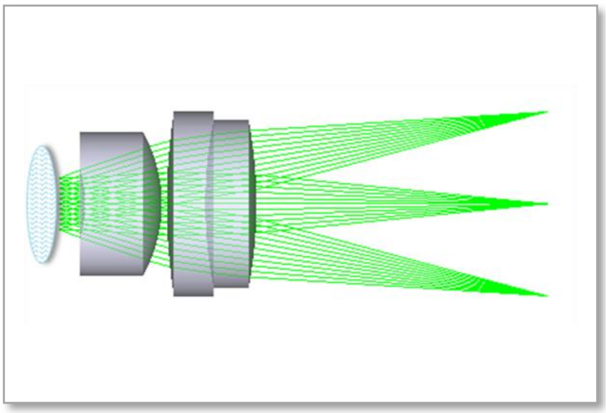
Minimizing thermal defocus effects in liquid lens based autofocus imaging systems using partial passive optical athermalization (PPOA)

Optical imaging systems that use liquid lens modules for autofocus are subject to thermally induced focus variation due to the impact of temperature on the fluid components. This white paper illustrates how to minimize such effects through the application of basic optical imaging principles. In particular, it is shown that, in an arrangement where the liquid lens module is mounted in front of a fixed focus lens, thermal defocus of the final image is minimized when the liquid lens's focal length is set to infinity, and the fixed focus lens is set to focus at some distance other than infinity. In this paper, we refer to such a condition as "partial passive optical athermalization".



1. Introduction

Today's smart miniature imaging systems would consist of a compact variable focus element, which may be a voice coil motor, liquid lens, or perhaps even an electrically variable liquid crystal lens.[1] While the logic for performing autofocus function is provided by an embedded system controller, the compact variable focus element provides the physical means to focus the image produced by a miniature imaging system. In recent times, liquid lenses have been packaged into compact liquid lens modules (LLMs) that are readily available as off-the-shelf commercial products.[2, 3] As such, they are an appealing solution for customized miniature imaging systems that require variable focus control. LLMs are relatively compact, have fast response times, and have high reliability. However, the focal length of liquid lenses are, to a larger degree compared to glass lenses, susceptible to variations in temperature. As a result, the final image formed by an optical imaging system that includes a liquid lens component may shift in its focal position whenever the temperature of the liquid lens changes. If the temperature is time dependent, then so is the thermal defocus, resulting in possible image blur during the course of image capture at the camera's sensor.

In smart cameras, thermal defocus of the image may be compensated through the use of calibration procedures that take advantage of an embedded system controller that would have been integrated with the imaging system. During factory calibration, measured values of the liquid lens's focal length f versus temperature T at a variety of conditions would be stored as look up tables (LUTs) in a system on module (SoM).[4] Calibrated thermistors may be mounted at appropriate locations inside the LLM to measure temperature. During operation of the imaging system, measured temperatures inside the LLM may be fed back into the SoM, which can then apply an algorithm to determine the appropriate liquid lens's focal length for active defocus compensation in response to changes in temperature. The SoM then communicates with driver electronics to make all of the proper focus adjustments.

But perhaps in some other cases, design constraints may prohibit the inclusion of thermistors into the LLM. In such cases, how would one manage thermal defocus effects? In this white paper, we describe how this may be done through the application of basic imaging principles. In particular, we show that in an arrangement where the LLM is mounted in front of a fixed focus lens (FFL) to provide focus adjustment, thermal defocus of the final image is minimized when the liquid lens's focal length is set to infinity, and while in this state, the FFL is set to focus at some distance other than infinity. In this paper, we refer to such a condition as partial passive optical athermalization (PPOA).

2. Optical System Design with Liquid Lens for Variable Focus Adjustment

In this section, we begin with a brief overview of how to integrate a LLM with a FFL (i.e., a lens whose position is fixed relative to the image sensor in a camera). Perhaps the most straightforward way to use a LLM as a variable focus element in an imaging system is to mount the LLM in front of a FFL as illustrated in Fig. 1.[5, 6] The principle of operation for such a configuration is that, as the object is shifted between its near and far positions relative to the imaging system, the liquid lens's front focal length[7] is made to change accordingly such that light from the object emerges as parallel rays from the liquid lens prior to entering the FFL. The rays from the object are then said to be collimated by the liquid lens. In this way, the FFL's focus is fixed at infinity and is said to be operating at "infinite conjugates". The FFL remains at a fixed position and focuses the collimated rays onto the image sensor, which is located at the back focal position of the FFL. The image sensor also remains fixed in its position. In the following section, we shall see that the infinite conjugate arrangement between the LLM and FFL is actually not the ideal optical setup when thermal defocus effects are present.

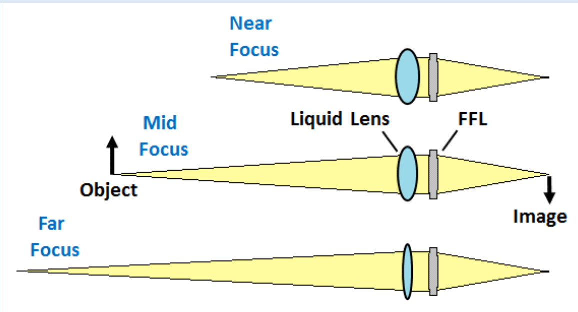


Fig. 1 Focusing with a LLM mounted in front of a FFL using infinite conjugate setup for the FFL.

PARTIAL PASSIVE OPTICAL ATHERMALIZATION

Applying the "chain rule" from calculus, the instantaneous rate of change of back focal distance b with respect to temperature T for a liquid lens based imaging system is

$$\frac{\mathrm{d}b}{\mathrm{d}T} = \frac{\mathrm{d}b}{\mathrm{d}f} \times \frac{\mathrm{d}f}{\mathrm{d}T} \qquad \text{Eq. 1}$$

where f is the focal length of the liquid lens. The quantity $\mathrm{d}f/\mathrm{d}T$ is an inherent property of the liquid lens, but $\mathrm{d}b/\mathrm{d}f$ may be controlled by design. For a system whose liquid lens is mounted closely in front of the FFL, $\mathrm{d}b/\mathrm{d}f$ is

$$\frac{\mathrm{d}b}{\mathrm{d}f} = \frac{F^2}{\left[f - F\left(\frac{f}{S} - 1\right)\right]^2} \qquad \text{Eq. 2}$$

where F is the focal length of the FFL, and S is the object distance. This suggests that $\mathrm{d}b/\mathrm{d}T$ is reduced if f is large, and if $S > F$. As this partially reduces thermal effects on image focus position (and does not involve actively varying f as a function of T), it may be regarded as "partial passive optical athermalization" (PPOA).[8]

3. Applying the Basics: Partial Passive Optical Athermalization (PPOA)

In theory, it is possible to minimize thermal defocus effects even if no active focal length compensation is performed on the liquid lens. As is explained in the colored panel on partial passive optical athermalization (PPOA), image defocus from thermal effects is reduced whenever the focal length of the liquid lens is large. In fact, note from Eq. 2 that $\mathrm{d}b/\mathrm{d}f = 0$ as f approaches infinity, which means that $\mathrm{d}b/\mathrm{d}T = 0$ also in this limit. This suggests that a preferred optical configuration between the LLM and FFL is to set the liquid lens's focal length to infinity at the object's nominal working distance.[13] Under this condition, the liquid lens essentially acts as a simple window through which the FFL looks, and the FFL focuses the transmitted light onto an image sensor located at a fixed distance behind the FFL (Fig. 2b). In Fig. 2b, since the FFL focuses light coming from a finite object distance, it is said to be operating at "finite conjugates". When the object is at the near focus and far focus positions, focusing is performed by setting the liquid lens to have a finite positive focal length when the object is at the near focus position (Fig. 2a), and a finite negative focal length when it is at the far focus position (Fig. 2c). In this way, the nominal WD may be regarded as the mid-focus object position. At this position, $\mathrm{d}b/\mathrm{d}T = 0$ because f is infinite, so the imaging system becomes essentially invariant to small changes in temperature.

As an illustrative concept design example of an imaging system with PPOA, consider the modelled imaging systems shown in Figs. 3a and 3b using the Zemax optical design program[14], where a LLM is mounted in front of a simple compact FFL, whose focal length is 10 mm (i.e., F = 10 mm in Eq. 2). In the Zemax models, the LLM is modelled as a thin ideal lens (i.e.., it is a so-called "paraxial lens model"). As a representative example, we have assumed the use of the Arctic 25H LLM from Varioptic.[2] According to the specifications provided at the Varioptic website, this liquid lens's focal length may be varied from f = –200 mm to infinity, and from f = +77 mm to infinity. In this concept design, the object's nominal WD is chosen to be 250 mm (i.e., S = 250 mm in Eq. 2). Recall that the condition for a PPOA design requires f to be infinite at a chosen nominal WD. In Fig. 3a, f has been set at 10^4 mm, which is virtually "infinite" relative to the dimensions of the imaging system. Additionally, since $S > F$, this system satisfies the PPOA condition. As a comparison, in Fig. 3b, f has been set at 250 mm, which is the "infinite conjugate" setup described in section 2 of this paper, and therefore, does not satisfy the PPOA condition. The optical rays in the figures have been color coded (blue for Fig. 3a and green for Fig. 3b) for purposes of clarity. In Figs. 3a and 3b, the systems are at constant temperature, and the liquid lens focal lengths are unperturbed. In Figs. 4a and 4b, we have assumed that the temperature has changed in such a way that the liquid lens's focal length has increased by 50% (i.e., $f = 1.5{\times}10^4$ mm in Fig. 4a, and $f = 1.5{\times}250$ mm in Fig. 4b). Note that the simulated image in Fig. 4a remains virtually unchanged, while the image in Fig. 4b has been blurred by thermal defocus. Comparison between the two simulated images in Figs. 4a and 4b illustrates that the PPOA configuration in Fig. 4a has reduced sensitivity to temperature variation.

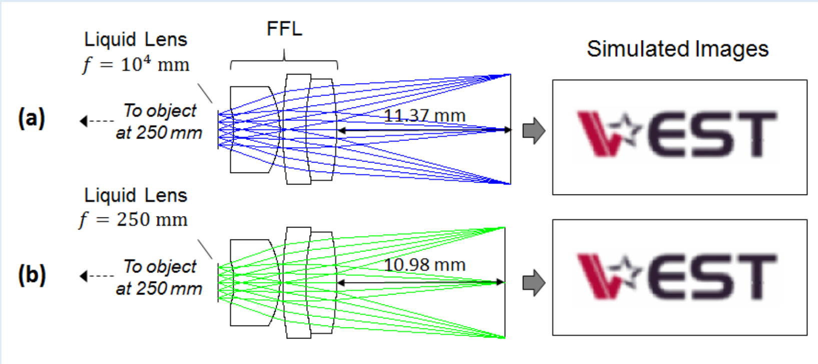


Fig. 3 Image simulation (constant temperature). (a) Finite conjugate setup (satisfies PPOA condition). (b) Infinite conjugate setup (does not satisfy PPOA condition).

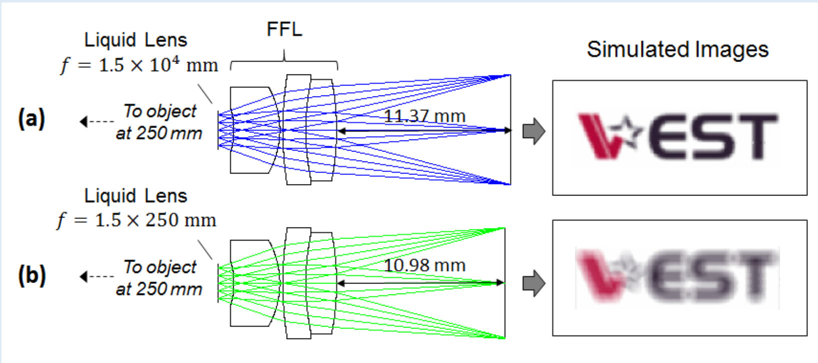


Fig. 4 Image simulation (changed temperature). (a) Finite conjugate setup (satisfies PPOA condition). (b) Infinite conjugate setup (does not satisfy PPOA condition).

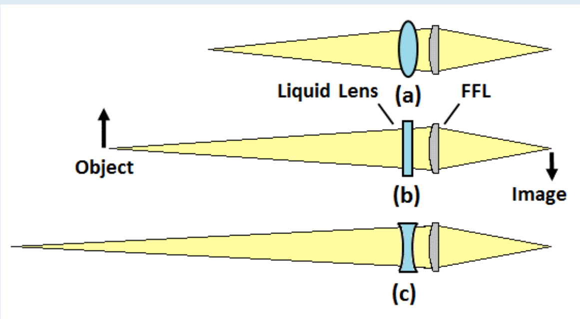


Fig. 2 Finite conjugate setup with LLM in front of FFL. (a) Near Focus. (b) Mid Focus. (c) Far Focus.

4. Conclusion

For imaging systems that use LLMs as variable focus elements without active temperature feedback (such as the use of a thermistor), thermal defocus of the final image is minimized by setting up the FFL to image at finite conjugates, resulting in a partially athermalized system. In this white paper, we have referred to this configuration as partial passive optical athermalization (PPOA).

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1. T. V. Galstian (editor), *Smart Mini-Cameras*, (CRC Press, 2014).

2. See, for example, http://www.varioptic.com/.

3. See, for example, http://www.optotune.com/.

4. For more information about embedded system controllers and SoMs, please visit http://apc-vest.com/

5. See, for example, ref. 1, pp. 149 – 179.

6. E. Simon *et al*., "Optical design rules of a camera module with a liquid lens and principle of command for AF and OIS functions," *Proc. SPIE* **7849**, doi: 10.1117/12.871634

7. We are using the term "focal length" synonymously with the more technical term known as "effective focal length".

8. Minimizing thermal defocus by setting the liquid lens's focal length to some specific value has also been suggested in Optotune's datasheet for their EL-10-30C electrically tunable lens product series (see ref. 3). Although this concept may be regarded as a type of passive optical athermalization for liquid lens systems, it is actually quite distinct from those commonly discussed in available literature where liquid lenses with different thermal properties for their refractive index are carefully chosen such that thermal defocus effects from one lens essentially cancels the effect from another lens (e.g., see Refs. 9 – 11). In other systems, athermalization of liquid lenses is taken to mean the action of actively varying the liquid lens's focal length in response to temperature changes as is discussed in the introduction of this white paper (see also Ref. 12).

9. H. W. Epps and D. G. Fabricant, "Athermalizing Refractive Optics with Fluid Lenses," *Publications of the Astronomical Society of the Pacific* **114** (2002), pp. 1252 – 1259.

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12. J. V. Choudhary *et al*., "Optical Design of Variable Focus Liquid Lens for Camera Phone Application," in International Conference on Optics & Photonics, poster PS2.D.13.

13. We are borrowing the term "working distance" (WD) from machine vision, which refers to the distance between the object and the "front" of an imaging system. The front of an imaging system may be regarded as the front vertex of the first lens of the imaging system, or the front flange of the mechanical housing of the imaging system. In the present context, the "nominal WD" of an imaging system refers to the distance from the front surface of the imaging system to the position where the object ordinarily lies. Hence, the nominal WD is also the object distance for which the lens has been optimized during the process of lens design.

14. www.zemax.com.