Proceedings of the 4th International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/2026.37090

Research on Dynamic Regulation Mechanism of Embodied Tactile Feedback Based on Stimuli-Responsive Wrinkled Interfaces

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Abstract. Human-computer interaction in embodied intelligent systems is moving from visual and auditory dominance toward multimodal bodily perception. Tactile feedback has become a key perceptual channel in teleoperation, soft robotics, and immersive interaction. Traditional vibration feedback can provide basic cues, but its feedback pattern is relatively fixed. It is difficult to form continuous and computationally controllable tactile regulation according to contact states and user operations. Stimuli-responsive wrinkled interfaces can generate reversible surface morphological changes under thermal, pressure, or electrical stimulation. Thus, wrinkle wavelength, amplitude, and stimulation intensity can serve as adjustable tactile parameters. Based on this issue, a wrinkled interface composed of a PDMS elastic substrate and a responsive polymer film was constructed. Pressure sensors, a temperature control module, a signal acquisition system, and machine learning models were used to analyze the relationship among interface morphology, tactile signal features, and user behavioral responses. The experimental results show that dynamic wrinkled feedback outperforms no tactile feedback and fixed vibration feedback in texture recognition, contact force discrimination, response time, and task workload. This study shows how these wrinkle structures can be used as dynamic tactile coding elements within embodied intelligence systems. These structures offer a much more natural and tunable method of providing feedback.

Keywords: Embodied Intelligence, Tactile Feedback, Stimuli-Responsive Interface, Wrinkled Surface, Human-Computer Interaction

1. Introduction

With the rise of embodied intelligence, human-computer interaction will be transformed from unidirectional channels like visual perception or hearing to a combined process where body sensation, action control, and environment coupling come into play [1]. Consequently, haptic feedback has been developed as another sensory channel in virtual operations, teleoperation, and cooperative soft robotics. Conventional haptic systems are made up of vibrotactile motors, air-driven actuators, or elastic touch sensors, which can give some clues but fail to implement morphologically

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variable surfaces, controllable haptic patterns, and computable perception of users simultaneously [2]. Haptics based on stimuli-responsive wrinkle surfaces can create controllable surface deformations triggered by heat, electricity, or mechanical force, and the wrinkle wavelength, height, and direction could act as codes to modulate tactile information [3]. This project will focus on the interaction between interface morphology, tactile stimuli, and behavioral response from material level to application level, including wrinkle surface fabrication, tactile signal sensing, computational recognition, and behavioral measurement.

2. Literature review

2.1. Embodied intelligence and tactile interaction

The concept of embodied intelligence highlights the point that intelligent activity arises not just from algorithm-based computation but from body organization, physical interaction with environment, and immediate feedback processes [4]. Within this context, tactile interaction assists action validation, risk assessment, and action correction. In human-machine cooperation and tele-operation scenarios, visual feedback can be compromised due to occlusion, delay, or scale issues; however, tactile feedback can assist the operator assess the level of applied force, texture, and operation constraints. Although advances such as electronic skin and wearable haptic devices have greatly advanced tactile perceptual capacity, there have been less improvements in tactile feedback capabilities, with tactile outputs being confined mostly to a predefined level of intensity or a set of preprogrammed modalities.

2.2. Stimuli-responsive wrinkled interfaces

Generally speaking, stimuli-responsive wrinkled surfaces consist of a soft elastic base layer and an active thin film layer. If there is a difference between the two components in terms of modulus, expansivity, or the degree of strain release, a regular or hierarchical pattern will be created on the surface [5]. What matters about the patterns is not only that they vary the roughness but also that they can produce discernible tactile sensations by wavelength, amplitude, direction, and arrangement. Due to their inherent sensitivity to stimuli, smart polymers, thermo-responsive films, and electro-active materials ensure the reversibility of the process of surface wrinkling, thus making the physical foundation for dynamic touch coding possible [6]. While materials science has already proved the feasibility of manipulating such structures, embodied interaction calls for their transformation into tangible touch feedbacks.

2.3. Computational modeling of dynamic tactile feedback

Tactile feedback generated dynamically must be supported by computational models for linking the mechanical properties of materials, sensing signals, and human perception, rather than relying on demonstrations of morphological changes on the surface alone [7]. Finite element modeling can help understand the distributions of contact forces, strains, and variations of frictional force depending on wrinkle formation parameters. In addition, information regarding the contact forces, reaction times, and intensities of stimuli can be collected using pressure sensors, temperature controls, and microcontrollers [8]. The classification of tactile states can be achieved through machine learning algorithms. Moreover, with the application of closed-loop control, stimulus input can be modified

DOI: 10.54254/2755-2721/2026.37090

based on users' operational states, and thus dynamic tactile feedback can become an embodiment-based interactive experience [9].

3. Experimental methods

3.1. Preparation and parameter design of wrinkled interfaces

The preparation of the wrinkled surface involved a sequence of steps comprising substrate pre-tensioning, activation, film deposition, and relaxation of the tensile strain. The PDMS prepolymer and catalyst were blended in a weight ratio of 10:1. The mixture was degassed under vacuum for 20 min, poured into a glass mold, and cured at 70 °C for 2 h. The cured substrate was cut into samples of 30 mm × 30 mm × 1 mm. The samples were fixed on a uniaxial stretching platform. Pre stretching strains of 20%, 30%, and 40% were applied, respectively [10]. Each strain was maintained for 5 min to stabilize substrate deformation. Oxygen plasma treatment was then conducted for 60 s to improve the surface energy of PDMS and the adhesion of the thin film. A thermoresponsive polymer film was deposited by spin coating at 2000 rpm for 60 s. The target film thickness was controlled at about 800 nm. After film drying, the pre strain was slowly released. Regular wrinkles were formed on the surface due to the modulus difference and strain mismatch between the film and the elastic substrate. At least five repeated samples were prepared for each group. Optical microscopy was used to capture surface textures. Wrinkle wavelength was determined using ImageJ software. Wrinkle amplitude and roughness were measured using a white light profilometer. The three groups, namely 20%, 30%, and 40% pre strain, represented low, medium, and high intensities of tactile texture. This enabled manipulation of the input variable in order to acquire tactile signals from users.

3.2. Tactile signal acquisition and computational modeling

The system for tactile signal acquisition included wrinkled samples of interface, thin film pressure sensors, a micro thermal control sheet, a temperature sensor, the friction sliding test unit, and STM32 microcontrollers. The wrinkled sample was attached to the testing platform. The pressure sensor was located beneath the sample to detect vertical forces applied to the interface. Thermal stimuli were generated by the thermal control sheet placed at the rear side of the sample; three stages of temperature, i.e., 25 °C, 35 °C, and 45 °C, were selected. Temperature changes of the interface were monitored by the temperature sensor. Mechanical stimulation was provided by a vertical mechanical stimulator that applied three levels of contact force, 0.5 N, 1.0 N, and 1.5 N. It then performed short distance sliding at a speed of 10 mm/s to simulate finger pressing and sliding touch. Each combination of wrinkle parameters and stimulation conditions was tested 30 times. The sampling frequency was set at 100 Hz. Contact force, friction response, temperature change, and response time were recorded. The raw signals were first processed by median filtering to remove transient noise [11]. Normalization was then conducted. Peak force, average friction coefficient, response delay, signal stability, and frequency domain energy were extracted as features. The tactile output intensity was jointly described by wrinkle amplitude, wrinkle wavelength, and stimulation intensity, as shown in Formula (1).

$$T_o=\alpha A+\beta\frac{1}{\lambda}+\gamma S+\varepsilon \tag{1}$$

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Here, T_o represents tactile output intensity. represents wrinkle amplitude. λ represents wrinkle wavelength. S represents thermal or pressure stimulation intensity. α, β, and γ are regression weights. ε is the measurement error. In the modeling stage, the extracted signal features were input into a random forest model and a lightweight neural network for comparative training. The classification targets were set as three tactile states, namely smooth texture, weak texture, and strong texture. The Softmax function was used to output the probability of each tactile state, as shown in Formula (2).

$$P(y=k|x)=\frac{e^{W_k x+b_k}}{\sum_{j=1}^{K} e^{W_j x+b_j}} \quad (2)$$

Here, x is the tactile signal feature vector. k represents the tactile category. W_k and b_k are the model weight and bias, respectively. K is the number of categories. The dataset was divided into a training set, a validation set, and a test set at a ratio of 70%, 15%, and 15%. Accuracy, F1 score, and the confusion matrix were used to evaluate model recognition performance.

3.3. User experiment and evaluation indicators

The user experiment adopted a within subject repeated measures design. Each participant experienced three conditions, including no tactile feedback, fixed vibration feedback, and dynamic wrinkled feedback. Twenty four participants were recruited. All participants had normal hand tactile perception. The task procedure was explained before the experiment, and informed consent was obtained. Prior to the actual experiment, there was a training phase set out for participants where they interacted with three kinds of wrinkled interfaces and carried out six operations. This helped them get acquainted with the nature of feedback provided, although the exact parameters were not revealed beforehand. There were three formal tests which comprised virtual button press, remote object grasp and surface texture recognition. For the virtual button press test, the participants determined whether they had pressed the button based on their haptic feedback. For the remote object grasp test, a mechanical hand was employed to grab the objects with varying degrees of softness and the participants regulated the grasping force by the feedback received. The texture recognition test required the participants to identify if the interface was smooth, weakly-textured or strongly-textured. A Latin square design was applied to the sequence of three types of feedback for balance reasons related to fatigue and learning factors. The system would automatically register recognition accuracy, reaction time, percentage of error, contact force variations, and time to finish the test. Post-task surveys about tactile perception clarity, trust in operating the task, and NASA-TLX workload measurement would be performed after each series of tasks. Analysis of Variance for Repeated Measures was used to analyze the differences between the three types of feedback.

4. Results

4.1. Regulation performance of wrinkled tactile feedback

According to the test results under different wrinkle parameters and feedback conditions, dynamic wrinkled feedback showed better performance in tactile recognition, contact force discrimination, and signal stability. As is seen from Table 1, the accuracy of texture recognition in the absence of tactile feedback was 68.4%, the accuracy of contact force discrimination was 71.8%, and the mean response time was 1.42 s. It shows that participants heavily used vision and subjective experience in the experiments. With the fixed vibration feedback, the accuracy of texture recognition increased to

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79.2%. However, it was difficult to recognize different contact forces using this type of tactile feedback since the vibration was too basic. Using dynamic wrinkled feedback, the accuracy of texture recognition increased to 88.9%, the accuracy of contact force discrimination increased to 89.6%, the mean response time decreased to 1.08 s, the variation coefficient of contact force decreased to 0.18, and the accuracy of model classification was 88.7%.

Table 1. Regulation performance under different tactile feedback conditions

Feedback condition	Texture recognition accuracy	Force discrimination accuracy	Mean response time	Force variation coefficient	Model classification accuracy
No tactile feedback	68.4%	71.8%	1.42 s	0.31	72.5%
Fixed vibration feedback	79.2%	81.5%	1.24 s	0.24	80.6%
Dynamic wrinkled feedback	88.9%	89.6%	1.08 s	0.18	88.7%

4.2. Behavioral response under embodied interaction tasks

Figure 1. Behavioral response distribution under different feedback conditions

From the results above, it is observed that dynamic wrinkled feedback can enhance operation performance in embodied interaction. In this case, as illustrated in Figure 1, the x-axis shows the error rate, the y-axis shows the NASA-TLX workload score, while the bubble size indicates the tactile clarity score. For the case of no tactile feedback condition, the error rate was 17.6%, the workload was 55.4%, and the tactile clarity score was 2.61. The findings show that the absence of tactile cues led to increased cognitive workload in decision-making. However, with fixed vibration feedback, the error rate was lowered to 10.9%, the workload was reduced to 46.2%, but the bubble was still positioned at medium workload level. Finally, under dynamic wrinkled feedback, the error rate was lowered to 6.8%, the NASA-TLX score was 39.7%, and the tactile clarity score was

DOI: 10.54254/2755-2721/2026.37090

enhanced to 4.35. Thus, it can be stated that dynamic wrinkling feedback enhances tactile distinguishability and reduces the cognitive workload of users in remote grasping, virtual button pressing, and texture recognition operations.

5. Discussion

The experimental results show that the advantage of dynamic wrinkled feedback mainly comes from the mappable relationship between material morphology and tactile signals. Wrinkle wavelength and amplitude change the contact area, friction response, and local pressure distribution of the interface. This allows users to obtain clearer tactile distinctions under different operational states. Compared with fixed vibration feedback, wrinkled feedback is not a single intensity cue. It forms a feedback pattern closer to real contact through surface structural changes. The computational model further shows that force variation, response delay, and stability indicators in tactile signals can be used to identify different tactile states. It should also be noted that long-term cyclic stability, individual differences in tactile sensitivity, and miniaturized integration may still affect practical application performance. Future work can further optimize material durability and closed-loop control strategies.

6. Conclusion

A research process for the dynamic tactile feedback mechanism of stimuli-responsive wrinkled interfaces was established, covering interface fabrication, signal acquisition, computational modeling, and user experiment evaluation. The results show that wrinkle wavelength, amplitude, and stimulation intensity can form recognizable tactile features. The machine learning model is capable of accurately classifying smooth, weak, and strong textures. Dynamic wrinkling feedback performs better than static feedback and no feedback conditions in terms of accuracy of texture recognition and detection of contact force. It also helps in reducing the error rate and workload of the process. The system connects material, computation, and human interaction. It gives a realistic approach to designing tactile feedback system for embodied intelligent systems.

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