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Enhancing Tactile Estimation by Integrating Thermal Information from a Controlled-Temperature Flexible FBG-based Tactile Sensor

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I. Introduction

Recent advances in human-robot interaction have placed growing demands on tactile sensors that are not only accurate but also mechanically compliant. In applications such as medical robotics, prosthetic devices, and collaborative systems, sensors must detect subtle tactile cues while remaining noninvasive and safe for contact with humans or delicate materials [1]. Among various sensing modalities, tactile sensing is uniquely capable of capturing surface texture such as roughness and cold-warm sensation beyond the reach of vision or audition. Human touch naturally combines multiple modalities: surface texture is primarily inferred through vibrations produced during lateral motion across a surface, while thermal perception arises from the heat flux exchanged upon contact with an object of different temperature [2]. For robotic systems to emulate this dual-modality sensing, both vibration and temperature change data must be captured and interpreted in a coordinated manner. However, realizing such integrated functionality in a single, compact, and flexible tactile sensor remains a substantial technical challenge. Fiber Bragg grating (FBG) sensors offer a promising solution for addressing this challenge. Owing to their optical function, FBG sensors are inherently immune to electromagnetic interference and exhibit high sensitivity to both mechanical strain and temperature change. Their small form factor and flexibility make them ideal for integration into artificial skin or wearable devices [3]. While previous studies have effectively leveraged FBGs for detecting vibrations associated with surface roughness or slip, relatively little work has explored their potential in multimodal contexts involving thermal perception [4]. This underutilization limits their applicability in scenarios where similar textures must be differentiated based on heat-related cues. In response, we present a flexible tactile sensor based on an FBG that simultaneously captures vibration and temperature change during contact. This dual-sensing approach enables neural-network-based prediction of human tactile evaluations, bringing robotic tactile sensing one step closer to natural, human-like perception.

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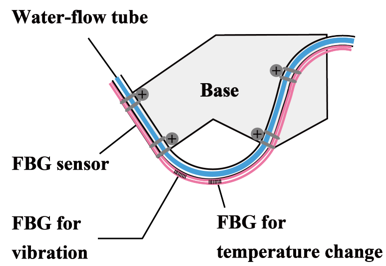


Fig. 1. Tactile sensor structure

II. Sensor Design and Data Collection

The proposed tactile sensor is composed of three main components, as it is shown in Fig. 1: an FBG sensor, a water-flow tube maintaining a constant temperature at the sensor, and a base for mechanical stability. The optical fiber of FBG sensor is attached to the outer surface of the water-flow tube. Two sensing points are positioned along the fiber: one placed where vibration occurs during surface tracing, and the other where the sensor makes contact with the object to detect temperature changes.

A central feature of the sensor is its ability to maintain surface temperature using internal water circulation. To enable accurate detection of heat flux, the sensor must be warmer than the object it contacts. Without this temperature difference, heat flux becomes negligible, as is the case when the object remains at ambient temperature and the sensor is also at the same temperature. To overcome this, the sensor maintains its surface at approximately 36°C, emulating human skin thermoregulation. This setup ensures a consistent thermal gradient upon contact with room-temperature materials and draws inspiration from the physiological mechanism by which blood flow maintains human skin temperature.

To evaluate the sensor's performance, five representative materials—aluminum, acrylic, rubber, wood, and concrete—were selected for their diverse surface textures and thermal properties. Square-shaped samples of 50 mm on each side were prepared for each material. These materials cover a wide range of tactile sensations in terms of roughness, hardness, and heat conductivity, making them suitable for multimodal sensing validation.

To obtain ground truth data for tactile estimation, a sensory evaluation experiment was conducted involving 13 participants (mean age: 22.3 ± 0.72 years). Each participant rated 20 tactile evaluation terms (e.g., rough, moist, cold) on a 7-point unipolar scale without visual information of samples. The experiment protocol was approved in advance by the

Bioethics Board of the Faculty of Science and Technology, Keio University (2023-002).

Among the five materials, rubber was selected as the target for estimation. Compared to the other materials, it received more moderate and evenly distributed ratings across the 20 evaluation terms, with fewer extreme values. Such a distribution minimizes boundary bias in the target labels, which can otherwise distort error metrics and obscure subtle differences in model performance. Therefore, rubber was used as the test material to mitigate the influence of label distribution artifacts and to enable a more interpretable evaluation of estimation accuracy.

Training data were collected from four materials—aluminum, acrylic, wood, and concrete—for both vibration and temperature measurement. For vibration measurement, the sensor was placed in contact with the sample surface and moved horizontally at a constant speed of 10 mm/s for 2 s. During this period, time-series data were sampled at 10 kHz, resulting in 20,000 vibration data points per measurement. Water circulation was not applied during vibration measurement. For temperature measurement, the sensor—preheated to 36°C via internal water circulation—was vertically lowered onto the sample and kept in contact for 1 s. Temperature data were sampled at 10 kHz, resulting in 10,000 temperature data points per trial. These procedures were repeated for each of the four training materials. The same protocol was applied to the rubber sample, which was used exclusively for testing. Each material was measured 10 times, yielding a total of 50 measurements (5 materials × 10 repetitions).

Collected data were standardized, scaled between –1 and 1, and smoothed with a moving average filter to ensure consistency across measurements and reduce noise. These preprocessing steps were necessary because FBG sensors detect relative changes in strain or temperature rather than absolute values.

III. NN-based Estimation of Tactile Perception

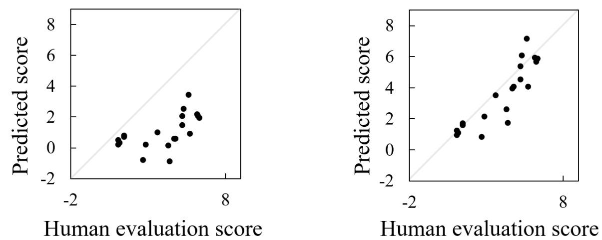
To investigate how different types of sensor data input affect tactile perception estimation, two neural network models were developed. The first model, referred to as the Vibration model, used only vibration data obtained from the vibration measurement, constructed from 20,000-point time-series signals per trial, to assess how well surface texture alone can explain tactile impressions.

The second model, referred to as the Vibration + Temperature model, combined 20,000 vibration data points from the vibration measurement with 10,000 temperature data points from the temperature measurement. This configuration was designed to test whether integrating thermal information improves estimation performance while maintaining a consistent trial structure.

Both models were implemented as fully connected three-layer neural networks. The input consisted of sensor data (vibration or vibration + temperature), and the output was a 20-dimensional vector representing estimated scores for evaluation terms. Hyperparameters including the number of hidden units, activation functions, and dropout rate were optimized using Optuna. Table I summarizes the search space for each parameter. The best-performing model was trained for 1000 epochs and evaluated on rubber data.

TABLE I
Hyperparameters tuned using Optuna and search spaces

Hyperparameter	Search Space
Number of Hidden Units	64, 128, 256, 512, 1024, 2048, 4096
Activation Functions	ReLU, Sigmoid
Dropout Rate	0.01, 0.5, 1.0



MSE = 11.04

MSE = 1.06

(a) Vibration model

(b) Vibration + Temperature model

Fig. 2. Correlation between estimated scores and human evaluation scores

IV. Results and Discussions

Fig. 2 shows the correlation between estimated scores and actual human evaluation scores for each modality individually, note that the plots represent 20 evaluation terms. The Vibration model which used 20,000 vibration points produced the highest errors (MSE = 11.04), indicating that vibration information alone was insufficient for accurately estimating tactile perception in the context of the present sample set. In contrast, the Vibration + Temperature model, which maintained the sensor at 36°C and used 20,000 vibration points and 10,000 temperature points, achieved significantly better performance (MSE = 1.06), capturing the trend of tactile evaluations for the test material (rubber). These findings confirm that maintaining the sensor temperature near human body temperature considerably enhances the reliability of thermal features, demonstrating the potential of an FBG-based sensor utilizing body-temperature data to achieve human-like robotic tactile perception.

References

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