [137]. Two pairs of adjacent toroidal lenses were also employed to develop a zoomable telescope [138]. However, physical movement was still needed, which resulted in low reliability of the zoomable telescope system. Adaptive liquid lenses offer a promising solution to the development of a zoomable telescope. Valley *et al* developed a 4× zoom Galilean telescope lens consisting of two active flat liquid crystal diffractive lenses and two fixed refractive lenses, as depicted in figure 18. One fixed refractive solid lens was used to collimate entering light rays, and an object was placed on the front focal point of the fixed refractive lens. Another fixed refractive lens was placed behind another liquid crystal diffractive lens to focus the collimated emergent light rays onto a CCD image sensor. When there were no voltages applied to the two liquid crystal diffractive lenses, the object was imaged without magnification, as shown in figure 19(b). When two voltages were applied to the two liquid crystal diffractive lenses the resulting focal lengths of the two liquid crystal diffractive lenses were −50 cm and +100 cm, as shown in figure 18(a). The image was minified by a factor of 0.5× , as shown in figure 19(a). Similarly, when the two voltages applied to the two liquid crystal diffractive lenses were changed, the focal lengths were +100 cm and −50 cm, respectively (as shown in figure 18(b)), and the image was magnified by a factor of 2.0× , as shown in figure 19(c) [139].

4.4. Projector

To meet the requirements necessary for projection of an image of different sizes onto a screen, a zoom lens was needed. A traditional zoom projector lens consists of several optical elements, some of which are movable [140–142]. A scaled Fresnel diffraction method without a zoom lens was used to design a lensless zoomable holographic projector [143]. However, a complicated numerical calculation was needed. An active optical zoom projector system without mechanical moving parts was proposed by Wang *et al.* As shown in figure 20(a), the key optical part of the zoom projector mainly consisted of a solid lens, a liquid lens, and a spatial light modulator. The liquid lens was placed behind the spatial light modulator, and their distance was 20 cm. The aperture of the spatial light modulator was 3.5 mm. The focal lengths of the liquid lens and the spatial light modulator can be electrically tunable individually. The magnification of the proposed projector can be changed from 1/3 to 3/2 while keeping the image plane stationery by applying voltages to the liquid lens and spatial light modulator, as shown in figure 20(b). When the focal length of the spatial light modulator changed from 24 mm to 28 cm, the focal length of the liquid lens varied from 90 cm to 27.5 mm accordingly to keep the image plane stationary [144]. Lin *et al* demonstrated a 3.7× optical zoom holographic projection system using a combination of a liquid crystal lens and an encoded Fresnel lens on the liquid crystal on silicon (LCoS) panel. The zoom magnification is electrically adjusted by tuning the focal length of the liquid

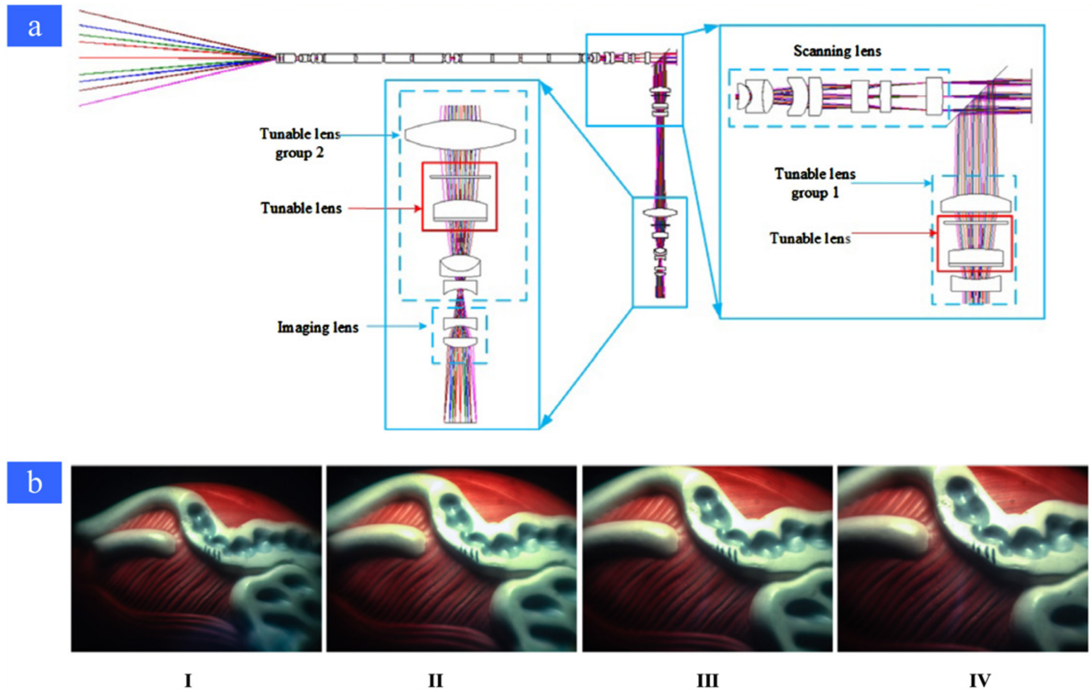

Figure 17. (a) The optical design layout of the continuous optical zoom imaging system for a high magnification probe. (b) Imaging of a bladder model at different zoom ratios: (I) 2×; (II) 2.33×; (III) 2.67×; (d) 3×. Reproduced with permission from [136].

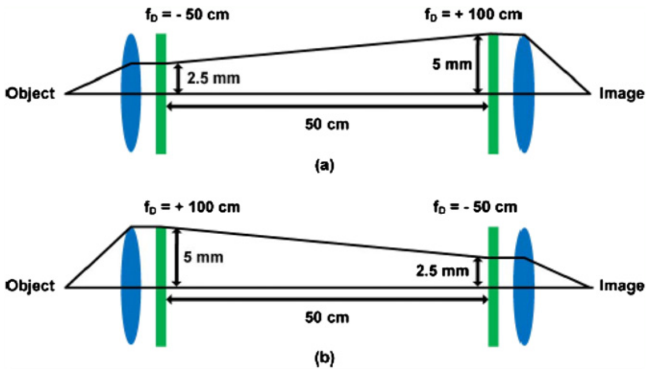

Figure 18. A schematic of a zoom Galilean telescope using two liquid crystal lenses. (a) Zoom out. (b) Zoom in. Reproduced with permission from [139].

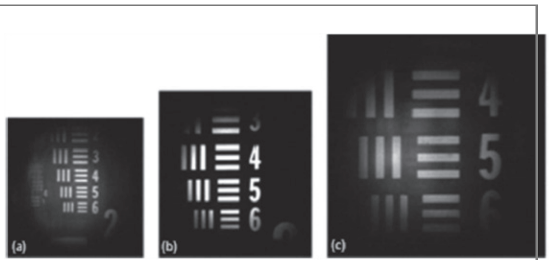

Figure 19. Zoom imaging results. (a) Zoom out (0.5×). (b) No zoom. (c) Zoom in (2.0×). Reproduced with permission from [139].

crystal lens and the encoded Fresnel lens. As shown in figure 20(c), the optical system consisted of a laser diode, a solid lens, a reflective LCoS panel with a Fresnel lens (LC-R 1080, HOLOEYE), a liquid crystal lens with a 2 mm aperture, and a projection lens. The magnification of the intermediate image depended on the focal lengths of the liquid crystal lens and the Fresnel lens. The focal length of the liquid crystal lens can be switched from infinity to 16 cm when the applied voltage is increased from 0 V to 120 V. The response time of the LC lens was around 1 s. The images of Bart Simpson produced by the proposed holographic projector using a liquid crystal lens with different zoom ratios are shown in figure 20(d) [145, 146]. A high-speed projection system with dynamic focal tracking technology based on a liquid lens was designed by Wang *et al.* The system consisted of three solid lenses, a high-speed adaptive liquid lens (EL-10-30, Optoune), a high-speed camera, and

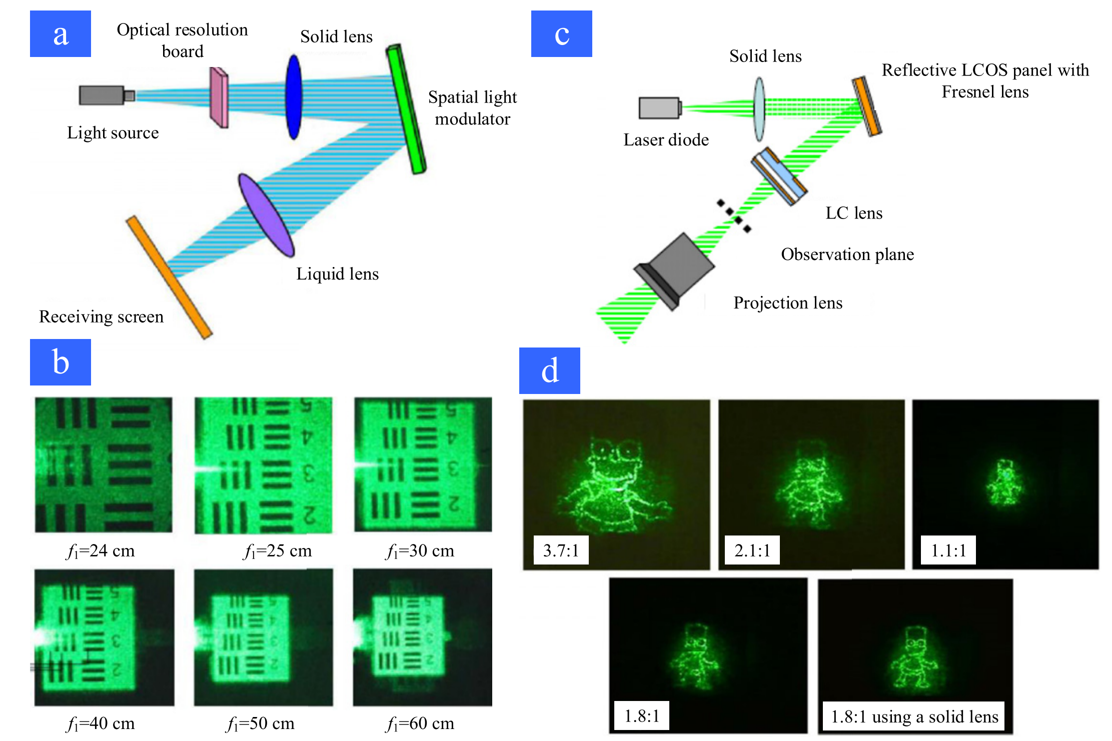

Figure 20. (a) The structure of the active optical zoom projector system. (b) Images of the object of different sizes on the screen. Reproduced with permission from [144]. (c) The structure of the proposed optical zoom holographic projector using a liquid crystal lens. (d) The images of Bart Simpson produced by the holographic projector using a liquid crystal lens with a zoom ratio of 3.7:1, 2.1:1, 1:1, and 1.8:1, and the image with a zoom ratio of 1.8:1 produced by the holographic projector using a solid lens. Reproduced with permission from [146].

a high-speed projector (LightCrafter 4500, TI DLP). The dynamic projection range varied from 0.5 m to 2.0 m. The optics system can control the adaptive liquid lens to modify the projection focal length to project a well-focused projection image [147–149].

Besides imaging systems, optical zoom using adaptive lenses can also be employed in other application areas, such as beam expanders [150, 151], holography displays [152–155], and so on.

5. Opportunities and challenges

Adaptive liquid lenses exhibit appealing features due to compact structure, tunable focal length, fast response speed, efficiency, and flexibility. They provide a powerful alternative to traditional solid lenses. Compared with the traditional solid lens with fixed focusing power, adaptive liquid lenses give a more flexible approach and are regarded to be the next-generation miniaturized optical lenses, especially suitable for those devices where installation space is constrained. They can enrich the optical zoom imaging technology and solve scientific problems of optical zoom imaging systems. This paper reviews the developments in optical zoom imaging systems using adaptive liquid lenses. Because adaptive liquid lenses are free from the physical displacement between optical elements, they can significantly reduce the number of moving groups and operation complexities of optical zoom imaging systems. According to the number of adaptive liquid lenses, we broadly divide the current optical zoom system using adaptive lenses into two categories: multiple adaptive liquid lenses, and a single adaptive liquid lens. Three different working principles (liquid crystal, polymer elastic membrane, and electrowetting effect) of adaptive liquid lenses employed in the optical zoom imaging system are represented in this review paper. Some representative optical zooming imaging applications using adaptive liquid lenses are introduced, such as consumer electronics, biomedical imaging, telescopes, and projectors. We present the opportunities for and challenges of the optical zoom system using adaptive lenses below.

From the aspect of the configuration of the optical zoom imaging system, the configuration that uses multiple adaptive liquid lenses is more popular compared with that which uses a single adaptive liquid lens. It has a large zoom ratio because of the existence of multiple adaptive liquid lenses. Moreover, several solid lenses can be added and the surface shape of the solid lenses can be optimized to correct some optical aberrations. Therefore, the image quality of the optical zoom imaging system is relatively high. However, the structure of the optical zoom imaging system based on this configuration is often complex and the cost is high because multiple adaptive liquid lenses are needed and each adaptive liquid lens usually requires an independently controlled actuation unit. Furthermore, a precious alignment between the multiple adaptive liquid lenses is required, which results in assembly difficulty. A synchronized actuation of multiple adaptive liquid lenses would be a concern for such a configuration. The calculation process for the surface shape of each adaptive liquid lens for the desired zoom ratio is complicated since every adaptive liquid lens has a tunable surface. For the configuration that uses a single adaptive liquid lens, it is structure compact. However, the manipulation of a single adaptive lens is complicated because at least two actuators need to be introduced synergistically. Moreover, such a configuration makes it difficult to achieve a continuous zoom ratio since there is only one adaptive liquid lens.

From the aspect of the working principles of the adaptive liquid lenses employed in the optical zoom imaging systems, such a system based on liquid crystal is shock-resistant and has good stability as well as low power consumption. It is suitable for an optical zoom imaging system where a small aperture of the adaptive liquid lenses is needed (less than 5 mm). However, the polarization dependence and the limited aperture are the main drawbacks of this principle, which cause low efficiency and low resolution. Moreover, there is the desire for liquid crystal lenses with a large aperture (more than 10 mm) and higher optical power to be developed and then employed in optical zoom imaging systems. Compared with liquid crystal lenses, elastomer–liquid lenses and electrowetting lenses are polarization independent. Moreover, they can provide a larger aperture while preserving a wider tunable focal length range. However, hydraulic and pneumatic actuators are often needed for adaptive liquid lenses based on a polymer elastic membrane. Therefore, optical zoom imaging systems based on this working principle may suffer from a bulky size and fluid leakage. The thickness of the polymer elastic membrane is often controlled at 50–100 μm because a thin polymer elastic membrane may result in the permeation of optical fluid. Moreover, the deflection of the polymer elastic membrane is often nonlinear and the surface profile of such adaptive lenses is not a standard spherical shape due to the edge effect and the gravity effect. Therefore, the imaging quality of the optical zoom imaging system using this actuation mechanism should be further improved. The gravity effect of the adaptive liquid lenses with a small aperture can be negligible for such an actuation mechanism when the deflection of the polymer elastic membrane is much smaller than the aperture of the adaptive lens. However, the influence of the gravity effect increases drastically as the aperture increases. Several methods have been proposed to reduce the gravity effect, including the use of a non-uniform thickness profile of the membrane [156], using elastic force instead of surface tension [116, 157], and mechanical-wetting [62]. The actuation mechanism of the electrowetting effect can realize optical zoom imaging with fast response speed because it is directly electrically controlled. The response time is highly correlated with the driving voltage, the aperture of the liquid lens, and the properties of the optical mediums (such as fluid viscosity and wetting hysteresis), and so on. Compared with the elastomer–liquid lenses, the electrowetting lenses are capable of generating a more smooth surface shape due to surface tension. Therefore, electrowetting lenses can provide higher optical quality of the optical zoom imaging systems. More importantly, the gravity effect of such an actuation mechanism can be weakened by using two optical mediums with matched densities. However, the driving voltage of the state-of-the-art electrowetting lenses is high (typically about 60 V) and the optical power is low as well as the aperture is limited, which restricts its further applications in optical zoom imaging.

Compared with the traditional optical zooming system based on solid lenses, the current optical zooming system using adaptive liquid lenses has little adequate imaging quality. The main reasons behind this issue may be listed as follows: (1) the tunable optical power of the adaptive liquid lens is often relatively small, with the result being that the dynamic range of the zoom ratio of the optical zoom imaging system is narrow. Therefore, it is difficult to compensate for the optical aberrations without compromising the miniaturization and the whole operating range of the refractive power of the adaptive lens. (2) An optimized aspherical surface is hard to obtain in adaptive liquid lenses. However, solid lenses with an aspherical surface are often used to correct optical aberrations. Several approaches have been proposed to achieve an aspherical surface for adaptive liquid lenses, including an inhomogeneous electric field [158], replacing one end of the adaptive liquid lens with an aspherical surface [159], and integration of an adaptive liquid lens with an aspherical lens [160]. (3) By choosing suitable optical liquids, some aberrations can be corrected and the optical performance can be improved. However, the number of known liquids that possess a suitable and certain combination of properties such as refractive index, Abbe number, transparency, and viscosity, is very limited. If more optical liquids are available, the range of correctable aberrations can be widened.

Moreover, although the size of the adaptive liquid lenses can be reduced to some extent, the space dimension of the actuation unit of the adaptive liquid lenses is relatively large. Some novel actuation units of small sizes are expected to be developed and then employed in optical zoom imaging systems for miniaturization. From the above analysis, there are some compromises made with regard to image quality, overall dimension, aperture, zoom range, response time, and cost in state-of-the-art optical zoom imaging systems using adaptive lenses. In conclusion, the optical zoom imaging system using adaptive liquid lenses needs to be greatly enhanced to make it suitable for a greater number and a wider range of applications. Fortunately, the rapid development in optofluidics and adjacent technologies makes it promising that these challenges will be overcome.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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