Sensors and Actuators A 179 (2012) 62–69

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

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

Flexible microfluidic normal force sensor skin for tactile feedback

Ruben D. Ponce Wong[a], Jonathan D. Posner[b], Veronica J. Santos[a,*]

[a] Mechanical and Aerospace Engineering, Arizona State University, Tempe, AZ, USA
[b] Mechanical Engineering, Chemical Engineering, University of Washington, Seattle, WA, USA

ARTICLE INFO

Article history:
Received 13 October 2011
Received in revised form 5 February 2012
Accepted 14 March 2012
Available online 29 March 2012

Keywords:
Capacitive sensor
Conductive fluid
Flexible sensor
Microfluidic force sensor
Sensor skin
Soft lithography

ABSTRACT

Robotic applications often require robust tactile sensing capabilities on curved surfaces, such as artificial fingertips. Flexible tactile sensors could be conformally wrapped around curved digits and could enhance grip by cushioning impacts and increasing the effective contact area during grasp. Flexible microfabricated devices that use thin film or solid electrical components are susceptible to failure due to cracking and fatigue. Conductive fluids have been used as transduction media, electrical connections, and in resistance-based pressure and bend sensors. In this work, a flexible and multilayer capacitive microfluidic normal force sensor is developed with a 5 × 5 taxel array. The sensor uses liquid metal-filled microfluidic channels as the capacitive plates and conductive interconnects. The sensor is microfabricated using soft lithography microfabrication techniques and consists of multiple layers of PDMS microchannels filled with the liquid metal alloy Galinstan and air pockets that modify the mechanical and electrical properties of the sensor. A single taxel is calibrated for normal forces ranging from 0 to 2.5 N, is shown to provide repeatable measurements of static uniaxial loads, and follows the loading and unloading phases of low-frequency dynamic loads (0.4–4 Hz). The sensor prototype has a spatial resolution on the order of 0.5 mm, performs reliably when wrapped around a surface having a curvature similar to that of a human finger (1.575 cm^{-1}), and has been shown to tolerate curvatures as high as 6.289 cm^{-1}. The deformable liquid capacitive plates and heterogeneous PDMS-air dielectric medium can be designed to tune the sensor's sensitivity and range. The sensor prototype provides greater sensitivity at low loads, a feature which can be exploited for robotic applications in which light touch is important.

1. Introduction

There are three primary sensing modalities employed in microelectromechanical systems (MEMS) force sensors: resistive, piezoelectric, and capacitive [1]. Resistive sensors detect mechanical stimuli by producing changes in resistance. Traditional high sensitivity, resistive strain gauges typically have issues such as fragility and low flexibility. Recently, some of the existing limitations have been addressed, for instance, with the development of conductive polymer composites [2–4]. Piezoelectric sensors generate voltage as applied forces are measured. Piezoelectric composites are flexible and chemically resistant but inappropriate for static loading and prone to output signal drift. Capacitive sensors, the focus of the present work, typically consist of pairs of plates whose capacitance is increased as the distance between opposing plates decreases or the permittivity of the dielectric medium between the plates increases. Capacitive sensors offer advantages such as high sensitivity, tunable spatial resolution when used in an array configuration [1], and a simple, well-known governing equation. Electrical capacitance depends on the geometry of and distance between the electrodes and dielectric properties of the material between the electrodes.

1.1. Capacitive sensors

For many applications, capacitive sensors are created by embedding conductive metal plates in flexible materials such as the polydimethyl siloxane (PDMS) polymer. The conductive plates are typically created using metal deposition techniques such as evaporation [5,6], electroplating [7], or sputtering [8]. Although the polymeric packaging is relatively robust to mechanical deformations and chemical degradation, the conductive plates and interconnects are susceptible to failure due to fractures and fatigue. Even a small crack in a plate or connect can result in the irreparable loss of electrical connectivity and failure of the sensor [9]. Fabrication of curved, doped nano-ribbons that can withstand significant deformation [10] and the deposition of spiral copper wire around a nylon wire that elongates when stretched [11] have been used to provide electrical connections in flexible substrates.

* Corresponding author at: Arizona State University, 501 E. Tyler Mall, ECG 301, MC 6106, Tempe, AZ 85287-6106, USA. Tel.: +1 480 965 3207; fax: +1 480 727 9321.
E-mail addresses: Ruben.Poncewong@asu.edu (R.D. Ponce Wong), jposner@uw.edu (J.D. Posner), Veronica.Santos@asu.edu (V.J. Santos).

0924-4247/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2012.03.023

Capacitive sensors have sensitivity and tunable spatial resolution [1]. Arrays of capacitors have been used for a wide range of applications. Capacitance-based micro tactile sensor arrays are capable of detecting mN forces with negligible cross-talk between sensing elements, although hysteresis can be an issue [12]. A macro-scale pressure sensor made of fabric detected pressure fields with magnitudes of hundreds of fF capacitance spread around a 1 m^2 area [13]. A sensor capable of measuring phase fraction distribution of two-phase flows via permittivity variations was developed to distinguish between different types of dielectric media between the capacitor plates [14]. A tactile sensor capable of measuring normal and shear forces was created by depositing an array of gold thin films in PDMS and using 2 × 2 taxels as a single sensing unit [7,15].

1.2. Fluids in MEMS sensors

Fluids have been integrated into a variety of MEMS sensors for different applications. For instance, a vibration sensor was developed which had chambers filled with a NaCl solution [16]. Mechanical vibrations induced motion of the electrolyte's ions, allowing the measurement of vibrations over a wide range of frequencies. For tactile sensing, a sensor was created by filling microchannels with a NaCl solution [17]. Mechanical deformation applied pressure to the reservoirs, displaced fluid, and produced measurable changes in resistance. A macroscale fluid-based tactile sensor called the BioTac (SynTouch, Los Angeles, CA) uses fluid as a transduction medium for both electric current and mechanical vibrations [18]. This multimodal sensor consists of an elastomeric skin that has been inflated away from a rigid, fingertip-shaped core by a weakly conductive fluid [19]. An array of impedance electrodes embedded in the rigid core is used to measure changes in impedance as the fluid flowpath is altered by mechanical deformation. A hydrophone is used to measure vibrations at the skin-object interface. Each of these three sensing devices utilizes fluids encapsulated by elastic materials.

Recently, fluids have been used as wires to connect sensing elements with external circuitry. A liquid metal alloy called Galinstan has been used in MEMS devices to create robust wire paths capable of being bent, twisted, and stretched. Galinstan-filled microchannels enabled the powering of LED lights despite the bending and twisting of the device [20]. In another application, a stretchable force and temperature sensor was created with carbon nanotubes and Galinstan electrical connections embedded in PDMS [21]. Galinstan is a fairly conductive (0.435 Ωm electrical resistivity [22]) fluid created by Geratherm (Geschwenda, Germany) for use in thermometers as a nontoxic substitute for mercury [23]. Galinstan is a eutectic metal alloy composed of gallium, indium, and tin [22]. The voltammetric [22] and electromagnetic [24] properties of this relatively new compound have been recently established. A eutectic metal alloy composed of only gallium and indium (eGaIn) has been used in the design of a pressure sensor [25] and bend sensor [26,27,45]. A PDMS skin having microchannels filled with eGaIn was wrapped around a human finger. Deformation-induced changes in resistance of the fluidic electrical circuit allowed for the measurement of joint angles as the finger was bent.

1.3. A capacitive microfluidic normal force sensor

Tactile sensing is a field of great interest due to its potential impact on robot-assisted surgery and robotic grasp and manipulation, among other applications. In many cases, visual and acoustic feedback alone does not provide the information necessary for decision making. A classic case is that of an amputee who accidentally crushes or drops an object with his prosthetic hand due to inadequate tactile information about the hand-object interaction. Many review articles have discussed the complexity of the sense of touch and the many challenges that remain for artificial touch sensors [1,28,29]. Some of the sensor design requirements for robotic applications include robustness, sensitivity, fine spatial resolution, fast dynamic response, and flexibility [29].

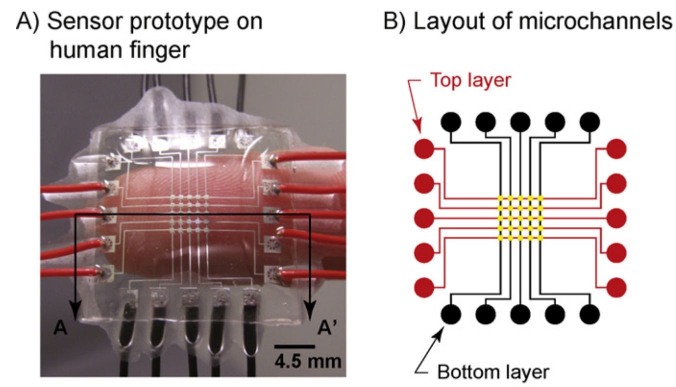

Fig. 1. Capacitive microfluidic normal force sensor skin. (A) A completed prototype shows the Galinstan embedded within the transparent PDMS. The 2D schematics in Fig. 2 correspond to the cross-sectional view at A–A′ (black line). (B) Wire paths from the top half of the sensor run horizontally (red) while those from the bottom half run vertically (black). The square capacitive taxels (yellow) represent the overlapping areas of the wire paths from both halves of the sensor. (For interpretation of references to color in this figure legend, the reader is referred to the web version of this article.)

PDMS-based capacitive tactile sensors have been developed to measure normal forces [2,7,12] and shear forces [15], to determine the elasticity of a contacted object [30], and to distinguish between different types of textures [31]. For MEMS and microfluidic applications, PDMS offers advantages such as non-toxicity, high degree of flexibility, chemically inert nature, simple processing techniques, low cost, and impermeability to liquids [32–35]. Thus, PDMS provides protection from the environment for the embedded sensor electronics. The existing PDMS-based tactile sensors use embedded solid metal films [7,12,15,30,31] or carbon nanotubes [2] in a protective PDMS material. These designs are prone to failure when deformed, for example around a robotic finger, and are therefore challenging to implement in robotic applications where conformal wrapping of curved surfaces or robustness to repetitive deformation is necessary.

In this work, we present a flexible, capacitive, microfluidic sensor for normal force sensing with microchannels filled with Galinstan that serve as both the flexible wire paths and the conductive metal plates that make up the capacitive sensing units. Novel features of the sensor include its deformable capacitive plates and heterogeneous, deformable dielectric medium. The prototype has a 5 × 5 array of individually addressable 0.5 mm × 0.5 mm taxels. The liquid metal-filled microfluidic channel design ensures the robustness of the sensor as there are no solid components that can crack and fail. The multilayer design allows for nonlinear tuning of the sensor response to the desired load. We present the sensor's spatial resolution and quantify the response of the capacitive sensor on flat and curved surfaces. Details of the sensor's design, fabrication, calibration, validation, and overall functional assessment are presented in this work to show the potential of using conductive fluids for sensor electronics.

2. Methods

2.1. Prototype fabrication

The capacitive, microfluidic sensor (Fig. 1A) is fabricated using soft lithography and consists of two materials: a flexible elastomer