

Tactile design of manipulator fingers based on fingertip/textile friction-induced vibration stimulations

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ABSTRACT – REZUMAT

Tactile design of manipulator fingers based on fingertip/textile friction-induced vibration stimulations

Textile-like soft and flexible products are widely used in our daily life. Understanding the relationship between the tactile sensations of textiles and the tactile stimuli is essential for developing humanoid robot's finger haptic system, especially for certain kind of robot systems such as service robots and exploratory robots. This paper built a frequency space that can qualitatively represent a roughness sensation of textiles by a developing independently random match algorithm in combination with neurophysiological features of cutaneous mechanoreceptors. The experimental results show that the sum of amplitude in frequency range between 18 and 118 Hz can effectively describe the roughness sensory of textile with accuracies of 98.5%. In other words, by applying the sum of amplitude in frequency range between 18 and 118 Hz could successfully match roughness sensation of textiles, and it will help engineer of humanoid robot design manipulator finger haptic system in textile field.

Keywords: vibration, frequency space, roughness sensation, textile

Proiectarea tactilă a degetelor pentru manipulare bazată pe stimularea vibrațiilor induse de vârful degetului/frecarea materialului textil

Produsele ușoare și flexibile precum materialele textile sunt utilizate pe scară largă în viața noastră de zi cu zi. Înțelegerea relației dintre senzațiile tactile ale materialelor textile și stimulii tactili este esențială pentru dezvoltarea sistemului haptic al degetelor robotului umanoid, în special pentru anumite tipuri de sisteme robotice, precum roboții pentru manipulare și roboții de explorare. Această lucrare a dezvoltat un spațiu de frecvență, care poate reda calitativ senzația de rugozitate a materialelor textile, prin elaborarea unui algoritm independent aleatoriu ce combină caracteristicile neurofiziologice ale mecanoreceptorilor cutanați. Rezultatele experimentale arată că suma amplitudinii în intervalul de frecvență cuprins între 18 și 118 Hz poate descrie în mod eficient rugozitatea senzorială a materialelor textile cu o precizie de 98,5%. Cu alte cuvinte, aplicând suma amplitudinii în intervalul de frecvență cuprins între 18 și 118 Hz, s-ar putea obține cu succes senzația de rugozitate a materialelor textile și va ajuta la dezvoltarea sistemului haptic al degetelor robotului umanoid pentru domeniul textil.

Cuvinte-cheie: vibrație, domeniu de frecvență, senzație de rugozitate, material textil

INTRODUCTION

Tactile sensing is an important ability for a humanoid robot which interacts in a complex environment. It can be achieved by deriving a spatial vibration signal from the fingertip sliding across material's surface and then generating a proper stimulating signal to the manipulator fingers [1–2]. In this context, to sense and evaluate materials characteristics, understanding the relationship between tactile sensations and vibration stimuli is critical. Especially, for textile products that are widely used in our daily life, the tactile system of robots should have the ability to identify and discriminate textile materials with acceptable accuracy.

On the other hand, neurophysiologists and psychologists have acknowledged the importance of vibrotactile signals in understanding human tactile perception. It has been observed that four cutaneous

mechanoreceptors can give us the ability to estimate tactile qualities in fingertip. They are SAI units (Merkel cells), SAII units (Ruffini corpuscles), RA units (Meissner corpuscles) and PC units (Pacinian corpuscles), respectively. Among them, SAI units are sensitive to low-frequency vibration, frequency range from 2 to 16 Hz. These units transmit the information about pressure and structure of objects to the brain. The RA units are most sensitive to tangential force and can be easily excited by the frequency range between 2 and 60 Hz. The PC units, however, are very sensitive to mechanical transient vibrations in high frequencies, in the range of 40 to 500 Hz. The SAII units are sensitive to the lateral stretching and the sensitive frequency range is from 100 to 500 Hz [3–4].

Some study results have indicated that the intensity and energy density of vibration signals have great

influence on the sensations of roughness/smoothness [5]. And the vibration spectrum distribution have an effect on the sensation of softness [6]. Moreover, some researchers set frequency domain according to receptor characteristics to analysis tactile sensation but they hypothesis that the frequency bands are independent [3–4, 7]. However, although a tactile sensation is related to the vibration signals, an investigation of vibration frequency domain between the provided tactile stimuli and the achieved perception is still mysterious. Especially, for textile materials composing of fibers and yarns, the friction-induced vibration signals of textile and fingertip are more complex and include vibration components from high frequency to low frequency. Different vibration domain contains different material characteristics. Among them, the high frequency components depend on the surface hairiness and microscopic textures, and the low frequency signals are due to the main surface pattern textures of textiles. So to understand how vibration frequency domains affect textile tactile perception is considered a key to improve the communication efficiency in the design of manipulator fingers in the textile field.

This paper uses random matching algorithm to seek a vibration frequency space which can qualitatively represent roughness sensation. Here the frequency domain of fingertip/textile vibration signal is arbitrarily divided into ten frequency sub-bands, and the amplitude of each divided frequency domain is calculated. Noteworthy, each frequency sub-band is a matrix space. Meanwhile, the sum of amplitude in each frequency domain is used to match roughness sensation of textiles. The well-matched vibration frequency space will efficiently represent the tactile sensation of textile and throw light on a tactile design of manipulator fingers.

EXPERIMENTAL WORK

Materials and method

To seek the ranges of frequency to predict roughness sensation, four random fabrics which are obvious surface textures were chosen as experimental materials in our experiments. The specification parameters were shown in the table 1, and their stereoscopic microscope images were presented in figure 1.

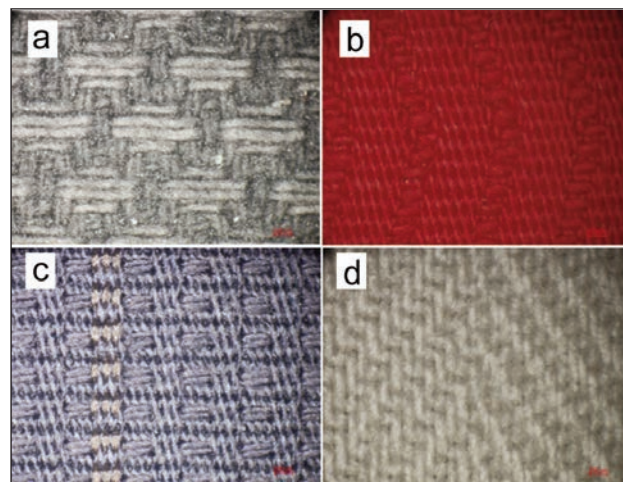


Fig. 1. Four random fabrics

Evaluation conditions

Four fabrics were preconditioned for 24 h before evaluation and tests were performed in standard atmosphere ($20\pm 2^\circ\text{C}$ and $65\pm 5\%$ relative humidity). The sensory evaluation method refers to AATCC Guidelines for the Subjective: Evaluation of Fabric Hand [8]. To obtain reliable results, strict controlled procedures have been implemented and the evaluation has been performed in blind condition for replicating thrice. Subjects were eighteen men and twelve women, aged from 18 to 24, and most of them were textile background.

Friction-induced vibration signal acquisition

To control the applied normal load and the relative sliding velocity, the finger is fixed and the experimental samples are moved from left to right at a constant speed. A low mass (0.8 g) accelerometer (Model 356A01) with high sensitivity (1 mV/mm/s^2) is applied on the finger nail to measure global vibrations (figure 2, a). Notice, the mass of accelerometer has not effect on the signal [9]. At the same time, the force transducers (500 mV/lb, Model 208C01) are placed below the sample holding platform for monitoring the global contact force. During sliding process, the normal applied load is about 0.8 N and the scanning speeds are 10 mm/s for textile. This is because the scanning speeds are commonly in the range 10 mm/s to 50 mm/s, higher for hard objects and lower for textile [10–12].

Table 1

SPECIFICATION PARAMETERS				
No.	Warp x Weft density (yarns/10 cm)	Count (Ne)	Composition	Weight (g/m ²)
1	95 × 64	16 × 16	Cotton 100%	244
2	65 × 100	40 × 32	Cotton 100%	208
3	175 × 108	40 + 150D × 40	Cotton 95.5% / Terylene 4.5%	175
4	78 × 59	12 × 8	Cotton 100%	341

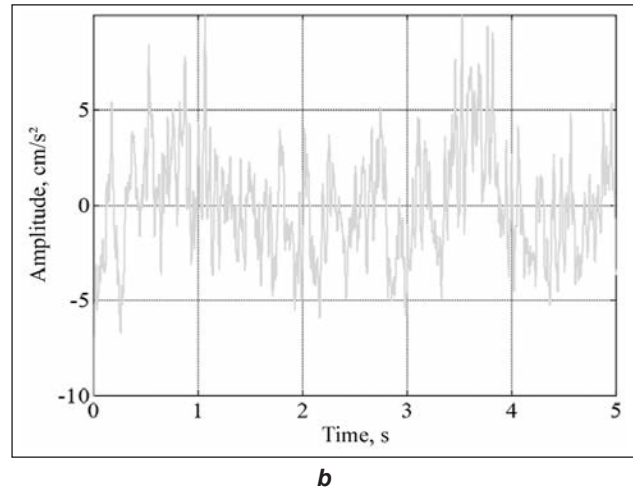
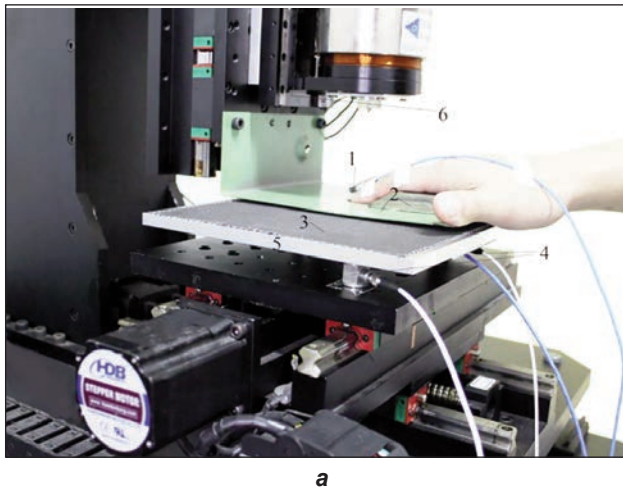


Fig. 2. Signal acquisition: *a* – Schematic diagram: 1 – Accelerometer, 2 – finger supports, 3 – textile sample, 4 – force transducers, 5 – base plate, 6 – 3D motion control platforms; *b* – vibration signal of sample A

Frequency space of friction-induced vibration signals

Using the random matching algorithm, the frequency bands of fingertip/textile vibration signal were divided arbitrarily into ten sub-bands with different width. Considering the frequency response characteristics of the mechanical receptors [3, 13], narrow bandwidths are set for the lower frequency bands, whereas wide bandwidths are used for higher frequency bands.

Here, $f_0 = 0$, $f_{10} = 500$, and f_i values are natural numbers between 0 and 500.

$$\begin{aligned} f_1 &= f_0 + \{1, 2, \dots, 10\}; \\ f_2 &= f_1 + \{1, 2, \dots, 20\}; \\ f_3 &= f_2 + \{1, 2, \dots, 20\}; \\ f_4 &= f_3 + \{5, 10, \dots, 50\}; \\ f_5 &= f_4 + \{5, 10, \dots, 50\}; \\ f_6 &= f_5 + \{5, 10, \dots, 50\}; \\ f_7 &= f_6 + \{10, 20, \dots, 100\}; \\ f_8 &= f_7 + \{10, 20, \dots, 100\}; \\ f_9 &= f_8 + \{10, 20, \dots, 100\}; \end{aligned}$$

Meanwhile, the sum of the amplitude spectra within each of above sub-bands was calculated. The sum of the amplitudes in the j_{th} sub-band for material i was determined as follows:

$$a_{ij} = \int_{f_{j-1}}^{f_j} a_i(f) df \quad (1)$$

where f and $a_i(f)$ are the frequency and amplitude, respectively.

And then, a search procedure is made for all of sub-band widths (f_0 – f_{10}) to find an optimized match between the vibration frequency space and roughness perception.

RESULTS AND DISCUSSION

Roughness sensation scores

To avoid the personal reference difference of each assessor's score, the tactile evaluation data was

normalized firstly, the Grubbs tests are performed to reject the abnormal value, which were probably affected by accidental factors in subjective experiment such as fatigue etc. The magnitude estimation method was used to quantify tactile roughness of four fabrics, and the scores are shown in figure 3.

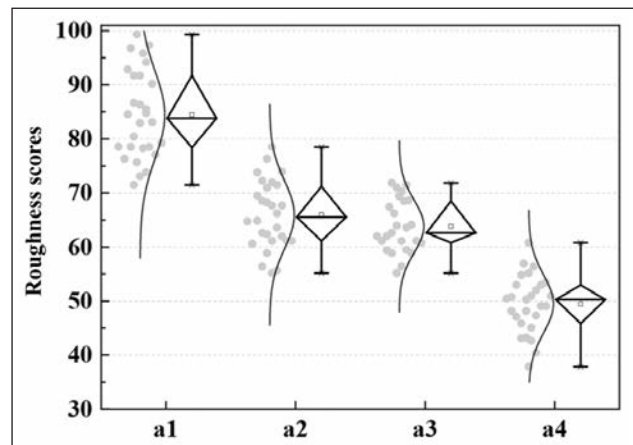


Fig. 3. Tactile roughness of four random fabrics

Frequency sub-bands

The random matching algorithm is used to calculate the frequency space, all of frequency domains are shown in table 2. It is noteworthy that each sub-band is a matrix. The size of matrix is the number of each frequency sub-bands. Next, the sum of acceleration amplitude in each of frequency sub-bands is calculated according to Equation (1). At the same time, the amplitude of each the frequency sub-band is imported in to a three-dimensional space (500 Hz × 500 Hz × Amplitudes). In this way, the contour of Amplitude-Frequency shows the amplitude distribution in each frequency space, as shown in figure 4.

In figure 4, the brighter color illustrates the bigger amplitude. Interestingly, the main amplitude is mainly distributed within 0–100 Hz. But it is still not clear which frequency sub-band can influence the roughness sensation. Some researchers have concluded

FREQUENCY DOMAIN				
$f_0 - f_1$	$f_1 - f_2$	$f_2 - f_3$	$f_3 - f_4$	$f_4 - f_5$
(0–10)	$\begin{pmatrix} 1 & \dots & 21 \\ \vdots & \ddots & \vdots \\ 10 & \dots & 30 \end{pmatrix}$	$\begin{pmatrix} 2 & \dots & 22 \\ \vdots & \ddots & \vdots \\ 30 & \dots & 50 \end{pmatrix}$	$\begin{pmatrix} 3 & \dots & 53 \\ \vdots & \ddots & \vdots \\ 50 & \dots & 100 \end{pmatrix}$	$\begin{pmatrix} 8 & \dots & 58 \\ \vdots & \ddots & \vdots \\ 100 & \dots & 150 \end{pmatrix}$
	$f_5 - f_6$	$f_6 - f_7$	$f_7 - f_8$	$f_8 - f_9$
	$\begin{pmatrix} 13 & \dots & 63 \\ \vdots & \ddots & \vdots \\ 150 & \dots & 200 \end{pmatrix}$	$\begin{pmatrix} 18 & \dots & 118 \\ \vdots & \ddots & \vdots \\ 200 & \dots & 300 \end{pmatrix}$	$\begin{pmatrix} 28 & \dots & 128 \\ \vdots & \ddots & \vdots \\ 300 & \dots & 400 \end{pmatrix}$	$\begin{pmatrix} 38 & \dots & 138 \\ \vdots & \ddots & \vdots \\ 400 & \dots & 500 \end{pmatrix}$

that the intensity of vibration signals has a great influence on roughness sensation [14]. The random research results for the maximum sum of amplitude in all frequency sub-bands are shown in figure 5. It shows that the maximum sum of amplitude appears in the range from 18 to 118 Hz. Therefore, it can hypothesize that the sum of amplitude in this frequency sub-band could represent roughness sensation. Moreover, the frequency range conforms with

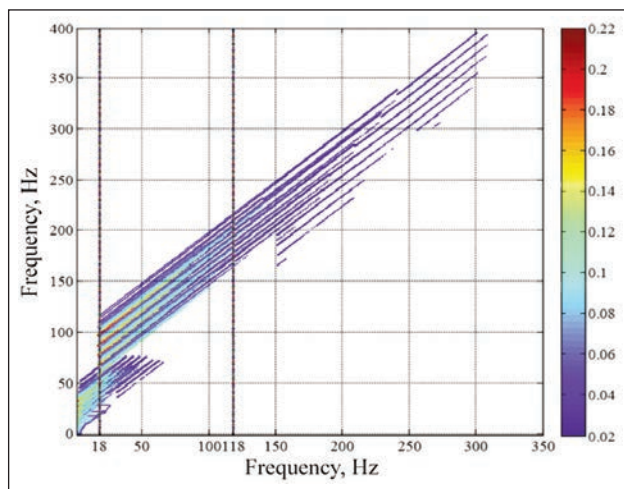


Fig. 4. Contour of Amplitude-Frequency spectrum

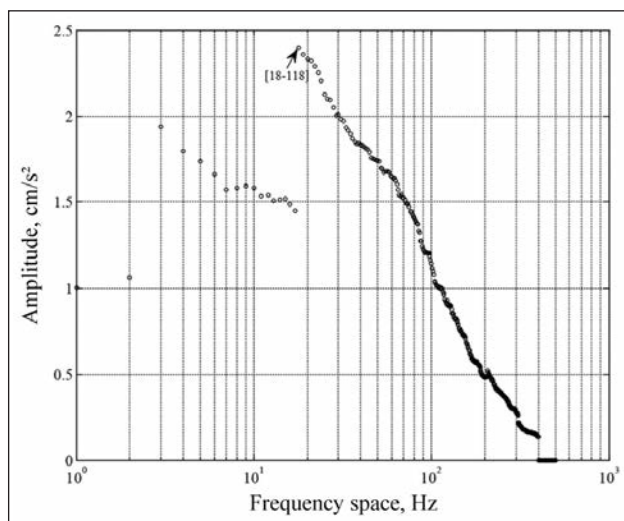


Fig. 5. Acceleration amplitude of different frequency space

the neurophysiology results and the width of sub-band included is narrow previous studies [3–4, 14].

Vibrotactile frequency Space Matched with Roughness sensation scores

To investigate how accurately the vibration signals of textiles could estimate the roughness sensation, the normalization value of amplitude which searched frequency sub-band (18–118 Hz) is compared with sensory evaluation. Figure 6 shows the comparison of the vibration and estimated value. Inspiringly, the tendency of vibration signals accord with the sensory evaluation but the value is smaller than sensory evaluation. This could be due to signal attenuation in acquisition process. At the same time, we calculate the lin's concordance correlation coefficients [15] of vibration value and sensation evaluation value, the correlation coefficients is 0.985 illustrating that searched frequency sub-band is effective for representing roughness sensation.

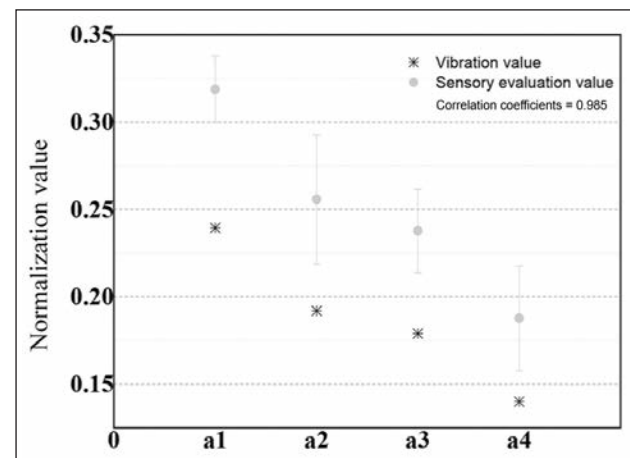


Fig. 6. Vibration and estimated value of four random fabrics

CONCLUSION

This study matched successfully the fingertip/textile vibration signals and the roughness sensation with a random matching method. The experimental results demonstrate that the sum of amplitude in frequency space between 18 and 118 Hz can describe the roughness sensory of textile with accuracies of approximately 98.5%, although the intensity of amplitude is

lower than sensory evaluation. Such a frequency space can be helpful for the analysis and design of humanoid robot's fingers considering that human textural precepts are multidimensional. And it is also meaningful the manipulator fingers to identify and discriminate textile materials.

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