Sensors and Actuators A 279 (2018) 433–441

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Roughness discrimination with bio-inspired tactile sensor manually sliding on polished surfaces

Longhui Qin, Yilei Zhang*

School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, 639798, Singapore

ARTICLE INFO

Article history:
Received 30 January 2018
Received in revised form 9 June 2018
Accepted 27 June 2018
Available online 28 June 2018

Keywords:
Bio-inspired tactile sensor
Roughness discrimination
Polished surfaces
Signal decomposition
Machine learning

ABSTRACT

As an important application of tactile sensing, the capability of texture discrimination is desired in many researches, such as artificial limbs, dexterous manipulation, and humanoid haptic mechanism, etc. In this research, a bio-inspired tactile sensor containing two perpendicular sensing films was developed and manually controlled to slide across 15 polished surfaces with different roughness. Algorithms of discrete wavelet transform (DWT), sequential feature selection (SFS) and extreme learning machine (ELM) were combined together to form a signal processing system for signal decomposition, feature selection and roughness discrimination respectively. Factors affecting roughness discrimination accuracy were evaluated and compared with human tactile sensing capability. Particularly, influences of starting point and sliding duration on discrimination accuracy were analyzed to identify the optimal signal period for the following analysis. Effects of sampling rate on the discrimination accuracy were then investigated using the ELM classifier. Another two typical classification models, k-nearest-neighbor (kNN) and support vector machine (SVM), of different parameter configurations were compared with ELM in surface roughness discrimination. Results showed that the developed method based on manual sliding of the developed tactile sensor is capable of providing a surface roughness discrimination accuracy of 72.93 ± 10.48% with the real polished surfaces.

1. Introduction

There are mainly four kinds of functionally distinct mechanoreceptors including fast-adapting types (FA-I and FA-II) and slow-adapting types (SA-I and SA-II), which play key roles in tactilely sensing our external surroundings [1]. How to understand and utilize the capability of tactile sensing involves multiple disciplinary researches, which has attracted more and more attentions in many areas, such as artificial limbs, human-interactive robots, and medical tools etc. Recent trend on the development of tactile sensors focuses on mimicking functions and capabilities of biological mechanoreceptors, including three-axis force measurement, contact region estimation, slippage detection and object recognition etc. [2–6]. Among a variety of applications, texture recognition attracted more and more attentions. With a metal strain gauge symmetrically placed across the middle of a diaphragm in each sensor, a polymer-based microelectromechanical systems (MEMS) tactile sensor array was developed to classify five different textures while a correct classification rate of 68% was achieved [7]. An artificial finger was designed [8] to recognize eight natural surfaces with different textures, in which strain gauges and polyvinylidene fluorides (PVDFs) were randomly embedded in two layers. In another research, one thin PVDF film was used as the sensitive element in a fabric texture sensor system due to its high piezoelectric effect and unique physical properties [9], where a total classification rate as high as 98.7% was obtained in classifying five fabric surface textures. A nanogenerator-type tactile sensor capable of transmitting the texture and sliding motion information was reported in [10], in which these information was outputted in the form of a sequence of electric pulses. Discrimination of aluminum and five sanding sheets was realized with a magnetic tactile sensor to detect slow and fast surface deformations [11].

As an important part of texture, surface roughness is a key property of objects, the discrimination of which is challenging but so far receives few research attentions. A 2 × 2 array of four MEMS tactile microsensors was integrated to discriminate roughness in passive-touch and active-touch experiment [12], which revealed that frequency transformation of the signals was very helpful in detecting roughness information. How roughness was sensed in human body as well as its spatial acuity were investigated by assessing the results of a grating orientation task and a roughness discrimination task [13], which revealed the neural mechanism

* Corresponding author.
E-mail address: ylzhang@ntu.edu.sg (Y. Zhang).

https://doi.org/10.1016/j.sna.2018.06.049
0924-4247/© 2018 Published by Elsevier B.V.

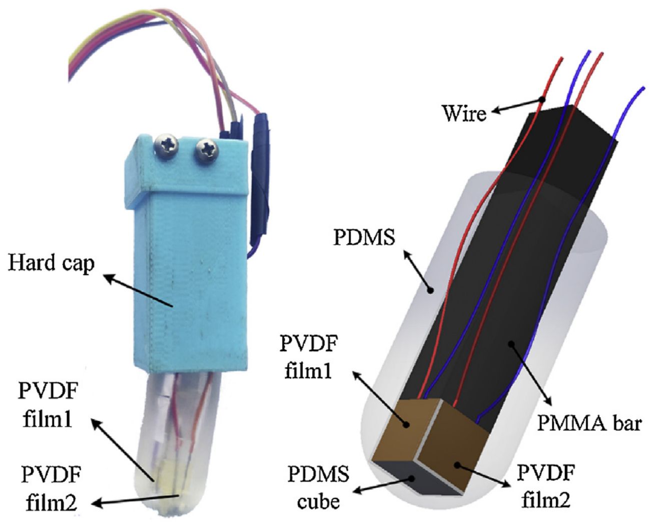

Fig. 1. Bio-inspired tactile sensor with a hard cap (left) and its inner structure (right).

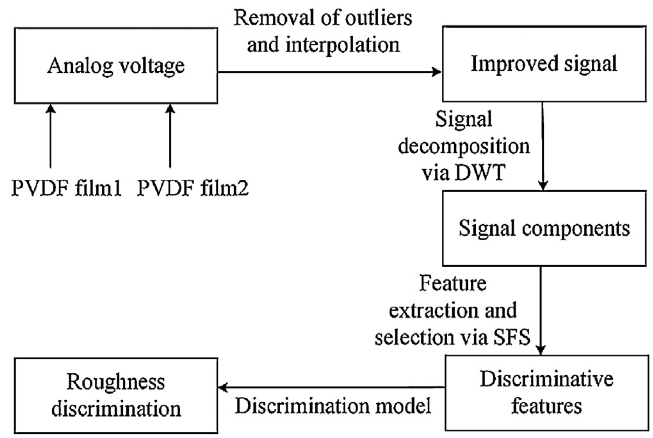

Fig. 2. Flowchart of signal processing for surface roughness discrimination.

underlying roughness perception for fine textures. After demonstrating the ability of PVDF thin film sensors to mimic FA-I type mechanoreceptors [3], we developed a bio-inspired tactile sensor containing two perpendicular PVDF films and manually controlled it to slide across different commercial roughness surfaces [14]. Then a set of enhanced signal processing methods was proposed to improve the discrimination accuracy greatly [15]. Compared with motor control, manual control of tactile sensor resembles human behavior better, which provides not only convenient and robust discrimination of surface roughness, but also a platform to systematically explore the neural mechanism of human haptic system. Before the manual sliding process could be broadly utilized, factors affecting it should be carefully investigated.

In this paper, 15 polished surfaces with roughness parameter Ra ranging from 0.44 μm to 4.43 μm were prepared. A biomimetic tactile sensor was held by hand to actively slide across these surfaces, where the sliding speed increased from 0 m/s to roughly 0.09 m/s, maintaining the speed before it stopped at the ending point. After analyzing the original signals, outliers were removed and six statistical features were defined. Algorithms of discrete wavelet transform (DWT) and sequential feature selection (SFS) were applied to select the most discriminative features. Next, extreme learning machine (ELM) was employed to construct the classifier. Discrimination accuracies based on different starting point and sliding duration were compared to identify the optimal signal period. Effects of sampling rate on roughness discrimination accuracy were also discussed. Finally, two other classification models, k-nearest neighbors (kNN) algorithm and support vector machine (SVM), were compared with ELM in roughness discrimination accuracy.

2. Bio-inspired tactile sensor

As discussed above, a variety of tactile sensors capable of recognizing textures or roughness has been developed based on different operation principles and design methods. PVDF film was chosen as the sensing element for roughness discrimination, whose capacity to mimic human FA-I type mechanoreceptors had been proved in our previous work [3]. In order to enhance the sensitivity, two PVDF films were placed perpendicularly. Fig. 1. illustrates the bio-inspired tactile sensor with a hard cap and its inner structure. Similar in size to human fingers, the sensor mainly comprises a PMMA (polymethyl methacrylate) bar in the center, two PVDF films perpendicularly attached to a PDMS (polydimethylsiloxane) cube, and a PDMS shell, which plays the role of bone, mechanoreceptors, and skin respectively. Both PVDF films were proved important in providing discriminative features for roughness discrimination [15].

To improve the previous fabrication procedure [14], conductive paste was replaced using adhesive tape in the present sensor fabrication to attach the PVDF films onto the PDMS cube, which enhanced signal strength and reduced fabrication time. Furthermore, sampling rate of analog signals outputted from the PVDF films was increased to 20 kHz, which was higher than the previous 1 kHz. Considering the high sensitivity of the developed tactile sensor, a hard cap was added to avoid interference from operator's grasping forces. In order to solve the worn issue of PDMS, a use and throw type of protection layer could be adopted. A calibration sample and algorithm would help ensure the repeatability after the replacement.

3. Methods

With the bio-inspired tactile sensor, analog signals were measured from the two sensing films, which were sensitive to vibration stimuli generated during the sliding procedure. Statistical features could be extracted from the analog signals and inputted into a classifier [14]. A set of signal processing methods was proposed to improve the discrimination accuracy [15]. In this paper, analog voltage signals from both films were processed according to the frame given in Fig. 2. Outliers existing in analog voltage signals from both PVDF films were removed before decomposed via DWT into signal components. Features were extracted and selected using algorithm of SFS for the most discriminative features, which were finally fed into a discrimination model to recognize roughness.

3.1. Removal of outliers

When the tactile sensor was held to manually slide across a surface, a lot of factors during the process may bring in random outliers, such as instability of contact force and sliding speed, environmental vibrations, and other noises from surrounding environment. Most outliers occurred like randomly distributed spikes that should be removed because statistical features might be very sensitive to outliers especially for small data size.