Large aperture tunable-focus liquid lens using shape memory alloy spring

Nazmul Hasan, Hanseup Kim, and Carlos H. Mastrangelo

Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, Utah 84112, USA

*carlos.mastrangelo@utah.edu

Abstract: A tunable-focus large aperture liquid lens is constructed using shape memory alloy (SMA) springs as actuators. The lens mainly consists of a shallow liquid-filled cylindrical cavity bound by a thin compressible annular rim and encapsulated by a flexible circular membrane on the top of the rim and a rigid circular plate at the rim bottom. The lens optical power is adjusted by a controlled compression of the annular rim via actuation of the three shape-memory alloy (SMA) springs. Since the volume of the cavity liquid is constant, the rim compression bulges the flexible membrane outward thus reducing its radius of curvature and the lens focal length. The fabricated tunable lens demonstrated an optical power range of 0-4 diopters utilizing a driving voltage less than 3V. Lens optical wavefront profiling was done using a Shack-Hartmann sensor displaying a RMS wave front error of 0.77 µm and 1.68 µm at 0 D and + 4 D. The aperture diameter and thickness of the fabricated lens are 34 mm and 9 mm, respectively, while weighing 16.7 g.

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1. Introduction

A tunable focus lens, unlike a regular lens, is capable of adjusting focal lengths from a single lens structure according to external signals. Due to tuning capability, it finds its uses in various applications including digital cameras, microscopes, telescopes and light projectors. In particular, today there is great interest in the development of low-weight tunable focus lenses for imaging applications because they can potentially replace the much bulkier and heavier mechanically adjustable variable zoom compound lenses used pervasively.

Adjustable-focus lenses have been implemented using several different technologies and actuation mechanisms [1–3]. The Alvarez lens consists of two plano-convex-concave lenses moving laterally against each other to change the focal length of the combined lenses [4]. Depending on the distance of lateral movement of its two lenses, it, however, loses the field of vision and suffers from a visible gap, imperfections, and friction in the sliding glass surfaces. Another adjustable focus lens mechanism has been implemented by utilizing graded index-changing liquid crystals (LC) [5,6]. Liquid crystal (LC) directors reorient with the external electric field and changes the refractive index, eventually leading to change in focal length. Despite some advantages of low power consumption, direct voltage actuation and compact designs, LC lenses are unable to produce large and continuous phase changes; thus, its use has been limited to small (< 1cm)-aperture and Fresnel type lenses. A third approach utilizes liquid filled lenses with volume or shape changing mechanisms [7–9]. In liquid lenses, usually a cylindrical hollow chamber is encapsulated by a flexible membrane with one or more transparent optical fluids filling the chamber. The lens shape and power can be adjusted by fluid displacement in or out of the chamber or by squeezing the chamber thus deflecting the soft membrane. Several different deformable liquid lens actuation mechanisms have been demonstrated including electrostatic actuation, dielectric elastomer actuation, and piezoelectric actuation [8]. In contrast to LC lenses, liquid lenses have been realized with large apertures [8–11], but these lenses require external or peripheral liquid reservoirs and displacement mechanisms which significantly increase their footprint and weight.

In this paper we demonstrate the fabrication and testing of a compact tunable liquid lens actuated by low-weight shape memory alloy springs. The lens consists of a reservoir bound by a rigid transparent circular plate at the bottom and a flexible membrane at the top. In this lens, the fluid is stored behind the curved lens surface thus eliminating the need for external reservoirs. The absence of external liquid reservoir, light weight, and the large aperture are the main advantages of this lens. We present the design, fabrication and optical testing of these devices.

2. Basic lens configuration

Figure 1 shows the structure of the lens. A rigid lens back plate and a flexible membrane are attached to two sides of a compressible annular sealing rim implementing a plano-convex or plano-concave lens. The membrane and back plate are 41 mm in diameter. The annular rim width and height are 3.5 mm and 5 mm respectively. This produces a 41 mm diameter lens with a 34 mm aperture. The top membrane consists of a 0.75 mm-thick layer of...
polymethylsiloxane (PDMS) and the bottom rigid back plate is made with 1.5 mm thick acrylic. The rigid washer, 1.5 mm thick of the same width as the rim is used to hold the membrane in place. The lens rim has three cylindrical notches spaced 120° apart, used for housing three SMA springs. The diameter of each spring wire is 500 µm and post-deformation length (martensite state) is 9 mm. Each spring and holder weighs 1.2 g. Both ends of the SMA springs are soldered to rigid flat copper contact pads. These contact pads are also tightly attached to the washer and back plate by screws. The lens liquid is inserted into the lens chamber by a small hole in the back plate which is later hermetically sealed and plugged by a screw.

The height of the annular sealing rim is the initial height, $h_0$. The amount of fluid introduced into the chamber sets the initial shape and power of the lens. If the initial power is set to zero, fluid is introduced until the elastic membrane is made flat. In the absence of any applied force, the rim retains its initial height, $h_0$. When the SMA springs are electrically actuated, they squeeze and compress the elastic rim and the height, $h$ of the fluid chamber decreases to, $h<h_0$. Since the liquid trapped inside the lens chamber cannot leak outside, to maintain the total volume of the liquid constant, the flexible membrane bulges outward (thus producing a positive power) as shown in the example of Fig. 1(b). The higher the compression is, the higher the optical power of the lens.

Fig. 1. Schematic showing the fluid lens construction. The lens consists of a top elastic membrane that produces the lens curved surface, a rigid bottom plate and a compressible notched annular rim of height $h_0$. The interior of the lens cavity is filled with an optical fluid and the cavity is compressed at the rim with three vertical spring actuators spaced 120 degrees apart. (a) Lens in planar state, (b) Lens in convex state with compressed rim height $h<h_0$, and (c) exploded view showing the lens components (excluding the spring actuators).

3. Lens power versus rim deflection

According to Fig. 1, the lens is cylindrical shaped in no focusing state. After squeezing the side ring, the flexible membrane becomes convex making the lens a plano-convex one. The lens optical power is given by the lens maker’s equation,

$$P = \frac{1}{f} = (n-1) \left[ \frac{1}{R_1} - \frac{1}{R_2} \right] + \frac{(n-1)d}{nR_1R_2} = \frac{n-1}{R}. \tag{1}$$

Here, $R_1$ and $R_2$ are the radii of curvatures of the lens at each interface surface, $d$ is the mid plane lens thickness, and $n$ is the index of refraction of the liquid medium. For a plano-convex lens, $R_2 = \infty$ and $R_1 = R$. This makes the lens optical power independent of the thickness. The liquid volume of a lens with rim inner radius $r$, and height $h$ is [7],

$$V_l = \frac{\pi}{3} (R - \sqrt{R^2 - r^2})^2 \cdot (2R - \sqrt{R^2 - r^2}) + \pi \cdot r^2 \cdot h = \pi \cdot r^2 \cdot (h + \frac{r^2}{4 \cdot R}), \tag{2}$$

where $R\gg r$. Using Eq. (1), the fluid volume is expressed in terms of the optical power as,
For a variable focus lens, since the liquid volume is constant, any change in the power must originate from the change in the rim height. Taking the differential of Eq. (3) and setting it to zero, we obtain a direct relationship between lens power and height of the annular sealing rim,

$$\Delta P = -\frac{4(n-1) \cdot \Delta h}{r_r^2}. \quad (4)$$

For example, a lens with rim inner radius of 17 mm (34 mm aperture) with optical liquid of index 1.33, a power change of 4 diopters requires a change in rim height of $\Delta h = 0.9$ mm. This is the minimum thickness of the rim possible. The force required to squeeze the rim is proportional to the rim strain ($\Delta h/h_0$), the rim area, and the elastic modulus of the rim. A lower compression force is required if the rim height is made large, but doing so makes the lens heavy. This illustrates a basic tradeoff between the actuator force requirements and the lens weight. For the lens implemented here, the lens thickness measured from the top washer to the bottom back plate is 9 mm.

4. Actuator selection

The vertical force squeezing the rim is applied using actuators. If we ignore the force required to deflect the thin elastic membrane, the actuator force required to produce strain, $\Delta h/h_0$ on the annular sealing ring is,

$$F_{act} = -\pi \cdot (r_r^2 + w_r^2 - r_r^2) \cdot E_r \cdot \frac{\Delta h}{h_0} = -k_r \cdot \Delta h, \quad (5)$$

where $r_r$ is the annular ring’s inner radius, $w_r$ is the width of the annular ring, $E_r$ is the Young’s modulus of the rim material, and $k_r$ is the spring constant of the rim and reasonably assumed as constant. If we utilize a very flexible 3M VHB tape rim with Young’s modulus of ~200 kPa, it serves the purpose of both robustness and compressibility [12,13]. For, $r_r = 17$ mm, rim width $w_r = 3.5$ mm, rim height $h_0 = 5$ mm, and $\Delta h/h_0 = 0.1$, the calculated required actuator force, $F_{act}$ is 8.2 N, and the average actuation energy is $E_{act} = 4.1$ mJ. This large force and strain requirement excludes almost all common driving micro-mechanisms [14]. Since a low weight is desired, we selected an actuation mechanism that has a high actuation energy density. Shape memory alloy (SMA) materials can produce actuation energy densities of ~7 J/g; thus yielding actuators that have very low mass [14]. SMA materials have the ability to return to their predetermined shape from their deformed state when heated [15]. The shape change is caused by a phase change from austenite to martensite state or vice-versa which reconfigures the atomic lattice. Below the transformation temperature, SMA has low yield strength and can be deformed easily. In the most common SMA actuators configuration, the SMA length is set to the initial desired dimension and when heated, the SMA shrinks producing a negative strain. The shape memory alloy, NiTi is capable of $\varepsilon_{SMA} \sim 1\%$, reversible linear strain recovery for an effective life as high as 10$^7$ cycles (provided the detwinning strain threshold is not exceeded) [16,17]. The Young’s modulus of NiTi is typically 40 GPa in cold state and 85 GPa in the hot state [15]. For example, a 0.5 mm diameter SMA wire can thus produce as much as 8 kN of force simply due to the change in elastic modulus between the two phases.

SMA wires can produce very large forces but cannot produce large strains. Our lens requires strains of about 10% and much lower forces; therefore, it is necessary to use an SMA actuator with a leverage mechanism that trades strain with force. A compact leverage mechanism is an SMA helical spring [18,19]. A helical spring expands or contracts along its
main axis by torsion of a wire wound up in a helix [20]. The spring consists of a wire of diameter \(d\) wound up in a helix with \(N\) loops and loop diameter \(D\) has spring constant,

\[
k = \frac{G \cdot d^4}{8 \cdot N \cdot D^3}.
\]

Here, \(G = E/(1 + \eta)\) is the spring shear modulus, \(E\) is the Young’s modulus, and \(\eta\) is Poisson’s ratio. Note that the larger the number of turns is, the smaller the spring constant. The relationship between the spring internal shear strain \(\theta\) and the spring linear strain \(\varepsilon_s\) is,

\[
\varepsilon_s = \frac{\pi}{W} \left( \frac{D}{d} \right)^2 \cdot \theta \leq \frac{\pi}{2 \cdot W} \left( \frac{D}{d} \right)^2 \cdot \varepsilon_d.
\]

Where, \(W = 1.5\) is the spring Wahl correction factor. By making \(D > d\), the maximum linear strain of the helical spring can be made many times larger than the SMA linear strain detwinning threshold \(\varepsilon_D < \sim 1\%\). Helical SMA springs provide temperature-dependent deflections as its Young’s modulus, \(E\) is a function of temperature [18]. At low temperature, the three SMA springs of default length, \(h_a\) are stretched to length \((h_a + h_r)\) matching the initial rim thickness, \(h_p\) plus the thickness of incompressible top washer, membrane and back plate, lumped together as \(h_s\). After the springs are mounted on the elastic rim they are released compressing the rim and reaching an equilibrium length \(h_c < (h_0 + h_d)\). The equilibrium length is determined from a force balance between the cold spring force and the rim restoring force,

\[
h_c = \frac{(k_c \cdot h_c + 3 \cdot k_c \cdot (h_s + h_r))}{(3 \cdot k_c + k_r)},
\]

where \(k_c\) is the cold SMA spring constant. Note that \(h_a + h_s \geq h_c \geq h_r\) and the maximum displacement is less or equal to \((h_c - h_r)\). If the SMA springs are next heated, the springs stiffen compressing the rim further. The shrinkage produces a change on the rim height of,

\[
\Delta h = -\frac{3 \cdot k_c \cdot (T_{aw} - k_c) \cdot (h_s + h_r - h_c)}{(3 \cdot k_c + k_r) \cdot (3 \cdot k_c + k_r)}.
\]

Where, \(T_{aw}\) is the average spring temperature and \(k_c(T_{aw})\) is the average hot spring constant from Eq. (6). Equation (9) can be combined with Eq. (4) to determine the optical power change for a given average spring temperature. Note that when heated, a real SMA spring is subject to temperature gradients; hence resulting in a smooth variation of \(k_c\) with average temperature \(T_{aw}\). Equation (9) tells us that, this reversible actuation mechanism requires both the initial elastic stretching of the cold SMA spring and a sufficient actuation force in the hot SMA state. If the springs are much softer than the rim, they will produce very little compression force and negligible \(\Delta h\). On the other extreme, if the springs are much stiffer than the rim, the initial cold spring stretching, \((h_c - h_r)\) is small also producing negligible \(\Delta h\). For maximum \(\Delta h\), the spring constants for the cold SMA springs and rim must be appropriately matched. For our lens, the spring constant for the VHB rim used was \(\sim 8.2\) kN/m. The NiTiCu SMA springs used (Kellogg’s Research Labs) had wire diameter of 500 µm, mandrel diameter of 900 µm, a pitch of 500 µm and 15 turns. The transition temperature for NiTiCu SMA wires was 45°C. The effective net spring constant, \(3 \cdot k_c\) was 9.2 kN/m in the cold state. Finally the SMA springs are electrically heated; hence their average temperature is approximately proportional to the square of the applied voltage.

5. Lens fabrication

The adaptive lens fabricated is shown in Fig. 2(a). The annular sealing rim is constructed from 3M VHB4910 acrylic elastomer which can sustain strains as high as 77% [12,13]. Five layers of VHB4910, 1 mm-thick tape were bonded together to produce an initial undeformed rim.
thickness of 5 mm. The annular shape of the rim was laser cut from the tape stack using a VLS 3.60 Laser Platform 60W CO₂ laser with laser power 100% and speed 1%. As the rims cut from the VHB tape were very sticky, a 1 µm thick parylene-C film was deposited around the rim for both physical and chemical insulation. The rigid back plate and top washer were made with 1.5 mm thick transparent acrylic. The elastic membrane was made with polydimethylsiloxane (PDMS). SYLGARD 184 Silicone Elastomer was (10:1 ratio of base and curing agent) coated on an acrylic petri dish. The PDMS uncured mixture was cured in an oven at 60 °C for 6 hours to form 840 µm thick PDMS membranes. The PDMS membrane and acrylic back plate are adhesively attached to the annular VHB ring, and the entire assembly has better than 90% optical transmittance. Deionized water was used (n = 1.33) as the optical liquid. The method we used was immersion followed by weak evacuation. After venting, the cavity is sealed while completely immersed in deionized water. This produces bubble-free chambers. We next examine the lens before actuation and testing using a Shack-Hartmann sensor to determine the flatness of the lens.

The SMA helical springs were laser spot welded to flat 0.6 mm thick copper tabs as shown in Fig. 2(b). Each SMA spring assembly was inserted at the outer rim notches and screwed to the top rim washer and the back plate as shown in Fig. 2(a). The weight of the completed lens and actuator assembly was 16.7 g.

6. Experiments

6.1 Optical Test Setup

Lens power, focal length and wavefront measurements are made using a Shack-Hartmann wavefront sensor (SHS) (WFS150-7AR from ThorLabs) and a collimated LED light source (M625L3-C1 from ThorLabs) with wavelength 625 nm. We utilize the proximity technique for measurement of the focal length and a relay lens system for measuring the wavefront aberrations [21,22]. In order to measure the focal length, the collimated light source was placed 50 cm apart from the lens as shown in Fig. 3(a). The test lens was clamped in vertical orientation in close proximity to the wavefront sensor (~1.4 cm between test lens and SHS lenslet array). Since the beam is collimated, the lens focal length, \( f_i = R \) (radius of curvature of incoming light) - L (separation of test lens and sensor) [21].

The proximity focus measurement technique works very well but only captures a small portion of the lens light, as the diameter of the SHS sensor (~4.6 mm) is much smaller than the liquid lens aperture. In order to approximately capture the entire light field from the lens, we also constructed a 4f afocal relay lens system that feeds all lens light into the sensor as shown in Fig. 3(b) [22]. As the LED light source goes through an iris and a beam expander (Thor Labs GBE 10A) combination, it produces a highly collimated light beam 30 mm in diameter. The focal lengths of the first and second lens of the relay system are \( f_i = 20 \)
cm and $f_2 = 3$ cm, respectively (Thor Labs LA 1253-A and LA 1085-A). The test lens is placed $f_1$ away from the first relay lens. After the light beam passes through the test lens, the afocal relay lenses, placed $f_1 + f_2 = 23$ cm apart, collect all the light and reduce the beam diameter by ~6.6 fold. The SHS is placed $f_2$ away from the second relay lens. It is also possible to measure the focal length of the test lens using the relay lens system but the observed focal lens is $f_2(1 + (f_0 \times f_2/f_1^2))$. Note that, since a beam reduction is required ($f_2/f_1 << 1$), the influence of the lens focal length on the entire system focal length (as measured by the SHS) is greatly reduced; hence the proximity technique is preferred for focal measurements. The relay lens setup (with no test lens) produced aberrations with RMS wavefront error ~0.17 µm.

![Fig. 3. (a) optical set up for proximity technique, (b) 4f optical set up using Shack-Hartmann sensor, and (c) wave front from SH sensor at lens power + 4 D.](image)

### 6.2 Lens Power Measurements

Lens power measurements were made using the proximity technique at the lens center under various actuation conditions. At zero voltage, the liquid lens was in planar state and lens optical power was approximately zero. When a DC voltage, $V$ is applied to the SMA spring, resistance heating occurs producing a temperature increase proportional to the electrical power $= 3V^2/R_s$. Here, $R_s$ is the resistance of each SMA spring. The initial value of each spring resistance is around 0.96 Ω. Figure 4(a) shows the measured lens power as a function of applied voltage $V$.

![Fig. 4. (a) Lens power versus SMA spring voltage and (b) Lens power versus rim height. The standard deviation of the lens power were less than 3%.](image)

The three springs were connected in parallel with the power supply. Three MOS switches are used to control the pulse width of the applied voltage. Each voltage is applied for 10 seconds to measure the focal length. Figure 4(a) shows that the lens power increases slowly...
with voltage in the beginning and the slope increases rapidly after 1.8 V. This is attributed to
the nonlinearity of power generation versus applied voltage and the temperature dependence
of the SMA resistivity which increases in the beginning but falls to a lower value with further
temperature increase [23].

Figure 4(b) shows the lens power as a function of height change of the annular sealing
rim. The rim height was measured using a caliper. The measured power is close to the
calculated value. For a 1 mm deformation (20% strain), the VHB acrylic rim behaved
elastically. Hysteresis was not observed upon cyclic actuation, and all measurements were
made with the lenses in a stable state. Considering other factors constant, the change in lens
optical power depends on the actuation voltage and current compliance. With 2.2 V, it takes
approximately 4 seconds to change lens power from 0 to + 1 D. The response time of the
SMA actuators is determined by the thermal time constant of the springs and roughly
proportional to the square of the unwound spring length and inversely proportional to the
SMA thermal diffusivity. We have not made any attempts to improve the speed of the
actuator as that is beyond the scope of this paper. The drift of the lens deflection under cyclic
excitation was also measured as follows. The actuation voltage was set to 2.7 volts
corresponding to a power of 4.02 diopters. The lens was actuated on and off for several
hundred cycles, each cycle 10 seconds on and 60 seconds off. The deflection of the lens
power drifted approximately 1.2% after 500 actuation cycles. This gives an estimation of lens
life time for extreme actuation condition.

Next we captured video images recorded through the actuated liquid lens. The lens was
attached to a digital single-lens reflex camera with 40 mm focal length. The target object was
placed 14 cm apart from the camera-liquid lens setup. The autofocus camera adjusts its focus
as the lens changes its focal length. Figure 5(a) and 5(b) show two images recorded with SMA
lens at zero power and at a power of + 3 D.

Fig. 5. (a) Image of text recorded through liquid lens at its default state and (b) at a lens power
+ 3 D

The bottom part of the Fig. 5(c) has some distortion. The root cause is gravity-induced
vertical coma aberration. The weight of the liquid makes the membrane deformation at the
bottom of the lens to be somewhat higher than at the top. The amount of coma can be much
reduced by using a thicker PDMS membrane or a high membrane tension [24]. For example
doubling the PDMS thickness reduces the coma by 8-fold. At higher optical power, vertical
coma is also reduced which is apparent in Fig. 5(d) [25]. In addition, we took photographs of
a USAF 1951 1X R1DS1P resolution target through the lens with fixed focus camera at test
lens power of + 3 D. The camera was at fixed focus with 55 mm lens and the test lens was
attached with the camera. The target bar was kept 10 cm apart from the test lens. The chart
resolution cutoff was about 28 lp/mm.
6.3 Lens Wavefront Measurements, Lens Quality and Discussion

To evaluate the lens optical performance, the Zernike coefficients of the lens were measured using the 4f relay lens system for both lens optical powers 0 and + 4 D. The Zernike coefficients at lens power 0 D were: (Astig-45 = −0.108 µm, Astig-90 = −0.492 µm, Trefoil-Y = 0.03 µm, Coma-X = −0.536 µm, Coma-Y = 0.236 µm, Trefoil-X = −0.083 µm, Spherical = −0.006 µm) producing an RMS wavefront error of 0.77 µm. For + 4 D optical power the Zernike coefficients were (Astig-45 = −0.738 µm, Astig-90 = −0.81 µm, Trefoil-Y = 0.992 µm, Coma-X = 0.67 µm, Coma-Y = 0.166 µm, Trefoil-X = −0.317 µm, Spherical = −0.292 µm) producing an RMS wavefront error of 1.68 µm.

The 80% encircled energy radius of the point spread function (PSF) at 0 and + 4 D are 0.079° and 0.107° respectively. The largest source of aberrations was coma at 0 D and Trefoil at + 4 D. The coma aberration is produced by gravity as the weight of the liquid produces a larger pressure at the bottom of the membrane than at the top, and the coma decreases with increased lens power. The Trefoil aberration at + 4 D is caused by the three SMA actuators spaced 120° apart. Spherical aberration at 0 D is very small and has a larger value at + 4 D as the lens profile becomes more parabolic. The lens profiles that are obtained with liquid-filled diaphragm lenses are not spherical but bell-shaped [26]. Because of the bell-shape membrane deflection these type of lenses experience spherical aberrations, especially at higher powers.

While the measured wavefront errors are larger than desired (< 0.5 µm), both Coma and Trefoil aberrations can be mostly eliminated with the utilization of a thicker membrane and a more rigid, thicker lens rim. Coma can also be largely eliminated if the lens diameter is reduced. Since the diaphragm deflections are proportional to the fourth power of the radius, a five-fold reduction in the radius reduces aberrations by ~600 fold. Such improvements have been observed in very small aperture liquid lenses [27].

Although we have used water as the lens fluid, a higher refractive index liquid can be used to produce a higher optical power for the same height change. Glycerol (n = 1.47) and ethylene glycol (n = 1.43) are improved choices that do not swell the elastic PDMS lens membrane. Furthermore, although the convex profile of the lens has been demonstrated here, it can be tuned as a concave lens as well simply by under-filling the cavity prior to the seal.

7. Conclusion

A tunable focus large aperture liquid lens actuated by shape memory alloy springs has been fabricated and tested. The liquid lens has a 34 mm aperture, 9 mm thickness and weighs 16.7 g, 10 times lighter than similar aperture liquid lenses. The lens is capable of changing its optical power between 0 and 4 diopter with a low 3V voltage operation and the response time of the lens was approximately 4 seconds. The RMS wavefront aberrations for this lens at 625 nm were 0.77 µm and 1.68 µm at powers of 0 D and + 4 D, respectively. With utilization of thicker PDMS membranes, the aberration of the lens can be further reduced. The speed of the lens can also be increased by careful actuator design. These lightweight lenses have many potential applications for replacement of compound zoom lenses in portable imaging applications where large lens apertures are needed with smaller footprint and light weight.