Robotics and Autonomous Systems 71 (2015) 166–179

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

Interfacing robotic tactile sensation with human vibrotactile perception for digit recognition

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HIGHLIGHTS

- Embossed digit classification from tactile image & vibrotactile feedback to subject.
- Embossed digit recognition from tactile images by robot arm with 86.42% accuracy.
- Vibrotactile perception evaluation by classification from EEG with 71.53% accuracy.
- EEG features: AAR Parameters, Hjorth Parameters, and Power Spectral Density.
- Pixel based and regional features extracted from tactile images.
- Fuzzy *k*NN classifier is used.

ARTICLE INFO

Article history:
Available online 31 December 2014

Keywords:
Human–computer interaction
Digit recognition
Tactile pressure image
Vibrotactile stimulus
Electroencephalogram
Fuzzy *k*-nearest neighbor

ABSTRACT

To achieve human like functionality, artificial arms are required to be incorporated with the sense of touch that can be achieved by affixing tactile sensors to them. The user operating these artificial arms, for any Human–Computer Interactive task, should be able to perceive the same tactile sensation as is acquired by the tactile sensor fitted artificial arms. This work is an initial step to interface artificial tactile sensations of robots with human perception. Pressure distribution images are acquired while a robot arm fitted with a tactile sensor palpates embossed digits (0–9) and are classified. The image classification results are transmitted via control signals as vibrotactile stimuli to humans using vibration motors attached on their backs. Vibrotactile stimulus is chosen as a feedback sensation in an attempt to not engage visual/auditory channels such that the work can be extended in a multitasking environment in future. Vibrotactile stimuli are also essential for a person using prosthetic arm, suffering from sensory-motor disabilities that inhibit the use of the audio and/or visual sensory channels as well as for applications such as tele-operation. Electroencephalogram (EEG) signal analysis during vibrotactile stimulus presentation as well as subjects' response evaluation show that vibrotactile stimuli for particular digits as recognized from tactile data is capable of imparting information from artificial somato-sensation to humans. Fuzzy *k*-Nearest Neighbor classifier classifies both tactile images and vibrotactually stimulated EEG signals online with average accuracies of 85.25% and 72.60%, and runtimes of the order of 0.11 and 35 s respectively.

1. Introduction

Efficient maneuvering of robotic or prosthetic arms not only comprises of having human-like motion, but also accounts for the somato-sensations as felt by humans while tactually exploring objects. Incorporating tactile sensation is very essential in robotic/prosthetic devices in order to impart human like robotic regulation, simultaneously enhancing control, and precision while performing real world explorations [1]. Somato-sensation in artificial arms can be achieved by affixing tactile sensors over their finger and palm surfaces. The human operator who is operating a robotic arm during tele-operation, rehabilitation or any other human–computer interaction, needs to actually perceive the same sensation as is felt by the tactile sensor attached robotic arm. Thus there is a need

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http://dx.doi.org/10.1016/j.robot.2014.12.010
0921-8890/

to bridge the gap between the machine intelligence parts of the robotic tactile sensation with the human perception. Moreover, for efficient control of devices with Human–Computer Interface (HCI)/rehabilitative aids, a continuous feedback signal to the user is necessary [2,3]. Considering these requisites, this work is a preliminary step to interface the tactile information acquired while the robotic arms explore objects/surfaces with the human perception of those objects/surfaces in the form of vibrotactile stimulus.

In HCI applications, visual, audio, or tactile feedback has been used on many occasions [3–5]. However, people in need of a rehabilitative aid/ prosthetic hand may have vision/hearing problems or paralysis such that these sensory inputs may not be applicable for feedback. Again, in situations where object recognition is used as an assistive tool in a multitasking environment, the visual/auditory channels may be engaged in other activities. Contemplating these scenarios, vibrotactile stimulation/display is an effective way of feedback in HCI problems [6,7] and can be applicable in such situations. Several receptors on the human skin, like Merkel's receptors, Meissner's corpuscles, or Pacinian corpuscles can perceive mechanical vibrations on the skin with high spatial resolutions and convey precise information to the central nervous system at a very high speed [7]. Hence vibrotactile mechanisms have been used in applications that invoke alternative sensory means [8–11]. Various parameters determine the perception of vibrotactile stimulation, including the body part used, the frequency, intensity (in terms of force) as well as duration of vibration [7,10].

In [12], a vibrotactile reading device has been presented bypassing the necessity of audio feedback aiding the visually impaired with Braille knowledge. Significant vibrotactile stimulation based studies include use of vibrotactile tactor array for studying users' sensitivity to tactile apparent motion speed [13], vibrotactile feedback device for spatial guidance [14], as well as tele-manipulation and haptics [11], development of notions of linear and circular apparent movements through vibrotactile cues [15], distinction of alphanumeric letters on the basis of vibrotactile stimulations [16] among many others. Vibrotactile displays can be made from vibrating DC motors [17].

In this work, the tactile information obtained from a tactile sensor attached robotic arm are processed and analyzed to recognize objects, which in turn generates control signals to activate vibration motors. The vibration motors, attached on the subjects' active skin surface over their clothing, are actuated by specific patterns corresponding to each of the objects under exploration, to provide vibrotactile stimulus. In this study we have considered embossed numbers (0–9 digits) on plane surfaces, as the objects to be explored by the robot arm. Our aim is to recognize the embossed digits from the tactile data acquired while the robotic arm fitted with tactile sensors explores the same. The ultimate objective is to make the user understand the digits as recognized artificially from the tactile information, by imparting vibrotactile stimuli to them. Six vibration motors are attached on the subjects' backs to provide them the sensation of each digit similar to the seven-segment display of the numbers. Brain signals of the subjects are analyzed by processing Electroencephalogram (EEG) responses while vibrotactile stimulations are provided to the subjects. The use of EEG in brain computer interface (BCI) is popular because of the simple acquisition and processing, non-invasiveness, high temporal resolution and ease of real time implementations associated with EEG signals [18]. EEG analysis as well as the manual assessment of the subjects' responses are performed to evaluate the effectiveness of vibrotactile stimulation in conveying the information of the numbers which are explored by the robotic arms. This technique can find applications in various areas of HCIs, tele-navigation, robotics surgeries, and control of rehabilitation aids among others, according to the objects explored.

Previous works [1,19–21] have explored tactile sensation in robotic applications, while recognition of letters and alphanumeric characters from vibrotactile stimulation has also been studied [12,16]. However, to the best of the authors' knowledge, the present work is a novel approach to interface robotic tactile sensory information in terms of pressure images with human perception from vibrotactile stimulus for understanding embossed digits which are palpated by a robot arm, through brain response analysis as well as manual assessment of the subjects.

The rest of the paper is structured as follows. In the second section, the materials and methods of the undertaken approach are explained. The experiments follow in the third section. In the fourth section the experimental results have been discussed. In the fifth and final sections, the conclusions are drawn and future scopes of work are stated.

2. Materials and methods

The present work is based on two modules. The first module is concerned with the identification of embossed digits from pressure distribution images obtained by a tactile sensor wrapped robot arm. The classification of the pressure images generates control signals that activate particular patterns of vibration on the human back to recognize the digits corresponding to those patterns of vibrations in the second module. The interpretation of the vibrating patterns representing the digits by the subjects is studied from the analysis of EEG signals as well as their verbal responses. The complete course of work is illustrated in Fig. 1.

2.1. Embossed digit recognition from tactile sensor images acquired using robot arm

The entire process of embossed digit recognition from tactile images is described in this subsection.

2.1.1. Data acquisition

A robot arm available in our laboratory, affixed with the tactile sensor around its fingers is controlled by an operator to make it touch plane surfaces embossed with digit patterns to generate pressure distribution images. The images obtained are in the RGB format with different regions colored in accordance with the given pressure in those regions thereby providing distinctions in the embossed digits on the basis of pressure regions.

2.1.2. Tactile image pre-processing and feature extraction

The pre-processing of the acquired images involves three steps:

(i) *RGB to gray conversion*: The RGB images are converted into gray images for computational simplicity. This is implemented by computing a weighted sum of the R, G, and B values as the new gray intensity value according to (1). Equal weights are not assigned to R, G, and B to account for the fact that the human eyes perceive the green components most, followed by red and blue. The conversion retains the luminance according to the Rec. 601 standard [22] while eliminating hue and saturation from the image.

$$I = 0.2989 * R + 0.5870 * G + 0.1140 * B. \quad (1)$$

(ii) *Image Registration*: Images acquired by the sensor using the robot arm may be misaligned (translated or rotated such that their orientation is changed) during the process of acquisition, hampering digit identification. By image registration all images are aligned with reference to a base image by means of spatial transformations. In the present work an iterative intensity based registration technique [23] has been used. In this method, given a base image I_1, the misaligned image I_2 is first subjected to a rigid transformation involving rotation and translation and then a similarity metric defined by the mean