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Invited

Arbitrary Focusing based on Nano-Second Multi-Exposure and TAG Lens

Hiromasa Oku[1], Kazuki Yamato[1,2], Keita Yasutomi[3], and Shoji Kawahito[3]

h.oku@gunma-u.ac.jp
[1]Graduate School of Science and Technology, Gunma University, 1-5-1 Tenjin-cho, Kiryu, Gunma 376-8515, Japan
[2]Graduate School of Regional Development and Creativity, Utsunomiya University, 7-1-2, Yoto, Utsunomiya, Tochigi 321-8585, Japan
[3]Research Institute of Electronics, Shizuoka University, 3-5-1 Johoku, Nakaku, Hamamatsu Shizuoka 432-8011, Japan
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ABSTRACT

This paper reports imaging methods using a resonant type liquid lens and nano-second multiple-exposure. The response time of focusing is negligible, which makes it possible to adjust the focal length at each frame, and to capture multiple focal plane images simultaneously using multi-tap lock-in pixel image sensor.

1 INTRODUCTION

A conventional vision system consists of an optical system and an image sensor, in which the optical system performs the function of projecting light sources distributed in a three-dimensional (3D) space onto a two-dimensional (2D) plane. An image can be acquired by measuring this projected light intensity distribution with a 2D image sensor. Since this projection function can be achieved by using a pinhole alone, a refractive optical element such as a lens is not always necessary, but only an aperture, that restricts the light passing through it, is essentially necessary. However, since pinholes alone provide only a very low amount of light, most cameras in the real world use lenses to collect more light. However, by using a lens, the camera can focus only at a limited distance, and therefore manual or automatic focus adjustment mechanisms are required.

However, the response time of the conventional focus adjustment mechanism is relatively slow, and it was especially difficult to change the focal length for each frame of image sensor.

This paper presents an imaging method using a tunable acoustic gradient index (TAG) lens with a resonant frequency of several tens kHz, and multiple exposures of several hundreds ns. Since the response time of the focal length can be regarded as practically zero, the proposed method makes it possible to adjust the focal length at each frame, and even to capture multiple focal length images simultaneously within one frame using a multi-tap lock-in pixel image sensor.

2 TAG LENS

Since the methods described in this paper relies on a device called a tunable acoustic gradient index (TAG) lens, we explain this device first.

A TAG lens is a kind of liquid lens that can oscillate the focal length at frequencies from several tens of kHz to several hundreds of kHz[1]. This device excites the resonance of axisymmetric density waves (ultrasonic waves) in a transparent liquid sealed in a cylindrical container, and the generated axisymmetric refractive index profile works as a lens. When an appropriate vibration mode is selected, the refractive index profile becomes a single-mode vibration that is an axisymmetric Bessel function, and the refractive index distribution $n(r,t)$ inside the medium is as shown below.

$$n(r,t) = n_0 + n_a J_0\left(\frac{\omega r}{v}\right)\sin\omega t\ , \qquad (1)$$

where t is time, r is radial distance from the axis of symmetry, n_0 is the static refractive index, J is a Bessel function of the first kind, ω is angular frequency and v is the speed of sound in the medium. The constant n_a depends on ω, the physical properties of the acoustic medium (the initial refractive index, the speed of sound and the effective kinematic viscosity), and the peak inner-wall velocity.

In the vicinity of the axis, Eq.(1) can be approximated as

$$n(r,t) = n_0 + \left(n_a - \frac{n_a\omega^2}{4v^2}r^2\right)\sin\omega t\ . \qquad (2)$$

The effective lens power $\delta(t)$ for the TAG lens can be denoted as

$$\delta(t) = \frac{Ln_a\omega^2}{2v^2}\sin\omega t, \qquad (3)$$

where L corresponds to the length of the TAG lens.

However, TAG lenses cannot be fixed at a specific focal length because of the resonance phenomenon. This property makes it particularly difficult to capture images at a specific focal length. Assuming that the resonant frequency is 69 kHz, the period of one cycle is about 14.5 μs. If we want to take images only at a specific focal length from this oscillation, it is necessary to take images at an exposure time sufficiently shorter than 14.5 μs at the moment of the specific focal length. However, such a very short exposure time does not produce an image with a practical brightness. Because of this problem, the use of TAG lenses for image formation has not been common in the past.

3 PRINCIPLE OF ARBITRARY FOCUSING

Multiple exposure is one of the methods to capture

images with practical brightness using TAG lens[2].

Let's consider a camera that can make multiple exposures synchronized with external signals during the taking of a frame. The multiple exposures are scheduled at when the focal length is a specific focal length to capture the image with the focal length. Here, we consider that the image is being captured at 1000 fps and the duration of one frame is 1 ms. When the focal length is oscillating at 69 kHz, the focal length moves back and forth 69 times within 1 ms. Except for the apex of the vibration, it passes through a specific focal length once on the way and once on the way back, which results in 138 passes in 1ms, twice as many as 69. Thus, the camera can do 138 multiple exposures at the given focal length. By accumulating faint photoelectrons at each pass, the brightness of the image can be enhanced. Fig.1 shows the schematic figure of this principle.

The in-focus position can be selected by the timing of the exposures. Thus, the focal length used for imaging can be changed within the oscillation period. Since this period is quite short, such as 14.5 μs in the case of 69 kHz, the response time of the focal length can be regarded as practically zero. And the camera can select arbitrary focal length in frame-by-frame manner.

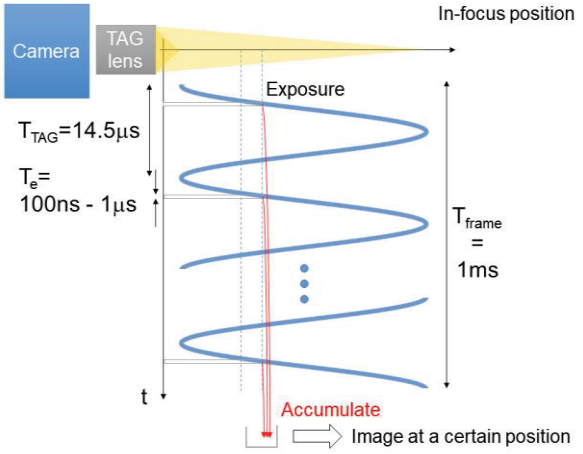

Fig. 1 Principle of focus selection by exposure timing

4 EXPERIMENTS

In order to realize the above principle, a camera that allows the timing of multiple exposures to be freely specified is necessary. However, there is no conventional camera that satisfies this function. Thus, we have developed and used special imaging devices. Here, we explain the two results. One was to modify an existing camera to enable multiple exposures at arbitrary times, and the other is to use a multi-tap lock-in pixel image sensor, which was originally developed mainly for a TOF sensor.

4.1 Temporally Coded Exposure Camera and its application to 3D tracking of swimming cell

Temporally Coded Exposure (TeCE) camera[2] was a camera that had been modified from an existing image sensor to enable multiple exposures in response to an input signal from external sources. The exposure signal was generated in an FPGA in synchronization with the trigger signal output from the TAG lens to enable frame-by-frame imaging at an arbitrary focal length. The developed TeCE camera had the pixel size of 640x480, monochrome, and the maximum frame rate of 1000 fps. Furthermore, the TeCE camera was able to directly transfer images acquired at 1000 fps to the memory of the computer (PC), so that the visual information can be processed in real time with the rate of 1000 Hz.

To demonstrate the validity of the TeCE camera, it was applied to 3D tracking of a freely swimming cell[3].

First, we introduced a TAG lens into the relay lens system of a microscope and developed a high-speed 3D camera module composed of a TeCE camera and a TAG lens as shown in Fig.2(a). This module was able to be connected to the camera port of an optical microscope to change the focus position to an arbitrary position in each frame. It also enabled us to measure three-dimensional information of an object at high speed by adopting appropriate image processing algorithm.

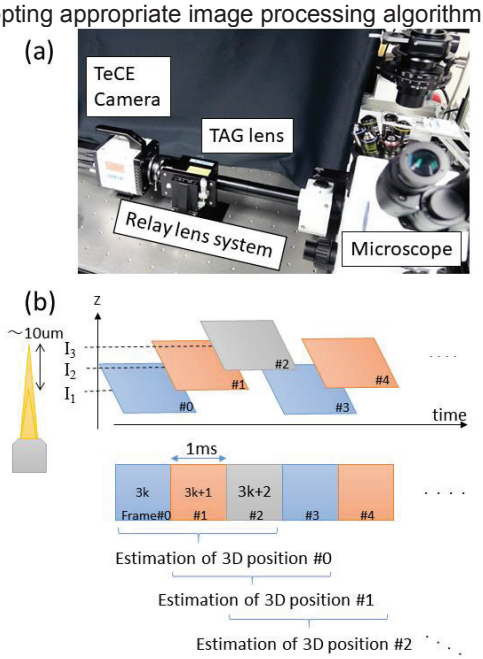

Fig. 2 Photograph of the developed 3D tracking microscope system (a) and schematic figure of 3D estimation algorithm (b)[3]

In order to measure 3D position of a cell, the focus position was changed at each frame, as shown in Fig.2(b), in the order of bottom, middle and top. If a set of three images taken, the set always contains one image each from the top, middle and bottom positions. Although the measurement time of each image differs, it

is possible to estimate the 3D information of the object from these three images assuming that the object hardly moves in 3 ms. In fact, this condition was mostly satisfied with the *Chlamydomonas*, which was a kind of motile cell used in this study.

Based on the above method, 3D tracking of *Chlamydomonas* was successfully achieved with bright-field and phase-contrast observation methods. The 3D position of the target was estimated from the information on the distribution of focus and the center of gravity in the three images. The specimens were placed in a container with the culture medium, and the position of the container was controlled by a motorized stage with XYZ axes so that the target was always kept in the center of the field of view volume to realize 3D tracking.

Fig.3 shows the image sequence during the tracking using the phase contrast method and the three-dimensional trajectory obtained from the tracking results. In our experiments, we also succeeded in tracking the specimens by bright-field observation, showing that we can change the illumination method by changing the processing algorithm.

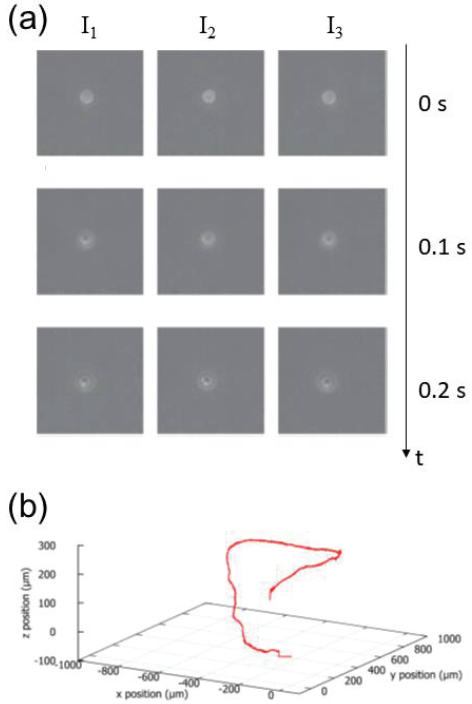

Fig. 3 Image sequence while tracking the specimen with phase contrast method (a) and its reconstructed 3D trajectory (b)[3]

4.2 Simulfocus Imaging

Next, we introduce a quasi-simultaneous multi-focus imaging technique named Simulfocus Imaging[4], [5]. This technique was developed for measuring an entire object distributed in the depth direction beyond the depth of field (DOF) with high resolution in a single shot.

Simulfocus imaging can acquire multiple focal planes in one shot by synchronizing a TAG lens and a multi-tap lock-in pixel image sensor[6]–[8].

The multi-tap lock-in pixel image sensor is a special image sensor that can execute multiple exposures at an arbitrary timing during a single shooting, just like the TeCE camera. In addition to this, the sensor includes a number of photoelectron storage units called TAP in each pixel, and the destination unit can be freely selected for each exposure. Since one image can be acquired for a single storage unit, and the image sensor has a number of storage units, the multi-tap lock-in pixel image sensor can acquire multiple images in one shot. By assigning a specific exposure timing to each unit and synchronizing the exposure timing with the focus fluctuation of the TAG lens, it is possible to simultaneously acquire images in different focal planes.

Fig.4 shows a conceptual diagram of Simulfocus imaging. This figure represents the synchronization between the focus fluctuation of the TAG lens and the multiple exposures of the lock-in pixel image sensor. Note that the case where the number of taps of the lock-in pixel image sensor is four is shown as an example.

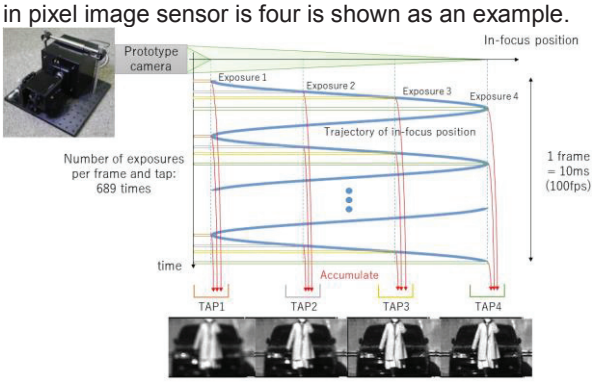

Fig. 4 Schematic diagram of Simulfocus Imaging[4]**. In this figure, 4-tap lock-in pixel image sensor with 100 fps, which was used in our experiments, is assumed.**

Simulfocus imaging was evaluated in the telescope and microscope configuration.

In the telescope configuration, the measurement objects were cards displaying numbers, held by 4 persons, as shown in Fig.5(a), and the Fig.5(b) shows the results. The lower images in Fig.5(b) show images obtained by applying an edge detection filter to the upper images, as the evaluation criteria of the degree of focus. As shown in Fig.5(a), the edge of the card displaying "1st" was detected in the edge detection result of TAP1. In the same manner, the edges of the cards displaying "2nd", "3rd" and "4th" were detected in TAP2, TAP3, and TAP4, respectively. Therefore, different focal planes could be acquired for each TAP.

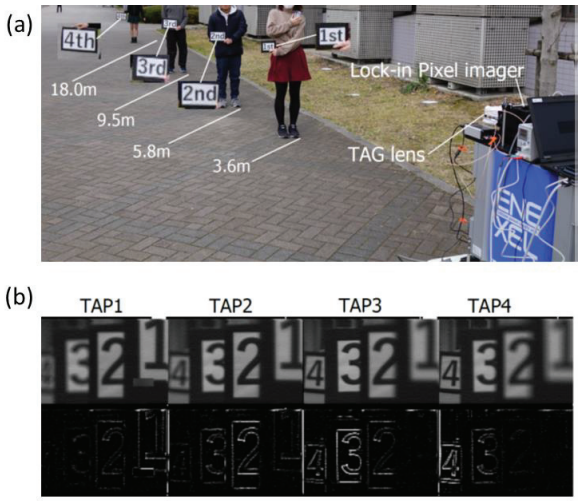

Fig. 5 Simulfocus Imaging with telescope configuration[4]**. A photograph of the experimental setup (a) and the captured image by the lock-in pixel image sensor (b). The lower row in (b) shows the extracted edge of the captured image to indicate in-focus places.**

In the microscope configuration, the TAG lens was placed into the relay lens system which transport magnified image by microscope to the image sensor. Freely swimming cells, *Chlamydomonas*, were observed with the objective lens of the magnification of 50 times using bright field illumination. Four images with different depth were quasi-simultaneously captured as shown in Fig.6. Four images with different in-focus position were successfully captured at the same time.

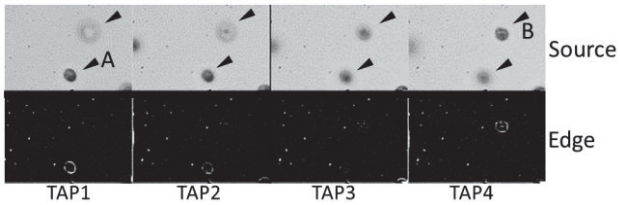

Fig. 6 Simulfocus Imaging of cells (*Chlamydomonas*) with microscope configuration[4]**. While the cell indicated as A is in-focus in TAP1, the cell B is in-focus in TAP4.**

In this paper, we have presented only the still images, but it is also possible to take movies. Demonstration videos of cells, humans, and other subjects are available on YouTube[1].

5 CONCLUSIONS

This paper explained a quasi-arbitrary focusing method using a TAG lens and multiple exposures of several hundreds ns. As applications of this method, high-speed focus switching applied to 3D tracking of a cell and Simulfocus Imaging were described.

[1] https://youtu.be/3Vt9jv77MDc

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