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Liquid-state motion sensing☆

Hansong Zeng, Yi Zhao *

Laboratory for Biomedical Microsystems, Department of Biomedical Engineering, The Ohio State University, 294 Bevis Hall, 1080 Carmack Road, Columbus, OH 43210, USA

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ABSTRACT

This paper demonstrates a liquid droplet-based motion sensing system which has the advantages of simple fabrication, low power consumption and digital signal processing. The sensor consists of a dielectric substrate patterned with an array of microelectrodes, and a saline droplet as the proof mass. Once an external linear acceleration is applied, the inertial force moves the droplet on the micropatterned substrate. The acceleration is determined from the movement profile detected by the microelectrodes. In order to enhance the threshold and the sensitivity of motion sensing, two surface treatment approaches are utilized to create superhydrophobic surfaces. The result shows that the minimal sliding angle that can move a 20 μl droplet on the superhydrophobic surface is lower than 1°, corresponding to a threshold of lower than 0.017 g. A lumped-parameter model is developed to estimate the dynamic behavior of the proposed system. The result shows that the frequency response of the droplet-based sensor is more significant at low frequencies than at high frequencies, which is distinct from solid-state accelerometers. Measurement under a constant acceleration shows that the predicted value derived from the measurement has a good match with the actual applied acceleration, validating the proposed system as a viable alternative for motion sensing.

1. Introduction

Detection of motion parameters, such as linear acceleration and angular change, is critical for a dynamic system. For example, motion detection is a key element of industrial applications including inertial navigation, passive automotive safety systems and simulation of space microgravity [2,3]. Increasingly smaller motion sensors have generated a great deal of interest among the booming gaming industry, where sensors serve as the interface between the gaming systems and the player.

There long has been a practice of determining motion parameters using a solid-state MEMS sensor (i.e., accelerometer or gyroscope) that has high precision, low cost and small size [4]. In such a sensor, the motion change induces change of mechanical strain, displacement, or resonant frequency shift of the solid-state proof mass. A piezoresistive, piezoelectric or capacitive sensing component converts such change into electrical signals that can be recognized and processed [5,6].

Although effective, solid-state motion sensors are limited to a certain extent by complex fabrication and packaging processes. In these sensors, free-standing microstructures usually serve as the proof mass, and are fabricated by surface micromachining (patterning and releasing). Since the sensing performance is highly sensitive to fabrication imperfection [7], the tools for fabricating, characterizing and calibrating these free-standing structures must have high precision. Moreover, extraordinary attention is paid in the packaging process, not only to reduce damping effects but also to protect the mechanically fragile, free-standing structures. Meanwhile, in sensors using piezo-materials, the sensing performance is largely determined by the homogeneity, sensitivity and linearity of the piezo-sensing materials, which all vary with deposition conditions [8]. In addition, the sensitivity and the measurement range of a solid-state motion sensor often are intrinsically coupled, which makes it difficult to develop a sensor with a very high-level of sensitivity and a large measurement range, simultaneously [9,10].

In this work, we demonstrate a new concept of motion sensing that utilizes a liquid droplet as the inertial proof mass. Externally applied acceleration induces an inertial force on the droplet and moves it over the substrate. The droplet movement is detected by the time sequence of the electrical impedance measurement using microelectrodes patterned on the substrate. The externally applied acceleration is derived from droplet motion characteristics based on a droplet dynamics model. Unlike solid-state counterparts, a liquid-state motion sensing system requires minimal configuration and fabrication complexity. Meanwhile, the acquisition of digital signals solely depends on the electrical impedance between the measuring electrodes, which are not affected by the magnitude of external acceleration. Therefore, the sensitivity of the measurement is decoupled from the measurement range. Digital signal

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* Corresponding author. Tel.: +1 614 247 7424; fax: +1 614 292 7301.
E-mail address: zhao.178@osu.edu (Y. Zhao).

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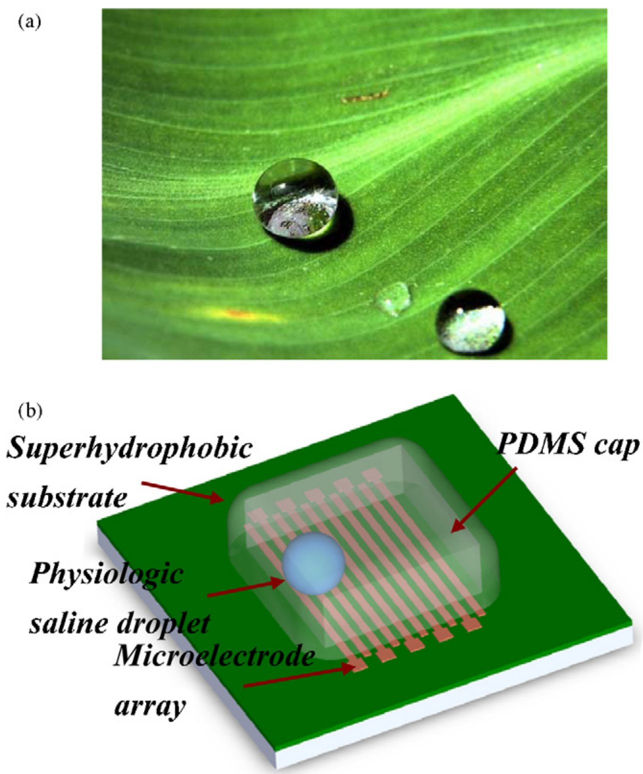

Fig. 1. The concept of liquid droplet-based motion sensing. (a) The work is inspired by observing a drop of dew moving on the hydrophobic surface of a lotus leaf. (b) Schematic configuration of a liquid-state motion sensor.

processing also makes the sensor less vulnerable to external electric/magnetic disturbance. This is especially important for slow motion detection, e.g. body movement.

2. Design and analysis

2.1. Concept of liquid-based motion sensing

The concept of liquid-based motion sensing is inspired by a natural phenomenon shown in Fig. 1(a), where a drop of dew on the hydrophobic surface of a lotus leaf is susceptible to a tiny external perturbation [11]. The relative movement of the droplet with respect to the leaf can be used as a measure of the external perturbation. Based on this observation, an engineered liquid droplet-based motion sensing system is designed, which consists of a hydrophobic substrate patterned with an array of microelectrodes (Fig. 1(b)). Like the dew rolling over the lotus leaf, the motion of the ionic droplet depends on the externally applied acceleration and surface hydrophobicity of the substrate. As it moves over the surface, the conductive ionic droplet changes the electrical connection states of the microelectrodes, thus allowing the motion characteristics of the droplet to be determined.

In order to demonstrate the concept of liquid-state motion sensors, a simplified one-dimension prototype with one-time sensing capability is developed in this work. An array of microelectrodes is patterned on a planar dielectric substrate to detect the motion profile of the liquid droplet. Dual-axis and continuous sensing can be implemented by patterning an array of bi-layered microelectrodes on a curved substrate.

2.2. Lumped model for droplet dynamic study

A lumped-parameter model is developed to quantitatively understand the droplet dynamics that govern the sensing performance (Fig. 2). As seen from a coordinate system attached to the substrate, the driving force is in the opposite direction of the externally applied acceleration and has a magnitude of $m \times a$, where m is the mass of the droplet and a is the acceleration to be determined [12]. In order to move the droplet, the driving force must overcome the capillary force caused by the dynamic contact angle hysteresis that resists the droplet motion [13]. Once the droplet moves on the surface, it is subjected to a damping/friction force which includes air damping as well as contact-line friction [14]. To simplify the analysis without significantly affecting the accuracy, it is assumed that the damping/friction force linearly relates to the droplet velocity. The governing equation of the droplet can be expressed as:

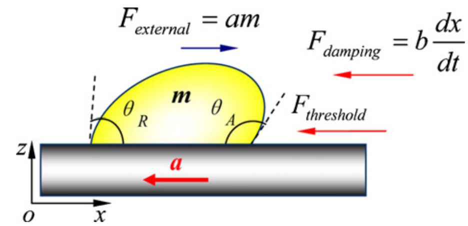

Fig. 2. Illustration of the droplet dynamics during motion. The driving force of droplet motion is induced by the external applied acceleration (a with the red arrow) and is proportional to the mass of the liquid droplet. The motion of the droplet is governed by the driving force, the capillary force which is induced by dynamic contact angle hysteresis between the advancing contact angle (θ_A) and receding contact angle (θ_R), the air damping and the contact-line friction. The relative motion between the droplet and the substrate occurs once the capillary force is overcomed. For analysis simplicity, it is assumed that the damping/friction force is linearly related to the traveling velocity of the droplet. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} - (m \times a - F_{threshold}) = 0 \quad (1)$$

where x is the relative displacement, b is the damping/friction coefficient and $F_{threshold}$ is the capillary force. For a 20 μl ionic droplet (0.9% saline) used in this work, m = 20 mg.

The threshold ($F_{threshold}$) in Eq. (1) is an important parameter that determines the minimal acceleration that can be detected by the sensing system. In order to obtain a small dynamic contact angle hysteresis, a low surface wettability is required. This is usually performed by changing the surface topography, surface chemistry or both [15–17]. In this work, surface hydrophobicity is regulated using two independent approaches. Fig. 3(a) shows the first approach in which a layer of silica nanoparticles (average diameter 7–10 nm) is spin-coated on the surface (at 1000 rpm for 10 s), followed by immersion into an aqueous HDFT solution (3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluoro-1-decanethiol, Sigma–Aldrich®, CA, USA). The silica nanoparticles create nano-roughened surface topography, while the HDFT solution assembles a molecular layer of fluorocompound on the surface to further increase surface hydrophobicity [18]. After the treatment, the sliding angle of a 20 μl (about 20 mg in weight) saline droplet is measured around 4°, corresponding to a threshold of 0.07 g (g being the gravity). Fig. 3(b) shows the second approach for regulating the surface hydrophobicity, in which the surface is treated with atmospheric plasma of CF_4–H_2–He. Both fluorocompound deposition and surface roughening are involved in the process [19]. Using this approach, the sliding angle of a 20 μl saline droplet is below 1°, corresponding to a threshold lower than 0.017 g.

Following the threshold determination, the damping/friction coefficient is estimated by optical motion analysis. Fig. 4(a) illustrates the experimental setup for analyzing the droplet motion characteristics. A precise tilting stage is used to apply a constant acceleration to the saline droplet. The motion of the droplet is recorded by a high-speed digital camera at a frame rate of 40 frames