Design of high-performance adaptive objective lens with large optical depth scanning range for ultrabroad near infrared microscopic imaging

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Abstract: We report on the theory and design of adaptive objective lens for ultra broadband near infrared light imaging with large dynamic optical depth scanning range by using an embedded tunable lens, which can find wide applications in deep tissue biomedical imaging systems, such as confocal microscope, optical coherence tomography (OCT), two-photon microscopy, etc., both in vivo and ex vivo. This design is based on, but not limited to, a home-made prototype of liquid-filled membrane lens with a clear aperture of 8mm and the thickness of 2.55mm ~ 3.18mm. It is beneficial to have an adaptive objective lens which allows an extended depth scanning range larger than the focal length zoom range, since this will keep the magnification of the whole system, numerical aperture (NA), field of view (FOV), and resolution more consistent. To achieve this goal, a systematic theory is presented, for the first time to our acknowledgment, by inserting the varifocal lens in between a front and a back solid lens group. The designed objective has a compact size (10mm-diameter and 15mm-length), ultrabroad working bandwidth (760nm - 920nm), a large depth scanning range (7.36mm in air) — 1.533 times of focal length zoom range (4.8mm in air), and a FOV around 1mm × 1mm. Diffraction-limited performance can be achieved within this ultrabroad bandwidth through all the scanning depth (the resolution is 2.22 μm - 2.81 μm, calculated at the wavelength of 800nm with the NA of 0.214 - 0.171). The chromatic focal shift value is within the depth of focus (field). The chromatic difference in distortion is nearly zero and the maximum distortion is less than 0.05%.

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1. Introduction

Large depth scan is very important for both in vivo and ex vivo three dimensional (3D) volume imaging of bio-tissue. The most common examples of biomedical imaging instruments are confocal microscope [1,2], optical coherence tomography (OCT) [3–5], and two-photon microscope. In confocal microscope, light needs to be focused onto the specific layer of the tissue to which the pinhole is set conjugated for filtering out the scatter light from different out-of-focus layers. The depth scan is usually achieved mechanically by moving either the sample or the optics for refocusing. In the OCT system, a range of depth scan can be obtained either by moving the reference mirror (time domain), or by selecting the depth information spectrally (Fourier domain). The refocusing is also needed for selecting a zero delay line, where the sensitivity is the highest, and for imaging different volumes of interest.

Mechanical movement causes vibration and artifacts in live imaging. In addition, the traditional zooming or focusing systems are composed of several optical elements and some of these elements need to be moved. These systems tend to be bulky, complicated, expensive, and inconvenient to miniaturize. There is an urgent need nowadays for simpler, lighter, and more compact optical devices with faster zoom and without mechanical movement [6–13].

Adaptive liquid and liquid crystal lenses are two novel types of optical devices, which can change the focus without moving lenses. This character enables an optical zoom system with lower costs and complexity, a potential for miniaturization, and a faster adjustment [6–27]. Liquid crystal lenses [6, 24, 25] are based on tuning the refractive index using spatially variant electrical fields. Liquid lenses are based on changing the shape and thickness of the liquid(s) and mainly consist of electrowetting liquid lens [14, 18, 20–22] and liquid-filled membrane lens [15, 27–29]. Currently some of the liquid lenses are commercially available [31, 32]. The liquid lenses have wide applications in cameras, projectors, mobile phones [14, 17, 20], capsule endoscopes [22, 27], microscopes [33, 34], etc. In general, liquid lenses allow large tunable power range with a small applied voltage [e.g., 7–13].

The liquid-filled membrane lens changes focus dramatically by changing its shape. It suffers from aberrations (e.g. spherical aberration on axis), especially at a large numerical aperture (NA) value. The aberrations need to be compensated for high-performance imaging. Moreover, further reduction of its focal length may be needed in general microscopy. Thus a compound adaptive objective that combines several solid lenses with the liquid lens would be very useful and attractive in the field of microscopic imaging.

To accommodate the applications of such a compound adaptive objective lens in both confocal microscope and OCT imaging, it must provide high performance in broad bandwidth and even ultrabroad bandwidth for ultrahigh resolution OCT imaging. This is a challenging task. It is also beneficial to have an adaptive objective lens which allows an extended depth scanning range that is larger than the focal length zoom range, since this will keep the magnification of the whole system, NA, field of view (FOV), and resolution more consistent.

The purpose of this paper is to present a general theory and a method for the design of a compact adaptive compound objective lens for ultrabroad bandwidth, deep penetration and large depth scan with high resolution using liquid lens as zooming mechanism. A ~0.2 NA is preferred to achieve a decent image quality and a long working distance. The NIR wavelength is preferred since it has more penetration in the tissue due to the water abortion window [35]. This objective is designed to use in both confocal microscope (narrow waveband, e.g. 800nm), and OCT system (ultrabroad band, e.g. 760nm - 920nm). The aberrations (e.g. spherical aberration, coma, etc.) arise from the change of the shape of the liquid lens should be minimized for the whole zooming range, and the chromatic aberration also needs to be compensated.

This paper is organized as follows. Section 2 introduces the prototype liquid-filled membrane lens in our lab. Section 3 introduces the theory for the design of an adaptive objective lens with larger optical depth scanning range than focal length zoom range. Section
4 shows a design example of the high-performance objective lens with large optical depth scanning for ultrabroad bandwidth. Conclusions and discussions are given in the last section.

2. Home-made liquid-filled membrane lens prototype

One of the key components in this adaptive optical scanning objective is the liquid lens. Here we use a home-made plano-convex liquid-filled membrane lens as an example. It is driven by electromagnetic force and the applied voltage is less than 8 volts. The tunable power (inverse of the focal length which is measured in meter) can be more than 100 diopter (D). The power tuning mechanism is hydro pressure on a large deformable elastomer membrane containing transparent liquid. One of these large deformable elastomers is polydimethylsiloxane (PDMS). PDMS is a thermos curable elastomer whose Young’s modulus is 750 kPa, only 1/250 times that of silicon. Thus, its membrane can be deformed more compared to other conventional membranes such as silicon oxide and silicon nitride [28]. The details of our home-made liquid lens are described previously [6–13].

As shown in Figs. 1(a)-1(b), this liquid lens is mainly made of three layers in which the liquid is enclosed. The acrylic base substrate in the middle layer defines the locations and sizes of both the reservoir and the lens. The reservoir has a diameter of 15mm while the lens has a diameter of 10mm; the center distance between them is 20mm. There is a small channel between the reservoir and the lens for liquid transmission and also an injection port in the reservoir side for injecting liquid. The diameter of these two channels is 0.75mm. The soda lime float back glass on bottom provides flat surface for both the reservoir and the lens. The PDMS membranes on top of reservoir and lens provide the flexibility to deform the surface. The PDMS membranes are made by molding and heating the liquid PDMS material. The flatness and de-bubbles must be guaranteed to keep the best performance. The thickness of PDMS membranes for the reservoir and the lens are 1.2mm and 0.5mm respectively.

![Fig. 1. Working principle of the liquid-filled membrane lens.](image)

The working principle of the liquid lens is shown in Fig. 1(c). While the reservoir gets stimuli from the pressure on top of its membrane, the liquid is squeezed from the reservoir chamber into the lens chamber through the channel between them. Then the membrane surface of the lens is reacted accordingly to acquire the change of focus. The clear aperture of the lens is ~8mm and the total aperture is around 10mm. The total thickness of this liquid lens is only 2.55mm when the membrane is flat. The tunable power range of 0-20D of the liquid lens is considered in this paper for the design of the compound adaptive lens since this is a more accessible range with good quality, as well as it already provides a large depth scanning.

Compared with the traditional zoom lens that changes focus by lens displacement, the liquid lens provides a larger range of tunable power and is more compact. However, a single liquid lens has a plano-convex shape which suffers from aberrations (e.g. spherical aberration on axis) at a big NA value that need to be compensated when high optical performance is required. Besides, even the 50 mm focal length (corresponding to 20D in power) is still much bigger than the requirement of the general microscope. To have better optical performance and smaller focal length range, a group of solid lenses are required to be paired with this liquid lens.
3. Design philosophy

3.1 Liquid lens geometrical optics

The geometry of this plano-convex liquid lens is shown in Fig. 2(a) as well as its two principal planes. The principal planes of a lens system are the presumed planes at which all the refraction happens. In this case, one of its principal planes is located at the vertex of the membrane and the other is located at the junction between the membrane and the substrate. The power of the lens can be calculated based on the radius (r) of the membrane and the refractive index n [36, 37]

\[ P_{\text{liquid}} = \frac{n-1}{r} \]  

(1)

If the aperture is D, and the distance between the two principal planes is \( \Delta t \) (\( \Delta t \) is in the range 0 - T), we have

\[ r = \frac{\Delta t}{2} + \frac{D^2}{8\Delta t} \]  

(2)

Substituting Eq. (2) into Eq. (1), we can get

\[ P_{\text{liquid}}(\Delta t) = \frac{8(n-1)\Delta t}{4\Delta t^2 + D^2} \]  

(3)

When membrane side faces the front, its front principal is shifted during refocusing, as shown in Fig. 2(a); when the membrane side faces the back, its back principal is shifted during refocusing, as shown in Fig. 2(b); the shift is equal to the change of the center distance.

Fig. 2. Schematic of liquid lens. (a) shows the geometry of liquid lens with aperture “D”, principal planes’ distance “\( \Delta t \)” (0 - T), and radius of membrane surface “r”. While the power of liquid lens changes, the front principal plane in (a) and back principal plane in (b) are shifted accordingly.

3.2 Initialization of the model for the compound adaptive objective lens

To have an objective with larger NA (smaller focal length under the same entrance pupil size) and higher image quality than single liquid lens, we need to combine this liquid lens with other solid optics.

In the initial model, we simply use two positive lenses as this solid optics, as shown in Fig. 3(a). There are three potential locations to insert the liquid lens: in front of the first lens, in between the two lenses, and behind the second lens. The preference is as follows. The first position (in front of the first lens) is the best position considering the aberration correction since it is the nearest location to the pupil plane (or can be the pupil plane). However, additional protection glass is needed at this position. The second position (between the two lenses) is close to the best aberration correction location. The first lens can be used as the protective lens so that no additional protection glass is needed. Furthermore, the first positive lens converges the incident beam and thus the size of the beam onto the liquid lens is reduced, allowing the center area with better imaging quality to be used at this location. The third
position is the worst option because it is farthest from pupil and is the location nearest to the sample, making it vulnerable to contamination.

Thus, we choose the second position to insert the liquid lens. The membrane side is placed towards the front group. This arrangement guarantees less spherical aberration generated by the curved side, as shown in Fig. 3(b).

To further reduce the aberrations, a simple positive lens for each group may not be enough. We may need to use the lens group instead. So, we call the optics before the liquid lens as the front group and the optics after liquid lens as the back group.

3.3 Power distribution in the front and the back lens groups

We insert the liquid lens between a front group and a back group, as shown in Fig. 4, which uses principal planes to represent the lens or the lens group. The solid lines indicate the front principal planes while the dashed lines indicate the back principal planes. \( L \) is the total length of the objective from its first surface to the last surface, which is preferred to be smaller for a compact design. \( d_{\text{front}} \) is the distance between the first surface of the objective to the front principal plane of the front group, \( d_{\text{back}} \) is the distance between the back principal plane of the back group and the last surface of the objective. \( t_1, \Delta t, \) and \( t_2 \) are the thicknesses of the principal planes of the front group, the liquid lens, and the back group respectively, where \( \Delta t \) changes in the range of 0 - \( T \). When \( \Delta t = 0 \), the liquid lens is flat; when \( \Delta t = T \), it has the maximum curvature. \( d_1(\Delta t) \) and \( d_2(\Delta t) \) are the distances between the principal planes of the two neighboring lens group. \( P_1, P_{\text{liquid}}(\Delta t), \) and \( P_2 \) are the power of the front group, the liquid lens, and the back group, respectively. \( h_1, h_{\text{liquid}}(\Delta t), \) and \( h_2(\Delta t) \) are the heights of incident rays.
at each group. $F_{\text{m}}(\Delta t)$ is the working distance. $F(\Delta t)$ is the total focal length and $P(\Delta t)$ is the total power of the objective, $F(\Delta t) = 1/P(\Delta t)$. $F(\Delta t)$, $P(\Delta t)$, $P_{\text{liquid}}(\Delta t)$, $h_{\text{liquid}}(\Delta t)$, $h_2(\Delta t)$, $d_1(\Delta t)$, $d_2(\Delta t)$ and $F_{\text{m}}(\Delta t)$ are a function of $\Delta t$ ($0 \leq \Delta t \leq T$). Since a compact system is desired, there is no focusing inside this system. Assuming $h_1 > 0$, then $h_{\text{liquid}}(\Delta t) > 0$, $h_2(\Delta t) > 0$.

For an incident ray parallel to the axis on the first element, we have Eq. (4) to calculate the total power $P(\Delta t)$ for the system [36, 37]

$$P(\Delta t) = P_1 + \frac{h_{\text{liquid}}(\Delta t)}{h_1} \cdot P_{\text{liquid}}(\Delta t) + \frac{h_2(\Delta t)}{h_1} P_2,$$  \hfill (4)

where

$$\frac{h_{\text{liquid}}(\Delta t)}{h_1} = 1 - d_1(\Delta t) \cdot P_1,$$  \hfill (5)

and

$$\frac{h_2(\Delta t)}{h_1} = \frac{h_{\text{liquid}}(\Delta t)}{h_1} \cdot \frac{h_2(\Delta t)}{h_{\text{liquid}}(\Delta t)} = [1 - d_1(\Delta t) \cdot P_1] \cdot [1 - \frac{d_2(\Delta t)}{P_1 + [1 - d_1(\Delta t) \cdot P_1]}].$$  \hfill (6)

When the membrane of the liquid lens faces the front group, the front principal plane is shifted while the back principal plane is fixed during zooming. We have

$$\begin{cases}
    d_1(\Delta t) = d_1(0) - \Delta t, \\
    d_2(\Delta t) = d_2(0).
\end{cases}$$  \hfill (7)

When the membrane of the liquid lens faces the back group, the front principal plane is fixed while the back principal plane is shifted during zooming. We have

$$\begin{cases}
    d_1(\Delta t) = d_1(0), \\
    d_2(\Delta t) = d_2(0) - \Delta t.
\end{cases}$$  \hfill (8)

Let’s choose the configuration that the membrane of the liquid lens faces the front group and substitute Eqs. (5)-(7) into Eq. (4), then we can obtain the function for the total power $P(\Delta t)$, which is dependent on the power of the front group $P_1$ and that of the back group $P_2$, the distances between the lens groups $d_1(0)$ and $d_2(0)$, and the liquid lens parameters: refractive index $n$, aperture $D$, and the thickness $\Delta t$ ($0 \leq \Delta t \leq T$). When $\Delta t$ equals to 0 or $T$, the total power of the objective is expressed as $P(0)$ or $P(T)$, respectively, as in Eqs. (9) and (10):

$$P(0) = P_1 + [1 - (d_1(0) + d_2(0)) \cdot P_1] \cdot P_2. \hfill (9)$$

$P(0)$ is the lowest power (corresponding to the longest focal length) in the zoom range. Since the power of liquid lens $P_{\text{liquid}}(0) = 0$, we can assess its value using $P_1$, $P_2$, $d_1(0)$ and $d_2(0)$. If $P_1 > 0$, and $d_1(0) + d_2(0) > 0$, we can estimate that $P(0) < P_1 + P_2$. For $P(T)$, we have

$$P(T) = P_1 + [1 - d_1(0)] \cdot P_{\text{liquid}}(T)$$

$$+ [1 - d_1(0) \cdot P_1] \cdot \left[1 - \frac{d_2(0) - T}{1 - d_1(0) \cdot P_1}\right] \cdot P_2. \hfill (10)$$

$P(T)$ can be used to estimate the highest power (corresponding to the shortest focal length) in the zoom range. The power zoom range $\Delta P_{\text{max}} = P(T) - P(0)$ can be estimated as follows.
\[ \Delta P_{\text{max}} = P(T) - P(0) \]
\[ = [1 - d_1(0) \cdot P_1] \cdot \{P_{\text{liquid}}(T) + \frac{d_2(0) \cdot P_1}{1 - d_1(0) \cdot P_1} \cdot P_2 - \frac{d_2(0) - T}{1 - d_1(0) \cdot P_1} \cdot P_1 \}. \] \tag{11}

Since \( T \) is a small value, we can assume
\[ \frac{d_2(0) - T}{1 - d_1(0) \cdot P_1} \approx \frac{d_2(0)}{1 - d_1(0) \cdot P_1}. \] \tag{12}

In this case, we can simplify Eq. (11) as in Eq. (13):
\[ \Delta P_{\text{max}} = [1 - d_1(0) \cdot P_1][1 - d_2(0) \cdot P_1] \cdot P_{\text{liquid}}(T). \] \tag{13}

Equation (13) gives a direct approximation of the power zoom range. Under the given power and distances of the front group and the back group, if \( P_1 > 0, P_2 > 0, d_1(0) > 0, d_2(0) > 0 \), when \( d_1(0) \) and \( d_2(0) \) are increased, the power zoom range \( \Delta P_{\text{max}} \) is decreased.

3.4 Design with the depth scanning range larger than the focal length zoom range

The focal length zoom range of the compound objective lens \( \Delta F_{\text{max}} \) is defined as
\[ \Delta F_{\text{max}} = \frac{1}{P(0)} - \frac{1}{P(T)}. \] \tag{14}

It should be noted that different scanning depth is achieved by changing the focusing power (or the focal length) of the compound objective lens. However, due to the shift of the back principal plane of the objective lens during zoom, the depth scanning range is not equal to the zoom range of the focal length. Instead it equals to the amount of the change of the working distance, which is defined as the distance between the last surface and the focal point. The working distance \( F_b(\Delta t) \) can be calculated as
\[ F_b(\Delta t) = \frac{h_1(\Delta t)}{h_1} \cdot \frac{1}{P(\Delta t)} - d_{\text{back}}. \] \tag{15}

Then the depth scanning range can be expressed by
\[ \Delta F_{b(\text{max})} = F_b(0) - F_b(T) = \frac{h_1(\Delta t)}{h_1} \cdot \frac{1}{P(0)} - \frac{h_1(T)}{h_1} \cdot \frac{1}{P(T)}. \] \tag{16}

where
\[ \begin{bmatrix} \frac{h_1(0)}{h_1} \\ \frac{h_1(T)}{h_1} \end{bmatrix} = \left[ I - [(d_1(0) + d_2(0)) \cdot P_1] \right] \begin{bmatrix} 1 - d_1(0) \cdot P_1 & \frac{d_2(0) - T}{1 - d_1(0) \cdot P_1} \\ \frac{d_2(0) - T}{1 - d_1(0) \cdot P_1} & \frac{d_2(0) - T}{1 - d_1(0) \cdot P_1} \end{bmatrix} \begin{bmatrix} 1 - d_1(0) \cdot P_1 & \frac{d_2(0) - T}{1 - d_1(0) \cdot P_1} \\ \frac{d_2(0) - T}{1 - d_1(0) \cdot P_1} & \frac{d_2(0) - T}{1 - d_1(0) \cdot P_1} \end{bmatrix}^{-1}. \] \tag{17}

Comparing Eq. (14) with Eq. (16), we have
If we expect the depth scanning range to be larger than the focal zooming range, the following criteria needs to be met:

\[
\left[1 - \frac{h_1(T)}{h_1}\right] \cdot P(0) - \left[1 - \frac{h_1(0)}{h_1}\right] \cdot P(T) > 0.
\]

Substituting Eqs. (9)-(13) and Eq. (17) into Eq. (19), we have

\[
\left[1 - \frac{h_1(T)}{h_1}\right] \cdot P(0) - \left[1 - \frac{h_1(0)}{h_1}\right] \cdot P(T) = \left[1 - d_1(0) \cdot P_1\right] \cdot \left[d_2(0) \cdot P_2 - d_1(0) \cdot P_1\right] \cdot P_{\text{liquid}}(T).
\]

By checking Eq. (20), two solutions, expressed in Eq. (21) or Eq. (22), exist for Eq. (19):

\[
\begin{cases}
    d_1(0) < \frac{1}{P_1}, \\
    d_2(0) > \frac{P_1}{P_2} \cdot d_1(0),
\end{cases}
\tag{21}
\]

or

\[
\begin{cases}
    d_1(0) > \frac{1}{P_1}, \\
    d_2(0) < \frac{P_1}{P_2} \cdot d_1(0).
\end{cases}
\tag{22}
\]

The distance $1/P_1$ is the focal length of the front group. In order to have a compact objective lens, it is preferred not to have focusing inside the compound lens, which means $d_1(0) < 1/P_1$. Therefore, Eq. (21) can be adopted as the design criteria to achieve the goal of larger depth scanning range than the focal zooming range. From Eq. (20), we can also notice that, for the fixed values of $P_1$, $P_2$, and $P_{\text{liquid}}(T)$, if the product of $d_1(0)$ and $P_1$ is reduced while the product of $d_2(0)$ and $P_2$ is increased, the difference between scanning depth and focal zoom range can be further increased.

### 3.5 Initialization of the parameters before optimization

To summarize, based on the model we established, the general guidelines for the design of an adaptive objective lens with large optical depth scanning range are as follows:

1. The adaptive singlet lens is inserted in between the solid front group and the back group. The entrance pupil is in the front surface of the front group. The front group is used to protect the liquid lens from pollution. The liquid lens is positioned as near as possible to the entrance pupil and its membrane side towards the front group to reduce the spherical aberration.

2. To make the liquid lens as closer as possible to the entrance pupil, the front group needs to be simple in structure. So a singlet with a relative small value of power ($P_1$) is preferred. To meet the tunable range of the total power, $P(0) - P(T)$, as described in Eqs. (9)-(13), it is necessary to have a relatively large value of $P_2$ (the power of the...
back group). Furthermore, when taking aberration correction into account, it is better to have more than two lenses for the back group.

(3) To design the objective with the depth scanning range larger than the focal zoom range, the geometric parameters should be chosen based on Eq. (21). Generally speaking, a relatively smaller $d_1(0)$ and a relatively bigger $d_2(0)$ are preferred under the constraints of the total length $(L)$ and the fact that a relatively smaller power $P_1$ and a relatively bigger power $P_2$ are desired for the total power requirement.

Based on the above equations and analysis, we can assign the initial values and estimate the initial power distributions of the front and the back group, the possible focal zoom range, and also the depth scanning range before optimization. In the situation of $n = 1.41$ and $P_{\text{liquid}}(T) = 20\text{D}$, the maximum thickness of the liquid lens can be calculated as $T = 0.62\text{mm}$ based on Eq. (3). If the entrance pupil is $8\text{mm}$ in diameter (the total aperture $D$ of the lens assumed to be $10\text{mm}$), which equals to the clear aperture of the liquid lens, the center focal length is selected to be $\sim 20\text{mm}$, corresponding to the power of $50$ diopter. In this situation, the NA is $0.196$, and a resolution of $2.44\ \mu\text{m}$ can be obtained at the wavelength of $800\text{nm}$.

For example, let $P_1 = 15\text{D}$, $P_2 = 35\text{D}$, $d_1(0) = 2\text{mm}$, $d_2(0) = 13\text{mm}$. We can get the total power $P(0) = 42.13\text{D}$, and $P(T) = 53.12\text{D}$ with a total power tunable range of about $11\text{D}$. The corresponding focal length (measured from the back principal plane as defined above) is $18.82\text{mm} - 23.74\text{mm}$ with a $4.92\text{mm}$ focal zooming range. The depth scanning range (working distance change) is $7.67\text{mm}$. Further optimization is needed based on, but not limited by, this initial model to balance all the aberrations as well as to provide a compact configuration.

4. Design example of a tunable objective adapted to a 7.36mm depth scanning range

The initial model was optimized using Zemax optical design software (Zemax, LLC), which is based on a damped least square algorithm. The layout of the design example is shown in Fig. 5, which includes the front group, the liquid lens, and the back group. Each surface is numbered accordingly. To reduce the aberrations of each surface and the whole system, a doublet lens and two singlets are used at the back group. While the power of the liquid lens is changed, the working distance is changed correspondingly to provide a large depth scan.

![Fig. 5. Layout of the optical depth-scanning objective implemented with a focal tunable liquid lens, which includes front group, liquid lens and back group. Each surface is numbered accordingly.](image-url)
The zooming relation between the liquid lens and the whole objective lens is shown in Figs. 6(a)-6(b); they have an approximately linear relation in terms of the power change. The specifications of this design example are shown in Table 1, where six configurations are illustrated. The resolution is calculated at 800 nm, a typical wavelength for near infrared imaging. The overall length of this optical depth-scanning objective is 15mm (from surface #1 to surface #14). The entrance pupil is located at the front group, which has an aperture of 8mm. The angular field of view is designed as ± 2°, and the corresponding area in the focal plane is around 1 mm × 1 mm, which is the field of view of the object in practical applications. While the power of the liquid lens is tuned from 20.07 D to 0 D, the focal length of the lens system is varied from 18.2mm to 23mm, corresponding to a 4.8mm focal length zoom range. The working distance of the system is changed from 14.685mm to 22.045mm, giving a depth scan range of 7.36mm. The linear relation between the focal length change and the working distance change is shown in Fig. 6(c). This design guarantees an extended depth scan up to 1.533 times of focal zoom range, as well as keeps the magnification of the whole system, NA, field of view, and resolution more consistent, since these parameters are directly related to the change of focal length. When the depth scanning range is small (e.g., 1mm or less), the imaging performance of the lens system is almost a constant. When the depth scanning range is large, the imaging performance needs to be further calibrated as a function of the focusing depth. For the full depth scanning range (7.36 mm), the image height (field of view of the objects to be imaged) varies from 0.90mm × 0.90mm to 1.14mm × 1.14mm, NA varies from 0.214 to 0.171, and the resolution changes from 2.22 μm to 2.81 μm (calculated at the wavelength of 800nm).

**Table 1. Specification of the optical dept-scanning objective**

| Config. | Wavelength (nm) | Overall Length (mm) | Entrance pupil size (mm) | FOV (°) | FOV (mm × mm) | Power of liquid lens (D) | Focal length (mm) | Working distance (mm) | NA | Resolution (µm) *
|---------|-----------------|---------------------|--------------------------|--------|---------------|-------------------------|------------------|-----------------------|----|-------------------|
| 1       | 760–920         |                     |                          | ± 2    | 0.90 × 0.90   | 20.035                  | 18.2             | 14.685                | 0.214 | 2.22              |
| 2       |                 | 15                  | 8                        |        | 0.94 × 0.94   | 15.932                  | 19               | 15.955                | 0.205 | 2.32              |
| 3       |                 |                     |                          |        | 0.99 × 0.99   | 11.305                  | 20               | 17.511                | 0.196 | 2.44              |
| 4       |                 |                     |                          |        | 1.04 × 1.04   | 7.151                   | 21               | 19.041                | 0.187 | 2.56              |
| 5       |                 |                     |                          |        | 1.09 × 1.09   | 3.402                   | 22               | 20.551                | 0.179 | 2.69              |
| 6       |                 |                     |                          |        | 1.14 × 1.14  | 0                      | 23               | 22.045                | 0.171 | 2.81              |

*Calculated at wavelength of 800nm
The general parameters of the design example are shown in Table 2 (when the power of the liquid lens is zero) and the corresponding zoom parameters are shown in Table 3. We set an ideal reference at surface 3 during the optimization period, which keeps the overall length constant while zooming. The distance between the reference and the back surface of the liquid lens (back glass) is 4mm. Since the membrane is very thin (0.5mm), the thickness change is negligible during zoom. The thickness of the liquid lens is varied from 3.18mm (most curved) to 2.55mm (flat), and the maximum change in thickness is 0.63mm.

Figure 7 shows the chromatic focal shift in the wavelength range 760 ~ 920 nm, referenced at the center wavelength 840nm. Depth of focus of an imaging lens is defined as
\[ \text{DOF} = \pm \frac{\lambda}{2NA^2}. \]

We can use the wavelengths 760nm and 920nm to estimate the depth of focus in this ultra broadband as:
\[ \text{DOF}_{\text{broadband}} = -\frac{\lambda_{760}}{2NA^2} \approx +\frac{\lambda_{920}}{2NA^2}. \]

For the six configurations, the depths of focus is
\[ -8.30 \mu m \sim 10.05 \mu m, \]
\[ -9.04 \mu m \sim 10.95 \mu m, \]
\[ -10.87 \mu m \sim 13.16 \mu m, \]
\[ 11.86 \mu m \sim 14.36 \mu m, \]
\[ 13.00 \mu m \sim 15.73 \mu m, \]
\[ \text{respectively}; \]
while the chromatic chromatic focal shift value is
\[ -10.0 \mu m \sim 11.7 \mu m, \]
\[ -7.8 \mu m \sim 10.5 \mu m, \]
\[ -4.8 \mu m \sim 9.0 \mu m, \]
\[ -1.6 \mu m \sim 7.3 \mu m, \]
\[ 1.7 \mu m \sim 5.4 \mu m, \]
\[ 0 \mu m \sim 5.4 \mu m, \]
\[ \text{respectively}. \]

Comparing the chromatic focal shift value with depth of focus, we can conclude that, only in Config. 1, the maximum chromatic shift is slightly bigger than the depth of focus, but the difference is negligible. In all the other configurations, the maximum chromatic shift is much smaller than the depth of focus. So we can claim that the chromatic focal shift value is within the depth of focus of this broadband compound objective lens.

**Table 2. General parameters of the system (when liquid lens surface is flat)**

| Surface# | Comment       | Radius | Thickness | Material (index: Abbe No.) | Semi-Diameter |
|----------|---------------|--------|-----------|----------------------------|---------------|
| 1 (Stop) | Front group   | 22.255 | 1.5       | N-LAK34(1.73:54.5)         | 4.5           |
| 2        |               | 37.940 | 1.569     |                            | 4             |
| 3        | Reference     | Infinity | 1.450*    |                            |               |
| 4        | Liquid lens   | Infinity* | 0.5       | PDMS (1.40:40.6)           | 5             |
| 5        |               | Infinity* | 1.5*      | Liquid (1.47:54.6)         | 5             |
| 6        |               | Infinity | 0.55      | Soda lime (1.52:59.29)     | 5             |
| 7        |               | Infinity | 2.00      |                            |               |
| 8        | Back group    | -8.807 | 1.00      | N-SF6 (1.81:25.4)          | 4             |
| 9        |               | 209.455| 2.228     | N-BAK1 (1.57:57.5)         | 4.5           |
| 10       |               | -8.768 | 0.1       |                            |               |
| 11       |               | 121.210| 1.257     | N-LASF31 (1.88:41.0)       | 5             |
| 12       |               | -56.860| 0.1       |                            |               |
| 13       |               | 24.438 | 1.247     | N-LASF31(1.88:41.0)        | 5             |
| 14       |               | 59.538 | 22.045*   |                            |               |

*Zoom parameters

**Table 3. Zoom parameters of the system**

| Surface# | Config. 1 | Config. 2 | Config. 3 | Config. 4 | Config. 5 | Config. 6 |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Radius   | 4         | 20.158    | 25.350    | 35.729    | 56.481    | 118.734   | Infinity  |
| Radius   | 5         | 20.158    | 25.350    | 35.729    | 56.481    | 118.734   | Infinity  |
| Thickness| 3         | 0.820     | 0.952     | 1.098     | 1.228     | 1.345     | 1.450     |
| Thickness| 5         | 2.130     | 1.998     | 1.852     | 1.722     | 1.605     | 1.500     |
| Thickness| 14        | 14.685    | 15.955    | 17.511    | 19.041    | 20.551    | 22.045    |

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Figure 8 shows the spot diagrams for these configurations. For the same field, the spot patterns for different wavelengths are indicated by different colors. Four representative wavelengths, i.e., 760nm, 800nm, 840nm, and 920nm, are analyzed. These spots are scaled using the Airy disc at 800 nm (dark circle), whose radius is equal to $1.22\lambda/(2NA)$ for a circular, uniformly illuminated entrance pupil. Based on the Rayleigh criterion, the radius of the Airy disc equals to the minimum resolvable detail (diffraction-limited resolution), when the first diffraction minima of the image of one point source coincides with the maxima of another. If all the rays are well within the Airy disk, then the system is often said to be diffraction-limited. In Configs. 1 - 6, the radii of the Airy disc (diffraction-limited resolution at 800 nm) are 2.22 µm, 2.32 µm, 2.44 µm, 2.56 µm, 2.69 µm, and 2.81 µm, respectively. In Fig. 8(a), the spot size at 920 nm is just slightly larger than the Airy disc at 800 nm due to the chromatic focal shift, but it is still within the Airy disc calculated at 920 nm, which is 2.55 µm. In Figs. 8(b)-8(f), all the spots at different wavelengths, fields, are within the Airy disc calculated at 800 nm and we also verified that for wavelengths shorter than 800nm, the spots are within the corresponding Airy disc, indicating the diffraction-limited performance has been achieved for all the wavelengths, all the fields, and all the configurations.

![Fig. 8. Spot diagram of different configurations. (a) ~ (f): Configs. 1-6. Different colors indicates different selected wavelengths. The black circles are the Airy discs at 800nm under the corresponding NAs of the Configs. 1-6.](image)

Figure 9 shows the polychromatic diffraction modulation transfer function (MTF) curves for each configuration. MTF is the modulation as a function of spatial frequency for a sine
wave object. The MTF for a particular frequency is described as: $MTF = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{mid}})$, with $I_{\text{max}}$ and $I_{\text{min}}$ representing the highest and the lowest luminance. The light source is assumed to have a uniform spectrum in the broad wavelength range of 760 – 920 nm. Within the same bandwidth, the cut-off frequency of each configuration is determined by its numerical aperture. The MTF curves for different fields are all very close to the diffraction-limited cases, which clearly demonstrates this tunable compound objective lens enables excellent image quality over a broad range of spatial frequencies in these configurations. We also evaluated the performance at the frequency of 250 cycles/mm. The MTFs for all the fields of view at 250 cycles/mm are above 0.26, 0.28, 0.29, 0.28, 0.26, 0.24, respectively, for all the six configurations.

Figure 10 evaluates the relative distortion, which means the error in percentage of the image height across the whole field. Figure 10(a) calculates the relative distortion difference in the ultrabroad bandwidth from 760nm to 920nm. The maximum difference is only ~0.00007%. Therefore, we can claim that there is no chromatic difference in distortion. Figure 10(b) shows the relative distortion at wavelength of 800nm. Since there is no chromatic difference in distortion, Fig. 10(b) also shows the relative distortion at all the wavelengths from 760nm to 920nm. The distortion patterns for all the configurations are very similar and their differences are also negligible. The maximum distortion across the whole field is only 0.05%, which means there is no need to do any distortion calibration during post image processing and quantification.

![MTF curves for different configurations](image)

Fig. 9. Polychromatic Diffraction MTF of different configurations. (a) –(f): Configs. 1 - 6.
Fig. 10. Relative distortion. (a) Relative distortion difference at wavelength between 760nm and 920nm in Configs. 1 - 6. (b) Relative distortion calculated at wavelength of 800nm in Configs. 1 - 6.

5. Conclusion and discussion

The use of a liquid lens as a zooming mechanism into the dynamic objective can provide an efficient, compact, and cost-effective solution to construct biomedical imaging instruments. In this paper, we have presented, for the first time to our acknowledgment, a systematic theory to extend the depth scanning to a range that is larger than the focal length zoom range by inserting the liquid lens into a front and a back solid lens group. Then we have demonstrated a design example which has a compact size (10mm-diameter and 15mm-length), ultrabroad working bandwidth (760nm ~920nm), a large depth scanning range (7.36mm, calculated in air), and a field of view around 1mm × 1mm. Diffraction-limited performance can be achieved within this ultrabroad wave bandwidth in all scanning depth (the resolution is 2.22 μm ~2.81 μm, calculated at the wavelength of 800nm with the numerical number of 0.214 ~0.171). The chromatic difference in distortion is nearly zero and the maximum distortion is less than 0.05%.

There are also several other considerations about the design:

(1) This paper aims to provide a theory for the design of a liquid lens based high-performance adaptive objective lens with a large scan depth. For this purpose, a more general type of liquid lens is preferred which is only specified by its geometric optics properties, such as its diameter, thickness, curvature, and refractive index. Other non geometric optics related aspects, such as the actuation method and speed, are not considered in this paper. These aspects are very important for specific applications. Although the theory is deduced through the use of the liquid-filled membrane lens, the analysis method is robust and can be an excellent reference if other types of varifocal lens (e.g., liquid crystal lenses) are chosen.

The prototype of our home-made liquid-filled membrane lens is used only as an example to demonstrate the theory and the procedure of the design. The liquid lens presented in this paper is much thinner than the Optotune EL-10-30 and EL-10-30-C Series [32]. The thickness of our lens is 2.55mm ~3.18mm, while the thickness for EL-10-30 and EL-10-30-C Series is 9.7mm and 20.7mm respectively due to the size of their mechanical mounts. Our home-made liquid lens allows the whole compound adaptive objective lens with a compact size (10 mm-diameter and 15mm-length). One can easily use the commercial lenses instead to perform the similar design using the method presented in this paper.

(2) The theory is deduced by inserting the liquid lens in between the front and back solid lens groups. However, Eqs. (1)-(22) are also applicable when the liquid lens is inserted at other positions. If the liquid lens is inserted in the front, we can substitute $P_1 = 0$ into these equations; If the liquid lens is inserted in the back, we can substitute $P_2 = 0$ into these equations.
In this paper, the shape of the PDMS membrane of the liquid lens is assumed to be spherical for the typical aperture of the adaptive objective lens. The tunable power range needed in this paper can be easily achieved using our liquid lens. The shape of the membrane may be affected by other factors such as gravity and temperature, especially for larger aperture liquid lens. In that case, the change of the shape can be studied using finite element analysis and the result can be entered into the optical software to evaluate the optical performance.

In addition, both the membrane and the liquid are soft materials that are more sensitive to the temperature change in the environment. As a result, their mechanical properties (e.g., elasticity and stiffness) may change and the whole volume of the liquid may also change due to thermal expansion. An extreme example is that if the liquid is water, it would become solid below 0°C. Calibration of the focal length versus the temperature may also be needed.

In the same waveband, the lateral resolution is determined by the pupil size and focal length; the magnification is determined by the focal lengths of the objective and the tube lens (or other coupled focusing lens) which is used to focus the beam onto a detector or a intermediate image plane; and the field of view in the object plane is also affected by the magnification for the fixed size of the image (detector). So when scanning the different layers within the tissue for a large range, the lateral resolution, magnification, and field of view (distance) varies accordingly. Thus the further calibration of these parameters either on-line or off-line is needed.

When the adaptive objective lens is used in the confocal microscope, the increment in depth scanning can be in the order of the depth resolution of the confocal microscope, which is described as: \( \text{DOF} = \frac{\lambda}{(NA^2)} \), where \( \lambda \) is the average wavelength. When this adaptive objective lens is used in the OCT system, the increment in depth scanning can be in the order of the maximum ranging depth. For example, in the Fourier-domain OCT system, the maximum ranging depth and the increment in depth scanning can be in the order of \( Z \approx \frac{\lambda^2}{4\delta\lambda} \), where \( \delta\lambda \) is the wavelength sampling space (i.e, in FD-OCT, \( \delta\lambda = \Delta\lambda / N \); where \( \Delta\lambda \) is the bandwidth, \( N \) is the number of pixels of the linear CCD).

Based on the theoretical analysis in this paper, we have the capability to provide various types of design, such as the dynamic objective that works in the broadband visible range, or that has higher resolution with larger NA but smaller depth scan, etc. This paper is more about providing a methodology to the design of an objective implemented with tunable liquid lens as the zooming mechanism in biomedical imaging instrument, rather than only giving a design result. The usage of adaptive objective lens in biomedical imaging is still a multi-dimensional space that remains largely unexplored.

It should also be noted that nowadays it is popular that people use active wavefront correctors such as liquid crystal spatial light modulators or deformable mirrors to correct higher-order aberrations. They may also provide limited power for adjustment of focusing, but they are expensive and the package is big. Furthermore, they are usually in reflection mode, which makes the system bulky. The approach presented in this paper for optical depth scanning is more compact and cost effective.

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