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Design and fabrication of soft zoom lens applied in robot vision

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1. Introduction

The design theorem of traditional zoom lens uses mechanical motion to precisely adjust the separations between individual or groups of lenses; therefore, it is more complicated and requires multiple optical elements. Conventionally, the types of zoom lens can be divided into optical zoom and digital zoom. With the demands of the opto-mechanical elements, the zoom ability of lens system was dominated by the optical and mechanical design technique. In recent years, zoom lens is applied in compact imaging devices, which are popularly used in Notebook, PDA, mobile phone, and etc. The minimization of the zoom lens with excellent zoom ability and high imaging quality at the same time becomes a key subject of related efficient zoom lens design. In this decade, some novel technologies for zoom lens have been presented and they can simply be classified into the following three types:

(1)Electro-wetting liquid lens:

Electro-wetting liquid lens is the earliest liquid lens which contains two immiscible liquids having equal density but different refractive index, one is an electrically conductive liquid (water) and the other is a drop of oil (silicon oil), contained in a short tube with transparent end caps. When a voltage is applied, because of electrostatic property, the shape of interface between oil and water will be changed and then the focal length will be altered. Among the electro-wetting liquid lenses, the most famous one is Varioptic liquid lens.

(2) MEMS process liquid lens:

This type of liquid lens usually contains micro channel, liquid chamber and PDMS membrane which can be made in MEMS process, and then micro-pump or actuator is applied to pump liquid in/out the liquid chamber. In this way, the shape of liquid lens will change as plano-concave or plano-convex lens, even in bi-concave, bi-convex, meniscus convex and meniscus concave. It can also combine one above liquid lens to enlarge the field of view (FOV) and the zoom ratio of the system.

(3)Liquid crystals lens:

Liquid crystals are excellent electro-optic materials with electrical and optical anisotropies. Its optical properties can easily be varied by external electric field. When the voltage is applied, the liquid crystals molecules will reorient by the inhomogeneous electric field which generates a centro-symmetric refractive index distribution. Then, the focal length will be altered with varying voltage.

(4)Solid tunable lens:

One non-liquid tunable lens with PDMS was increasing temperature by heating the silicon conducting ring. PDMS lens is deformed by mismatching of bi-thermal expansion coefficients and stiffness between PDMS and silicon. Alternatively the zoom lens can be fabricated by soft or flexible materials, such as PDMS. The shape of soft lens can be changed by external force, this force may be mechanical force like contact force or magnetic force; therefore the focal length will be altered without any fluid pump.

All presented above have a common character that they process optical zoom by changing lens shape and without any transmission mechanism. The earliest deformed lens can be traced to the theory of "Adaptive optics" that is a technology used to improve the performance of optical systems and is most used in astronomy to reduce the effects of atmospheric distortion. The adaptive optics usually used MEMS process to fabricate the flexible membranes and combine the actuator to make the lens with the motion of tilt and shift. However, there has not yet a zoom lens with PDMS that can be controlled by the fluid pressure for curvature change. In this chapter, PDMS is used for fabricating the lens of SZL and EFL of this lens system will be changed using pneumatic pressure.

2. PDMS properties

PDMS, Dow Corning SYLGARD 184, is used because of its good light transmittance, a two-part elastomer (base and curing agent), is liquid in room temperature and it is cured by mixing base and curing agent at 25°C for 24 hour. Heating will shorten the curing time of PDMS, 100 °C for 1hour, 150°C for only 15 minutes. PDMS also has low glass transition temperature (-123 °C), good chemical and thermal stability, and contain flexibility and elasticity from -50 to 200°C. Since different curing parameter cause different Young's Modulus and refractive index, this section introduces the material properties of PDMS, including Young's Modulus, reflection index (n) and Abbe number (v) in different curing parameter.

2.1 PDMS mechanical property (Young's Modulus)
Young's Modulus is the important mechanic property in the analysis of the maximum displacement and deformed shape of PDMS lens. In order to find the relationship of curing parameter and Young's Modulus, tensile test is used, master curing parameters is curing time, curing temperature and mixing ratio.
The geometric specification of test sample is define as standard ASTM D412 98a , the process parameter separate as 10:1 and 15:1, cured at 100 °C for 30, 45, 60 minutes and 150 °C for 15, 20, 25 minutes. As the result, in the same mixed ratio, higher curing temperature and long

curing time cause larger Young's Modulus; in the same curing parameter, in mixed ratio 10:1 has larger Young's Modulus than 15:1. The mixed ratio 15:1 is soft then 10:1 but is weaker, so the fabrication of PDMS lens will use the ratio 10:1.

2.2 PDMS optical property (Refractive index and Abbe number)

Refractive index (n) and Abbe number (v) is the essential optic parameter of material optical properties in optical design. Spectroscopic Ellipsometer is used to inspect the n in wavelength 587nm, then discuss the nPDMS of mixed ratio 10:1 and 15:1 cured at 100°C for 30, 40, and 60min. The v is defined as follows:

$$V_d = \frac{n_d - 1}{n_F - n_C}$$ (1)

nF, nC, and nd is the refractive index at 486.1、656.3 and 587.6nm. The nd and ν d of PDMS is calculated according to the data by using least square method. As the result, curing parameter is not the key point that influences the optical properties of PDMS material; mixed ratio has more influence on optical properties. 10:1 has larger n and ν than 15:1. In this research, the n 1.395 and v 50 is used. Table.1 shows the comparison with PDMS and the other most used optical materials.

Materials	BK7	PMMA	COC	PC	PS	PDMS
Refractive index (n)	1.517	1.492	1.533	1.585	1.590	1.395
Abbe number (v_d)	64.17	57.442	56.23	29.91	30.87	50

Table. 1. Optical property of PDMS and common optical material

3. Methodology

This section introduces the design process of pneumatic SZL system; this system is divided into SZL unit and pneumatic control unit. As the PDMS material properties is obtained, then the optical design, optical mechanism, PDMS lens mold and mold inserts is consequently designed and experimentally fabricated. After assembly of the PDMS lens and optic mechanism, the SZL system is presented and investigated for its optical performance of desired EFL.

3.1 Design of pneumatic soft zoom lens unit

Components of the SZL unit are shown in Fig.1. The SZL unit includes BK7 lens and PDMS lens, the PDMS lens were designed with flat and spherical lens. The EFL is 33.56mm when using PDMS spherical lens and the EFL is 32.55mm when using PDMS flat lens. In order to simply verify this idea, optical performance of the SZL system is not the main purpose, thus diffractive optical elements and correct lens is a good choice to modify the aberration for better optical performance in this system. Mechanisms of SZL unit will be devised as barrel, O-ring, cell, retainer and spacer.
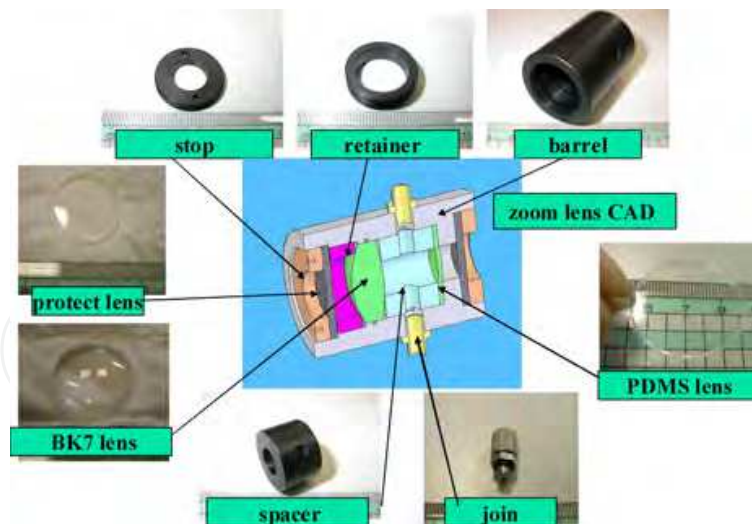
Fig. 1. Components of the soft zoom lens system.

3.2 SZL system

The SZL system assembly procedure is following these steps as show in Fig.2.: (1) PDMS lens is put into the barrel, (2) the spacer which constrain the distance between PDMS lens and BK7 lens is packed, (3) O-ring is fixed which can avoid air to escape, (4) BK7 lens is loaded and mounted by retainer, (5) BK7 protect lens is equipped with at both end of the SZL, and finally, the SZL system is combined with the SZL unit and pneumatic control unit with a pump (NITTO Inc.), a regulator, a pressure gauge and also a switch.
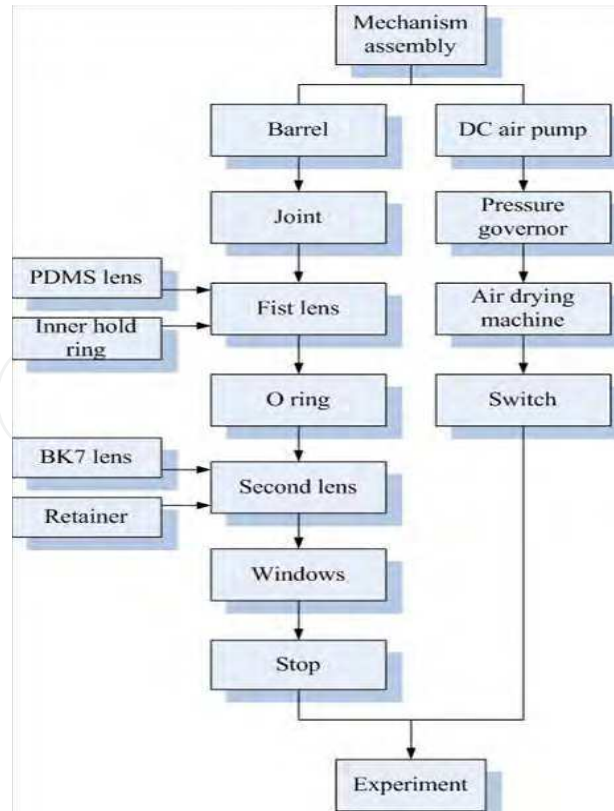
Fig. 2. Flow chart of SZL assembly process.

Fig. 3. Soft zoom lens system contain pneumatic supply device for control unit.

Fig.4. shows the zoom process of SZL system for variant applied pressures. The principle of SZL system is by the way of pneumatic pressure to adapt its shape and curvature, the gas input is supplied with NITTO pump and max pressure is up to 0.03 MPa. The regulator and pressure gauge control the magnitude of applied pressure, and there are two switches at both end of the SZL, one is input valve and the other is output valve.
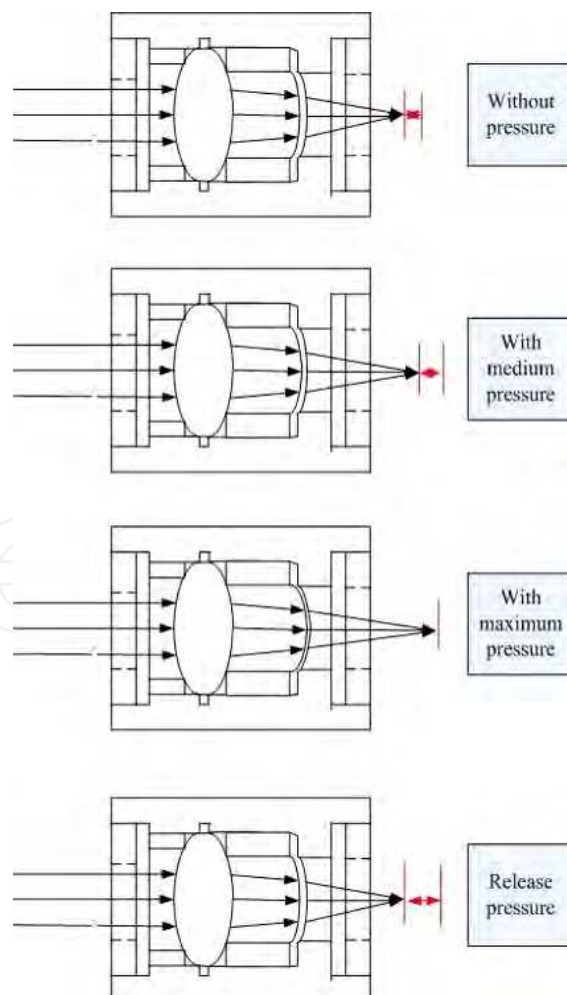

Fig. 4. Zoom process of the SZL during the pneumatic pressure applied.

3.3 PDMS lens mold and PDMS soft lens processing

The lens mold contains two pair of mold inserts, one pair is for PDMS spherical lens and another is for PDMS flat lens. Each pair has the upper and the lower mold inserts. The material of mold insert is copper (Moldmax XL) and is fabricated by ultra-precision diamond turning machine. Fig.4. shows the fabrication process. Since the PDMS lens is fabricated by casting, the parting line between the upper and the lower mold inserts need have an air trap for over welling the extra amount PDMS. At the corner of the mold are four guiding pins to orientate the mold plates.

The fabrication processes is shown at Fig.5. The fabrication process of PDMS lens is mixing, stirring, degassing and heating for curing. At first, base A and curing agent B is mixed and stirred with 10:1 by weight, then degas with a vacuum pump. After preparing the PDMS, cast PDMS into the mold cavity slowly and carefully, then close the mold and put into oven for curing. As the result, at curing temperature 100°C, PDMS lens can be formed after 60 min. Fig.6. is the PDMS lens of SZL unit. There are spherical lens and flat lens for experimental tests and they are fabricated at the same molding procedure.

| (a) PDMS cast into mold cavity | (b) Mold cavity full of PDMS |

| (c) Curing in oven | (d) After curing |

Fig. 5. Fabrication processes of PDMS lens.

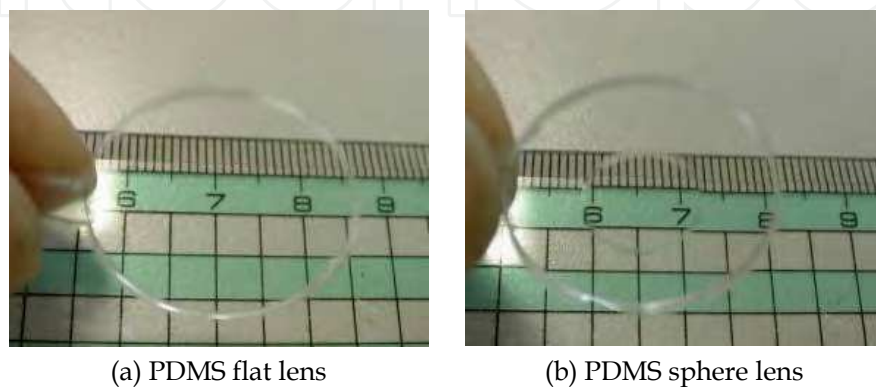| (a) PDMS flat lens | (b) PDMS sphere lens |

Fig. 6. PDMS lens of soft zoom lens system.

3.4 Deformation analysis of PDMS lens

In the deformation analysis of PDMS lens, the measured Young's Modulus and Poisson's Ratio of PDMS are inputted to the software and then set the meshed type, boundary condition and loading. The boundary condition is to constrain the contact surface between the PDMS lens and mechanism like barrel and spacer, and the load is the applied pressure of pneumatic supply device. Fig.7. shows the analysis procedure. As the result of the deformation analysis, comparing to the SZL with PDMS flat and spherical lens, the flat lens has larger deformation with the same curing parameter of both PDMS lens. Fig.8. shows the relationship of the maximum displacement versus the Young's Modulus of PDMS flat lens and spherical lens.
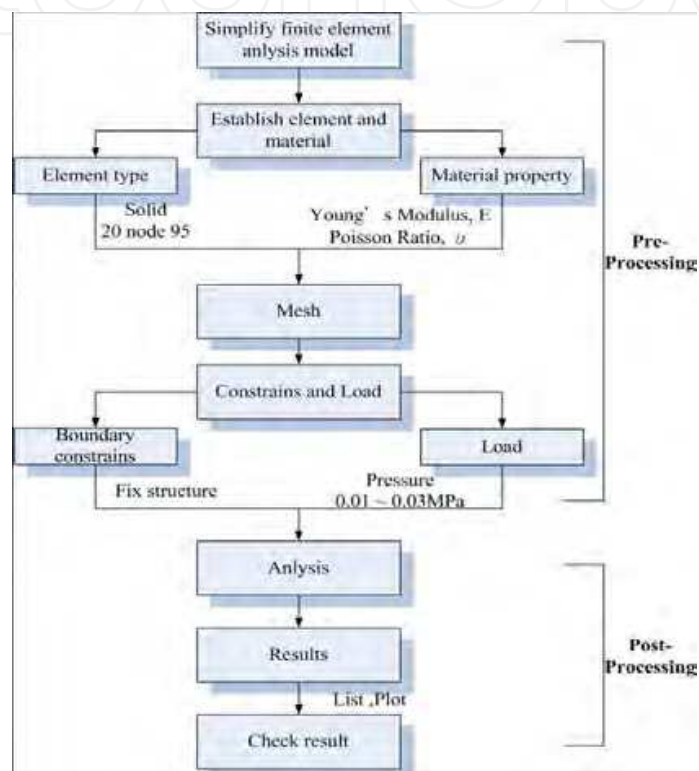
Fig. 7. Flow chart of PDMS lens deformation analysis.
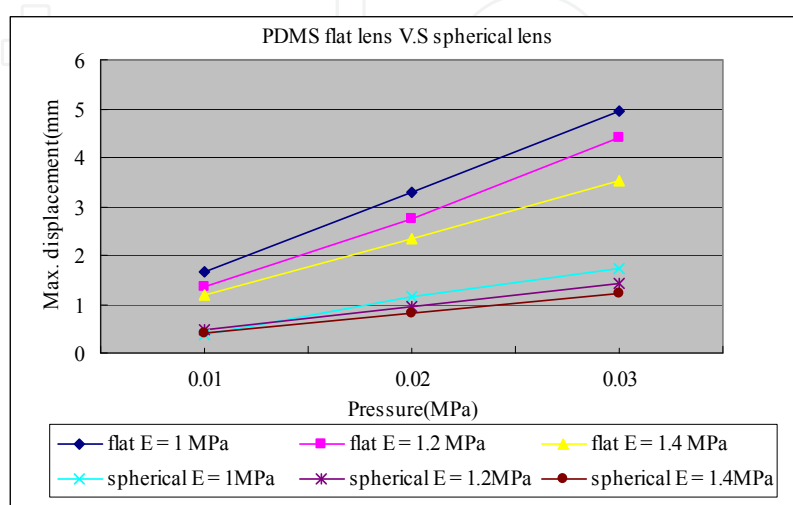
Fig. 8. Relationship of PDMS lens Young's Modulus and maximum displacement.

4. Results and Discussion

The EFL of soft zoom lens system is inspected by an opto-centric instrument (Trioptics OptiCentric) in a transmission mode show as Fig.9. The lens system with PDMS spherical lens are cured at 100°C for 60, 70 min and separately inspected at five conditions as 0, 0.005, 0.01, 0.015 and 0.02 MPa. The EFL of soft zoom lens with PDMS lens cured at 100°C for 60 min changes from 33.440 to 39.717 mm or increasing 18.77% during the applied pressure from 0 to 0.02 MPa. The EFL of soft zoom lens with PDMS lens cured at 100°C for 70 min changes from 33.877 to 39.189 mm or increasing 15.68%. PDMS lens cured at 150°C for 45 min changes from 33.254 to 37.533 mm or increasing 12.87%. The longer curing time or larger curing temperature affects the stiffness of elastomer and the Young's modulus increases for less deformable by the external force.
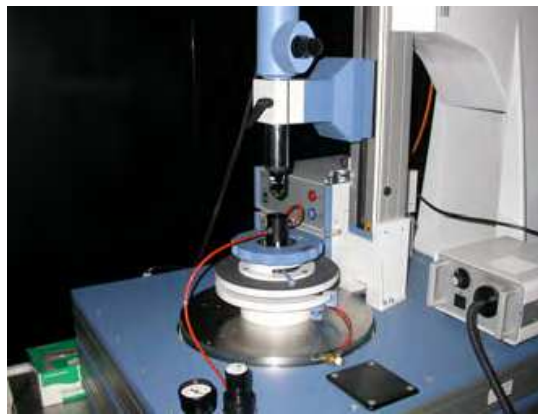
Fig. 9. The effective focal length measurement by using Trioptics.

For the PDMS flat lens cured at 100°C for 60 min, the EFL of this SZL system changes from 32.554 to 34.177mm or increasing 4.99%. Fig.10. is the relationship of applied pressure and EFL of soft zoom lens system. Fig.11. shows the relationship of applied pressure and system zoom ratio. The EFL of the SZL system with flat PDMS lens seems not changing conspicuously as that with PDMS spherical lens. The variation of thickness of the flat lens is not so obvious than that of the spherical lens due to the deformation induced by the pneumatic pressure. The repeatability of the soft zoom lens is also inspected for the SZL with PDMS spherical lens and is measured for 100 times. Result is shown in Fig.12.
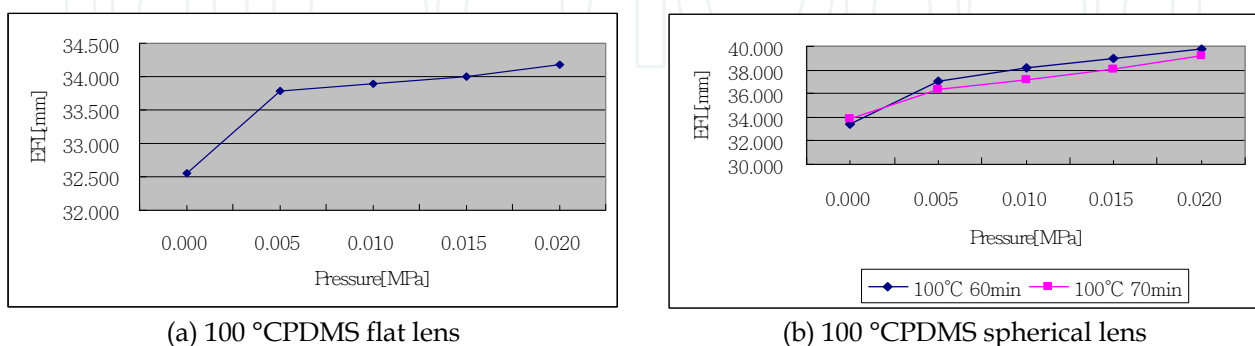

| (a) 100 °CPDMS flat lens | (b) 100 °CPDMS spherical lens |

Fig. 10. The relationship of applied pneumatic pressure and effective focal length with PDMS lens cured at 100°C.
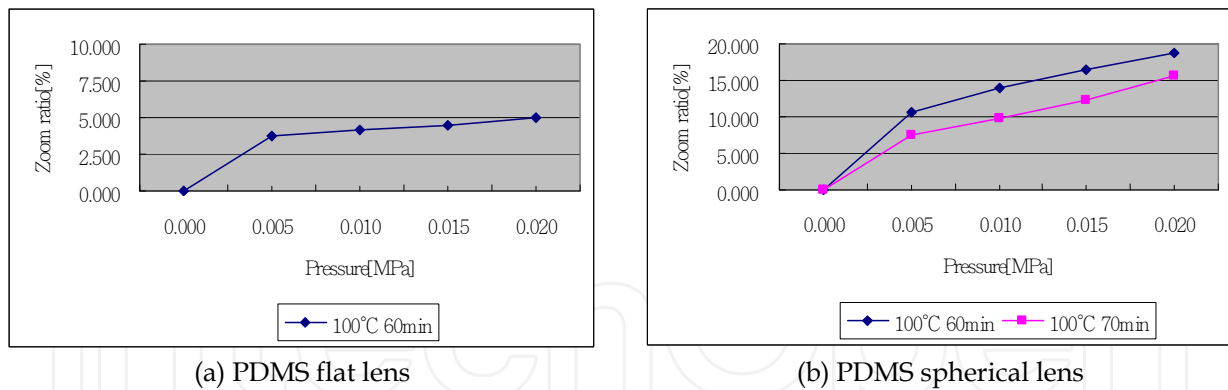
(a) PDMS flat lens   (b) PDMS spherical lens

Fig. 11. The relationship of applied pneumatic pressure and zoom ratio with different shape of PDMS lens.

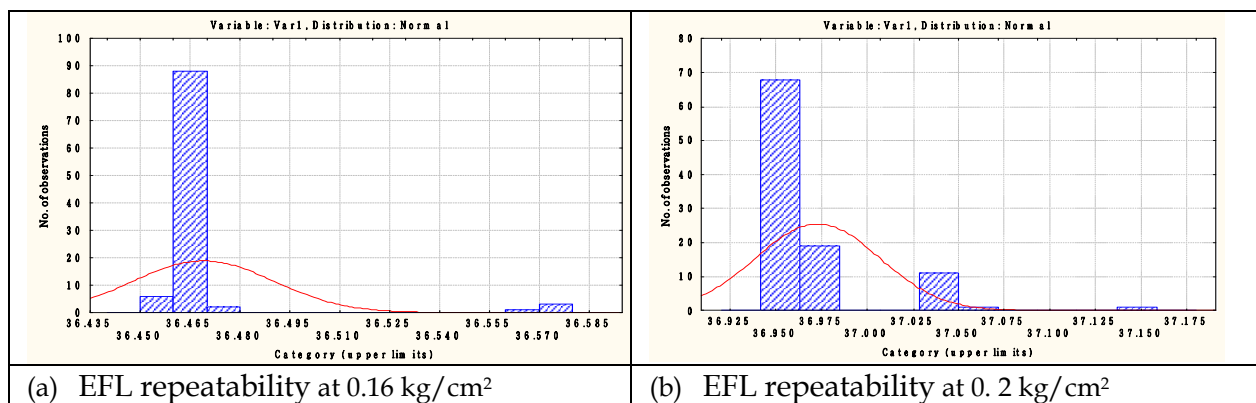| (a) EFL repeatability at 0.16 kg/cm² | (b) EFL repeatability at 0. 2 kg/cm² |

Fig. 12. The repeatability of the SZL system.

In order to comprehend the variation of EFL with zoom effect of the developed SZL system, a CCD imaging experiment was performed for verification. A mechanical adapter was design to assemble the SZL unit onto the CCD camera. Fig.13. shows the experimental setup of this imaging experiment. In this experiment, the ISO 12233 pattern was used and the object length from the pattern to the SZL unit was fixed to observe the acquired image from the CCD camera for the pneumatic pressure applied from 0 to 0.02 MPa. The captured image during the pressure applied for each applied pressure is from clear to indistinct as show in Fig.14. It is obviously verified the zoom effect of this developed SZL system with the fabricated PDMS lens.
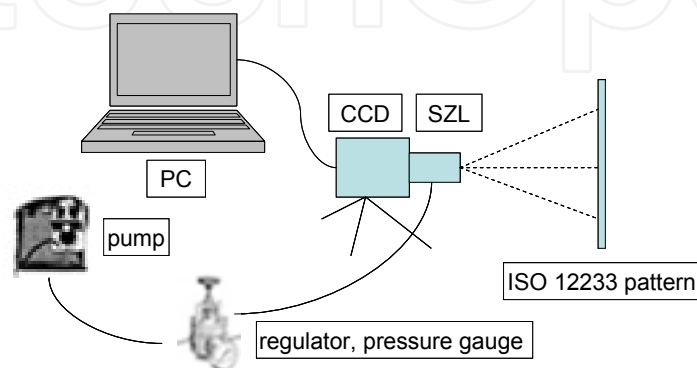

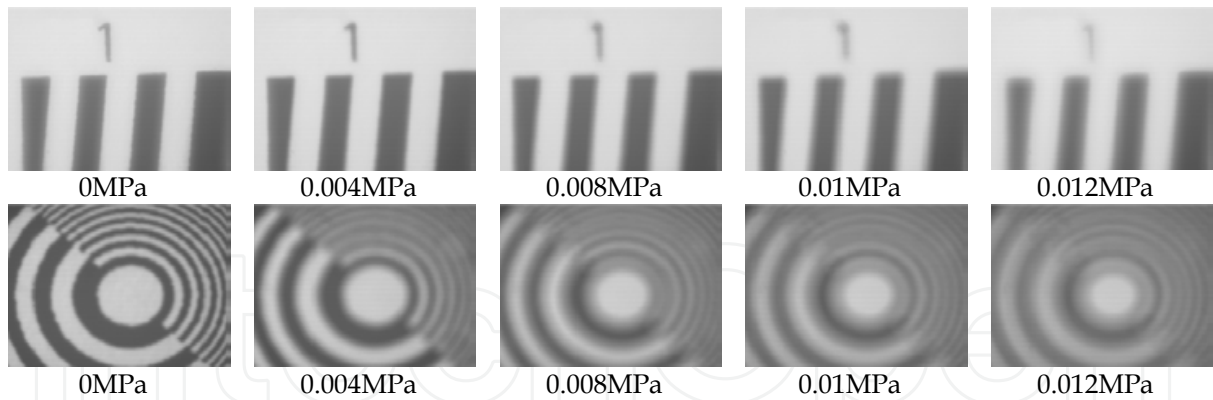Fig. 13. The experimental setup of the soft zoom lens system imaging.

Fig. 14. The image of soft zoom lens system from the image test.

As a summary of experimental results and discussion, EFL is direct proportion to the magnitude of the applied pressure during the EFL inspection. When the pressure is applied, the EFL of the system and shape of PDMS lens change. The major EFL variation occurs in the beginning of applied pressure. For example, when the pressure is applied from 0 to 0.005MPa the EFL variation of PDMS lens cured at 100°C for 60min is 3.577mm, then when the applied pressure is up to 0.02MPa the variation of EFL is 6.277mm, the variation between 0.015 to 0.02MPa is only 0.749mm. Fig.15. shows the relationship of EFL variation and pressure. Comparing to the SZL with PDMS flat and spherical lens, the flat lens has larger deformation with the same curing parameter, but the zoom ratio does not as good as spherical lens. According to the experimental result, the thickness, curing parameter and the geometry shape of the PDMS lens can influence zoom ability. Therefore, the imaging experiment was performed by the SZL system with spherical PDMS lens and the obtained image has been verified for its feasibility of zoom effect.

(a) 100°C PDMS flat lens   (b) 100°C PDMS spherical lens
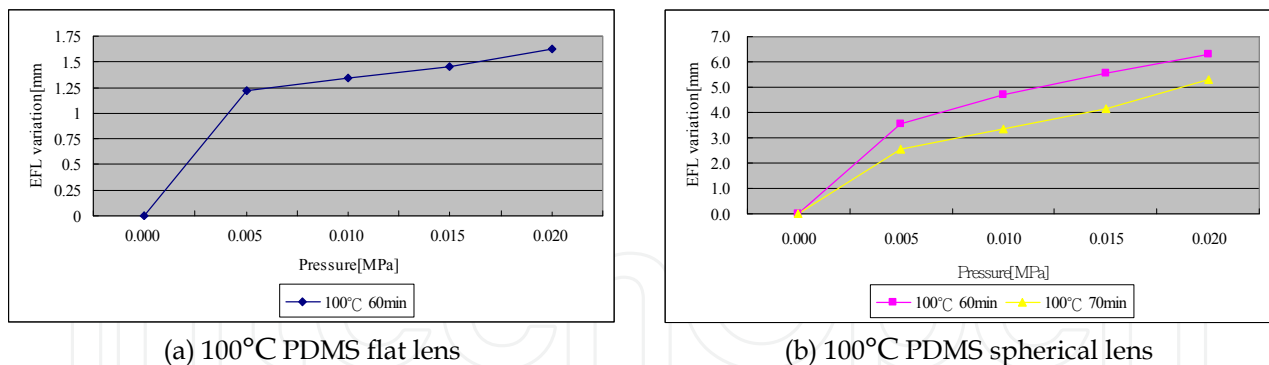
Fig. 15. The relationship of applied pneumatic pressure and variation of effective focal length.

5. Conclusion

Based on the experimental results, the novel design of this SZL system has been proved effectively for its zoom effects for image. The EFL of SZL system with PDMS lens cured at 100°C for 60 min changes from 33.440 to 39.717 mm or increasing 18.77% for the applied pressure from 0 to 0.02 MPa. The curing temperature and time significantly affects the stiffness of the PDMS lens and causes different results of EFL. Experimental results also show that zoom effects of the developed SZL system are significantly affected by the shape,

thickness of PDMS soft lens. The SZL system has been verified with the function of zoom ability.

In future, the deformed shape of PDMS lens after applied pressure needs to be analyzed and then the altered lens's shape can be obtained to be fit and calculated. It can be imported to the optical software to check the EFL variation after applying the pressure and also compare with the inspection data. Furthermore, it can find the optimized design by the shape analysis of PDMS lens when the pneumatic pressure is applied, then the correct lens is obtained to modify the optical image property. On the operation principle, we should find other actuator instead of fluid pump to change the shape of PDMS lens and EFL of SZL with external pressure for zoom lens devices. Further research will work on the integration of the SZL system with imaging system for mobile devices or robot vision applications.

6. Future work

As the result, the pneumatic control soft zoom lens can simply proof our idea that the effective focal length of zoom lens will be altered through the deformation varied by changing the pneumatic pressure. As we know, the deformed lens whether in pneumatic system or MEMS micro-pump system is not convenient to apply in compact imaging devices. In order to improve this defect, we provide another type of soft zoom lens whose effective focal length can be tuned without external force. Fig.16. shows one of the new idea, flexible material are used to fabricate the hollow ball lens then filled with the transparent liquid or gel. The structure like human eyes and its shape can be altered by an adjustable ring, thus the focal length will be changed.
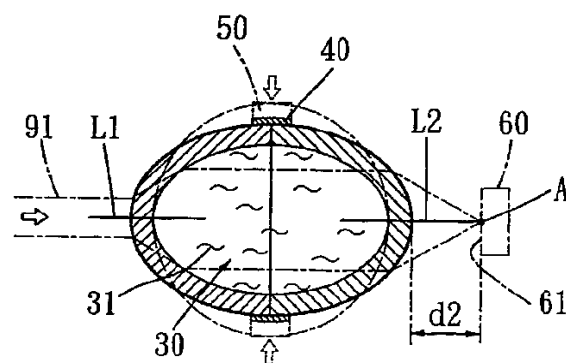

Fig. 16. The structure of artificial eyes.

Another one of the improvement of pneumatic control soft zoom lens is showed in Fig.17. This zoom lens can combine one and above soft lens unit, each unit has at least one soft lens at both end and filled with transparent liquid or gel then seal up. The zoom lens with two and above soft lens unit can be a successive soft zoom lens and the motion is like a piston when the adjustable mechanism is moved, the fluid that filled in the lens will be towed then the lens unit will be present as a concave or convex lens. Due to different combination, the focal length is changed from the original type. Those two type soft zoom lens will be integrated in imaging system which can applied in robot vision.
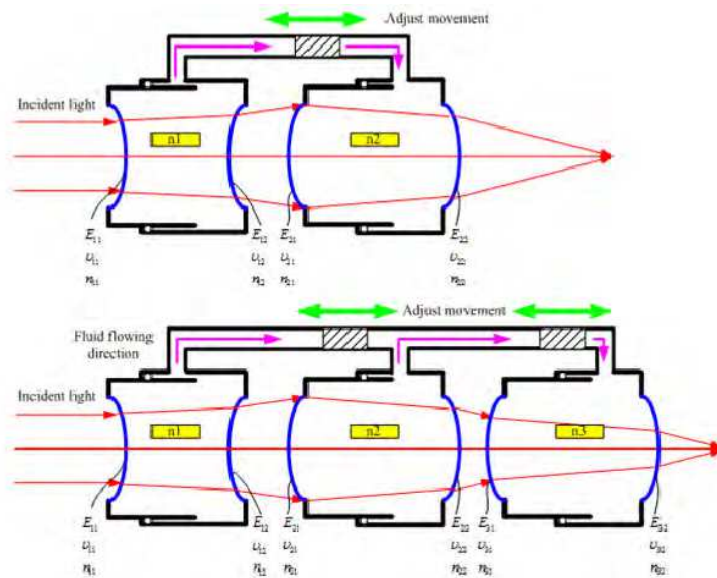
Fig. 17. The structure of successive soft zoom lens.

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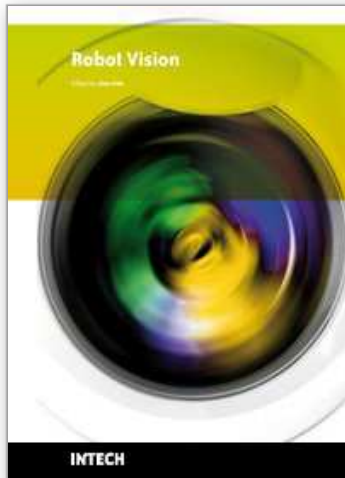
Robot Vision

Edited by Ales Ude

The purpose of robot vision is to enable robots to perceive the external world in order to perform a large range of tasks such as navigation, visual servoing for object tracking and manipulation, object recognition and categorization, surveillance, and higher-level decision-making. Among different perceptual modalities, vision is arguably the most important one. It is therefore an essential building block of a cognitive robot. This book presents a snapshot of the wide variety of work in robot vision that is currently going on in different parts of the world.

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