Theoretical and Applied Mechanics Letters 6 (2016) 11–20

Contents lists available at ScienceDirect

Theoretical and Applied Mechanics Letters

journal homepage: www.elsevier.com/locate/taml

Review

Mechanics of bioinspired imaging systems

Zhengwei Li, Yu Wang, Jianliang Xiao *

Department of Mechanical Engineering, University of Colorado Boulder, Boulder, CO 80309, USA

HIGHLIGHTS

- Two types of bioinspired imaging systems, i.e. tunable electronic eyeball cameras and artificial compound eye cameras, are introduced.
- Recent progresses in mechanics of these bioinspired imaging systems are reviewed.
- The impact of mechanics on related systems and future development of curvilinear optoelectronics are discussed.

ARTICLE INFO

Article history:
Received 7 October 2015
Accepted 26 November 2015
Available online 23 December 2015

Keywords:
Mechanics
Bioinspired imaging system
Eyeball camera
Compound eye camera
Stretchable electronics

ABSTRACT

Imaging systems in nature have attracted a lot of research interest due to their superior optical and imaging characteristics. Recent advancements in materials science, mechanics, and stretchable electronics have led to successful development of bioinspired cameras that resemble the structures and functions of biological light-sensing organs. In this review, we discuss some recent progresses in mechanics of bioinspired imaging systems, including tunable hemispherical eyeball camera and artificial compound eye camera. The mechanics models and results reviewed in this article can provide efficient tools for design and optimization of such systems, as well as other related optoelectronic systems that combine rigid elements with soft substrates.

Contents

1. Introduction

Evolution has created remarkable imaging systems with many attractive attributes [1–4]. For example, human eyes use simple optics to collect light rays from the environment and focus them onto a hemispherical retina to form sharp images [5,6]. This type of imaging system has the advantage of optimal photonic usage in order to guarantee maximum light sensitivity and high spatial resolution [1,2]. Another type of imaging system is compound eyes that are commonly found in arthropods. A compound eye is usually composed of hundreds or thousands of individual units, i.e. ommatidia, on a curved surface. Each ommatidium has its own optical lens and light detector for imaging purpose [5]. Such structures of compound eyes, although cause reduced resolutions, can provide very wide field of view angle, low aberration, high sensitivity to motion and infinite depth of field [7–9].

Due to their remarkable characteristics, bioinspired imaging devices have great potential in medical, industrial and military applications [10,11]. However, almost all biological eyes adopt curvilinear imagers [11], which does not comply with established optoelectronic systems that are hard, rigid and planar, owning to

* Corresponding author.
E-mail address: jianliang.xiao@colorado.edu (J. Xiao).

http://dx.doi.org/10.1016/j.taml.2015.11.011

the inherent 2D nature of established materials processing technologies and intrinsic brittle nature of inorganic semiconductor materials [12–14]. This mismatch in mechanics and forms greatly hinders the development of bioinspired digital cameras, with photodetector arrays wrapped onto curvilinear surfaces in order to achieve imaging performances comparable to biological counterparts.

Thanks to the progress of stretchable electronics, researchers have successfully realized curvilinear optoelectronics [15–24]. Mechanical stretchability and flexibility have been introduced into otherwise rigid and brittle optoelectronic systems by utilizing advanced mechanics principles and structural designs, so that photodetector arrays can be wrapped onto curvilinear surfaces without noticeably affecting their operating performance [25–31]. For example, Ko et al. [25] developed a fully functional hemispherical electronic eyeball camera that mimics the structure and function of human eye. In this work, silicon photodetectors were connected by buckled, stretchable interconnects to form a mesh layout, such that mechanical stretchability of the array is achieved. This layout of photodetectors was first fabricated in planar geometry, by using established semiconductor processing steps, and then transformed into hemispherical shape to resemble the geometry of retina in human eyes. Impressive imaging capability has been demonstrated with a simple plano-convex lens.

One drawback of this imaging design, adopted by both the electronic eyeball cameras and human eyes, is that the detector curvature is fixed. However, some recent progresses in optoelectronics require dynamically tunable optical properties in a controllable manner. Different tuning mechanisms, such as strain [32,33], hydraulics [34,35], stimuli-responsive hydrogels [36,37], and others [38–41] have been reported to achieve tunable optics. To achieve tunability in imaging systems, Jung et al. [42] designed a tunable hemispherical eyeball camera system, with curvatures of both the optical lens and the hemispherical imaging plane coordinately adjustable to realize zoom capability. In this design, the stretchable photodetector array was bonded onto a thin elastomeric membrane, which is then mounted onto a hydraulic chamber. By adjusting the hydraulic pressure, the deformed shape and thus the curvature of the hemispherical detector surface can be accurately controlled.

Compound eyes, commonly found in arthropods, represent a distinct imaging system from human eyes [43–48]. They offer unique imaging characteristics, such as very wide field of view angle, low aberration, high sensitivity to motion and infinite depth of field. Recently, Song et al. [43] have successfully designed and fabricated a digital camera that mimics the apposition compound eyes of insects. Arrays of elastomeric microlenses and stretchable photodetectors were separately fabricated and integrated in their planar geometries, which were then transformed into a hemispherical shape to realize the artificial compound eye camera. This digital camera exhibited an extremely wide field of view angle (160°) and infinite depth of field.

This article reviews recent progresses in mechanics of two types of bioinspired imaging systems. Mechanics of tunable hemispherical eyeball camera will be discussed in Section 2, and mechanics of artificial compound eye camera will be covered in Section 3. In the end, some discussion on future development of curvilinear optoelectronics is also included.

2. Mechanics of tunable hemispherical eyeball camera

The advantage of hemispherical electronic eyeball cameras over conventional digital cameras is that they can achieve superior imaging quality with simple optics [25,30]. This could lead to lighter, simpler and cheaper digital cameras. However, the disadvantage is that the fixed detector curvature limits their compatibility with changes in the non-planar image surfaces resulting from adjustable zoom. This issue was overcome by Jung et al. They designed a dynamically tunable hemispherical eyeball camera system [42]. In this system, the curvatures of both the lens and detector surface can be accurately controlled by hydraulic pressure. Schematic illustration of the system design is shown in Fig. 1(a). The camera consists of two main components, a tunable plano-convex lens (Fig. 1(a) upper frame) and a tunable hemispherical detector (Fig. 1(a) lower frame). An elastomeric polydimethylsiloxane (PDMS) membrane was used to seal a water chamber to form the tunable lens. Changing water pressure in the chamber caused the PDMS membrane to deform into hemisphere with desired radius of curvature, yielding tunable optical zoom. The tunable detector was realized by integrating a stretchable silicon photodetector array with a thin PDMS membranes, and then also mounted onto a water chamber. The radius of curvature of the detector can also be tuned by adjusting the water pressure in the chamber. Figure 1(b) presents an optical image of the tunable hemispherical electronic eyeball camera system. To realize imaging capability, curvatures of both the lens and detector have to be adjusted coordinately. Figure 1(c) shows four pictures of the same disc array object taken by the camera at different zoom.

Mechanics played important roles in design and fabrication of this camera. It was also critical for system operation, since it gave the relationships between the hydraulic pressure and the curvatures of the lens and detector surface. In addition, mechanics was vital to image post processing, as it provided position tracking of photodetectors during deformation. In the following, we review the mechanics of tunable lens first, and then discuss the mechanics of the tunable detector.

2.1. Mechanics of tunable lens

The PDMS membrane in the tunable lens is a nearly incompressible material, and its nonlinear mechanical behavior can be characterized by the Yeoh hyperelastic model, which gives the strain energy density as [49],

$$W = \sum_{k=1}^{3} C_k \left(I_1 - 3\right)^k , \tag{1}$$

where C_k are material constants, $I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$ is the first invariant of the left Cauchy–Green deformation tensor, and λ_1, λ_2, and λ_3 are the principal stretches. For PDMS, $C_1 = 0.29$ MPa, $C_2 = 0.015$ MPa, $C_3 = 0.019$ MPa, and $\lambda_1\lambda_2\lambda_3 = 1$ due to incompressibility [50].

As schematically illustrated in Fig. 2(a), the thickness of the PDMS membrane is t_{lens}, and radius of the opening of glass window is R_{lens}. During operation, water pressure p is applied to deform the PDMS membrane to a hemispherical shape with apex height H. The radius R and spherical angle $\varphi_{\max}$ of the hemisphere are obtained as

$$R = \frac{R_{\text{lens}}^2 + H^2}{2H}, \qquad \varphi_{\max} = \sin^{-1} \frac{2R_{\text{lens}}H}{R_{\text{lens}}^2 + H^2}. \tag{2}$$

The principal stretches in meridional and circumferential directions are

$$\lambda_r = \frac{\varphi_{\max}}{\sin\varphi_{\max}}, \qquad \lambda_\theta = \frac{\sin\left(\frac{r}{R_{\text{lens}}}\varphi_{\max}\right)}{\frac{r}{R_{\text{lens}}}\sin\varphi_{\max}}. \tag{3}$$

The principal stretch in the thickness direction is $\lambda_z = 1/(\lambda_r\lambda_\theta)$. The principle of virtual work is used to determine the relationship between the applied pressure p and the geometry of the deformed