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A forefinger-like tactile sensor for elasticity sensing based on piezoelectric cantilevers

Ji Fu[a], Faxin Li[a,b,*]

[a] State Key Lab for Turbulence and Complex Systems, College of Engineering, Peking University, Beijing 100871, China
[b] HEDPS, Center for Applied Physics and Technologies, Peking University, Beijing 100871, China

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ABSTRACT

Current researches on tactile sensors are mainly focused on force sensing, but studies on elasticity sensing are very lacking. In this work, a forefinger-like tactile sensor is proposed with the functions of force sensing, contact prediction, and elasticity sensing. The sensor is made of a piezoelectric bimorph cantilever with a strain gauge for deformation monitoring. A cone-shaped tip is fabricated on the cantilever's free end to contact the testing sample. When the sensor approaches to the sample's surface, the bimorph cantilever is excited to vibrate in its flexure mode. Consequently, the vibration amplitude would shift regularly when the tip is close enough to the sample, leading to the contact prediction function. When the tip touches the sample, the sample's elasticity can be derived by tracking the contact resonance frequency of the cantilever-sample system. The functions of the proposed sensor were carefully examined and excellent performances were achieved. The proposed sensor is adaptive and may hold potentials in sample characterization in industry.

1. Introduction

The sense of touch is defined as sensing the object's properties through physical contact between the skins and the object [1,2]. Touch might be the most complex sensing modality compared to sight, hearing, smell, and taste, as it is not a simple transduction of one physical property into a bioelectric signal [3]. Typically through the sense of touch, one can obtain the contact force (or pressure) as well as the position, shape, and elasticity properties (stiffness or modulus) of the object. Similarly in intelligent systems, tactile sensors are defined as functional devices that can detect the given properties of an object through physical contact [3,4].

Tactile sensors are mostly made of smart materials and the commonly used transduction techniques include capacitive, piezoresistive, thermoresistive, inductive, piezoelectric, and magnetic principles [5]. Considerable promising results have been achieved in detecting the apparent properties of samples such as texture, orientation, position and consistency via force sensing. Commercial tactile sensors were even available in robot applications now [6]. However, few progresses were made on elasticity sensing, which might be due to the complexity and difficulty in developing such techniques.

Actually elasticity is one of the most important physical properties which can be used as an identification parameter for objects discrimination. For tactile sensing in robotic systems, exactly determining the object's elasticity is beneficial to deformation prediction in object gripping [7]. In bio-engineering, the elasticity sensing can be used for identification of cancerization in tumor tissues [8] or judging the maturity of fruits [9]. Thus, developing such an elasticity sensor could meet the urgent need of next generation robotic systems and biomedical instrumentations [10].

Actually, several types of tactile sensors had been proposed for elasticity sensing. Tanaka et al. [11] developed a bar-shaped tactile sensor, which has a polyvinylidene fluoride (PVDF) film placed on one end of the bar and a motor on the other end. When the sensor probe contacts the sample, the bar is driven sinusoidally at 50 Hz and different sample will have different voltage signal output. Hasegawa et al. [12] proposed a tactile sensor which consists of a diaphragm with a mesa structure to contact the sample, a piezo-resistive strain sensor at the periphery of the diaphragm, and a chamber for pneumatic actuation. Then, the spring constant of each object can be derived from the output voltage of the piezoresistance sensor. Peng et al. [13] presented a MEMS stiffness sensor which has multiple membranes with varying stiffness. When the sensor contacts the object, the stiffness can be obtained by measur-

* Corresponding author at: State Key Lab for Turbulence and Complex Systems, College of Engineering, Peking University, Beijing 100871, China.
E-mail address: lifaxin@pku.edu (F. Li).

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ing the relative capacitive shift of the different membranes. Based on flat indenter and compliance loading frame, these above sensors present common difficulties in measure stiff sample (say modulus larger than 10 MPa). Another disadvantage for these sensors is the lacking of precise mechanical models for contact description. Therefore for these sensors, the modulus can only be obtained by calibration, which is complex and may influence the measurement accuracy and repeatability.

In the early 1990s, Omata and Terunuma proposed a tactile sensor which can detect the stiffness of the sample based on the mechanical contact impedance method [14]. A one-dimensional resonator was brought into contact with the sample and the change of the contact resonance frequency (CRF) compared to its free resonance frequency was tracked to derive the sample's stiffness. Their tactile sensor was later applied to medical engineering for diseases diagnosis, remote minimally invasive surgery, and tumor characterization [15,16]. However, in their works, the sample's stiffness was always represented by the frequency shift and an exact stiffness or modulus value cannot be given. Moreover, their tactile sensor cannot sense the contact force, which had definitely limited its applications [14–17].

On the other hand, the Atomic Force Microscopy (AFM), which uses a micro cantilever with a tip to sense the sample's information including the force, roughness, and elasticity, can be regarded as a micro tactile sensor [18,19]. In AFM, the interaction force between the tip and sample is obtained by detecting the cantilever's deformation using a laser diode. There are two ways to obtain the surface roughness in AFM, one is the contact mode in which the tip is kept in contact with the sample and the cantilever's deformation is monitored; the other is the tapping mode in which the cantilever is driven to vibrate with a distance to the sample and the vibration amplitude is kept constant [20]. The sample's elasticity can also be detected using AFM, based on the force-displacement curve [21,22], or alternatively by tracking the cantilever-sample's contact resonance frequency (CRF) [23,24] (which is also known as Atomic Force Acoustic Microscopy, AFAM). Such a micro tactile sensor, i.e., AFM, has been proved to be quite effective in detecting the sample's properties at nanoscale. Intuitively, the principle of AFM can also be extended to macroscopic scale for tactile sensing in medical engineering and robotic systems, but such works are still lacking.

In this work, enlightened by the sensing principle of AFM, we propose a tactile sensor with the functions of contact prediction, force sensing, and elasticity sensing. The proposed sensor is based on a piezoelectric bimorph cantilever with a tip on its free end, which is similar to human forefingers and also AFM cantilevers. The contact force is monitored by a strain gauge bonded on the cantilever's surface. The working principle of the contact prediction is similar to the AFM tapping mode and the elasticity sensing principle is similar to that of AFAM. The proposed sensor is adaptive and could be used for in situ testing, which offers an effective and non-destructive solution for force and elasticity sensing.

2. Method

2.1. Basic concepts of elasticity sensing

Elasticity can be described by the reversible deformation behaviors under mechanical loads. Typically, the elasticity is measured by detecting the applied loads and the induced deformation, following which the elasticity information could be extracted based on mechanical models. Actually, human beings can also distinguish the sample's elasticity through sensing the deformation induced by the finger's pressure or force. Thus for elasticity sensors, the key problem to be solved is how to apply a prescribed load on the target object and measure the induced deformation [25]. In this work, unlike the conventional methods of elasticity measurement, we measure the sample's deformation by tracking the contact resonance frequency (CRF) of the cantilever-sample system.

Fig. 1 presents the basic structure of the forefinger-like tactile sensor. As can be seen, the sensor is made of a long steel cantilever with two PZT pieces bonded on both the up and under surfaces, forming a piezoelectric bimorph. The PZT pieces were thickness poled and can excite the cantilever into flexural vibration by voltages. A cone-shaped tip is fabricated onto the free end of the cantilever to contact the sample. An ultrasensitive strain gauge is bonded on the cantilever's up surface to monitor the contact force as well as the vibration responses under electric excitation. To get large detection sensitivity, the strain gauge is bonded near the fixed end of the cantilever, as shown in Fig. 1.

2.2. Working principle of the tactile sensor

The first function of this tactile sensor is contact-force sensing. Here the direct signal to be detected is the cantilever's strain, from which the cantilever's deformation can be obtained. When the tip contacts the sample, the contact force can be obtained by the Hooke's law, i.e., the relationship between the cantilever's strain and the contact force is linear and can be obtained by a calibration process.

The second function of the tactile sensor is contact prediction which can predict the contact event by detecting the equilibrium tip-sample distance when the tip approaches the sample. Before the sensor tip contacts the sample, the cantilever is electrically excited at a prescribed frequency, which is similar to the tapping mode in AFM. During the approaching process, the vibration amplitude of the cantilever would reduce when the vibrating tip touches the sample, although the equilibrium position of the cantilever tip is still apart from the sample. Thus the equilibrium tip-sample distance can be obtained if the vibration amplitude of the cantilever is known in advance. Such a prediction function is very useful for enhancing the safety and efficiency of the automatic systems. Note that to obtain a larger prediction distance, the excitation frequency is typically chosen near the resonance frequency of the sensor.

The third and most advanced function of the tactile sensor is elasticity sensing which can detect the modulus or stiffness of the sample through physical contact. Enlightened by AFAM, the elasticity of the sample is obtained by tracking the CRF of the cantilever-sample contact system. Here we just present the working principle briefly and more detailed information can be found elsewhere [26–28]. Fig. 2 presents the mechanical model of the cantilever-sample contact system showed in Fig. 1, where u is the distributed displacement of the cantilever relative to its initial position. As can be seen, the tip-sample interaction is simplified as a linear spring with the stiffness of k_t. Considering that the PZT pieces are much shorter than the steel cantilever, the sensor is then simplified to be an equivalent uniform cantilever with a length of L, equivalent thickness of a, width of b, equivalent Young's modulus of E, and equivalent density of ρ. During testing, the sensor is excited into flexural vibration and its governing equation can be given as

$$EI\frac{\partial^4 u(x,t)}{\partial x^4}+\rho A\frac{\partial^2 u(x,t)}{\partial t^2}=0 \quad (1)$$

where I is the moment of inertia and $I = ab^3/12$ for the rectangular cross section, A is area of the cross section. The mechanical boundary of the cantilever shown in Fig. 2 can be expressed as

$$u=0|_{x=0},\ \frac{\partial u}{\partial x}=0\Big|_{x=0},\ \frac{\partial^2 u}{\partial x^2}=0\Big|_{x=L},\ \textit{and}\ \ \frac{\partial^3 u}{\partial x^3}=\frac{k_t u}{EI}\Big|_{x=L}. \quad (2)$$