Sensors and Actuators A 208 (2014) 130–140

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

An arc-shaped polyvinylidene fluoride/ionic polymer metal composite dynamic curvature sensor with contact detection and scanning ability☆

Guo-Hua Feng*, Guo-Yan Chu

Department of Mechanical Engineering, National Chung Cheng University, Chiayi 621, Taiwan

ARTICLE INFO

Article history:
Received 15 September 2013
Received in revised form
30 December 2013
Accepted 31 December 2013
Available online 8 January 2014

Keywords:
IPMC
PVDF
SAW
Curvature
Contact detection

ABSTRACT

This paper presents a novel flexible dynamic curvature sensor with contact sensing functionality. The sensor is fabricated from a piezoelectric polyvinylidene fluoride (PVDF) film and integrated into an actuator fabricated from an ionic polymer metal composite (IPMC), which allows the curvature/contact-detection of various curved targets in direct contact with the device, and the curvature-sensing mechanism can also perform a scanning motion by using the electrically controlled IPMC actuator. This polymer-based sensor can detect large curvature changes and can dynamically sense any variations in curvature as a function of time. Moreover, the embedded contact function of the curvature sensor can monitor whether the target contacts a specific point of the sensor. This text details the device design, working principle, fabrication process, and testing procedure. The results show that more than 200% curvature change can be detected based on the fabricated device with a curvature radius of 6 mm. The contact function is verified by a 20% voltage amplitude increase, and the sensing mechanism scans a range of 2.7 mm with the 5 mm long handle portion of the IPMC actuator driven by a voltage of 8 V. The developed device could be applied to a dexterous robot for monitoring the changes in shape of a substance, or to a catheter for medical applications.

1. Introduction

Research on electroactive polymers (EAPs) for smart materials and structures has become a rapidly growing trend in recent years. With the characteristics of low weight, high strain, cost-efficient manufacturing, and flexible structure, EAP applications possess great potential in various fields and have gradually become more realistic. EAPs have been applied as actuators and sensors because they are capable of converting electrical energy into mechanical energy, and they are available in various shapes and dimensions. The study of EAP materials includes the following two major areas: (1) electronic EAPs and (2) ionic EAPs [1]. Electronic EAPs such as those working with electrostrictive, electrostatic, piezoelectric, and ferroelectric mechanisms are actuated by electric fields. They can maintain the induced displacement under a dc voltage supply, and can function in air without major limits. However, a high working electric field (e.g., >100 MV/m) is a drawback. Conversely, ionic EAP materials such as gels, polymer-metal composites, and conductive polymers are operated by diffusion of ions. Thus, an electrolyte for actuation is required. One advantage of ionic EAPs is that the actuation voltage can be relatively low (e.g., <10 V).

Among the various ionic EAPs, ionic polymer-metal composites (IPMCs) have been broadly studied because of their promising biomechanical and biomimetic applications [2]. Aside from other active materials, IPMCs possess soft properties and can be constructed as flexible structures that can be driven by low voltages for operation in aqueous environments. Thus, IPMCs are highly appealing for studies on underwater robotics [3]. Biomedical applications are also possible, including artificial muscles and endoscopy [4,5].

Moreover, the development of tactile/contact sensors for object recognition has become a substantial industry development, particularly regarding robotic arms. Numerous tactile sensors have been presented to recognize the shape, curvature, and hardness of a measured target, or to identify the composition of a target material. Specifically, the majority of existing curvature sensors employed to measure the curvatures of objects are based on optical sensing such as laser beam interaction or photogrammetry [6,7]. Precise installations are typically required for these sensors, and the optical properties of measured targets are limited. Hence, direct curvature-sensing with tactile sensors could be a more effective alternative because this method provides valuable data for functions such as localization and shape estimation. Among various developed curvature/tactile sensors, the piezoelectric PVDF film, a type of electronic EAP, plays a critical role [8], for example, in a tactile fingertip sensor,

☆ Selected Paper based on the paper presented at The 17th International Conference on Solid-State Sensors, Actuators and Microsystems, June 16-20, 2013, Barcelona. Spain

* Corresponding author. Tel.: +886 5 272 0411; fax: +886 5 272 0589.
E-mail address: imeghf@ccu.edu.tw (G.-H. Feng).

0924-4247/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sna.2013.12.039

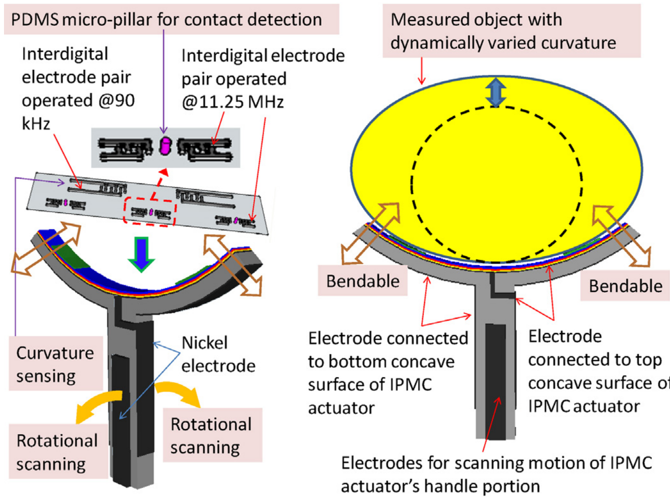

Fig. 1. Conceptual diagrams and working principle of proposed novel flexible dynamic curvature sensor with contact sensing and scanning functions.

fabricated from a PVDF film, for detecting a contact normal force and incipient slip [9]. Tada et al. also reported tactile detection using a fingertip comprising two silicon rubber layers of differing hardness with receptors of strain gauges and randomly distributed PVDF films [10]. The sensing mechanism is mainly based on measuring the output voltage variation related to the strain change due to external contact force. The strain change alters the piezoelectric PVDF material surface charge, resulting in output voltage variation.

In this study, ionic and electronic EAP materials are integrated to develop a novel device. The novelty of this work is to detect the variation of surface acoustic wave transmission on a piezoelectric PVDF film. Different from charge detection on a PVDF film, which the sensing area could affect the sensitivity, our method depends on the transfer function between the input and output so the sensing area is not a concern. A flexible PVDF curvature sensor on an IPMC-supported actuator is proposed to directly contact the surface of a measured target for curvature monitoring. Curvature/contact-detection based on a piezoelectric polymer with surface acoustic wave (SAW) devices and scanning motion with IPMC actuation are studied.

2. Device design and working principle

The proposed device comprises the following two main parts: (1) an IPMC comprised of a multi-electrode actuator; and (2) SAW sensors manufactured on a PVDF film (Fig. 1) [11]. The IPMC actuator is designed as two arc-shaped arms connected with a column-shaped handle. The developed IPMC actuator allows the arc-shaped arms to bend in a direction perpendicular to the curvature sensing direction, which facilitates the execution of the scanning motion of two arc-shaped arms. The SAW sensors possess the following two functions: (1) curvature sensing and (2) contact detection. During the curvature measurement, the tested object directly touches the flexible arc-shaped arms to acquire the detected signal. If the curvature of a tested object is larger than the fabricated arc-shaped arms, the object makes the arms expand. If the curvature of the object is less than the fabricated arms, an external force can be applied to make the arms contact the object. The design and sensing mechanism are detailed below.

2.1. IPMC/PVDF integrated device design guideline

Two designs of the interdigital transducer (IDT) pairs on a PVDF film are examined for curvature and contact detection (Fig. 2). The first IDT pair is designed as $M = N = 3$, $L = 5.54$ mm, $a = 320$ μm, and the length and width of the electrode are 700 μm and 200 μm, respectively. This SAW device is attached to the front surface of the arc-shaped arms of the IPMC actuator as a curvature sensor. The second IDT pair is designed as $M = N = 3$, $L = 1.55$ mm, $a = 100$ μm, and the length and width of the electrode are 300 μm and 50 μm, respectively. The SAW device is employed as a contact sensor. The dimensions of the first SAW sensor are larger than the second sensor because the sensing area of the first sensor design is aimed at the two arc-shaped arms caused by the measured object. The second sensor focuses on detecting a specific location to monitor whether the tested object is attached at that point. The different periodic lengths of the two IDT designs possess dissimilar central frequencies. The sinusoidal waves with distinctive operational frequencies are used as inputs, and the layout of the second IDP pair is prevented from detecting the transmission region of the first IDT pair to minimize the interference of both IDT transmitted signals. Furthermore, a micro-structured PDMS pillar is fabricated in the center region of the second IDT pair. This allows the local stress to be produced easily on the wave transmission area while the tested object is attached to the top surface of the micro-pillar. The two IDT pairs are integrated into a single piece of PVDF film to simultaneously detect the global curvature change and to perceive the contact motion.

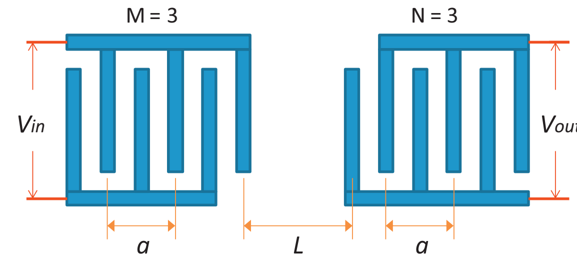

Fig. 2. A schematic model of IDT to identify the design parameters in this study.

The design of the IPMC actuator includes the arc-shaped arms and a column-shaped handle (Fig. 1). The two arc-shaped arms have a curvature radius of 10.7 mm, and the length between the two endpoints of the arms is 16.1 mm. The width and thickness of each arm are 2.0 and 0.5 mm, respectively. The dimensions of the column-shaped handle is 11 mm × 3 mm × 2 mm. Four electrodes are designed on the surface of the IPMC structure to form the active region. One electrode pair, which simply covers the front and back surface of the column-shaped handle, is responsible for the bending motion of the handle. In this study, the sensing performance of the constructed IPMC device is also examined. The arc-shaped arms are designed as active elements, and top and bottom surfaces of the arms are deposited with electrodes. The electrodes are linked to the side electrodes of the IPMC handle. Thus, the electrical property of arc-shaped arms can be monitored, and the arms are subjected to a bending motion.

2.2. Sensing principle of the first design of the SAW sensors as the curvature sensors

The SAW sensors form a diced piezoelectric PVDF film to detect the change in curvature while the arc-shaped IPMC arm contacts the object. Consider a SAW device constructed by an IDT fabricated on a surface of piezoelectric polymer film (e.g., the PVDF) (Fig. 2). The electrodes on the left represent the force generators, which convert an electrical voltage input to a mechanical force output. The force produces a surface acoustic wave to propagate on the PVDF film. Subsequently, the IDT electrodes on the right detect the generated surface acoustic wave by converting a strain into an electrical voltage output.