JMEMS Letters

Flexible Miniaturized Camera Array Inspired by Natural Visual Systems

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***Abstract*— We report on a flexible microcamera array inspired by natural visual systems. The camera array is a hybrid artificial visual system that combines the large field of view (FOV) of compound eyes together with the high resolution of mammalian eyes. The camera array allows for maximum flexibility and instantaneous reconfigurability to observe a wide FOV. The microcamera array takes advantage of different fabrication techniques including 3-D printing and ultraviolet (UV) liquid phase photopolymerization, as well as utilizing flexible polymers. The array consists of three miniature cameras, each composed of a 1 mm^2 stand-alone image sensor and a 0.9-mm-diameter microlens. The lenses were fabricated by utilizing the surface tension of UV curable transparent polymers on Teflon coated substrates. The structure of the array was fabricated using 3-D printing. The miniaturized cameras were connected by a flexible and stretchable polymer. Images from the cameras in the array were stitched together to provide an FOV of 130°. [2013-0242]**

***Index Terms*— Compound eye, miniaturized camera array, liquid phase photopolymerization, microlens, flexible electronics.**

I. Introduction

NATURE has been a vital source of inspiration to many researchers in the field of optics due to the plethora of natural visual systems [1]. The most common visual systems include the mammalian eyes and the apposition compound eyes of insects [2]. The mammalian eyes, also referred to as camera type eyes, are a single aperture imaging system with one multi-pixel photosensor [1]. The main advantage of the mammal eye is the high resolution achieved when compared with compound eyes [2]. The apposition compound eye consists of a large number of distinct optical systems called ommatidia arranged on a curved surface. Each ommatidium comprises of a lens, a rhabdom for guiding the incoming light, and a photoreceptor cell [1], [3]. In analogy, the apposition compound eye can be thought of as an array of 1-pixel cameras on a spherical surface [4]. The compound eye offers a large field of view (FOV), superior motion detection, and extended depth of field at the expense, however, of low spatial resolution [5]–[9].

Most of the current research on imaging systems at the microscale has been inspired by compound eyes in an effort to realize artificial compound eye systems, which could potentially be used in many fields including security and surveillance, machine vision, or medical procedures [5], [10]. The reasons behind this effort is that compound eyes are considered the smallest known natural visual system, allowing for parallel image processing, and having a very low power consumption [11]. The main casualty of such an effort would be the resolution which is inherently low in compound eyes.

Based on the description of both visual systems above, it can be deduced that the optimal imaging system would be an artificial system that combines both the merit of large FOV inherent in compound eyes and the merit of high resolution inherent in camera type eyes. With the recent advent of ever smaller stand-alone image sensors [12], such a system can be realized. In this letter, we utilized these recent capabilities of miniaturized image sensors and integrated them with flexible polymers to realize a flexible miniaturized camera array inspired by both compound eyes and camera type eyes. The miniaturized camera array is integrated with a flexible polymer allowing for instantaneous variation in the FOV. This flexible miniaturized camera array achieves a large FOV using only a fraction of the number of cameras otherwise needed in a large non-flexible array.

Manuscript received July 31, 2013; revised September 20, 2013; accepted September 27, 2013. Date of publication October 17, 2013; date of current version November 25, 2013. This work was supported by the U.S. National Science Foundation through the Emerging Frontiers in Research and Innovation program under Grant EFRI 0937847. The work of B. Aldalali was supported by Kuwait University through its graduate student scholarship program. Subject Editor J. A. Yeh.

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Digital Object Identifier 10.1109/JMEMS.2013.2284406

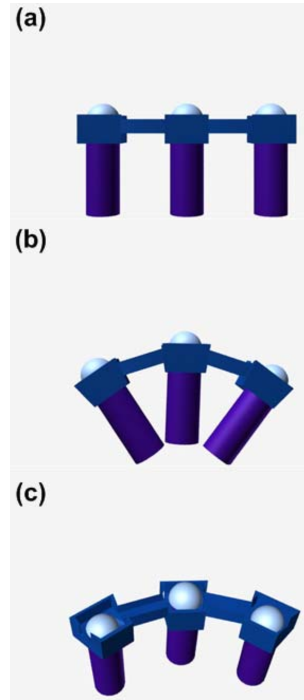

Fig. 1. Layout of the flexible miniaturized camera array. (a) Camera array is on the same plane. All cameras are aligned vertically. (b, c) Camera array is flexed into different configurations to increase the FOV.

II. Principle and Structure

Fig. 1 shows different configurations of the miniaturized camera array structure. The array consists of three 3 mm × 3 mm camera brackets shown in blue connected by 3-mm thin plastic bridges. The camera brackets along with the mold for the bridges were fabricated

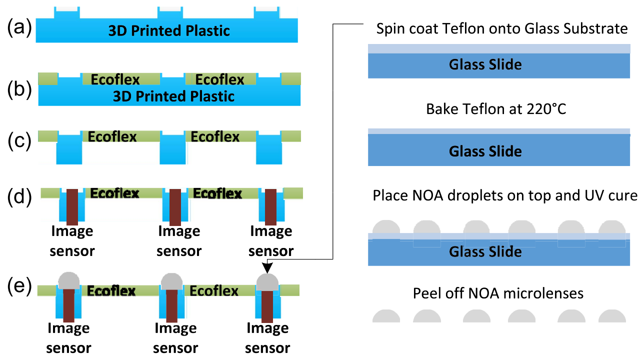

Fig. 2. Fabrication process of our flexible miniaturized camera array. (a) Structure is fabricated using a 3D printer. (b) Ecoflex is poured onto the area surrounding the image sensors as well as onto the connecting bridges between the image sensors. (c) Structural bridges are removed by cutting away the bridge edges. (d) Image sensors along with their fiber connections are attached to the structure. (e) NOA microlenses are placed on top of each of the image sensors. The NOA microlenses are fabricated as per the inset shown on the right.

by utilizing the technique of 3D printing (rapid prototyping). The fabrication method of the microlenses was chosen based on the requirement for a wide angle lens for each camera in the array. A wide angle lens would minimize the number of cameras required to achieve a certain FOV. Images from each of the cameras in the array can then be stitched together to provide a panoramic view [13].

III. Fabrication

The fabrication process is divided into two sub processes: the fabrication of microlenses and that of the camera array structure.

A. Lens Fabrication

The microlenses were fabricated by ultraviolet (UV) curing of a photopolymerizable prepolymer NOA 73 (Norland Products, Cranbury, NJ, USA) [14]. NOA 73 is a UV curable optically transparent adhesive which is not very viscous. Fig. 2 (on the right) shows the fabrication process of the NOA microlenses. Teflon (Dupont, Wilmington, Delaware, USA) was spun onto a glass substrate at 500 rpm for 40 s to provide a thin hydrophobic layer. The substrate was then baked at a temperature of 215 °C for 15 min. After the substrate cooled down, drops of NOA 73 were placed onto the Teflon coated substrate using a syringe tip. Due to the hydrophobic Teflon coating, the NOA drop formed a lens shaped structure.

B. Camera Array Structure

Fig. 2 shows the fabrication process of the camera array. The structure was fabricated using rapid prototyping (Viper Si2, 3d Systems, Rock Hill, SC, USA). For the bridges, we needed a material that is very flexible and soft to allow the array to change orientation easily. After experimental trial, we chose a silicone rubber, Ecoflex (Smooth-On, Easton, PA, USA) over the commonly used polydimethylsiloxane. Ecoflex is very soft and flexible and can elongate to 900% of its length [15]. As Fig. 2(c) shows, uncured Ecoflex was poured on top of the bridge and all around the image sensors. After the Ecoflex was cured, both edges of each 3D-printed bridge were cut off while the Ecoflex bridges were kept intact to realize the flexible bridge connections. The image sensors were then attached to the brackets. Each image sensor (Awaiba Lda, Funchal, Portugal) is 1 mm × 1mm and has a total of 250 × 250 pixels. Finally NOA microlenses were assembled on top of the corresponding image sensors and aligned to match the focal length to the distance to the image sensors.

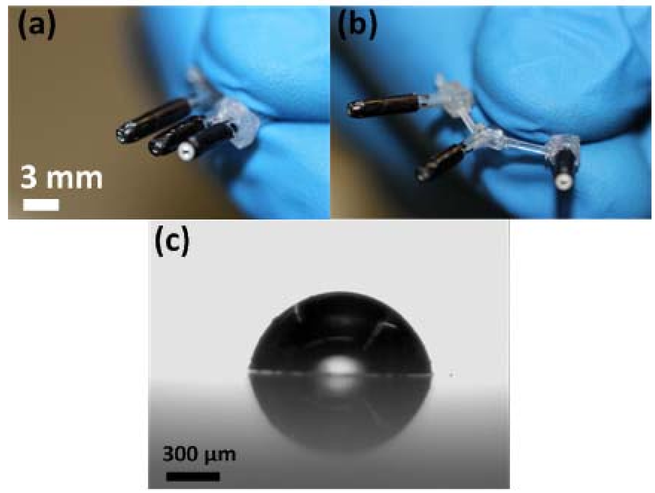

Fig. 3. Flexible miniaturized camera array. (a) Image of the camera array in the natural compact state. Each camera is facing approximately the same scene. (b) Image of the camera array while flexed. Each camera is facing a relatively different scene. (c) Profile of the NOA microlens taken with a goniometer. The lens has a diameter of 0.9 mm and a focal length of 0.8 mm.

IV. Results

A. Device Analysis

Fig. 3 shows the images of the flexible miniaturized camera array along with the NOA microlenses. Fig. 3(a) is an image of the camera array in its compact state and the cameras are facing the same scene from slightly different angles. Fig. 3(b) is an image of the camera array when flexed where each camera is facing a different scene and the stretched Ecoflex is clearly visible. The array can be mechanically flexed using an umbrella-like structure Fig. 3(c) is a close-up of a NOA microlens taken by a goniometer (OCA 15+, DataPhysics Instruments Inc., Germany). The final NOA microlenses have a diameter of 0.9 mm and a focal length of 0.8 mm. The surfaces of the microlenses were smooth with an average roughness of 62 nm. The surface roughness of the microlenses was measured using a white light interferometer (Zygo NewView 6300, Zygo Corporation, Middlefield, CT, USA).

B. Image Analysis

Fig. 4 shows the individual images taken by each miniaturized camera along with the final stitched image. Fig. 4(a–c) are the individual images taken by the left, central, and right cameras, respectively. The resolution of each of the images is 248 × 248 pixels. Fig. 4(d) is the final stitched image using the software PTGui (New House Internet Services, Rotterdam, Netherlands). The resolution of the stitched image is 643 × 366 pixels. As can be seen from Fig. 4(d), the stitching was smooth with no visible seams between the images. Note that some objects were out of focus as our microlenses have low f number (∼1), thus relatively shallow depth of field.

The maximum FOV provided by the array was approximately 130°. The FOV was calculated by adding the FOV of the individual cameras minus the overlap between the cameras. The overlapping FOV between two neighboring cameras was estimated to be 10°.

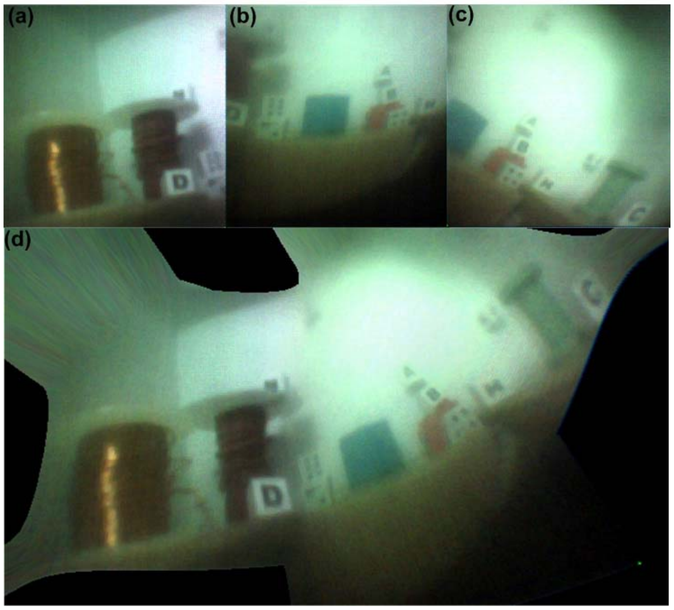

Fig. 4. Individual and stitched images from the camera array. The resolution of each individual image is 248 × 248 pixels. (a) The image captured by the left camera. (b) The image captured by the central camera. (c) The image captured by the right camera. (d) The stitched image with a resolution of 643 × 366 pixels.

V. Conclusion

We realized a flexible miniaturized camera array inspired by and combining the merits of natural animal eyes of both mammals and insects. The camera array can be instantaneously reconfigured spatially to provide a changing FOV. The microlenses for the miniaturized cameras were fabricated by UV photopolymerization of NOA and had wide angles. The fabrication took advantage of 3D printing and flexible polymers. With the flexibility and instantaneous reconfigurability, the miniaturized camera array consisting of only three cameras can offer a large FOV of 130°. Future work includes increasing the number of cameras in the array for even larger FOV, as well as development of algorithm for higher image quality and 3-dimensional rendition of the scene.

Acknowledgment

The authors thank C. Li, A. Kanhere, and C. Huang for technical discussions and help. The 3D printing was conducted at the University of Wisconsin-Madison rapid prototyping consortium. This research utilizes National Science Foundation supported facilities at the University of Wisconsin.

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