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High-Speed Liquid Lens for Computer Vision

Hiromasa Oku and Masatoshi Ishikawa

***Abstract*— We report a high-speed liquid lens, called a *Dynamorph Lens* (DML), and its applications in the field of computer vision. The developed lens uses a liquid–liquid interface as a variable refractive surface. The interface shape is controlled by the volume of a liquid chamber using a high-speed piezostack actuator. A developed prototype demonstrated both millisecond-order response speed and practical optical performance. A high-speed focusing vision system that can adaptively control its focal length in based on visual feedback by using the DML prototype coupled with a high-speed imager is also proposed. High-speed autofocusing within 15.8 ms and focus tracking of a moving object were demonstrated using the developed system. The DML prototype was also applied to high-speed focus scanning of a camera lens at 500 Hz. An image sequence was captured at 8000 fps through the lens so that every eight images were captured with a different focus, and a 1000 fps video with extended depth of field was successfully synthesized.**

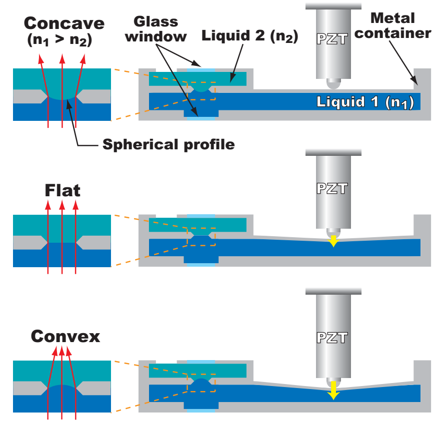

Fig. 1. Schematic cross-sectional view of the ideal structure of the proposed lens, showing (a) convex, (b) flat, and (c) concave lenses.

I. Introduction

A camera lens serves a critical function in computer vision: it projects objects in a three-dimensional scene onto a two-dimensional image plane where a digital imager is placed. Without a lens, the imager could acquire only very blurred, low-resolution images.

Since the camera lens works as an optical filter placed at the first stage of image processing, proper setting of the optical characteristics, such as the angle of view and focal position, is essential for computer vision. In particular, when the scene changes dynamically, as in a vision system mounted on an autonomous robot, adaptive control of the optical characteristics depending on the scene is important to achieve the optimal image processing performance. Furthermore, three-dimensional information, such as a depth image, can be obtained by processing two or more images captured with different focal lengths of the lens [1]. Therefore, dynamic control of the optical characteristics is an important function in computer vision.

However, dynamic lens control has been rarely employed in computer vision systems. The reason is that the response time for changing the optical characteristics is too slow; it takes a considerably longer time ($>$ 100 ms) than the single-frame period ($\sim$ 33 ms) of most conventional imagers. This is a critical bottleneck particularly for visual feedback systems that are commonly used in visual servo control. Therefore, there has long been a need for suitable high-speed optical systems.

With the rapid development of electronic and information technologies, both the frame rate of imagers and image processing speed are becoming faster. Considering recent studies showing that a kilohertz-order feedback frequency is effective for visual feedback systems [2], millisecond-order response time is ideal for adaptive optical systems designed for computer vision.

In this paper, we report a high-speed liquid lens, called a *Dynamorph Lens* (DML), that achieved both millisecond-order response speed and practical optical performance. The developed lens uses a liquid–liquid interface as a variable refractive surface. The surface shape is controlled by the volume of a liquid chamber using a high-speed piezostack actuator. A high-speed focusing vision system that can adaptively control its focal length based on visual feedback using the DML prototype coupled with a high-speed image processor is also proposed. High-speed autofocusing and focus tracking of a dynamically moving object were demonstrated using the developed system. The DML prototype was also applied to high-speed focus scanning of a camera lens at 500 Hz so that one scan took only 1 ms. With this system, a 1000 fps video with extended depth of field was successfully synthesized.

II. Dynamorph Lens

Variable-focus lens technologies have rapidly progressed recently [3], [4]. One of the potential advantages of a variable-focus lens is a high-speed response time. Such lenses can change their focal length in a very short time, because a slight change of the refractive surface shape results in a large shift in focal position.

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H. Oku and M. Ishikawa are with the Graduate School of Information Science and Technology, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan { Hiromasa_Oku, Masatoshi_Ishikawa} @ipc.i.u-tokyo.ac.jp

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Fig. 2. Photograph of the dynamorph lens prototype [5].

TABLE I

SPECIFICATIONS OF THE DYNAMORPH LENS PROTOTYPE.

Lens aperture	3 mm
Deformable plate diameter	24 mm
Liquid 1	Ultra pure water
Liquid 2	Poly-dimethyl-siloxane (PDMS)
Kinematic viscosity (PDMS)	5000 centistokes (cSt)
Refractive index (water)	1.33
Refractive index (PDMS)	1.40

We developed a new liquid lens using a liquid–liquid interface that can arbitrarily control the focal length in milliseconds and achieve practical imaging performance [5]. This lens dynamically changes the curvature of the interface by means of liquid pressure, as shown in Fig. 1. Two immiscible liquids, indicated as liquids 1 and 2, are infused in two chambers, and they are interfaced at a circular hole that functions as an aperture of the lens. This interface works as a refractive surface due to the different refractive indices of the two liquids. One chamber (the lower chamber in Fig. 1) is equipped with a deformable wall that a piezostack actuator (PZT) thrusts to change the chamber volume. When the piezostack actuator extends, the lower chamber volume decreases, and the surplus liquid volume presses the interface to change its shape from convex to concave. Since this lens morphs its interface dynamically, we call it a *Dynamorph Lens*.

Although the displacement of the piezostack actuator can be controlled at a frequency on the order of kilohertz, its stroke is quite short, about 10 μm. Since this is too short to achieve a sufficient range of refractive power, a built-in motion amplifier [6] is used. The area of the deformable wall pressed by the piezostack 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.

When the two liquids have different densities, the interface will be distorted depending on the direction of gravity. The gravity effect can be eliminated by matching the liquid densities [3], [4].

Based on the above design, a prototype with an aperture diameter of 3.0 mm and a deformable-wall diameter of 24.0 mm was developed. Its photograph is shown in Fig. 2, and its specifications are shown in Table I. The density difference between water (0.997 g/cm^3) and PDMS (0.975 g/cm^3) is sufficiently small for the aperture diameter of 3 mm.

Fig. 3 shows optical characteristics of the prototype. Wavefront errors of the prototype were measured with a Shack-

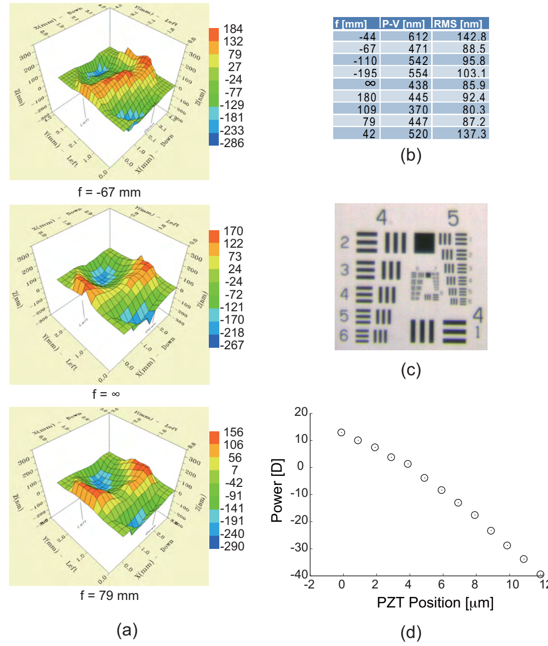

Fig. 3. Optical performance of the prototype [5]: (a) Wavefront-error distribution at the exit pupil of the lens when its focal length f was -67 mm, ∞, and 79 mm. (b) Peak-to-valley (P-V) and root mean square (RMS) wavefront errors. (c) A photograph of a USAF 1951 chart captured by a CMOS imager through the prototype with $f = 80$ mm and object-side numerical aperture of 0.045. (d) Refractive power (inverse of focal length, D = 1/m) versus the displacement of the actuator.

Hartmann wavefront sensor with a metal halide lamp. During the measurement, the prototype was placed vertically with the aperture plane parallel to the direction of gravity; that is, the interface deformation due to gravity was maximum. A practical level of optical performance was confirmed even with the maximum gravity effect.

The response time of the prototype was measured to be about 2 ms by capturing high-speed video through the prototype while switching its focal length every 10 ms. An image of a capacitor was captured by a high-speed camera at a frame rate of 2200 fps through the prototype coupled with three commercial static (non-variable focus) lenses. Figure 4 (a) shows the captured image sequence from $t = -2$ to 4 ms. The focus was initially at the top of the capacitor at $t = -2$ ms. A focus switch instruction was input to the piezostack actuator at $t = 0$ (b), and it responded in about 0.5 ms (c). The image sequence shows that the focus position started to move farther away at about $t = 0.6$ ms and reached the substrate at about $t = 1.5$ ms. As a measure of focus, we adopted the Brenner gradient [7]:

$$B = \Sigma_i^N \Sigma_j^M [I(i,j) - I(i+m,j)]^2 \qquad (1)$$

with $m = 2$. Here, B is a numerical index of the amount of detail included in the digital image. A large B means that the area of the summations included in the calculation of B is in focus. To show the focus shift quantitatively, two focus measures were calculated for two different areas of the captured image: the top of the capacitor and the substrate. The profile of the focus measures also showed the 1.5 ms response of the focus switching (d). The distance from the substrate to the top of the capacitor was 11.6 mm (e).

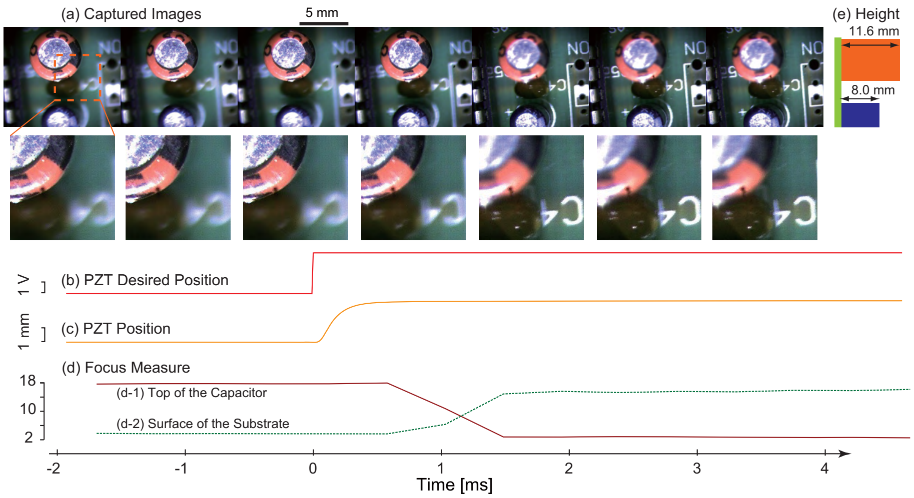

Fig. 4. Step response of the prototype [5]. (a) Image sequence captured at 2200 fps through the prototype. (b) Voltage input to the actuator and (c) resulting position. (d) Focus measures (Brenner gradient—see text) of two regions, the top of the capacitor and the substrate, extracted from the captured images. (e) The capacitor was 11.6 mm in height.

In summary, the prototype DML achieved both practical optical performance and a high-speed response time of 2 ms.

III. High-Speed Focusing Vision System

A computer vision system equipped with the DML can dynamically control its optical characteristics based on acquired images. In particular, if the total period for image acquisition and processing is matched with the response time of the DML, dynamic and adaptive control of the optical characteristics can be achieved without any loss of bandwidth. Thus, we propose a new vision system, called the *high-speed focusing vision system*, composed of high-speed image processing technology and a high-speed lens system based on the DML. State-of-the-art high-speed computer vision systems can acquire and process one image in 1 ms[8], which is almost matched with the period of the lens system ($\sim$ 2 ms).

The high-speed focusing vision system can control its focal position quickly and adaptively depending on the dynamic scene. High-speed zooming is also possible if two or more DMLs are combined and controlled simultaneously. This function is ideal for robot vision because the scene to be recognized tends to change dynamically and quickly with the motion of the robot itself, and also, a high visual feedback rate is essential for stable and prompt control of robots.

IV. Experiments

A. Setup

A prototype of the high-speed focusing vision system was developed for experiments. The system is composed of an imaging optical system with a DML, a high-speed image processor system for high-speed visual feedback, a high-speed camera to record images at high frame rate for monitoring, and a personal computer (PC) to control the whole system.

The imaging optical system was designed using ZEMAX (optical CAD software) so that it worked as a macro lens

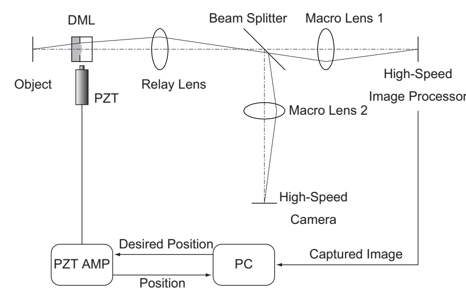

Fig. 5. Schematic diagram of the system connection and the imaging optics of the developed high-speed focusing vision system. PZT: piezoelectric actuator, PZT AMP: PZT driver, PC: control computer.

whose focal length could be controlled by the DML. Fig. 5 shows the optical configuration and the system connection of the developed system. The high-speed image processor and the high-speed camera were mounted coaxially using a beam splitter so that both cameras acquired images at the same focus depth.

A Column Parallel Vision 4 (CPV4) system was adopted as the high-speed image processor [9]. The CPV4 is an image-transfer-type high-speed image processor system using a gray-scale CMOS imager; it has a frame rate of 1000 fps when the region-of-interest (ROI) is set to 128×128 pixels. The imager is coupled with 128×128 programmable processing elements (PEs). The PEs are controlled in a single-instruction multiple-datastream (SIMD) fashion. The CPV4 can also output the captured or processed images via a camera link interface. In this experiment, the original images were directly output to the personal computer (PC), described below.

A Phantom V 4.3 camera (Vision Research) was adopted as the high-speed camera for monitoring. This camera can record 512×512 pixel color images at a frame rate of 2200 fps and starts recording in response to an external trigger signal.

A PC (Windows XP, Xeon 2.8 GHz processor) was used

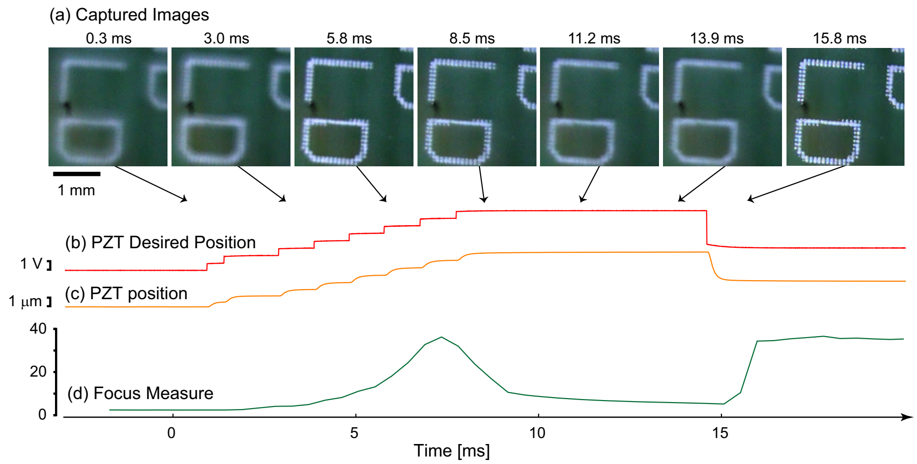

Fig. 6. Experimental results for high-speed autofocusing of an electronic substrate. (a) Image sequence captured by the high-speed camera at 2200 fps. (b) Instruction voltage input to the piezostack actuator. (c) Displacement of the actuator measured by a built-in sensor. (d) Focus measure (Brenner gradient) calculated by the PC.

for image processing and DML control. The images captured by the CPV4 were input via the camera link interface. The PC was also equipped with a D/A converter board to send a voltage instruction to the amplifier of the piezostack actuator. Although this PC needs to process images every 1 ms, the time resolution achievable in Windows XP is coarser even when using a high resolution timer (minimum resolution of 1 ms), and it failed to maintain the timing at a rate of about once every ten cycles. Thus, precise timing was measured with a data logger NR-600 (Keyence) instead. This data logger logged the desired position of the piezostack actuator, its actual position measured by a built-in displacement sensor, and the trigger signal input to the high-speed camera as an analog voltage.

The DML prototype was driven by a piezostack actuator (P-841.10, Physik Instrumente) with a working range of 15 μm and a natural frequency of 18 kHz.

B. High-Speed Autofocusing based on Contrast Measurement

Autofocusing is an essential function for modern imaging systems. There are several ways to realize an autofocus function. One common method is contrast measurement, which finds the best focus position by detecting the maximum contrast of images. This technique is commonly used in video cameras and digital cameras.

The contrast method needs to acquire two or more images at different focus positions and evaluate their contrast. Since the focusing speed of conventional optical systems is slow, the autofocusing process tends to take a long time (typically $\sim$ 1 s). This problem could be solved by our high-speed focusing vision system. Thus, we implemented the contrast method of autofocusing in the prototype system.

As a measure of focus, we adopted the Brenner gradient B shown in (1). It is empirically known that the Brenner gradient profile can be approximated by a Lorenz function when the focus is near the correct focus [10]:

$$B(z) \simeq \frac{\alpha}{\beta + (z - z_0)^2} \qquad (2)$$

where z is the the object plane depth, z_0 is the depth of the object, and α and β are parameters depending on the environment, such as the texture of the object etc. Note that the reciprocal of B is a quadratic function of z with its vertex at $z = z_0$.

The autofocus algorithm is as follows:

1) Set the object plane at the nearest point.
2) While scanning the object plane from near to far with the DML, capture object images with the CPV4. (In practice, the focus measure of each image was extracted in real time at almost 1000 fps.)
3) After the focus scanning, detect the maximum focus measure from the profile of the focus measures by fitting the profile using (2). Then, instruct the piezostack actuator to move to the estimated best-focus position.

There were time delays due to the response time of the DML and the image transfer from the high-speed vision system to the PC memory. Since there was no focal-length sensor in the DML prototype, the PC could not determine the actual focal length of the DML, i.e. the object plane position. Thus, these delays were estimated in advance, and the object plane positions were estimated based on these delays and the instruction sent to the DML.

Fig. 6 shows the result of the autofocusing when the object was the surface of an electronic substrate. The focus scanning process started at $t = 0$ ms and finished at around $t = 14$ ms. The peak of the focus measure was observed at about $t = 7.5$. After the focus scanning process, the focus was controlled to the estimated correct focus position. The entire autofocus process finished at $t = 15.8$ ms. Note that the total autofocus period of 15.8 ms is shorter than the typical frame period (30 to 40 ms) of conventional vision systems.

C. Focus Tracking

Next, a dynamic focus control experiment was conducted. The purpose of this experiment was to track the correct focus for a dynamically moving object.

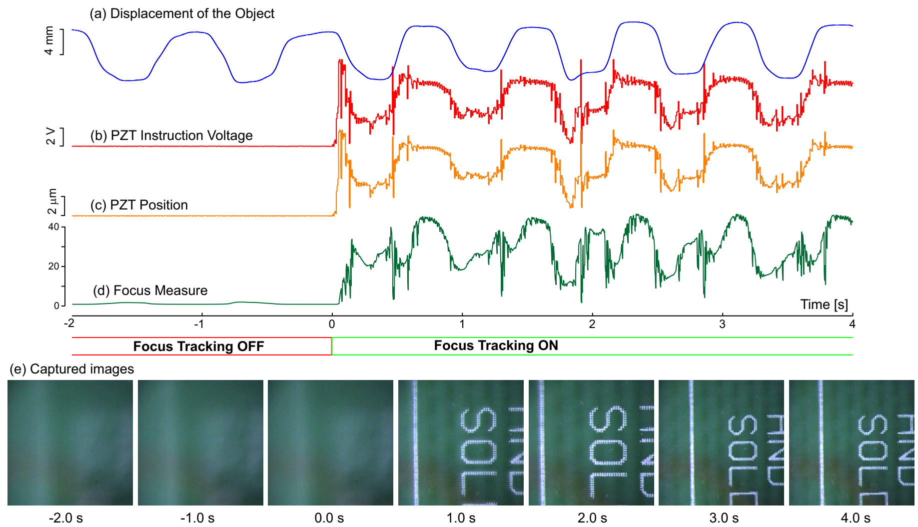

Fig. 7. Results of the high-speed focus tracking experiment: (a) Depth of the substrate. (b) Instruction voltage for the piezostack actuator. (c) Displacement of the actuator. (d) Focus measure (Brenner gradient). (e) Images captured by the high-speed camera at 200 fps.

For this purpose, a quick estimation of the target depth is important. Thus, we developed a technique that vibrates the object plane position around the target. Three images were captured at near, correct, and far focus positions and their focus measures were measured to estimate the object's depth. Then, the center of the vibration was adjusted to be the object position estimated from the latest three focus measures.

The detailed algorithm is described here. The depth of the object plane at step k is denoted as z_k.

1) Capture an image I_k at depth z_k, and extract its focus measure B_k. (The Brenner gradient was used as the focus measure.)
2) Estimate the object depth $\hat{z}_k$ from the last three depths z_{k-2}, z_{k-1}, z_k and the corresponding focus measures B_{k-2}, B_{k-1}, B_k. (We assumed the Lorenz function relation (2) for the estimation.)
3) Set the next object plane depth z_{k+1} as follows:

$$z_{k+1} = \begin{cases} \hat{z}_k & (k \bmod 3 = 0) \\ \hat{z}_k + \delta z & (k \bmod 3 = 1) \\ \hat{z}_k - \delta z & (k \bmod 3 = 2) \end{cases} \quad (3)$$

where δz is the amplitude of the vibration of the object plane for stable depth estimation. Without the vibration, the estimation becomes unstable when the target stops, since the three pairs of values (z, B) become almost the same vector and the estimation becomes very sensitive to the noise included in the focus measures.
4) Increment k and go back to 1).

In this algorithm, the movement of the moving object is assumed to be negligible. This assumption is valid when the target movement during one step is sufficiently smaller than δz.

In this experiment, the electronic substrate serving as the object was fixed on a manual linear stage along the optical axis of the high-speed focusing vision system. The depth of the substrate was measured by a laser displacement sensor (LK-G155, Keyence) whose output was recorded by the data logger.

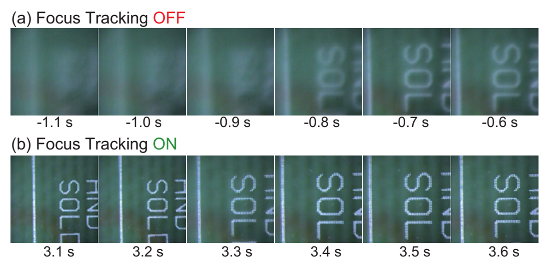

Fig. 8. Image sequences captured with focus tracking control turned off (a) and on (b).

Each cycle of the algorithm was processed every 5 ms. The object depth was estimated from the last three focus measures obtained in the last 15 ms. A small shift δz was realized by using an instruction voltage shift of 0.2 V; δz was about 0.2 mm in the setup. Thus, the shift speed of the object plane was about 40 mm/s ($= 0.2/0.005$). To neglect the object movement, the object speed should be slower than 40 mm/s.

Experimental results of focus tracking are shown in Fig. 7. The focus tracking was started at $t = 0$. From the images captured by the high-speed camera (Fig. 7), the image was successfully kept in focus.

Fig. 8 shows two image sequences: one was captured when the focus was fixed (a), and the other one was captured when the focus tracking was enabled (b). They were recorded with almost identical trajectories of the object's depth. The object images were kept in focus with focus tracking (b), whereas all images were blurred without focus tracking (a).

With our algorithm, image sets formed of one correctly focused image and two slightly defocused images are repeated in a recorded image sequence. If a focused image

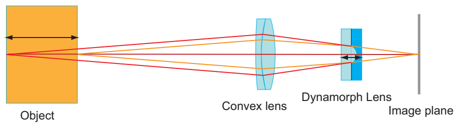

Fig. 9. Schematic diagram of the developed variable-focus camera lens using the DML [11].

sequence is needed, it can be obtained by selecting every third focused image and discarding the other two defocused images, and outputting the selected images with a three times longer duration (15 ms).

V. Focus Stacking of High-Speed Phenomena

Here, another experimental result without high-speed visual feedback is described. Focus stacking is an image synthesizing technique for extending the depth of field of images. A series of images captured at different focus positions is used as source images. For each pixel, or small region, the source image that includes the best focus for the pixel or region of interest is found. By synthesizing an image from the pixels or the regions that show the best focus for each region, an entire in-focus image is obtained.

Since focus stacking needs an image sequence captured at different focus positions, and this process is slow with the conventional lenses, as described above, focus stacking has been applied to only stationary targets. This problem can also be solved by using our DML [11].

A camera lens system composed of a solid convex lens and the DML prototype was developed (Fig. 9) to enable rapid focusing. The Phantom V4.3 high-speed camera (Vision Research) was mounted to record images at 8000 fps. A 500 Hz triangular wave was input to the piezostack actuator to shift the object plane from one end of the object to the other end in 1 ms.

Because the scanning speed was quite fast, focus stacking could be applied to the images captured by this lens system even when the object was dynamically moving. As the dynamically moving object, six pieces of string were employed. Weights were fixed at the ends of each string so that they swung back and forth.

Every 1 ms, eight images at different focus positions were obtained. By applying focus stacking to each set of eight images, a 1000 fps completely in-focus movie with extended DOF was obtained. Free software called Combine ZM [12] was used to synthesize the images.

The results are shown in Fig. 10. Extended DOF was confirmed from the focus-stacked images even when the targets were dynamically moving.

VI. Conclusion

In this paper, we reported a high-speed liquid lens, called a *Dynamorph Lens* (DML), and its applications in the field of computer vision. A developed prototype demonstrated both millisecond-order response speed and practical optical performance. A high-speed focusing vision system that can adaptively control its focal length based on visual feedback using the DML prototype coupled with a high-speed imager is also proposed. High-speed autofocusing within 15.8 ms and focus tracking of a moving object were demonstrated using the developed system. The DML prototype was also applied to high-speed focus scanning of a camera lens at 500 Hz. An image sequence was captured at 8000 fps through the lens so that every eight images were captured with a different focus position, and a 1000 fps video with extended depth of field was successfully synthesized from these images.

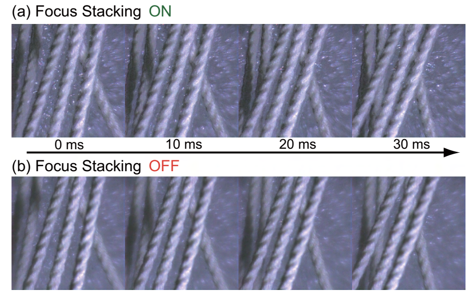

Fig. 10. Focus stacking results of swinging strings [11]: (a) 1000 fps images with extended DOF, and (b) 1000 fps images captured with a fixed focus position.

VII. Acknowledgments

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