Textile & Leather Review

ISSN 2623-6281 | www.tlr-journal.com | 10.31881/TLR

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How to cite: Ruan Y. Development and Application of Urban Interactive Public Art Installations Based on Smart Textile Structures. Textile & Leather Review. 2026; 9:5421-5443. https://doi.org/10.31881/TLR.2026.5421

How to link https://doi.org/10.31881/TLR.2026.5421

Published:27 April 2026

Development and Application of Urban Interactive Public Art Installations Based on Smart Textile Structures

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Article
https://doi.org/10.31881/TLR.2026.5421
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ABSTRACT

With the acceleration of urbanization, the public's demand for interactivity and cultural expression in public art has increased. Traditional static installations suffer from poor interactivity and high maintenance costs. Smart textile technology offers new opportunities for art installations, but faces challenges such as limited interaction, poor durability, and energy dependence. This study proposes a smart textile installation design framework based on the "human-fabric-environment" triadic interaction, integrating modular design and system processes (user research, scenario analysis, technology selection, and structural simulation) to achieve the fusion of art, technology, and culture. Three conceptual cases are developed to demonstrate the applicability of the proposed framework: 1) "Breath of Weaving," a community interactive wall with a sensor-to-light feedback delay of less than 0.5 seconds and a solar-assisted energy system; 2) "Wind-Speak Path," a smart sidewalk system featuring pressure sensing, light-shadow feedback, and a site-specific pedestrian activity map; and 3) "City Weaving: The Wall of Solar Terms," a culture-responsive textile installation integrating solar-term-based environmental responses and optional AR narratives. The cases further discuss energy self-sufficiency and durability as design targets, including energy autonomy and long-term outdoor service life. However, since the proposed parameters are based on conceptual design and preliminary estimates, their feasibility still requires prototype construction, experimental measurement, and long-term outdoor evaluation. Future efforts should focus on material optimization, cost control, and community co-creation. This study provides a design method and conceptual application cases for the use of smart textile technology in public art, promoting the fusion of technology and culture, and offering innovative solutions for smart city spaces and cultural heritage preservation.

KEYWORDS

smart textile technology, interactive art installations, public space, design framework, cultural expression

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INTRODUCTION

With the rapid acceleration of urbanization, public space art has become an important component of contemporary urban culture. However, traditional public art installations, typically presented as static sculptures or decorative objects, often lack sustained interaction with audiences and are difficult to adapt to the public's growing demand for participation, cultural expression, and immersive spatial experience[1,2]. Therefore, exploring how to integrate emerging technologies with public art to create interactive, sustainable, and culturally meaningful installations has become an important issue in contemporary design.

Smart textile technology provides a promising approach to this problem. Flexible fabrics integrated with sensors, actuators, conductive fibers, and programmable materials can respond to human behavior and environmental changes, expanding public art from static visual display to dynamic interaction [3-5]. Compared with conventional rigid electronic installations, smart textile structures offer advantages in flexibility, adaptability, and spatial integration, making them suitable for urban walls, sidewalks, plazas, and other public environments.

Nevertheless, existing interactive public art installations still face several challenges, including limited interaction modes, high maintenance costs, unstable outdoor performance, and insufficient connection with local cultural contexts [6-8]. In response to these issues, this study proposes a smart textile installation design framework based on the "human-fabric-environment" triadic interaction model. The aim is to explore how smart textile structures can support real-time interaction, environmental responsiveness, sustainability, and cultural expression in urban public art.

To achieve this, this study combines literature research, case analysis, design practice, and interdisciplinary research methods. Through literature analysis, the current status of smart textile technology and interactive art installations is reviewed; through case analysis, experiences from domestic and international interactive art installations are summarized; and through design practice, operational design solutions are proposed, followed by a technical feasibility analysis.

THEORETICAL BASIS AND RESEARCH STATUS

Technical Principles of Smart Textile Structures

Smart textile structures combine intelligent materials such as shape memory alloys (SMA), electrochromic fibers (ECF), and piezoelectric materials, giving traditional textiles the ability to dynamically respond to environmental changes[9,10]. These materials can deform or change color under external factors such as temperature, humidity, and pressure, and are widely used in interactive art and architectural installations. However, there are still challenges in the application of smart materials. For example, shape memory alloys have slow response times and limited durability, electrochromic fibers exhibit poor stability when exposed to outdoor conditions over time, and while piezoelectric materials can convert mechanical energy into electrical energy, improvements are needed to apply them efficiently and stably in art installations[11,12].

The integration of flexible sensors and actuators plays a key role in smart textile structures. Flexible sensors can detect environmental data such as temperature, humidity, and pressure and convert them into processable signals. While the sensitivity and response speed of sensors have continued to improve, ensuring stability and accuracy in complex environments remains a technical challenge. Actuators adjust the form of the installation based on feedback, but their stability and response accuracy need further enhancement, especially in high-load or complex environments[13,14].

The combination of woven electronics and low-power communication technologies enables electronic components to be embedded within textiles, expanding the functionality of fabrics. However, balancing the flexibility of the fabric with the integration of electronic components, while avoiding compromising the fabric's comfort and artistic quality, remains a technical challenge. Therefore, the application of smart textile structures in art installations still faces many challenges, especially in balancing performance with aesthetics. In the following design cases, these material limitations are addressed by assigning different response functions to different components: rapid touch feedback is mainly realized through flexible sensors, microcontrollers, pneumatic modules, and electroluminescent fibers, while shape memory alloys and color-changing fibers are used primarily for slower environmental or morphological responses.

Evolution of Urban Public Art and the Development of Interactivity

The form of urban public art has evolved from traditional static sculptures to interactive installations. In the past, public art mainly consisted of sculptures, with the audience existing solely as viewers. However, with the development of interactive art, public art installations have gradually transformed from mere displays into media that interact with the audience[15]. Interactive art makes the audience's actions part of the artistic creation, stimulating public engagement and creativity[16].

Despite the continuous development of interactive art, current installations generally rely on sensors and computing power, and instability and poor interactivity, particularly in long-term use, remain common issues. Outdoor installations, in particular, are often affected by weather and pollution, making it difficult for the technology to maintain reliability over extended periods[17]. While interactive art can engage the audience, the technical difficulties still exist, and improving the stability and sustainability of installations remains a key issue in the combination of art and technology.

Technical Implementation Pathways for Interactive Art

The realization of interactive art depends on the combination of sensors, feedback systems, artificial intelligence algorithms, and Internet of Things (IoT) technologies[18]. The sensor-feedback system is one of the core technologies in interactive art installations. Sensors detect environmental changes or audience actions, and the feedback system generates responses[19]. Although this technology enhances the interactivity of art installations, sensors still face challenges in terms of stability and sensitivity in complex environments, particularly in ensuring that multiple sensors work collaboratively and respond in real time.

Artificial intelligence algorithms provide personalized interactive experiences for interactive art. By using machine learning, the system can automatically adjust the behavior of the art installation based on the audience’s actions[20]. However, AI algorithms require high computational resources, and balancing computational performance with energy efficiency in low-power devices remains a bottleneck. Therefore, in practical installations, real-time responses should rely mainly on lightweight rule-based control or edge computing on-site, while cloud platforms are more suitable for non-real-time data storage, visualization, and long-term behavioral analysis.

The introduction of IoT technology enhances the remote control and data transmission capabilities of interactive art installations, enabling higher interactivity and scalability. However, IoT systems still face issues such as stability, information security, and device interoperability, particularly when multiple installations work together. Ensuring efficient operation and real-time data transmission during large-scale deployments remains a technological challenge.

Case Analysis and Insights

The Bruges “Common Thread” installation showcases dynamic connectivity of space through 3D woven structures, innovatively utilizing smart textile materials. However, this project faces issues of stability and long-term adaptability in outdoor applications. Specifically, the durability and wind resistance of the 3D woven structure could not effectively cope with harsh environments, limiting its practical application. Despite its technical innovation, the combination of materials and structure still needs breakthroughs, particularly in terms of adaptability to extreme weather conditions and long-term usage.

Janet Echelman's "Unnumbered Sparks" interacts with the audience through wind and light control mechanisms, demonstrating the potential of combining art and technology[21]. However, its stability under extreme weather conditions is a prominent issue, especially its high dependence on external environments, which affects the continuity of the interactive experience. The stability of the wind and light control technologies remains a significant challenge in the design.

Jenny Sabin's Microsoft campus installation provides a personalized interactive experience through textile light art driven by biometric data. Although this design is innovative, its high dependence on technological equipment, especially the applicability of devices in different environments, limits its widespread application. The high technical requirements make the stability of the installation in other environments a challenge.

The "Snowy Stars" project at the Beijing Winter Olympics adopts a modular woven structure to demonstrate the engineering application of smart textile technology. However, the installation still faces challenges in stability under extreme weather conditions, with insufficient long-term durability and environmental adaptability, affecting its performance in complex climate conditions.

Through the analysis of these cases, although smart textile technology provides innovative solutions for interactive art, there are still technological bottlenecks in terms of stability and environmental adaptability, especially under outdoor and long-term usage conditions. Future research needs to address these issues and improve the sustainability and stability of smart textile installations.

DESIGN CONCEPT AND METHODOLOGICAL FRAMEWORK

Design Positioning and Core Concept

Against the backdrop of the growing prevalence of smart textile technology, this study aims to explore how to integrate this cutting-edge technology with public art design. The core concept of this design revolves around the "human-fabric-environment" triadic interaction, emphasizing that the art installation is not only the artist's creation but also a medium for interaction between the audience and the environment. Specifically, the smart textile structure within the installation should have the ability to respond to environmental changes, interact with the audience, and adapt to the different urban spaces in which it is situated. Through the "human-fabric-environment" interaction, the smart textile installation can provide the public with an artistic experience, stimulating the audience's sense of participation, creativity, and social interaction.

First, the human element, as the subject of interaction, requires the art installation to not only meet visual needs but also respond in real-time to the audience's movements or touches, offering an immersive interactive experience. Second, the fabric, as the core material, must possess flexibility and adaptability, while also being able to house sensors, actuators, and other intelligent components. Finally, the environment refers to the urban public space in which the installation is situated; the art installation needs to blend harmoniously with the surrounding space and respond to changes in light, temperature, humidity, etc., ensuring stable operation under varying conditions. In this model, the environment is not treated only as a technical condition for operation, but also as a source of cultural signals. Light changes can be translated into day–night visual rhythms, temperature variations can correspond to seasonal transitions, and humidity or wind conditions can trigger changes in textile texture, color, or breathing rhythm. Through this mapping from environmental data to sensory feedback, the installation transforms natural urban changes into culturally readable expressions, such as seasonal imagery, local climate memory, or community-specific symbolic narratives.

The core goals of this design are to achieve sustainability, participatory engagement, and cultural expression. Sustainability means that the installation can operate stably over the long term in different environments, with material selection and energy efficiency management as key factors; participatory engagement refers to the audience's involvement in the installation through touch, vision, sound, etc., making them a part of the creative process; cultural expression emphasizes that the installation conveys and promotes local culture, history, or social values, making it not only visually appealing but also socially and culturally meaningful.

This study aims to propose a design framework that breaks the limitations of traditional public art and integrates deeply with modern technology, offering new forms of expression for urban public art spaces.

Design Principles

In the design of smart textile structures, ensuring the parallel development of artistic and practical functionality is essential. The following design principles provide theoretical support to achieve this goal.

Structural Flexibility and Environmental Adaptability is the primary principle of the design. Smart textile materials possess excellent flexibility and adaptability, allowing them to respond to environmental changes. Therefore, the design of the installation must be flexible enough to adapt to different climatic conditions, ensuring that the sensors and actuators function properly in changing environments. For example, the installation must remain stable in high temperatures, low temperatures, or environments with significant humidity changes while blending harmoniously with the surrounding environment and architectural landscape, balancing both art and practicality.

Low Interference, High Interactivity is the second core principle. Traditional interactive art installations often rely on direct intervention from the audience, which limits the sense of participation. Smart textile installations should offer flexible interaction methods, allowing the audience to perceive changes in the installation with minimal intervention. For instance, through touch, motion detection, or sound, small interactions from the audience could trigger changes in form or light-shadow effects, enhancing the immersive nature of the interactive experience.

Modularity and Maintainability are important guarantees for the design. The components of the smart textile installation should be modular in design, making later maintenance and replacement easier. As the installation typically integrates sensors, actuators, batteries, and other components, faults or performance degradation may occur after long-term use. Modular design not only simplifies the repair process but also reduces long-term maintenance costs, allowing the installation to be flexibly adjusted and upgraded based on different environments or needs.

Design Methods and Process

In terms of design methodology, this study combines user research, scenario analysis, technology selection, structural simulation, and interactive prototype design to propose a design framework for smart textile art installations that adapt to different urban environments. Below are the specific implementation methods for each design step.

User Research is the starting point of the design. By conducting research on the public and audience needs in different urban public spaces, feedback on audience interests, participation methods, and expectations for art installations is collected to ensure that the design can meet practical needs. The research content includes not only the audience’s artistic preferences but also their acceptance of interactive art installations and preferred interaction methods, laying the foundation for the subsequent design.

Scenario Analysis follows, aiming to analyze the characteristics, environmental conditions, and cultural context of the target urban space. During this process, by examining specific spaces, unique functional needs, environmental challenges, and cultural features are identified. For example, when designing the installation, factors such as sunlight, humidity, and temperature variations in the space need to be considered to ensure that the installation can adapt to these changes and align with the local culture.

Technology Selection is a critical step in the design process. Based on the research results and scenario analysis, appropriate smart textile materials, sensors, actuators, and energy management solutions are selected.

Technology selection should consider the adaptability of the materials, the response speed and accuracy of the sensors, the stability of the actuators, etc., ensuring that these technologies integrate seamlessly with the artistic effects.

Structural Simulation is an important step in verifying the feasibility of the design. Using methods such as computer-aided design (CAD) and finite element analysis (FEA), simulations of the smart textile structure are conducted to evaluate its performance under different loads and environmental conditions. For example, the shape changes of the installation under wind, temperature variations, or audience interactions are simulated to ensure stability and adaptability in actual applications. The deformation of the installation can be calculated using the following formula:

$$\sigma = E \cdot \varepsilon \tag{1}$$

where σ is stress, E is the elastic modulus, and ε is strain. This formula helps to verify the mechanical performance of the smart textile structure under different loads, ensuring its stability.

Interactive Prototype Design is the final step, combining the previous steps to integrate technology and art, simulating the interaction experience between the audience and the installation. At this stage, the feedback from the technology is used to adjust the response mechanisms of the installation, ensuring smooth interaction and the presentation of artistic effects. The interactive prototype design helps test the implementation of the technology and provides guidance for the development of the actual installation.

To visually demonstrate this process, Figure 1 illustrates each step from user research to interactive prototype design and their interrelationships. The diagram clearly shows the key tasks of each phase and the logical connections between the steps.

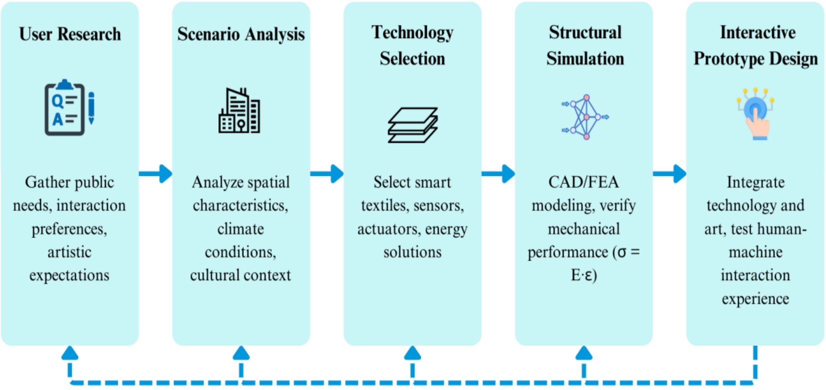

Figure 1. Design Framework for Smart Textile Art Installations

Additionally, in terms of energy management, the energy efficiency of the installation must also be evaluated. The energy collection efficiency can be calculated using the following formula:

$$\eta = \frac{P_{output}}{P_{input}} \times 100\% \tag{2}$$

where η is the system efficiency, P_{output} is the actual output power, and P_{input} is the input power. This formula helps us quantify the efficiency of the energy collection system and ensures that the installation can operate sustainably in real environments.

Through these steps and formulas, the design framework not only meets the artistic requirements but also conducts thorough quantitative analysis at the technical level, ensuring the feasibility and stability of the design solution.

Key Technological Support

The successful application of smart textile structures relies on technological support, particularly in the areas of smart textile structure design, sensor and feedback system integration, energy management, and outdoor protection strategies. During the design process, it is essential to consider the material properties, integration of electronic components, and environmental adaptability of the system. Whether in art installations or smart textile products, coordinating these technological elements is key to achieving both functionality and artistic expression.

In the design of smart textile structures, material selection is critical. Different smart materials exhibit varying performances in art installations, requiring precise selection to ensure the integration of their functionality with the artistic design. Material processing and weaving technologies are equally important, as they determine the flexibility, strength, and compatibility of the textile with intelligent components[22]. For example, embedding conductive fibers allows the fabric to become an integrated platform for sensors, actuators, and feedback systems, supporting the interactivity of the art installation.

The integration of sensor and feedback systems is crucial to interactivity. Sensors monitor environmental changes or audience actions in real-time, transmitting information to the actuators to produce visual, auditory, or motion effects[23]. The design must optimize the accuracy and response speed of the sensors to ensure that the installation can respond promptly to audience interactions. In this framework, time-sensitive interactions are processed by on-site microcontrollers or edge computing nodes, whereas cloud computing is mainly used for non-real-time data storage, visualization, and long-term pattern analysis. Additionally, the feedback system should dynamically adjust the shape of the installation based on audience behavior to enhance both the interactive experience and artistic expression. The use of high-sensitivity sensors, such as those based on nanotechnology, can significantly improve response speed and the smoothness of the interactive experience. More importantly, environmental sensing provides the basis for cultural expression. For example, light intensity may control the brightness and rhythm of textile illumination to represent the daily rhythm of the city; temperature and humidity data may be linked to seasonal color palettes or local climate symbols; and wind or rain information may be reflected through changes in fabric movement or surface texture. In this way, environmental data becomes an artistic and cultural input rather than a purely technical parameter.

Energy management and outdoor protection strategies are core elements for ensuring the stable operation of the installation. Smart textile installations typically need to be self-powered or operate with low energy consumption, so selecting appropriate energy collection methods is crucial. Solar and kinetic energy harvesting systems are common solutions, with solar power providing continuous electricity for the installation and kinetic energy harvesting offering supplemental energy through audience interaction, reducing dependence on external power sources[24]. Research has shown that combining solar and kinetic energy can improve energy efficiency, though its effectiveness is influenced by environmental conditions, so energy systems need to be optimized to ensure long-term stable operation.

Outdoor protection strategies are equally critical. The installation must be able to withstand environmental factors such as wind, rain, and UV radiation[25]. Using UV-resistant and waterproof fiber materials can enhance the durability of the installation. The structural design must also account for the impacts of wind, humidity, and temperature, and use simulation analysis to predict potential risks, taking protective measures to ensure the stable operation of the installation.

The Smart Textile Structure Diagram (Figure 2) illustrates how sensors, actuators, and the textile structure are integrated. The diagram explains the working principle of the smart textile installation, showing how the textile material supports electronic components, senses environmental changes through sensors, and drives actuators to generate artistic effects. Additionally, it highlights the integration of the energy management system, especially in terms of outdoor protection and energy collection, helping the reader understand the composition and working mechanism of the smart textile installation.

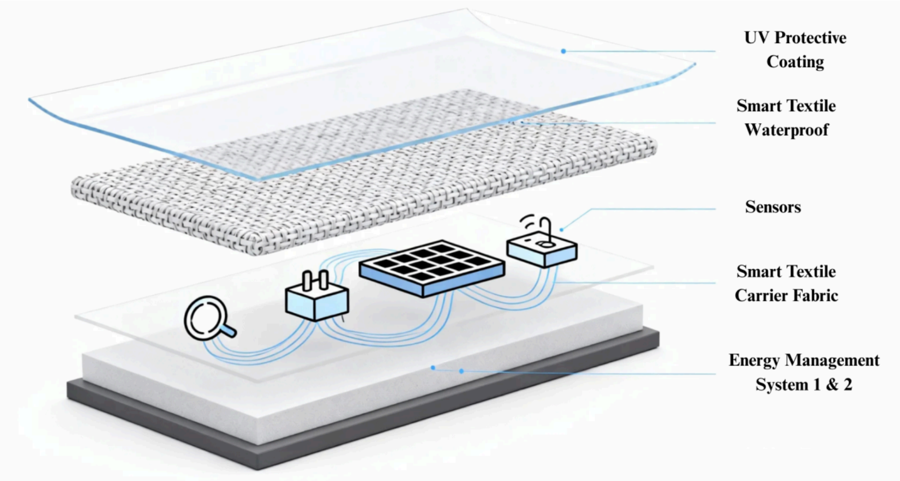

Figure 2. Smart Textile Structure Diagram: Integrated System of Sensing, Actuation, Energy Harvesting, and Environmental Protection

INNOVATIVE CONCEPT CASE DESIGN AND PRACTICE

Design Background and Problem Response

In the case analysis in Section 2, we identified key pain points in the current design of interactive art installations. Firstly, many interactive art installations feature limited interaction methods, resulting in low audience participation. Despite rapid technological advancements, the forms and methods of interactive art installations have not yet met the increasingly diverse demands of the audience. Traditional interaction methods, such as touch or simple motion sensing, while engaging some viewers, still fall short in terms of interaction depth and engagement, making it difficult to sustain long-term audience interest.

Secondly, high maintenance costs are another common issue. Many existing interactive art installations rely on complex sensor and actuator systems, which require frequent maintenance and updates. This is especially problematic in outdoor environments, where the devices are prone to weather and pollution damage, reducing the stability of the installations and increasing operational and maintenance costs. As a result, many art installations struggle to maintain long-term functionality, affecting their sustainability in urban public spaces.

Lastly, a lack of cultural context is a shortcoming in many interactive art installations. While many installations enhance interactivity through technological elements, they often overlook the integration with local culture. In some projects, the audience's interaction experience becomes disconnected from the cultural background or local characteristics of the installation, making it difficult for the installation to convey deep cultural meaning and resonate emotionally with the audience. Art installations should not just be displays, but vehicles for cultural transmission and interaction. How to combine cultural context with smart technology becomes a key task in design.

In response to these issues, this research proposes the following design goals: first, to innovate interaction methods and break through the limitations of traditional interactive art installations by designing more diverse and deeper interactive experiences; second, to adopt modular design and high-efficiency technology to reduce maintenance costs and improve long-term stability; and lastly, to ensure the design of the installation aligns with local culture, incorporating cultural context to enable the audience to experience deeper cultural meaning and foster emotional connections with the art installation.

To this end, we propose a completely new interactive art installation design solution based on smart textile technology, creating public art installations that deeply interact with the audience and the environment. By combining sensors, actuators, and intelligent control systems, the installation will respond in real-time to audience behavior, and through the changes in flexible textile materials, adapt its appearance to the environment, creating unique interactive effects. Additionally, the system will be designed for low energy consumption and high stability to reduce maintenance costs and ensure sustainability. At the same time, the design will incorporate local cultural elements, integrating cultural expression into the interaction process, so the installation not only provides interactivity but also serves as an important vehicle for cultural transmission.

Concept Case One: “Breath of Weaving” , A Breathing Community Interactive Wall

With the advancement of urbanization, the public walls of old communities urgently need updating. These walls are not only part of the city’s landscape but also carry the function of community culture and resident interaction. However, traditional wall renovations often face issues such as “static” (lack of change), “low participation” (residents are only observers), and “high maintenance costs.” To address these challenges, we propose the “Breath of Weaving” interactive art installation, aiming to transform static walls into dynamic artistic platforms that integrate environmental response, human interaction, and cultural expression through smart textile technology.

The core structure of the installation consists of three components: flexible smart fabric layers, distributed pneumatic actuators, and an embedded sensor system, designed to achieve the following performance goals (see Table 1):

Table 1. “Breath of Weaving” System Architecture and Performance Parameters

System Module	Key Components	Design Goals and Performance Parameters
Response Layer	Shape memory alloy (SMA) fabric, electroluminescent (EL) fibers	Surface temperature response threshold: ±3°C; sensor-to-light feedback delay for touch: <0.5 s; SMA-driven morphological response used for slower breathing effects; adjustable brightness range: 50–300 cd/m^2.
Actuation Layer	Micro pneumatic pumps, flexible airbag modules	One “breathing” cycle (expansion-contraction) duration: 2-4s; maximum deformation height: 5-10 cm (adjustable)
Perception and Control Layer	Capacitive proximity sensors, temperature and humidity sensors, microcontroller	Detection range: 5-30 cm (adjustable); data sampling frequency: 10 Hz; supports simultaneous processing of ≥20 touch points

The working principle of this installation follows a “perception-decision-response” closed-loop logic. When embedded sensors detect the presence or touch of residents, the signal is processed by the microcontroller, triggering responses in two layers: (1) Morphological Response: The pneumatic module drives local expansion of the fabric surface, with deformation magnitude correlating with touch intensity or duration, simulating a gentle “breathing” motion. (2) Visual Response: The electroluminescent fibers automatically adjust their light emission mode based on ambient light intensity (measured by a photosensitive sensor). For instance, during nighttime interactions, soft pulsating light effects are displayed, with each interaction’s light trail lasting 15-30 seconds, creating a brief light-shadow memory.

To assess its sustainability, we conducted an initial estimate of the energy system. The installation uses a “low-power sensing + efficient LEDs + solar-assisted” energy solution. Assuming that the 10 m^2 wall surface is fully integrated with flexible photovoltaic fabric, with a conversion efficiency of about 8% and four hours of effective sunlight per day, the system can theoretically collect approximately 3.2 kWh of energy daily. This output can support low-power sensing, lighting feedback, and several hundred interaction cycles, although the actual energy balance still requires prototype-based testing.

Figure 3 illustrates the interactive prototype and workflow of the installation, visually presenting the dynamic process from “triggering perception” to “morphological-light emission” coordinated responses. Through this quantified design, the installation not only aims for artistic expression but also sets clear technical benchmarks for response speed, environmental adaptability, and energy autonomy, offering an innovative solution for updating old community walls with both emotional warmth and technical feasibility.

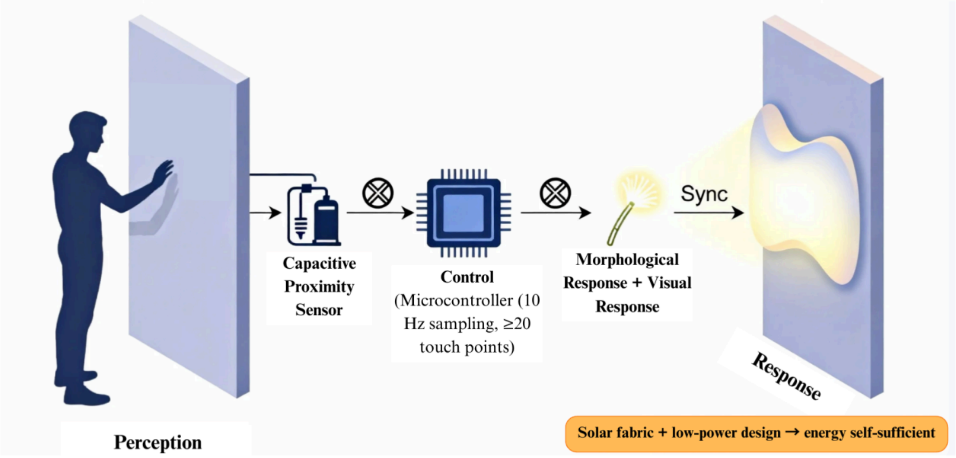

Figure 3. Closed-Loop Interaction Process of the Pneumatic-Electroluminescent Smart Textile Installation

Concept Case Two: “Wind-Speak Path”, A Woven Smart Sidewalk System

Traditional waterfront sidewalks, as linear public spaces, typically focus on functional passage and static landscapes, lacking dynamic interaction with pedestrian flow and data dimensions. To address this limitation, this design proposes the “Wind-Speak Path”, a woven interactive sidewalk system based on smart textile technology. The system aims to transform pedestrian footsteps on the selected sidewalk into real-time light-shadow art and quantifiable pedestrian flow data, thereby enhancing the vitality of the specific path and providing site-level pedestrian insights for public-space management.

This system is constructed using modular textile paving units, with each unit (recommended size: 1m × 1m) integrating three core layers. The specific technical composition and performance parameters are as follows (see Table 2):

Table 2. “Wind-Speak Path” System Architecture and Performance Parameters

Perception Layer	Encapsulated piezoresistive sensing fabric array, three-axis accelerometer (optional), waterproof and wear-resistant TPU protective surface layer	Pressure detection range: 20-100kg; Sensitivity: ±2%; Sampling rate: 10 Hz; Position accuracy: ±10 cm within each unit; sensor layer protected by sealed edges, drainage grooves, and replaceable anti-slip transparent TPU covering
Feedback Layer	Highly flexible LED light-guide fibers (silicone encapsulated), RGB programmable light control unit	Brightness: >150 lux (visible at night); Response delay: <100 ms; Supports 160,000 color variations and multiple dynamic lighting effects (ripples, following, accumulation modes)
Data and Energy Layer	Edge computing node (low-power MCU), flexible photovoltaic side strips, LoRa wireless transmission module	Daily photovoltaic charging per module: approximately 50 Wh under standard sunlight; Local preprocessing of data, uploaded with peak pedestrian count accuracy: >95%

Considering exposure to dirt, rain, and snow, the sensing units are designed as sealed modular components. The piezoresistive fabric array is embedded beneath a textured, transparent TPU protective layer, which transmits pressure while isolating the sensor from water and dust. Sealed edges, drainage grooves, and replaceable surface covers are used to reduce water accumulation and facilitate maintenance. In snowy or muddy conditions, baseline recalibration can reduce false triggering before cleaning.

The system workflow follows a three-phase model of “gait capture, real-time response, data accumulation”: (1) Interaction Trigger: When a pedestrian steps onto the sensing unit, pressure distribution data is captured in real-time. The system not only detects presence but also preliminarily determines gait characteristics (e.g., walking, running, jumping). (2) Lighting Response: The central controller drives the LED fibers in the corresponding area based on preset or adaptive algorithms. For example, a single step triggers a ripple-like expanding light halo; continuous steps generate a forward-extending “light path”; areas with crowd gatherings show gradients of brightness or color changes. (3) Data Generation and Visualization: All modules synchronize data through a wireless network, with a cloud platform generating a real-time site-specific “Pedestrian Activity Map” for this sidewalk segment. This map can present multi-dimensional information for the monitored path, such as heatmaps (pedestrian density), flow diagrams (movement direction and speed), and stop point analysis.

To assess its engineering feasibility, we conducted initial load and energy efficiency calculations. For a 50-meter long, 3-meter wide section of the sidewalk, assuming a daily pedestrian flow of 3,000 people, the following results are observed: (1) Energy: Integrated photovoltaic side strips are expected to generate approximately 7.5 kWh of power daily, fully covering the energy consumption of the LED system (estimated daily energy consumption of 4 kWh), with surplus energy used to power the sensors and communication systems. (2) Durability: The surface of the sensing fabric must be covered with a highly wear-resistant, waterproof, and anti-slip transparent protective layer, such as TPU, together with sealed joints and drainage grooves, to withstand more than 1 million footstep cycles and reduce the influence of dirt, rain, and snow on sensing accuracy. (3) Data Value: The generated heatmaps provide valuable insights for municipal management, such as facility usage rates, peak times, and bottleneck areas, enabling closed-loop optimization of public space design.

Figure 4 systematically presents the complete working principle of the “Wind-Speak Path” from footstep sensing, lighting response, to data aggregation. In summary, this design not only envisions a novel interactive art experience but also, through quantified human-machine interaction design and data feedback loops, offers an innovative example for smart city infrastructure that combines emotional warmth with scientific value.

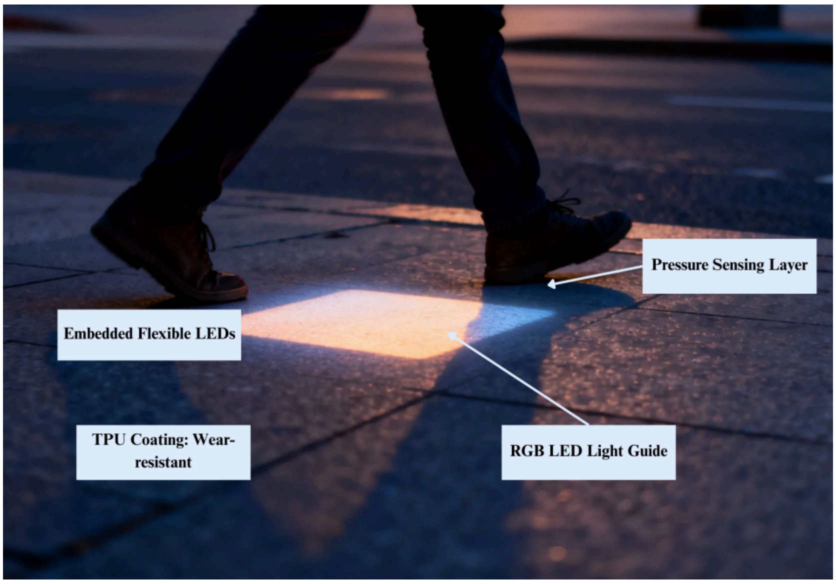

Figure 4. Schematic Illustration of "Wind-Speak Path": From Footstep Sensing and Light Response to Site-Specific Pedestrian Data Visualization

Concept Case Three: "City Weaving: The Wall of Solar Terms", A Culture-Responsive Textile Installation

Art installations in urban public spaces are gradually shifting from purely visual decoration to interactive mediums that carry cultural narratives and foster community identity. In response to the current limitations of public art, where cultural expression is often simplistic and the integration with modern technology feels forced, this design proposes "City Weaving: The Wall of Solar Terms", a culture-responsive installation that deeply integrates smart textile materials, environmental sensing, and augmented reality (AR) technology. It aims to transform the traditional Chinese "24 Solar Terms" culture into a perceptible, interactive contemporary public art experience, turning a static plaza wall into a dynamic cultural interface that tells local stories and resonates with natural rhythms.

The core of this installation is a multi-layer smart textile structure system. The specific technical implementation and performance goals are shown in Table 3.

Table 3. “City Weaving: The Wall of Solar Terms” System Composition and Performance Parameters

System Module	Core Materials and Technology	Key Performance Parameters and Design Goals
Environmental Response Layer	Encapsulated temperature- and humidity-responsive color-changing fibers, photochromic coating, shape memory alloy fabric	Color change trigger thresholds: Temperature ±5°C, Humidity ±15%RH; Full color transition time: <30 minutes; Shape memory recovery rate: >98%
Data Perception and Interaction Layer	Microclimate sensor array, Bluetooth beacons (iBeacon), camera modules (optional)	Environmental data sampling frequency: 1 sample/minute; Audience proximity detection range: 0.5-10 meters (adjustable); AR content call delay: <1 second
Content Presentation Layer	High-resolution outdoor transparent LED mesh for public visual feedback, mobile AR application for optional personalized narratives	LED pixel density: ≥10,000 points/square meter; Viewing angle: >160 degrees; AR content library: At least 24 sets of solar terms-themed dynamic images and audio stories
Control and Energy Layer	Edge server, flexible photovoltaic thin-film power supply system	System standby power consumption: <50W; Photovoltaic system daily power supply: ≥ 0.3-0.5 kWh/square meter (standard sunlight); Supports offline edge operation

The working principle of the installation is based on a threefold feedback loop of “environmental sensing, material response, digital enhancement.” First, the sensors embedded in the wall monitor temperature, humidity, and light intensity. When the data matches the threshold for a specific solar term (e.g., the temperature threshold for “Lichun”), the smart materials are triggered, causing the wall’s color and texture to gradually change, simulating the visual imagery of “spring’s awakening” in nature. For instance, higher humidity during “Grain Rain” may trigger blue-green light and ripple-like textile patterns, while lower temperature during “Beginning of Winter” may activate cooler tones and slower breathing movements. These responses allow environmental factors to be translated into recognizable cultural symbols associated with the 24 Solar Terms. Meanwhile, when the audience enters the Bluetooth beacon zone using a smartphone, the AR application provides optional stories, poetry, or local historical images related to the solar term. In this layered interaction, the smart textile wall creates a shared public atmosphere through color, texture, and light-shadow changes, while AR extends the cultural narrative at an individual level.

To ensure the cultural appeal and technological robustness of the installation, the content layer is designed as an online-updatable “digital solar term scroll,” created by local cultural institutions to ensure continuous content updates. In terms of energy, the installation integrates flexible photovoltaic thin films, which are expected to provide over 70% of the power needs, supporting low-power LEDs and edge computing devices. Initial simulation estimates suggest that, under protected and regularly maintained conditions, the 50-square-meter wall in the typical climate of East China may achieve a target service life of approximately 5 years for its core structural and control modules; however, exposed color-changing or electrochromic components would require periodic inspection and possible replacement, and the actual lifespan still needs to be verified through long-term outdoor testing.

Figure 5 illustrates the complete interactive process of the installation, from environmental data input, smart material color changes, to the triggering of AR content. In summary, “City Weaving: The Wall of Solar Terms” combines smart textile responses with optional AR narratives to connect seasonal culture, public spatial experience, and individual interpretation, offering a feasible design paradigm for enhancing cultural identity in smart city spaces.

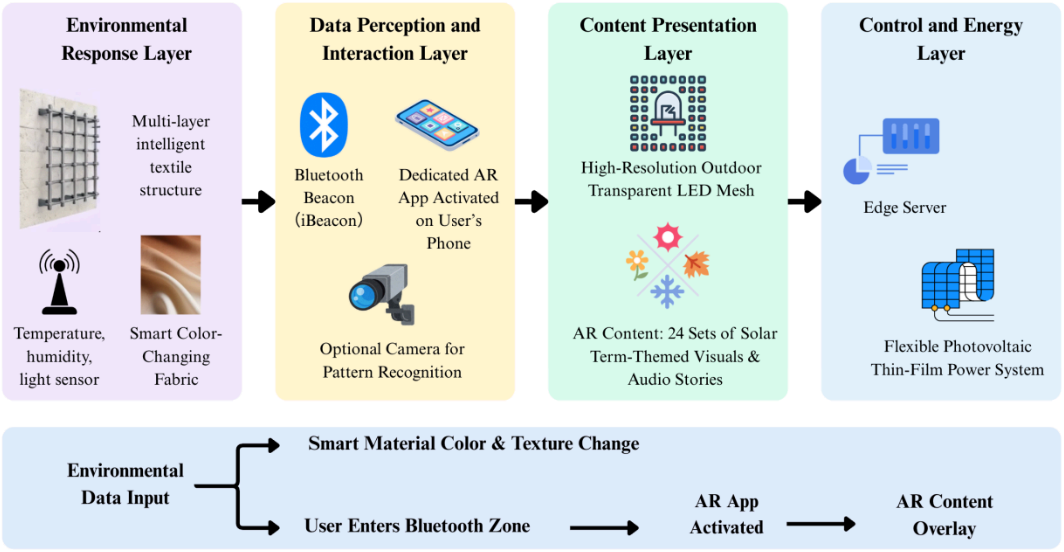

Figure 5. Interactive system diagram of “City Weaving: The Wall of Solar Terms.”

Technical Feasibility and Implementation Path Analysis

The three conceptual cases presented earlier demonstrate how smart textile technology can respond to the interactive and cultural needs of different urban spaces. This section evaluates the feasibility of implementation from the perspective of technological integration and, based on the quantified goals set in the previous cases (see Table 1, Table 2, and Table 3), distills the key technological pathways and implementation recommendations.

Overall, the technical feasibility of this study depends on the “material-energy-data” collaborative closed loop. To address the challenges of response speed, environmental stability, and sustainability mentioned in Chapter

2, the three cases involved the selection of appropriate technologies and parameter settings. The following table integrates and analyzes these technical points, clarifying the key implementation pathways (see Table 4):

Table 4. Key Technological Pathway Analysis for Smart Textile Art Installations

Technology Area	Core Solution	Implementation Key	Corresponding Case and Target Values
Smart Materials and Structure	Composite application of shape memory alloys, electrochromic fibers, and piezoelectric materials	1. Use layered composites and aging tests, including UV, temperature, humidity, and fatigue tests. 2. Seal pavement sensors beneath waterproof, wear-resistant TPU layers with edge sealing and drainage. 3. Match fast light feedback with slower deformation or color change.	"Breath of Weaving": light feedback delay <0.5 s; SMA supports slow breathing motion. "Wind-Speak Path": pressure range 20–100 kg; position accuracy ±10 cm. "City Weaving": color-change threshold ±5°C / ±15% RH; transition time <30 min.
Energy Management	Flexible photovoltaic + piezoelectric collection + low-power design hybrid energy supply	1. Budget energy by sunlight, pedestrian flow, interaction frequency, and lighting duration. 2. Use tiered wake-up and low-power modes. 3. Combine photovoltaics with storage for outdoor stability.	"Breath of Weaving": about 320 Wh/10 m² under four hours of sunlight. "Wind-Speak Path": about 7.5 kWh/day for a 50 m × 3 m section, covering 4 kWh/day LED demand. Target: energy self-sufficiency >60%.
Data and Interaction	IoT architecture, edge computing, low-power wireless communication (LoRa/Bluetooth)	1. Use edge nodes for real-time sensing and cloud platforms for data visualization. 2. Select LoRa or Bluetooth according to distance and data volume. 3. Apply anonymization and encryption.	"Wind-Speak Path": pedestrian count accuracy >95% under protected surface conditions. "City Weaving": Bluetooth/iBeacon AR delay <1 s. "Breath of Weaving": supports ≥20 simultaneous touch points.

Based on the above analysis, the implementation path for this study can be summarized as the "simulation-first, modular prototype iteration" strategy. First, CAD and FEA are used to simulate the mechanics and environmental behavior of the smart textile structure, verifying its safety and stability. Next, prototypes of key functional modules are developed and subjected to laboratory and simulated outdoor tests to obtain real-world performance data for design optimization. Finally, modular combinations are employed to adapt to different application scenarios.

While challenges remain in long-term durability and complex environmental energy balance, through quantitative design, modular verification, and mature technology integration, the smart textile interactive art installation proposed in this study demonstrates high technical feasibility. Its successful implementation depends on considering the integration of technological parameters, maintenance interfaces, and artistic expression early in the design phase, thus driving the installation from concept to sustainable urban application.

CONCLUSION

This study proposes and demonstrates a novel “Smart Textile + Urban Interactive Art” design framework, exploring the integration of smart textile technology with public art installations to support quantifiable, perceptible interactivity and cultural expression in urban spaces. The framework centers on the concept of “human-fabric-environment” triadic interaction, systematically addressing the pain points of traditional installations such as limited interactivity, maintenance difficulties, and lack of cultural context. Through three specific conceptual cases, this research not only demonstrates the flexibility of the framework but also establishes clear performance benchmarks at the technical level: the installation aims to achieve real-time sensing and light-feedback interaction with a perception-to-visual-feedback delay of less than 0.5 seconds, while slower material-driven deformation is treated as a gradual environmental or breathing response; through a hybrid energy solution (flexible photovoltaics and kinetic energy harvesting), it can achieve over 60% energy self-sufficiency in typical scenarios; and through modular and maintainable design, it sets a design target of approximately 5 years of outdoor service life for protected core modules, subject to prototype verification and long-term outdoor testing. These quantified design goals signify a paradigm shift in public art installations from static objects of appreciation to dynamic, sustainable, and data-interactive nodes in smart cities.

However, as a study focused on design framework and concept validation, it still has certain limitations. The primary limitation is that all feasibility analyses based on performance parameters (such as response time, energy output, and durability cycles) are derived from literature references and simulated calculations rather than actual measurements from prototype constructions. Therefore, key issues such as the long-term durability of materials in real-world complex environments, sensor accuracy drift under extreme climates, and system-level energy balance still need to be verified and optimized through subsequent prototype construction and long-term outdoor tracking tests. Additionally, while modular design aims to control costs, the initial investment in smart textile materials and integration processes remains high, and the full lifecycle economic model of the system still needs to be further developed.

Smart textile interactive art installations show broad potential in smart-city applications. The proposed framework can be extended to intelligent guidance, environmental information visualization, and community data interaction platforms. Future work should focus on functional prototypes, real-world testing, material optimization, cost control, and community co-creation, enabling this technology-art-humanities design approach to move from conceptual research toward practical urban-space applications.

Author Contributions

Yao Ruan is the sole author

Conflicts of Interest

The author declares no conflict of interest.

Funding

This research received no external funding.

Acknowledgements

Not applicable

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