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LayTex: A Design Tool for Generating Customized Textile Sensor Layouts in Wearable Computing

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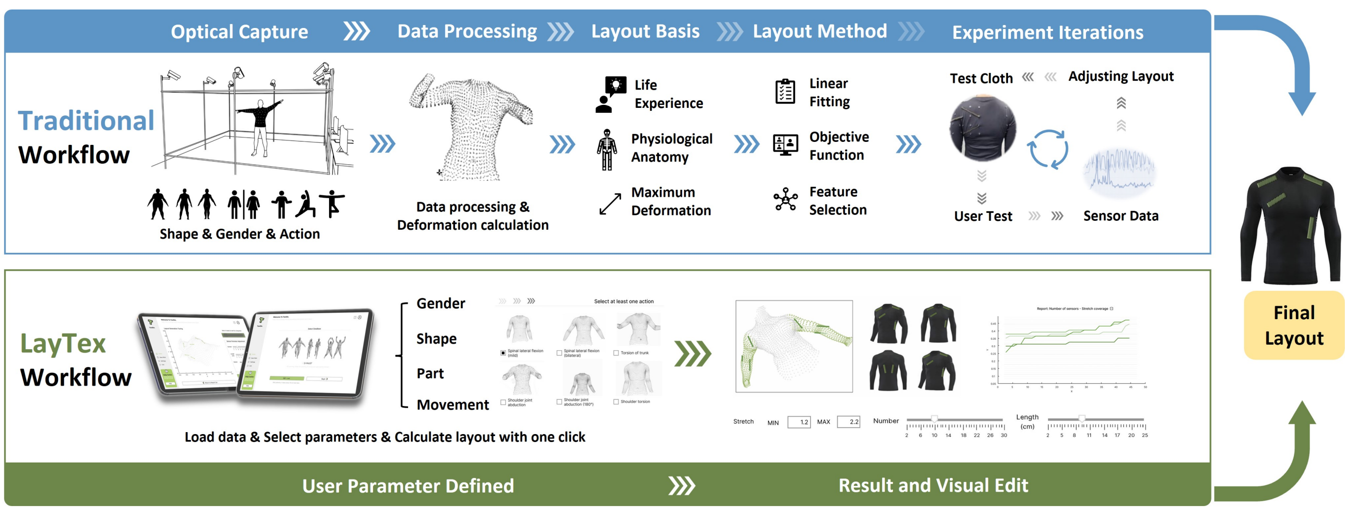

Figure 1: Different workflows between LayTex and traditional method on textile sensor layout research. Above: traditional method requires laboratory settings, expensive equipments, long procedures, and considerable time investment. Below: LayTex, as a compact design tool facilitated by algorithms, provides diverse, customizable sensor layout proposals in a more efficient approach.

ABSTRACT

Smart textile sensors have attracted increasing interest in the domain of wearable computing for human motion monitoring. Previous studies have shown that textile sensor layout has a major impact on the effectiveness and performance of wearable prototypes. However, it is still a trick and time-consuming issue to determine textile sensor layout in a quantitative approach as it involves figuring out the number, placement, and even orientations of sensors, yet there is no streamlined digital platform or tool specifically addressing this issue. In this paper, we introduce LayTex, a digital tool capable of generating layout proposals for personalized scenarios, which aims at facilitating designers and researchers to construct prototypes efficiently. The preliminary evaluation with designers on smart garments for scoliosis indicates that LayTex has great potential to lower the barriers and simplify the process of textile prototype construction.

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CCS CONCEPTS

• **Human-centered computing → User interface toolkits**; *Wireframes*; *Ubiquitous and mobile computing systems and tools.*

KEYWORDS

Textile Sensor; Layout Design; Design Tool; Wearable Prototype; Smart Wearable

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1 INTRODUCTION

Textile sensors have garnered increasing attention in the field of wearable-based human motion monitoring, owing to their desirable performance, comfort, and unobtrusiveness[13]. Among them, resistive textile strain sensors are commonly employed due to their capacity to accurately detect shape deformations, particularly in terms of length changes. These sensors have proven effective in applications such as activity classification and estimation of joint angles. As a result, they hold great potential in diverse fields, including rehabilitation, fitness, and entertainment.

However, as movement complexity and the number of degrees of freedom increase, it potentially necessitates the use of multiple sensors and complicated schemes for sensor placements in wearable systems. Previous research has demonstrated that the layout design of sensor networks significantly impacts both the performance and accuracy of motion capture [6], as well as the aesthetics and comfort of smart textiles. While the traditional workflow for identifying the textile sensors layout is complex and has high barriers. Currently, textile sensor layout strategies for motion capture are mainly based on anatomy and biomechanics [5] analysis, empirical experiences, sensor performance tests, and optical deformation measurements. Among them, deformation measurement is considered the most reliable strategy compared to others[2].

As shown in the blue part of Figure 1, the design process for the textile stretch sensor layout involved several steps, many studies followed the general pipeline of inviting subjects to wear tight-fitting garments with reflective markers and perform preset movements in the optical motion capture lab environment, and the set of marker points with the largest deformation would be selected as the references[9, 10], followed by the stage of feature selection [1]. However, this process has some drawbacks, including 1) the process of collecting motion data was labor-intensive and relied on a diverse range of body types and motion data support; 2) demanded a high level of expertise in computing, kinematics, and facility requirements; 3) the layout methods employed in these studies were limited to designing a single layout scheme for specific body parts and movements.

In this paper, we present LayTex, a platform that streamlines the design methods and processes of fabric layout and facilitates designers and researchers from multidisciplinary to dive into the field of strain sensors-enabled wearable systems for motion monitoring. In particular, LayTex utilizes a multi-objective optimization feature selection method to generate diverse sensor layouts in various scenarios, promoting the development of smart textile layout design. LayTex platform utilizes stretch deformation variables based on open-source human motion data as a fundamental basis. It is equipped with a set of universal layout methods that can customize sensors' layout and assist users in generating optimal fabric layout schemes according to set parameters to build textile prototypes quickly. We are committed to developing a user-friendly and versatile fabric sensor layout design tool with lower entry barriers while highly accessible and user-friendly. A preliminary study has demonstrated its promising performance, with significant improvements observed in both the efficiency and quality of designers' work. We are convinced that this design tool can further help the users to better determine the number, placement, and orientations of sensors in an efficient manner.

2 RELATED WORK

In recent years, there has been a growing body of literature exploring smart textile systems designed for monitoring human motion, including movement measurement and movement classification[8]. Notably, Mohsen Gholami et al.[3] proposed a system incorporating textile strain sensors on the pelvis, knee, and ankle to accurately estimate the sagittal, frontal, and cross-sectional angles of multiple joints during running, facilitating effective gait monitoring of runners. Li et al.[7] placed ten knitted conductive strain sensors around the knee joint to enable the identification of four different gait patterns, including running, walking, climbing, and descending stairs. Tavassolian et al.[11] located 4 sensors (with three sensors affixed to the front side of the pelvis area and one sensor affixed to the back side) to achieve multi-axes hip angle tracking. Previous studies have found that the performance of motion sensing can be affected by the layout of the sensor network when textile sensors are integrated into clothing[6]. Key factors encompass the foundation of the textile sensor layout and the method used to generate sensor positions. Previous studies[4] emphasized that measuring fabric deformation provides the most reliable means of determining optimal sensor positions.

The utilization of optical motion tracking to measure deformations on the human body was early introduced by Mattamann in his study [9]. He identified 12 positions on the back that showed relative deformations, which became the basis for sensor positioning. Mokhlespour [10] qualitatively analyzed the optimal sensor positioning for various movements based on Mattamann's findings, combining experience, anatomical theory, and deformation measurements. Meanwhile, Linh Q. Vu [12] utilized deformation measurements to identify the best sensor positions for estimating joint angles in the sagittal, frontal, and transverse planes through feature selection methods. Previous studies have mainly focused on specific movements and parts of textile prototypes, lacking universal applicability and widespread adoption. Current layout methods need further improvement to address the challenges. Furthermore, the absence of a unified standard and technical approach for textile layout remains a significant hurdle, compounded by the lack of effective design tools, resulting in technical barriers and limitations in textile sensing and sensor placement.

3 SYSTEM DESIGN AND DEVELOPMENT

3.1 User Research

By conducting extensive interviews with designers and researchers interested in smart textiles, we identified the fundamental needs of LayTex:

- **Low Threshold**: Textile sensor deployment often requires expensive optical capture data acquisition equipment and specific facilities, as well as knowledge in anatomy, computer development, mathematics, and practical skills in electronic components and fabrication. These high learning thresholds pose challenges for designers.

- **Customization**: Users need to explicit the customized textile sensor layout solutions for different motion capture needs, including different scenarios, genders, body types, movements, etc.
- **Visualization**: It is desired to have the ability to visualize the layout solutions, such as 3D human and clothing models, specific locations, and shapes of sensors, instead of solely relying on observations on the prototype garment.

3.2 System Design

LayTex is a design tool capable of generating diverse layout proposals of textile strain sensors. The system is designed to be modular based on designers' needs, allowing designers to achieve rapid textile sensor layout and updates through a simple and intuitive workflow. The modular structure eliminates the need for data collection and repetitive labor during the user's utilization. The system architecture and workflow of LayTex are shown in Figure 1. It consists of three main modules: the Data Loading Module, the User Parameter Customization Module, and the Result Viewing and Editing Module. Each module serves a specific purpose and contributes to the overall workflow of the system.

Data Loading Module: This module is responsible for facilitating access to an extensive open-source human body database. By loading this data once, LayTex minimizes response times during subsequent processing. This module ensures efficient handling of the input data, forming the foundation for subsequent layout generation steps.

User Parameter Customization Module: This module empowers users to define and customize various parameters related to their layout design. Users can specify scenarios, genders, shapes, parts, and monitoring movements for their design objects, as shown in Table 1. LayTex provides a range of basic options, including 11 selectable body parts and a library of 16 fundamental movements, enabling users to create personalized layout configurations.

Result Viewing and Editing Module: This module provides a user-friendly interface for visualizing and manipulating the generated layout solutions (As shown in Figure 2). Users are able to explore thumbnail images and 3D visualizations of the layouts generated by LayTex's core algorithms. Furthermore, the module incorporates a parameter panel that allows users to adjust the constraint conditions of the feature selection algorithm. This capability enables users to finely tune the layout results according to their specific requirements.

3.3 Algorithm

For layout results generation, LayTex has developed a multi-objective optimization algorithm model on the MATLAB platform. The model utilizes feature selection methods to determine the optimal number, position, and direction of sensors, enabling effective deformation capture.

LayTex innovatively introduces human motion data based on the D-Faust open-source motion database and constructs a dataset of dynamic surface deformations of the human body, consisting of three-dimensional temporal coordinate data of various body

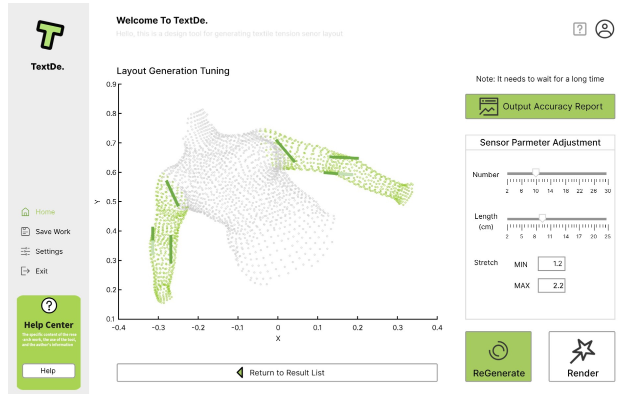


Figure 2: The users' interface of the editing module

types and different actions. And the model treats dynamic edges as features and transforms the sensor layout into a multi-objective optimization problem with the coverage of deformation stretch capture as the main objective. The model also integrates clustering algorithms to optimize the selection results.

The model formulates the ability to capture skin deformation on the human surface as the objective function, while the number and length of the layout sensors serve as the constraints, and the position and orientation of the sensors act as the decision variables. The specific feature selection algorithms are established by *extreme value, variance, covariance and correlation coefficient,* and *composite criteria.* The objective function is calculated by the K-means clustering method. Ultimately, the layout results are visualized in 3D.

4 A PRELIMINARY STUDY

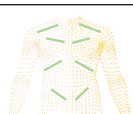
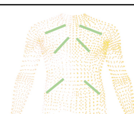
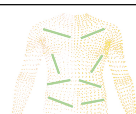
To evaluate the usability of the LayTex tool, we conducted a preliminary study in the form of a 1-day workshop consisting of four sessions: 1) brainstorm and concept(1h), 2) sensors layout generation (1h), 3) quick prototype construction (4h), and 4) prototype test(1h). We invited two smart garment designers with backgrounds in industrial design and interaction design as a team to join the workshop. They came up with the concept of designing a cost-effective, long-term smart garment that monitors and alerts the spinal posture for adolescents with scoliosis. In first two sessions, two designers achieved three optimal layout results through multiple iterations of optimization designs after receiving a brief training, and the schemes are shown in Table 2. The three schemes employ the same algorithm but exhibit distinct layouts. Scheme 1 and Scheme 3 utilize 8 sensors, with respective lengths of 6cm and 8cm, while Scheme 2 incorporates 6 sensors with an 8cm length. These layouts successfully captured over 85% of the deformation variables associated with the monitored movement combination, demonstrating their high effectiveness and accuracy.

In the prototype verification stage, based on the results generated by LayTex, scheme two was selected to make a preliminary smart textile prototype (as shown in Figure 3). Six resistive strain textile sensors with the same strain range selected in the LayTex were adopted. The prototype provided sensor monitoring data, and the

Table 1: User parameter customization

GENDER	SHAPE	PART		MOVEMENT	
Male	Severe obesity	Upper body	Lumbar vertebra	Spinal lateral flexion (2)	Torsion of trunk
Female	Obesity	Arm	Upper chest	Shoulder joint abduction (2)	Shoulder joint rotation
Unlimited	Normal	Neck	Shoulder	Shoulder torsion	Shoulder joint lifting
-	Normal thin	Spine	Whole waist	Elbow flexion and extension	Shoulder horizontal forward flexion
-	Thin	Back	Upper back	Hip joint flexion and extension	Hip joint flexion and external rotation
-	-	Front	User-defined	One-leg jump	Jump (3)

Table 2: Different layout Sschemes in a case

Scheme	1	2	3
Layout sketch			
Algorithm type	Type3	Type3	Type3
Number of sensor	8	6	8
Length of sensor	6cm	8cm	8cm
Coverage accuracy	85%	85%	90%
Redundancy	6.55%	12.75%	12.85%

RF (*Random Forest*) method achieved a classification prediction accuracy of 91%. The preliminary verification demonstrated that the sensor layout scheme generated by LayTex effectively fulfilled the primary motion capture requirements.

Interviews were conducted to assess the user experience of designers with the tool. Participants mentioned that LayTex can offer available sensor layouts with quantitative data support, and they were more confident about the solution. In terms of time efficiency, they also indicated that LayTex reduced the initial textile sensor layout construction time significantly compared to previous projects. And during the iterative design process, they also expressed the preference for visually presenting layout solutions in 3D and allowing real-time modifications without repeated prototyping.

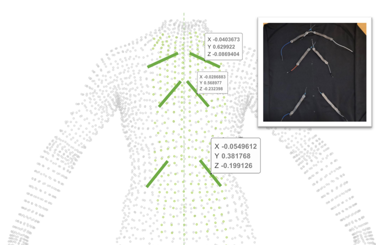


Figure 3: Preliminary Prototype Construction Results

5 DISCUSSION AND FUTURE WORK

LayTex is a design tool that generates customized textile sensor layouts for wearable motion monitoring. It efficiently reduces designers' energy consumption during layout studies and repetitive testing, while also lowering the technical and knowledge requirements for sensor layout. Consequently, it is anticipated that this tool will facilitate the widespread application and extensive development of smart textiles. Through preliminary prototype preparation, data testing, and analysis, LayTex has been verified to generate optimal layout schemes with essential motion capture capabilities. Moreover, LayTex expeditiously generates customized layout schemes to accommodate a range of parameters, such as sensor numbers, sensor lengths, sensor types, user genders, shapes, movements, and specific body parts, which allows users to engage in a more proficient and expeditious textile prototype preparation process. Meantime, some critical components need to be further investigated, such as module connection methods, sensor materials, and sensor performance.

Our future work will expand the motion database to form more motion combinations for various scenarios and attempt to integrate various sensor types, including pressure sensors and temperature sensors. Furthermore, personalized design functionality will be further developed, such as customizing clothing types (gloves, vests, bodysuits, etc.). We plan to introduce additional factors that influence the layout, such as scene characteristics and sensor substrate materials, to enhance the robustness of the generation algorithms. Simultaneously, we will improve the feature selection methodology by further optimization and integration of advanced selection techniques and comprehensive objective functions. These concerted efforts will culminate in improved accuracy and efficiency of the model. In addition, we intend to conduct a usability test for LayTex to validate its effectiveness.

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