A rapidly deformable liquid lens

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A piezoelectric actuator enables fast focusing of imaging systems.

Focusing is an essential function of imaging optics to acquire clear, detailed images. However, this adjustment of conventional systems is slow because of the long response time involved with physically moving lenses. This delay creates a bottleneck in image processing. A better focusing mechanism would permit faster imaging in a wide range of fields, such as microscopy, endoscopy, and computer vision.

One possible solution is to develop a variable-focus device that changes its focal length by deforming a refractive surface. This can result in significant changes with only a slight deformation of the surface, and so it should be possible to control such a small adjustment in a short time. There have been many studies of variable-focus devices using deformation of solid surfaces and liquid-liquid interfaces, and some of them have aimed to achieve a high response speed. However, combining both rapid response and practical imaging performance has proved very difficult.

We have developed a new rapid-response, variable-focus lens device that changes its focal length by deforming a refractive surface. This can result in significant changes with only a slight deformation of the surface, and so it should be possible to control such a small adjustment in a short time. There have been many studies of variable-focus devices using deformation of solid surfaces and liquid-liquid interfaces, and some of them have aimed to achieve a high response speed. However, combining both rapid response and practical imaging performance has proved very difficult.

We have developed a new rapid-response, variable-focus lens device. We used a liquid-liquid interface as the refractive surface because these are known to have an almost perfect spherical shape. We found that we could change and control its shape within a few milliseconds using a stack of piezoelectric actuators to convert tiny electrical currents into motion.

We used an interface with a pinned contact line (such that the boundary of the interface is fixed in a specific position) with an overdamped response to eliminate unwanted vibrations and achieve a fast response time. The interface shape was controlled by liquid pressure generated by a piezoelectric transducer (a stack of piezoelectric actuators) with a faster-than-10kHz response. Our device structure is shown in Figure 1. Two immiscible liquids are located in two chambers connected via a circular hole. A liquid-liquid interface is formed at the hole, which works as an aperture of the lens. This interface works as a refractive surface because of the different refractive indices of the two liquids. Since a vibrating liquid interface in a cylinder behaves like a damped harmonic oscillator, we used highly viscous oil to overdamp the response.

Figure 1. (a) Photograph of the prototype liquid lens. (b–d) Schematic diagrams of its focusing mechanism. PZT: Piezoelectric transducer. \( n_1, n_2 \): Indices of refraction. (© 2009 American Institute of Physics. Reprinted with permission.)

The lower chamber in Figure 1 is equipped with a deformable wall that the actuator pushes to change the chamber’s volume and the interface curvature. Since the working range of the actuator (\( \simeq 10\mu \text{m} \)) is too short to achieve a sufficient range of refractive power, we used a built-in motion amplifier. The area of the deformable wall pressed by the actuator (\( S \)) is much larger than that of the lens surface (\( s \)), so that the change in the lens-surface shape is approximately \( S/s \) times that of the deformable wall. Since this lens morphs its interface dynamically, we call it a ‘dynamorph’ lens.

The prototype achieved practical optical performance. Using a Schack-Hartmann wavefront sensor, we measured a minimum rms wavefront error of 80.3nm. A bar chart with 71.84 line pairs/mm was resolved by the lens with an object-side numerical aperture of 0.045. In addition to its optical performance,
Figure 2. Step response of the prototype. The top image sequence (a) was captured at 2200 frames per second through the prototype lens. (b) Voltage input to the actuator and (c) the resulting position. (d) Focus measures of two regions, the top of the capacitor and the substrate, were extracted from the captured images. (e) The capacitor was 11.6mm in height. (c) © 2009 American Institute of Physics. Reprinted with permission.  

our device is fast. We measured the minimum response time of approximately 2ms by capturing high-speed video images while switching focal length every 10ms. Using a high-speed camera, we were able to capture an image of a capacitor at a rate of 2200 frames per second through our prototype lens (coupled with commercial static lenses). Figure 2 shows the captured image sequence from $t = -2$ to $+4$ms. The results of our work are shown in short videos that are available online.  

In summary, we have developed a dynamorph lens, a high-speed liquid-lens structure driven by a stack of piezoelectric actuators. Our prototype has achieved a 2ms step response time and a minimum rms wavefront error of only 80.3nm. We expect this device to be useful for axial focus scanning for microscopes, focusing and zooming for camera lenses and machine vision systems, and beam-focus control in both laser machining and laser trapping. Presently, the wavefront error is not sufficiently small to achieve high optical resolution, and so we aim to improve the aperture structure to reduce the wavefront error. In addition, we plan to develop a stabilizing mechanism for our proposed structure to prevent temperature drift due to expansion of the liquid volume at higher temperatures.

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References
4. A 0.01s slow-motion movie of the focus switching. Credit: Hiromasa Oka, The University of Tokyo. http://spie.org/documents/newsroom/videos/002505/DMLStepFocusing_SPIENewsroom.mpg