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Enhanced surface roughness discrimination with optimized features from bio-inspired tactile sensor

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ABSTRACT

The ability of surface roughness discrimination is of great significance in the development of biomimetic robots and prosthetic limb as well as the research on humanoid tactile sensing. In our previous research, a bio-inspired tactile sensor was developed to discriminate different surface roughness. But its discrimination accuracy decreased greatly as the roughness became smaller. Furthermore, the discrimination accuracy declined when signals from an extra PVDF film parallel to the sliding direction were included. In this paper, enhanced surface roughness discrimination using the same bio-inspired tactile sensor was achieved, including: 1) discrete wavelet transform was applied at first to decompose the original sensing data into different scale and frequency components; 2) the most discriminative features were selected from as many as 80 features defined both in time and frequency domains based on components via the algorithm of sequential forward selection; 3) instead of kNN or SVM, extreme learning machine (ELM) was applied to discriminate surface roughness. It was found that the extra PVDF film parallel to the sliding direction could provide the feature that affects the discrimination accuracy the most significantly if its signals were decomposed and the feature was selected from the high order component. Furthermore, the neural network based ELM was shown to have better discrimination accuracy than kNN or SVM using the same dataset and features. With ELM, the discrimination accuracy was improved from 82.6% to 97.88%. The result indicates the importance of signal decomposition and feature selection for surface roughness discrimination based on the bio-inspired tactile sensor. The proposed framework could also be applicable to other researches in sensor development and signal processing.

1. Introduction

Surface roughness is one of the important object properties since it significantly affects many performances, such as friction characteristics, wear resistance, and fatigue life [1]. Inspired by human mechanoreceptors, efforts have been devoted to recognize surface roughness with tactile sensors. Biomimetic mechanoreceptors have been developed based on various transduction techniques, for instance, piezoresistive, piezoelectric, magnetic, optical, and capacitive [2].

Extensive researches have been carried out on surface texture classification using tactile sensors [3–5]. However, as a major component of surface texture, roughness has been explored much less. A cantilever sensor with a resolution of 10–20 nm was fabricated for contour and roughness measurement and high-aspect-ratio mirometrology was realized, which was significant in robust manufacturing of microparts [6]. A piezoresistive tactile sensor array was developed based on microfabrication technique, which was able to mimic the human slow adapting type-I (SA-I) mechanoreceptors in terms of density [7]. Therein the *k*-Nearest Neighbors (*k*NN) classifiers together with the wavelet features were employed to discriminate three gratings and high classification accuracy was achieved. It was also reported that a grating recognition system based on spike-like signal processing, in which the grating pattern was decoded via assessing the principal frequency in the spike frequency domain [8].

There are many kinds of tactile sensors different in material, structure, sensing element and so on. In addition to the simple fabrication process, the development of bio-inspired sensors could benefit from biological knowledges in tactile perception, which could not only help improve the sensor performance, but also enhance fundamental understandings in biological tactile perception. Therefore, inspired by the fast adapting type-I (FA-I) mechanoreceptors in human hands, which were associated with object manipulation and texture discrimination and responsible for measuring object slip, edges, and fine features [9], we designed and fabricated a biomimetic fingertip with two perpendicular polyvinylidene difluoride (PVDF) film sensors [10]. Considering

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intelligent algorithms had been widely applied to processing tactile information [11,12], kNN and support vector machine (SVM) were used to construct a multi-classifier. When employed to discriminate surface roughness, the highest classification accuracy of $82.6 \pm 10.8\%$ was achieved with only one PVDF film and single feature (Standard deviation, SD) applied. However, on one hand, the misclassification error increased rapidly for surfaces with small roughness. Furthermore, the discrimination capability declined when sensing data from both PVDF film sensors were used simultaneously.

Aimed at solving these problems and further improving the discrimination accuracy, we propose a series of methods to enhance the surface roughness discrimination with optimized features from bio-inspired tactile sensor. At first, instead of directly extracting features from the original signal, in which various components are mixed, discrete wavelet transform (DWT) will be applied to decompose it into components in different scales and frequency bands. Then several typical statistical features are defined and extracted in time and frequency domains based on the decomposed signal components. With both of the two PVDF films used, discriminative features are selected among 80 extracted features via the algorithm of sequential forward selection (SFS) to remove redundant features and reduce the dimensionality. Finally the selected optimal features will be inputted into the discrimination model, which is constructed by multi-classification extreme learning machine (ELM), to recognize surface roughness since ELM has been proved possessing outstanding performance in a variety of multi-classification applications [13–15]. Experimental results reveal that a test accuracy of 97.88% (standard deviation $\pm$ 4.7%) is achieved while the training accuracy reaches 97.63% (standard deviation $\pm$ 0.63%). Further analysis and a comparison with kNN and SVM indicate that the selected features maximize the boundaries among different surface roughness and the proposed ELM model possesses outstanding classification capability. In addition, signal component of PVDF film 2 will greatly improve the discrimination capability instead of reducing the accuracy.

2. Development of bio-inspired tactile sensor

2.1. Design and manufacture of bio-inspired tactile sensor

Considering that the FA-I mechanoreceptors in human fingertips are responsible for texture discrimination [9], we employ PVDF films as sensors to measure the vibratory signals produced in sliding between the artificial fingertip and surfaces. It has been proved that PVDF films are sensitive to vibratory stimuli and can be used to encode the stimuli information similar to the FA-I mechanoreceptors [16]. The developed artificial fingertip is shown in Fig. 1(a). It consists of two PVDF films, two polydimethylsiloxane (PDMS) layers with different stiffness and a polymethyl methacrylate (PMMA) bar, mimicking the FA-I mechanoreceptors, the epidermis and dermis, and the bone of a human fingertip respectively. The two PVDF films are perpendicular to each other as shown in Fig. 1(a). During sliding, one PVDF film (film 1) is chosen to be perpendicular to the sliding direction as shown in Fig. 1(b). In this way, the two PVDF films are able to 'feel' the induced vibration in different angles, which would provide useful information for surface roughness discrimination. More details of the biomimetic sensor can be found in the previous publication [10].

2.2. Experimental setup

The artificial biomimetic fingertip was slide across different test surfaces to perceive the surface roughness (shown in Fig. 1(b)). In order to simplify the operation and experimental setup, the sliding process was manually controlled at a speed around 0.24 m/s. The discrimination result is expected to be further improved if special devices are used to precisely control the sliding speed and normal load. Analog outputs from the PVDF films are amplified via a custom amplifier and digitalized via DAQCard (USB-6225, National Instruments, USA). Eight standard nickel test surfaces (Rubert & Co. Ltd., UK) with roughness values (Ra) of 50 μm, 25 μm, 12.5 μm, 6.3 μm, 3.2 μm, 1.6 μm, 0.8 μm, 0.4 μm (Fig. 1(c)) are tested. The sliding direction (Fig. 1(c)) is perpendicular to the plane of PVDF film 1 and parallel to that of film 2.

3. Methods

In the previous research [10], statistical features were extracted from the output signals in time domain and then inputted into the classification model directly. According to its conclusion, it would achieve the highest accuracy 82.6% with only one feature (SD) inputted into the kNN model (k = 9). Moreover, the accuracy became worse when the sensing data of both PVDF film 1 and film 2 were used simultaneously, which was attributed to irregular vibration caused by the thin film geometry during sliding. In this paper, we will further investigate the signals from both films and obtain improved discrimination accuracy.

3.1. Analysis of tactile signals

It has been proved that frequency components of the generated tactile signals were relevant to the spatial period of surface roughness [7], which justified the usage of FA-I type of tactile sensors to discriminate different roughness. But in time domain, the frequency characteristics are hard to be expressed completely. Signals in time and frequency domains of both PVDF film 1 and film 2 are shown in Fig. 2, in which every subfigure is plotted under a self-adapting scale in order to show details clearly.

In both time and frequency domains, the signal amplitude decreases in general as the sample roughness becomes smaller. This tendency turns to be weakened for smooth samples and PVDF film 2. In frequency domain, only surface 1 and 2 have obvious main lobes, i.e., components of different frequency bands are mixed together, making the discrimination of surface roughness rather difficult. It explains why it was difficult to obtain high discrimination accuracy when directly tackling the entire time-domain signals in previous research [10]. Furthermore, signals produced by PVDF film 2 are small and easy to be affected by noises, resulting in a worse discrimination accuracy when both films 1 & 2 were used in [10]. Besides, from the various frequency components, it is inferred that signals from PVDF 1 were affected more by non-constant sliding speed while signals from PVDF 2 were affected more by the induced vibration because the PVDF 1 thin film was parallel to the sliding direction while the thin film PVDF 2 was perpendicular to the sliding direction.

In order to improve the situation, a framework of signal decomposition, feature selection, and neural network is proposed to enhance discrimination accuracy of surface roughness based on tactile sensors (Fig. 3). Signals measured by PVDF film 1 & 2 will be pre-processed and decomposed into different components, based on which a set of statistical features will be defined and selected before put into the discrimination model.

3.2. Pre-processing of tactile signals

At first, the output time-domain signals will be decomposed into components in different scales and frequency bands. DWT based on orthonormal wavelet basis can be applied to characterize the local