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Hand Gesture Identification for Soft Controller regarding Human Behaviours

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Abstracts: In the context of the Internet of Things (IoT), gesture control offers a natural and convenient interaction method. Compared to traditional physical buttons or touchscreens, gesture control is more intuitive and flexible, making it highly suitable for smart clothing applications. This study focuses on analyzing the reliability of PET (Polyethylene terephthalate)-based piezoresistive thin-film sensors for hand gesture recognition, demonstrating their potential for smart clothing. A survey identified 13 common hand gestures frequently used in daily activities. Experimental results showed that the sensors effectively recognized these gestures, achieving a recognition accuracy of 99.4% through neural network modeling with the original design of 25 sensors. To simplify the design and improve reliability, a greedy algorithm was used to find a locally optimal solution, reducing the number of sensors from 25 to 6 while maintaining a recognition accuracy of 97%. This optimization significantly reduced system complexity, lowered costs, and made the product more environmentally friendly. In reliability testing, the original 25-sensor design had a failure rate of 7.69×10^{-5}, with the first failure occurring after 13,000 uses. The optimized design with 6 sensors exhibited a slightly improved failure rate of 7.64×10^{-5}, with the first error appearing after 13,082 uses. As testing continued, error fluctuations increased in both layouts, indicating that long-term sensor performance degrades over time. However, the optimized design notably enhanced the system's durability and reliability. In conclusion, this study confirms that PET-based sensors are not only reliable but also benefit from sensor quantity optimization, improving system durability and cost-effectiveness. These qualities make them highly suitable for integration into smart clothing's remote-control systems, offering a lightweight, durable, and efficient solution for future innovations.

Keywords: reliability, smart clothing, flexible sensor, remote control.

1. Introduction

In the context of Internet of Things (IoT), developing smart clothing has already been a trend and widely used in the medical industry(Fatima et al., 2024; Oh et al., 2024), human-machine interaction (HMI) (Wang et al., 2024; Li et al., 2024) and virtual reality(Kuo et al., 2023). Smart clothing can be seen as a system that facilitates interaction between body parts and sensors. In this field, the coordination between various body parts and different sensors is crucial. Among these, the hand, as one of the most frequently used parts of the human body, plays a vital role in smart clothing due to its wide range of possible gestures. There is some research on the interaction between the hand and the sensor. Zhao et al. (2024) introduced an innovative sensor array that leverages triboelectric and electrostatic effects for the detection and capture of diverse hand gestures (Zhao et al., 2024). Similarly, Yang et al. (2024) presented a stretchable epidermal sEMG sensor array system, enhanced through optimized materials and structural strategies, aimed at recognizing hand gestures and aiding in hand function rehabilitation (Yang et al., 2024; Zafar et al., 2023). The commonality among these studies lies in their use of flexible sensors instead of traditional ones. Traditional sensors, due to their fragility and low sensitivity, are unsuitable for smart clothing applications (Wang et al., 2021), which primarily rely on e-textiles and flexible sensors. In the context of smart clothing, flexible sensors demonstrate excellent performance in terms of sensitivity (Han et al., 2019), compatibility, and long-term durability, making them highly suitable for these applications (Pitcheri et al., 2024), especially in scenarios requiring frequent deformation (Zhang et al., 2024). Much research focuses on flexible pressure and simply defines flexible pressure sensors into three categories: piezoresistive, capacitive, and piezoelectric. (Xiao et al., 2018; Wang et al., 2021). Among them, the piezoresistive pressure sensor which need to complete the gesture control task is the research focus in this research. While there are limited studies using PET-based pressure sensors for gesture recognition, these sensors have shown stable sensing performance and excellent durability (Zhou et al., 2024), making them an ideal fit for this research. Therefore, we employ PET-based pressure sensors to test their ability to accurately recognize 13 hand gestures and evaluate their durability.

2. Objective and Importance of Research

2.1 *Research objectives*

(i) Identifying common hand gestures regarding human behaviours.
(ii) Validating the sensitivity of PET-based piezoresistive thin-film sensors for gesture controller.
(iii) Optimizing the PET-based piezoresistive thin-film sensors deployment of hand.
(iv) Investigating the reliability of the PET-based piezoresistive thin-film sensors while applying to the gesture controller.

2.2 *Research significant*

(i) By identifying common hand gestures related to human behaviours, this research aims to improve the accuracy and applicability of gesture recognition systems, thereby promoting the use of smart clothing and wearable devices in everyday life. Offers a basis for durability testing of flexible thin-film pressure sensors.
(ii) By validating the sensitivity of PET-based piezoresistive thin-film sensors, this research ensures their effectiveness and responsiveness in gesture controllers, which is crucial for achieving real-time and precise gesture recognition. Flexible thin-film pressure sensor gloves can serve as control interfaces for smart devices, offering a more convenient and multifunctional human-machine interaction method through gesture recognition.
(iii) Optimize deployment of hand sensors helps reduce the number of sensors while maintaining high accuracy, thus lowering costs and enhancing the user-friendliness of the devices.
(iv) By investigating the reliability of these sensors in gesture control applications, this research provides a solid foundation for the use of this technology in real-world scenarios, driving innovation in human-machine interaction, healthcare, and other fields.

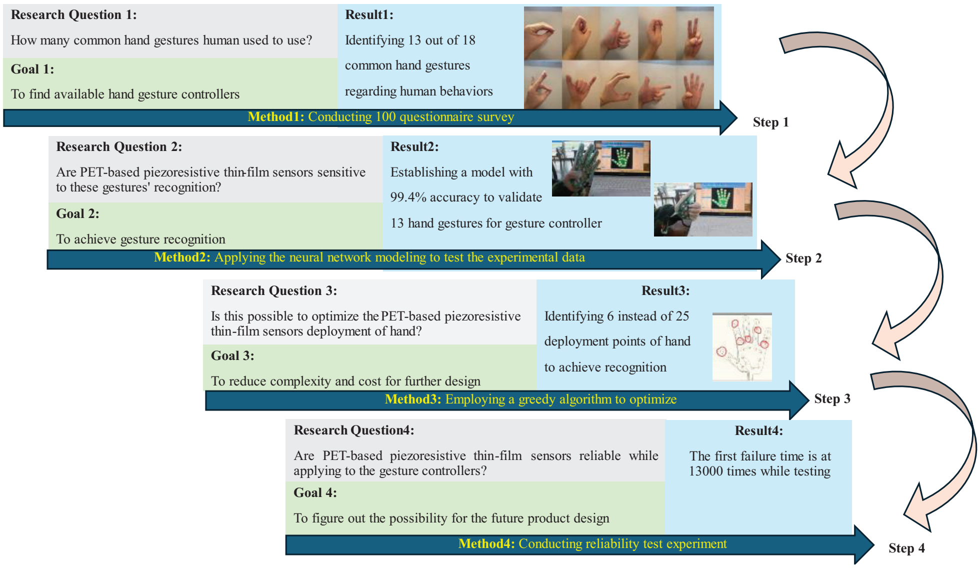

Fig.1: Research Framework

3. Experiment Design

3.1. *To achieve Research Objective i*

Sub-headings should be typeset in boldface italic. Capitalize the first letter of the first word only. Leave no space after the sub-headings; leave one space before.

3.1.1. *Input*

- This study interviewed 30 people to collect their commonly used gestures.
- Through a questionnaire survey, we screened the commonly used gestures collected from interviews. First, we analysed the survey results to identify gestures selected by more than 50% of participants. These high-frequency gestures were then chosen as the subjects for sensitivity analysis. Subsequently, we further filtered these gestures to retain the most representative ones for detailed study and analysis in the following stages.
- Excluding military, traffic, sign language, and sensitive gestures

3.1.2. *Output*

- Through the interviews, we collected the 18 gestures shown in the figure below (Fig.2).

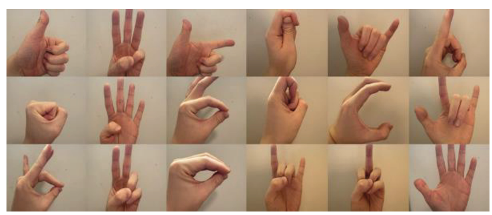

Fig.2: Hand gesture (18)

- The questionnaire results showed that 14 gestures were selected by 50% or more of participants (Table.1). After excluding one offensive gesture, 13 gestures remained (Fig.3).

Fig.3: Hand gesture (13)

Table.1: Survey results of 18 gesture

Type	Count	Percentage
1	54	51.92%
2	70	67.31%
3	30	28.85%
4	90	86.54%
5	72	69.23%
6	71	68.27%
7	17	16.35%
8	55	52.88%
9	59	56.73%
10	59	56.73%
11	52	50%
12	56	53.85%
13	44	42.31%
14	54	51.92%
15	34	32.69%
16	54	51.92%
17	59	56.73%
18	84	80.77%
Total	104	

3.2. *To achieve Research Objective ii*

3.2.1 *Input*

- In the experiment, a palm pressure sensor equipped with 25 piezoresistive thin-film pressure sensors will be used to perform 13 different gestures, with each gesture repeated 2000 times (Fig.4). Experimental data will be recorded, and based on the results, a neural network model will be developed. The aim is to test the sensitivity of the palm pressure sensor in recognizing the 13 gestures using the collected data.

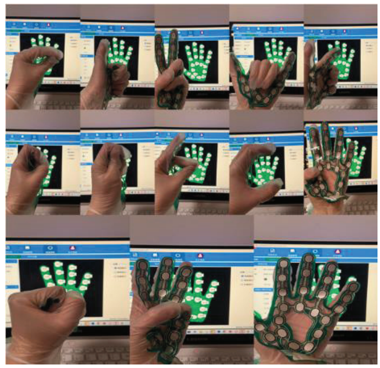

Fig.4: Experimental process picture

3.2.1 *Output*

- Using the recorded experimental data, we developed a neural network model for pattern recognition with an accuracy of 99.4%. The data distribution during training was 60% for training, 20% for testing, and 20% for validation.

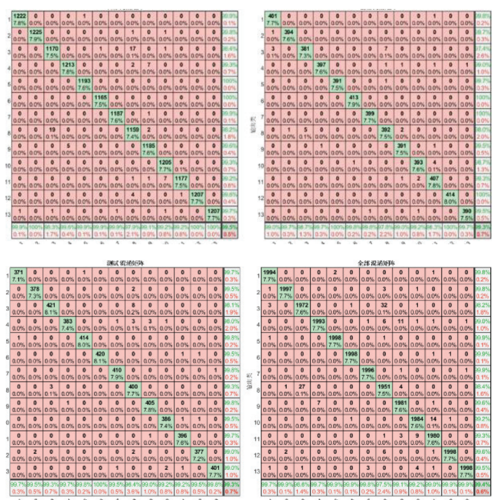

Fig.5: Confusion Matrix at the End of Training

3.3. *To achieve Research Objective iii*

3.3.1 *Input*

- Having too many sensors can cause discomfort for the wearer and increase costs. Therefore, finding a combination of a small number of sensors that still achieves high model accuracy is crucial. Due to the numerous possible combinations of 25 sensors, this study employs a greedy algorithm to identify a relatively efficient sensor combination. Definition of the greedy algorithm: The core idea of the greedy algorithm is to achieve a global optimum through local optimum choices at each step. In other words, the greedy algorithm always makes the best immediate choice without considering potential future scenarios. This strategy often results in high execution efficiency but does not guarantee the optimal solution in every case.

3.3.2 *Output*

- Through the analysis using the greedy algorithm, we found that retaining only 6 sensors (Fig.6) can achieve a model accuracy of 97%(Fig.8). This significantly reduces the cost of designing the gesture controller and enhances the comfort for the wearer. In addition, with further optimized features, this study has developed a product model (Fig.7).

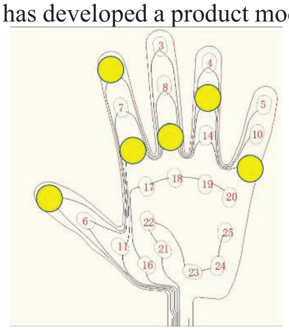

Fig.6: Optimized point map

Fig.7: Optimized Product Model

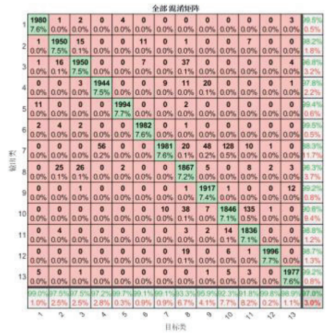

Fig.8: Confusion Matrix (6 sensors)

3.4. *To achieve Research Objective iv*

3.4.1 *Input*

This study explores the reliability of resistive thin-film pressure sensors. Observations reveal that when using a combination of 25 sensors, the system experienced its first failure after 13,000 uses, whereas with a combination of 6 sensors, the first failure occurred after 13,082 uses. To further investigate the durability of the sensors, the error values of the 25-sensor combination in a flat state were recorded at 13,000, 26,000, and 39,000 uses. Similarly, the error variations of the 6-sensor combination under the same conditions were recorded at 13,082, 26,000, and 39,000 uses. These data are used to analyze how the durability of the sensors changes with the number of users.

3.4.2 *Output*

- Test Results for the 25-Sensor Combination: From the data presented in Figure 9, it is evident that the error variation of the sensors changes significantly over time. At 13,000 uses, the average error was 0.000304, indicating relatively stable sensor performance. By 26,000 uses, the average error increased to 0.005672, nearly 19 times higher than at 13,000 uses. At this point, more sensors began to exhibit larger errors, indicating a notable decline in system stability. By 39,000 uses, the average error further increased to 0.025576, approximately 84 times the value at 13,000 uses, demonstrating significant degradation of the system after prolonged operation. Overall, as the number of uses increases, the sensor system's error progressively expands, with the long-term stability of the system showing a marked decline, especially by 39,000 uses.

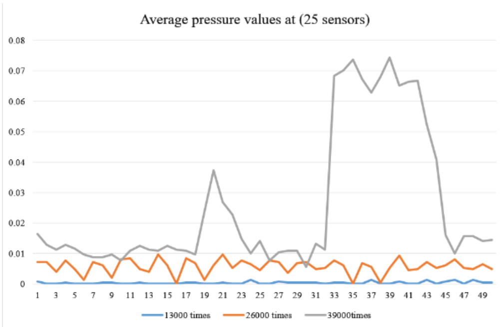

Fig.9: Error fluctuation diagram for 25 pressure sensors

Test Results for the Optimized 6-Sensor Combination (Fig. 10):

From the data in the table, it is clear that the error variation of the sensors changes significantly over time. At 13,082 uses, the average error was 0.0002, indicating relatively stable system performance, with most sensor errors close to zero. By 26,000 uses, the average error increased to 0.0038, which is 19 times higher than at 13,082 uses. At this point, more sensors exhibited error fluctuations, indicating the beginning of system performance degradation. By 39,000 uses, the average error further rose to 0.016433, approximately 82 times the value at 13,082 uses. At this stage, some sensors showed significant error increases, demonstrating noticeable performance deterioration and a marked decline in system stability after prolonged operation. Overall, as the number of uses increased, the sensor errors progressively expanded. Particularly at 39,000 uses, the system's long-term stability and durability showed a significant decline.

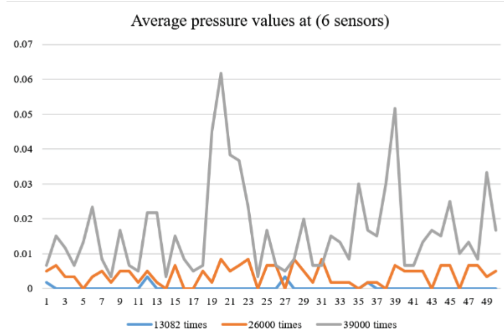

Fig.10: Error fluctuation diagram for 6 pressure sensors

- Reliability Comparison Between Pre- and Post-Optimization (Fig.11):

At the first measurement, the average error for the 6-sensor combination was 0.0002, while that for the 25-sensor combination was 0.000304, with the 25-sensor error being 1.52 times that of the 6-sensor combination. At the second measurement, the error for the 6-sensor combination increased to 0.0038, whereas the 25-sensor combination error rose to 0.005672, which is 1.49 times higher. By the third measurement, the error for the 6-sensor combination reached 0.016433, compared to 0.025576 for the 25-sensor combination, making it 1.56 times higher. Overall, the errors for the 25-sensor combination were consistently higher than those for the 6-sensor combination, with the difference ranging from 1.49 to 1.56 times. This indicates that the 6-sensor combination exhibits more stable performance over long-term use, with error growth being more gradual and the system demonstrating greater reliability.

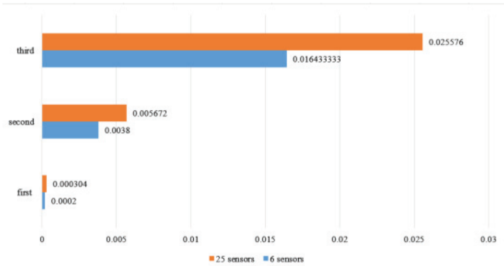

Fig.11: Reliability Comparison Between Pre- and Post-Optimization

4. Discussion

This study selected 13 gestures through interviews and questionnaires to ensure their intuitiveness and broad applicability. However, as gesture selection is influenced by individual habits, cultural backgrounds, and cognitive biases, a fixed set of gestures may not be suitable for all users. Therefore, future research could consider expanding the data collection scope to include a more diverse population, thereby enhancing the generalizability and applicability of the gesture library.

Regarding gesture recognition performance optimization, the experimental results indicate that the neural network model achieved 99.4% recognition accuracy with a 25-sensor configuration. When optimized to six sensors, the system still maintained 97% accuracy, demonstrating that reducing the number of sensors does not significantly compromise recognition performance. This optimization is particularly significant in reducing hardware costs and improving user comfort. However, in practical applications, the system may still be affected by the difference of individual hand movement habits and hand structure. Therefore, future research could further explore personalized gesture recognition systems, integrating on-site adaptive machine learning, allowing the system to locally fine-tune the gesture model based on the user's gesture style, force application pattern, and individual habits, thereby enhancing adaptability and recognition stability.

Furthermore, to ensure the long-term reliability of the system, durability testing indicates that sensor errors gradually increase with usage. Although the optimized six-sensor configuration exhibited lower overall errors than the 25-sensor configuration, both configurations experienced performance degradation over extended use, highlighting stability concerns in long-term applications. Therefore, future research should explore improvements in sensor materials, error compensation calibration strategies, and intelligent maintenance methods to enhance the system's durability. In particular, by integrating intelligent maintenance and predictive fault detection, the system can continuously monitor sensor performance in real time and make automatic adjustments before significant degradation occurs, further improving long-term stability and practical application value.

Conclusion

The study recognized 13 common hand gestures that can applied PET-based piezoresistive thin-film sensors for gesture controller. Through the observation of human behavior, sensitivity experiments, and reliability test, the results show the possibility of the using the minimum number of six sensors to recognize 13 hand gestures for further gesture controller use in smart clothing.

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