

Fabric computing: Concepts, opportunities, and challenges

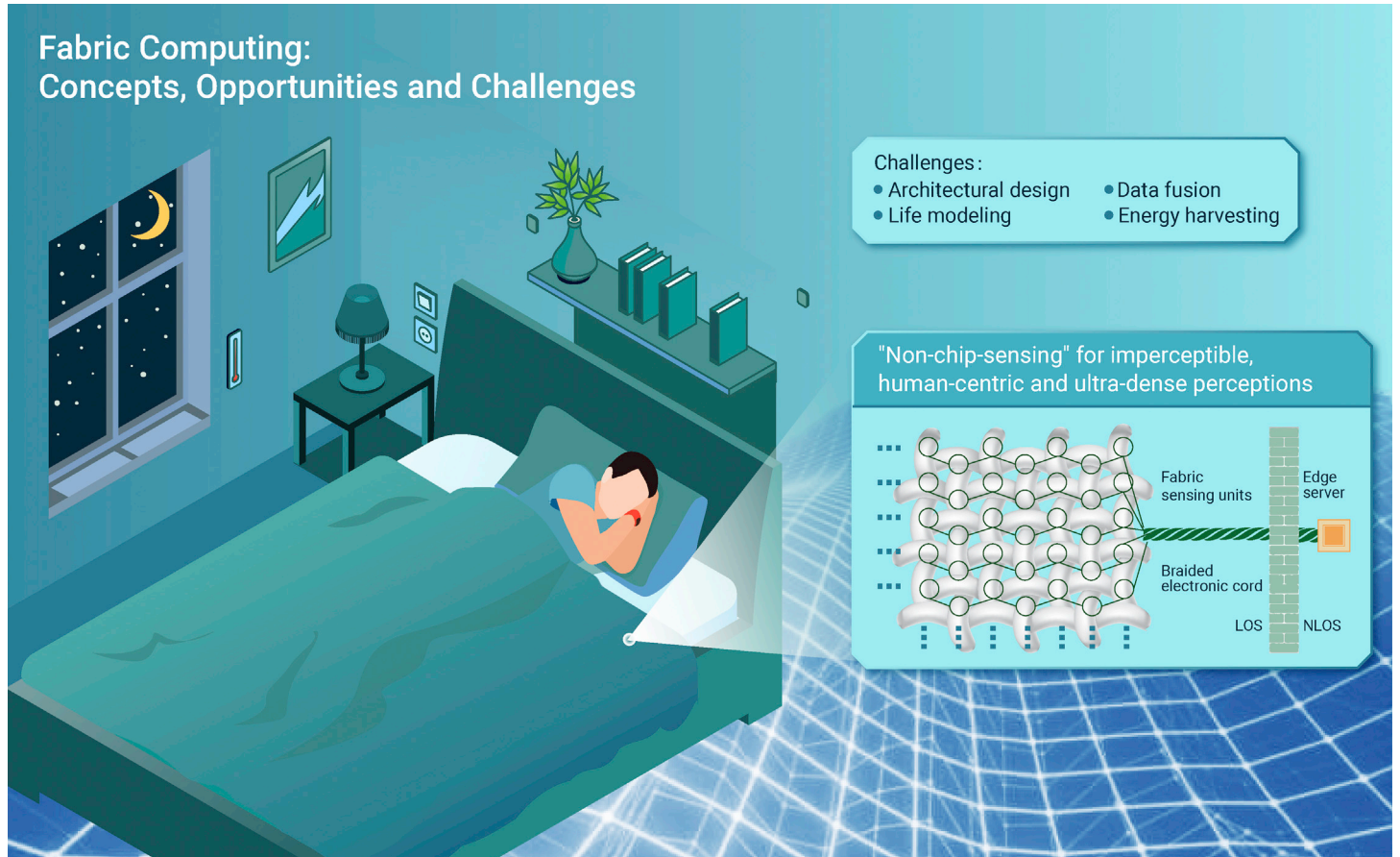
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Fabric computing constructs a non-chip sensing with non-disturbance and ultra-dense structure
- Multifunctional fibers obtain first-view sensory data; The value of sensory data will be distilled by intelligent fabric agents
- Potential cognitive applications can be enabled by integrating fabric computing with AI



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With the advent of the Internet of Everything, people can easily interact with their environments immersively. The idea of pervasive computing is becoming a reality, but due to the inconvenience of carrying silicon-based entities and a lack of fine-grained sensing capabilities for human-computer interaction, it is difficult to ensure comfort, esthetics, and privacy in smart spaces. Motivated by the rapid developments in intelligent fabric technology in the post-Moore era, we propose a novel computing approach that creates a paradigm shift driven by fabric computing and advocate a new concept of non-chip sensing in living spaces. We discuss the core notion and benefits of fabric computing, including its implementation, challenges, and future research opportunities.

INTRODUCTION

With the continuous development of information technologies, such as distributed computing, a new type of storage, and wireless communication, Mark Weiser's 1991 vision for the future of computing, i.e., pervasive computing, is becoming a reality.¹ Pervasive computing emphasizes the importance of people-oriented and integrating computing into our environment and daily life, while corresponding devices perform adaptive responses based on the users' behavior and environments.² Currently, pervasive computing utilizes existing silicon-based devices to form wireless sensor networks. This allows users to focus on enjoying the services brought to them without caring about the existence of the sensor devices deployed at the front end. Although diverting the users' attention has made silicon-based information technology seamlessly integrated into daily life, it has not completely hidden the technological entities. In addition, pervasive computing based on sensor networks also has challenges regarding comfort, esthetics, privacy, and so on. As silicon-lithography technology has almost reached its limit, the size of transistors is approaching their physical capacity, which also limits improvements in processor performance. The driving force of information technology, represented by Moore's law, is relenting and we are entering a post-Moore era.³ In an era when the margin of improvement for semiconductor integration technology is about to end, the stagnation of computing power has limited the development space for information technology, impacting all walks of life.⁴ To mitigate this effect, a solution should be proposed to expand the development of information technology from a different perspective.

The concept of multifunctional fibers that can see, hear, sense, and communicate was first proposed in *Nature Materials* in 2007.⁵ Following their introduction, multifunctional fiber and fabric technology based on multimaterial fiber manufacturing has attracted significant attention from academia and industry.^{6–8} Progress has been made in harnessing intelligence for fibers and fabrics,^{9–11} such as fibers containing digital-devices-enabled fabrics with data processing capabilities for applications in physiological monitoring, human-computer interfaces, and on-body machine learning.¹² Some intelligent fabric lighting/display systems are capable of wireless power transmission, touch sensing, photodetection, environmental/biosignal monitoring, and energy storage.¹³ Based on recent advances in the textiles mentioned above and materials disciplines, as shown in Figure 1, various innovative functions of perception and interaction can be realized by fabric computing, such as color changing, actuator controlling, thermal management, movement tracking, force sensing, distance estimation, temperature measurement, action trajectory detection, etc.

In this perspective, we propose a new fabric-driven computing paradigm, fabric computing for living spaces, to expand the development of information technology. The core improvement is to utilize numerous multimaterial and multifunctional fibers as multichannel and multimodal sensing units, and directly connect these sensing units with local processors through the woven structure of the fabric. This enables the computing mode to have non-chip sensing and interaction capabilities. The fabric-driven intelligent entity with sensing, feedback, computation, and interaction functions is called an intelligent fabric agent.¹⁴ The perception ability of multiple fabric agents has the characteristics of multifunctional fibers with ultra-high resolution, high sensitivity, and multiphysics perception. The new human-computer interaction mode constructed by the intelligent fabric system can realize a seamless connection between people and the environment in the living space. However, implementing the fabric computing system needs to address a series of challenges, such as the automatic system-based architectural design, data fusion of multiple fabric agents, life modeling in the intelligent fabric space, and energy harvesting via fabric devices.

The contributions of this paper can be summarized as follows: (1) in the post-Moore era, a new people-oriented computing paradigm in living space, i.e., fabric computing, is proposed to expand the development of information technology; (2) the concept and design issues of fabric computing are discussed; (3) the research challenges and opportunities of fabric computing are analyzed; (4) four application scenarios, which are health protection, behavior analysis, sleep monitoring, and mental health, are presented.

OPPORTUNITIES IN REVOLUTIONARY COMPUTING MODE

Transformation from semiconductor-driven to multicomposite-driven computing paradigms

Moore's law describes the trend of microprocessor development, i.e., that processor performance can double every 2 years, as shown in Figure 2A. The miniaturization of semiconductor components has always been considered the core to improve computer performance. Moore's law is closely coupled with the development of modern computers and is pervasively promoting scientific and technological progress and economic development.¹⁵ Since Bell Labs launched the first transistor computer in 1955, the following two main development directions of the computing paradigm have been promoted by the demand for computing power and portability, which have been combined in recent years.

Moore's law is both an improving force and a restricting factor for the development of modern information technology. The development of microprocessors, as revealed by Moore's law, has gradually slowed. As further miniaturization wanes, underlying silicon-fabrication improvements will no longer provide the predictable and widespread computer performance gains that society has enjoyed for over 50 years. However, in the post-Moore era, software performance engineering, algorithm development, and hardware downsizing can continue to make computer applications faster.

However, unlike the historical gains in semiconductor technology, which were so dramatically improved in the Moore era, the gains at the top of information technology will be opportunistic, uneven, and sporadic. Moore's law is approaching its physical limits and, while semiconductor technology might be able to produce transistors as small as 2 nm (20 Å), due to the economics of chip manufacturing,

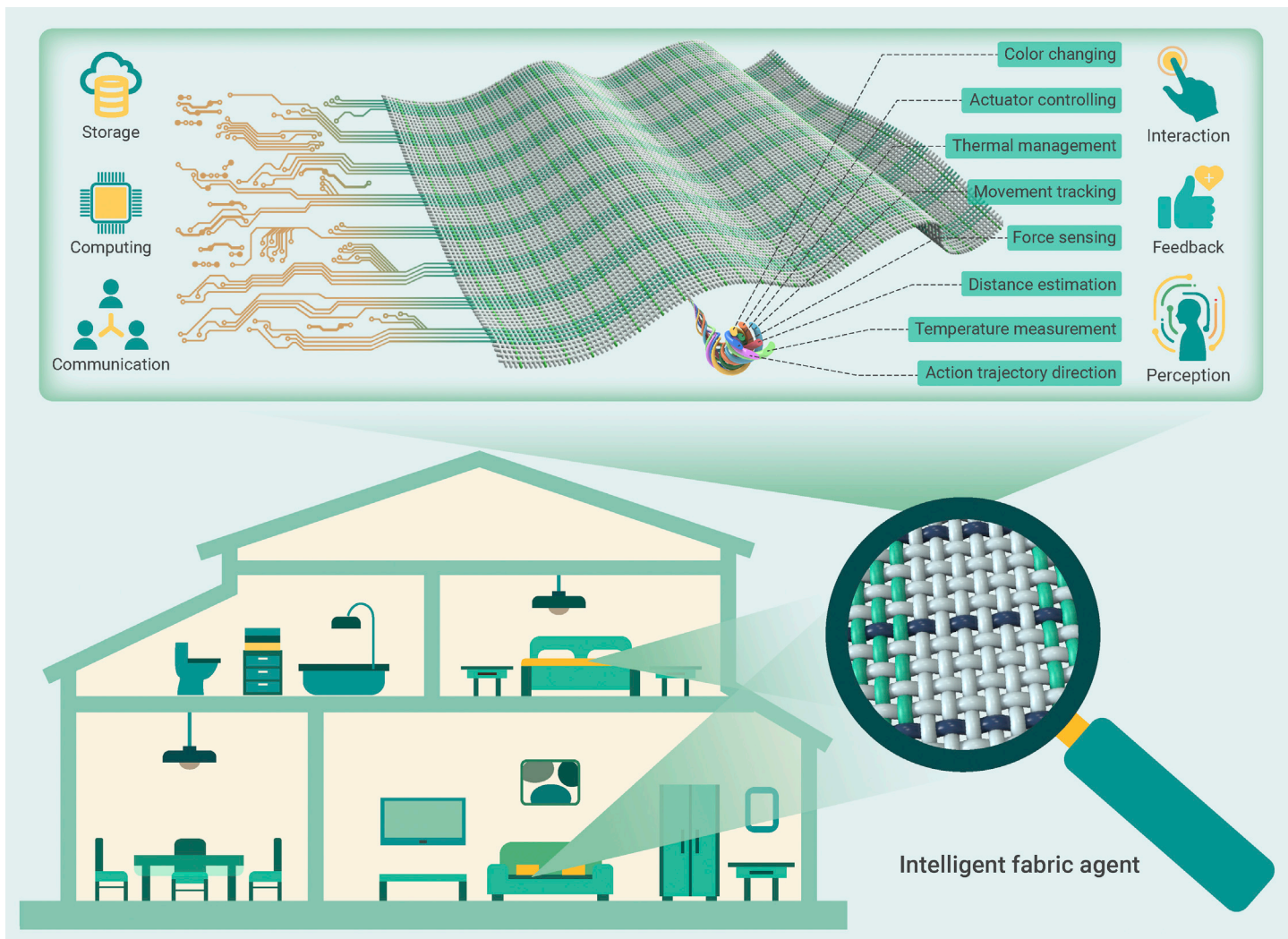


Figure 1. A new fabric-driven computational paradigm: fabric computing for living spaces Multimaterial and multifunctional fibers can be woven or knitted together with traditional fibers into flexible fabrics to create fabric computers that can sense, cache, store, analyze, alert, and act, while retaining their traditional qualities. This means the perception and interaction are imperceptible in the fabrics, which we call the multifunctional fiber agent.

miniaturization will probably end at around 5 nm due to the diminishing returns.¹⁶ Even if semiconductor technologists could make transistors down to the atomic scale, the cost of producing such chips would skyrocket.¹⁷

In addition, technological and trade constraints have hindered the development of semiconductor-driven computing paradigms. Semiconductor manufacturing, as a crucial link in the development of information technology, has become vulnerable to various dynamics, such as supply chain constraints due to the COVID-19 pandemic.

A revolutionary computing paradigm driven by advanced functional fibers

Woven fabrics from natural fibers such as cotton, hemp, linen, silk, and wool have been used by the earliest humans in almost all of the world's civilizations. The development of materials and textiles has aided the evolution of human civilization for thousands of years, improving people's quality of life and the pursuit of comfort and esthetics, as seen in Figure 2B.

With the development of emerging industries and technological progress, people have higher expectations for fabrics. Not only the pursuit of comfort and esthetics, but also multifunctionality is required, such as fabric integrating multiple functions (pressure, strain, shape, temperature, and humidity) in a single device to precisely monitor the real-time sensing and response to external stimuli.^{18,19} The multifunctional fabric is a pervasive, flexible, wearable technology that is more in line with the needs of everyday life and is an important, multifunctional, information-acquisition medium for daily activities. It contains various materials with a microscale structure that can express different physical characteristics, such as acoustic, force, electricity, light, magnetism, heat, etc. Such an advantage allows different materials to express the characteristics of the fiber in different

ways.^{20–25} Ultimately, it will realize various functions, such as human physiological signal monitoring,^{26,27} human activity recognition,^{17,28} and so on.

Nowadays, there are three methods to realize multifunctional fabrics: (1) integrating functional fibers into fabrics via weaving, sewing, and other means to achieve specific functionality. These functional fibers can be imparted with electronic functions on the surface through surface modification or inside the fibers by encapsulating electronically functional organic or inorganic materials, or constructing composite fibers through multimaterial fiber structure design to make them have electronic functions.^{5,12,29,30} (2) By interweaving configuration at the fiber level to realize the fabrics with specific functions. This kind of fabric is characterized by the incomplete function of a single fiber, and requires at least two groups of fibers combinations to achieve electrical connections.^{27,31} (3) Post-processing methods such as screen printing and coating on commodity fabrics, or stitching and bonding circuit components or sensors on commodity fabric substrates to complete specific functions.^{32–34} Compared with the post-processing methods, the former two methods can achieve multifunctionalities integration without sacrificing the breathability and comfort of the fabric. Among them, the core of functional fabrics is advanced functional fibers, which rely on the internal structural design and material selection of micro-nano fibers. Combined with a variety of advanced fiber-manufacturing technologies, fibers are endowed with functions, such as sensing, actuation, color changing, energy storage, thermal management, and antibacterial qualities.¹⁰

Intelligent fabric composed mainly of advanced functional fibers is an ideal carrier for integrating technology with daily life. Since it is invisibly hidden into clothing and home furnishings in the form of fibers or fabrics, it allows users to enjoy technological achievements without sensing their existence, giving users

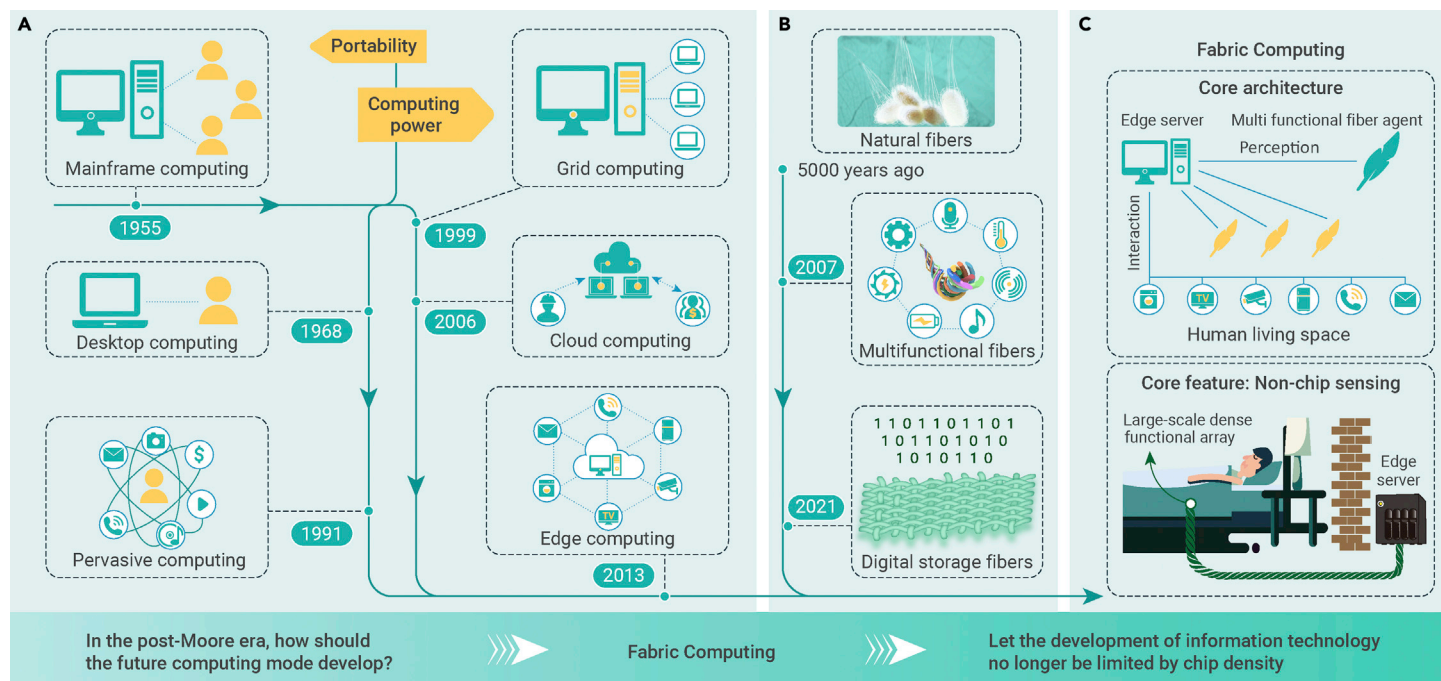


Figure 2. The future development direction of the computing paradigm (A) The two main development directions of the computing paradigm are portable computing mode and shared cluster computing mode. They are compensating each other in terms of computation intensity and user mobility. (B) A revolutionary computing paradigm driven by multi-material fibers. A wide range of material was combined to expand the basic function of fibers, such as sensing, actuation, color changing, energy storage, thermal management, and antibacterial, which can be woven or knitted together with traditional fibers into flexible fabrics to enable near-human sensing. (C) An illustration of fabric computing.

a space for freedom and without fearing invasion of privacy. Intelligent fabric can capture and process an amount of data released by our bodies. Covering the surface of our bodies, fabrics are exposed to a vast trove of acoustic, optical, electrical, biochemical, and biologic signals coming from our body, which can form a massive and valuable dataset. The combination of algorithms and AI fabrics can be used to analyze activity patterns and gain health insights. New fundamental correlations between human health and physiological parameters can be discovered. In other words, multifunctional fibers that are invisible to humans have ushered in a new era.

Fabric computing centered on non-chip sensing

Fabric computing breaks the limitation of chip density in the development space of computing paradigms, inherits and promotes the advantages of edge computing in ensuring computation power and interactive real-time performance, and further realizes the people-oriented idea of pervasive computing.

To better illustrate the characteristics of “non-chip sensing,” the comparisons of communication modes between non-chip sensing-based fabric computing and conventional Internet of Things (IoT)-sensing-based chip computing are presented in Figure 3. We introduce the term “line-of-sight (LOS) deployment area” in reference to the sensing coverage in the human living space. By comparison, the edge server can be hidden at the far end, without human activity. The non-LOS deployment has an advantage in terms of concealment.

As shown in Figure 3A, conventional IoT sensing requires numerous sensor nodes, each of which obtains sensory data at a particular location. Typically, the sensor nodes first forward collected data to a sink node, which further delivers the data to the edge server. If the sensor nodes are sparsely deployed, the bandwidth for the wireless connections between the sensor nodes and the sink node is affordable. However, in the case of an ultra-dense deployment of sensor nodes within a LOS area, the wireless performance would decrease significantly in terms of data rate, latency, and reliability due to the intrinsic feature of wireless channels. As shown in Figure 3B, under a similar deployment mode, the fabric-driven sensing connects sensing units with a local processor directly through the fabrics themselves, and thus avoids the huge number of individual wireless connections (Figure 3A). Therefore, fabric computing possesses the feature of “non-chip sensing,” which relaxes the constraints imposed by Moore’s law applied to the IoT sensing mode where each sensor node has a local processor in its sensor board. As an alternative communication style, sensor nodes can also be directly connected to the edge server without a sink node, as shown in Figure 3C. Like-

wise, the same result happens when comparing the non-chip sensing mode (Figure 3D) with the chip-based sensing mode (Figure 3C). In Figure 3D, the tentacles of all the fabric sensing units are integrated into a braided electronic cord, which directly connects the edge server.

Correspondingly, Figure 2C shows an example of a practical deployment scenario, where there is a large-scale dense functional array adopted by fabric computing. The length of the braided electronic cord is adjustable to reach the edge server. Thus, fabric computing has an overwhelming advantage over IoT-based sensing to enable ultra-dense sensing. If we further consider the deployment costs, the non-chip sensing applied by fabric computing is cost-effective, in addition to its high bandwidth, low latency, and high reliability.

Next, we illustrate the features of fabric-driven, non-chip sensing from three aspects, i.e., core architecture, features, and advantages.

Core architecture: fabric computing uses the fine-grained perception characteristics of functional fibers to construct intelligent fabric agents. In centralized network architecture shown in Figure 3, the edge server connects intelligent fabric agents through a wireless link (Figure 3B) or braided electronic cord (Figure 3D). The intelligent fabric agents connected by the edge server form a multiple fabric agent system. In addition to offering computing resources with cognitive intelligence, the edge server also provides a weak power supply for the fabric sensing units in the living space.

Core features: fabric computing incorporates the edge server into living space and hides it from human activity. Leveraging non-chip sensing can enable large-scale and dense perception arrays. Flexible functional fibers can achieve non-destructive sensing and interaction in various scenarios.

Core advantages: fabric computing has the following advantages in terms of sensing and interaction modes compared with the traditional computing mode driven by IoT technology: (1) achieving efficient perception with high fidelity; (2) achieving covert sensing with high reliability and low latency; and (3) achieving human-computer interaction naturally and immersively.

DESIGN ISSUES

Multifunctional fiber agent

We refer to the multifunctional fibers, with self-powering, sensing, feedback, data storage, processing functions, and other functions, which are constructed based on optoelectronic information technology and prepared by regulating the internal materials and structures of micro-nano fibers, as multifunctional fiber agents.

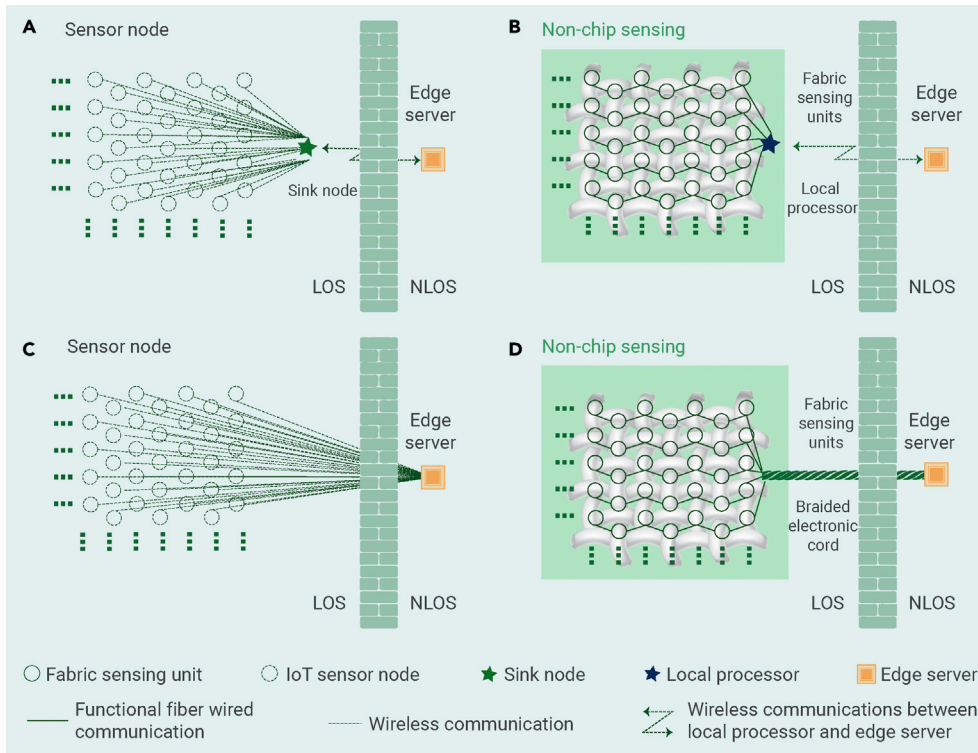


Figure 3. Communications between sensing units and edge servers (A) Conventional IoT-sensing-based chip computing with a local processor. (B) Intelligent fabric-enabled non-chip computing with a local processor. Each fabric sensing unit has a "tentacle." Multiple tentacles of the fabric sensing units directly connect to a local processor, which then forwards the processed data to the edge server either through a wired or a wireless communication. (C) Conventional IoT-sensing-based chip computing without a local processor. (D) Intelligent fabric-enabled, non-chip computing without a local processor. Each fabric sensing unit has a "tentacle." Multiple tentacles of fabric sensing units form a braided electronic cord, which connects to the edge server with a wire.

Intelligent fabric space

The concept of the intelligent fabric space comes from the smart space in pervasive computing, and it is expanded on this basis. As shown in Figure 4A, the smart space in a pervasive computing environment refers to a physical space embedded with computation, communication, and perception capabilities so that people can transparently obtain computing and information services at work and home. With the continuous development of information technology, various essential service components supporting pervasive

The multifunctional fiber agent has the ability of three-dimensional, high-precision perception, and feedback of multiphysical field information, such as sound, light, force, electricity, heat, and magnetism. Thus, it can realize human action recognition, human behavior analysis, physiological signal monitoring, group behavior judgment, etc. The multifunctional fiber agent can also capture, store, and process the vast amount of data released by our bodies; and our bodies can provide a multitude of acoustic, optical, electrical, biochemical, and biological signals, which can form a large and valuable dataset. The multifunctional fiber agent converts multiphysics information into multimodal analog signal data. Through analog-to-digital conversion and a wired communication network connection, it can achieve higher bandwidth, lower latency, and higher reliability than wireless transmission.

Intelligent fabric agent system

Using the multifunctional fiber agent as the basic element, a flexible, multifunctional, human-friendly fabric agent system with a two-dimensional structure is constructed by adjusting the array structure of the multifunctional fiber agent.

With the advent of the Internet of Everything, many heterogeneous devices are connected to the network. Efficient and smooth collaborative management between a large number of heterogeneous devices has become one of the difficulties. Autonomic computing, as a key technology to realize the vision of pervasive computing,^{35,36} can free managers from the burden of dealing with low-level but crucial affairs. Therefore, the autonomous capability of the system becomes an important indicator reflecting its design rationality and technology maturity.

In the intelligent fabric agent system, fabrics form the ultra-dense sensing array at the forefront of human-computer interaction can transmit fine-grained sensing data through conductive fibers. The system can reduce the difficulty of collaboration between heterogeneous devices, thereby ensuring autonomy.

First, each intelligent fabric agent carries out a preliminary calculation and the integration of large-scale fiber channel data, greatly reducing the number of devices connected to the edge server, thereby reducing the difficulty of the collaboration. In addition, the edge server undertakes the tasks of centralized analysis, service provision, and unified scheduling for each intelligent fabric agent. Since it is pushed to the farthest end of the users' activity, the computing power storage resources are not limited in size. Finally, the perception unit of the intelligent fabric agent is no longer just a single-modal, single-point data, but a modality of multi-channel network data that can express actual meaning, including rich contextual information in both time and space, which is highly interpretable.

computing have been gradually enriched. The architecture for efficient and smooth management, use, and integration of these components has become increasingly mature. In this smart space, the direct, quantitative transmission of sensory information and indirect transmission of conscious information can be realized.³⁷

However, pervasive computing cannot eliminate the interference of hardware devices for users and it is also difficult to solve security and privacy issues. These have become bottlenecks that can restrict the further opening up and promotion of smart spaces in the future. The intelligent fabric space refers to a typical fabric computing environment built around human centrality using a variety of heterogeneous intelligent fabric agents in the living space, which is characterized by integrating smart devices into every corner of life in the form of fabric. In the intelligent fabric space composed of intelligent fabric-based devices such as clothing, bed sheets, carpets, sofas, etc., the information collection of the physical world is realized and then the connection between the physical world and the digital world is realized. By endowing the fabric with functions, the intelligent fabric space may have various functions, such as human physiological signal monitoring, human activity recognition, acoustic fabrics, energy storage, color change, temperature regulation, and controllable actuation, which can provide more intelligent and user-friendly services for human beings. In addition to the functional requirements of information services, the design of an intelligent fabric space reflects people's requirements for esthetics and comfort (Figure 4B). This makes it easier to achieve the prospect of the seamless integration of information space, physical space, and user space. Due to its feature of hiding computing, storage, and communication at the far end of human-computer interaction, fabric computing can meet people's requirements for esthetics and comfort to the greatest extent. Since the technology is hidden from users, it eliminates the interference of hardware devices. Moreover, fabric sensing does not involve sensitive information related to identity features. Therefore, it reduces the risk of serious consequences of private data leakage.

At the same time, clothing, sheets, carpets, sofas, etc., can be incorporated into the creative design space, so that the perception boundary is pushed to the forefront of human-computer interaction. A more comfortable interactive experience makes users willing to accept and promote the intelligent fabric space (Table 1).

The fabric space retains the main idea of being human oriented, with the following key features: (1) *Heterogeneity of the agents*. Facing complex scenes in the future, the intelligent fabric agent exists in the form of various indispensable household appliances in daily life. (2) *Openness of the space*. In an open space,

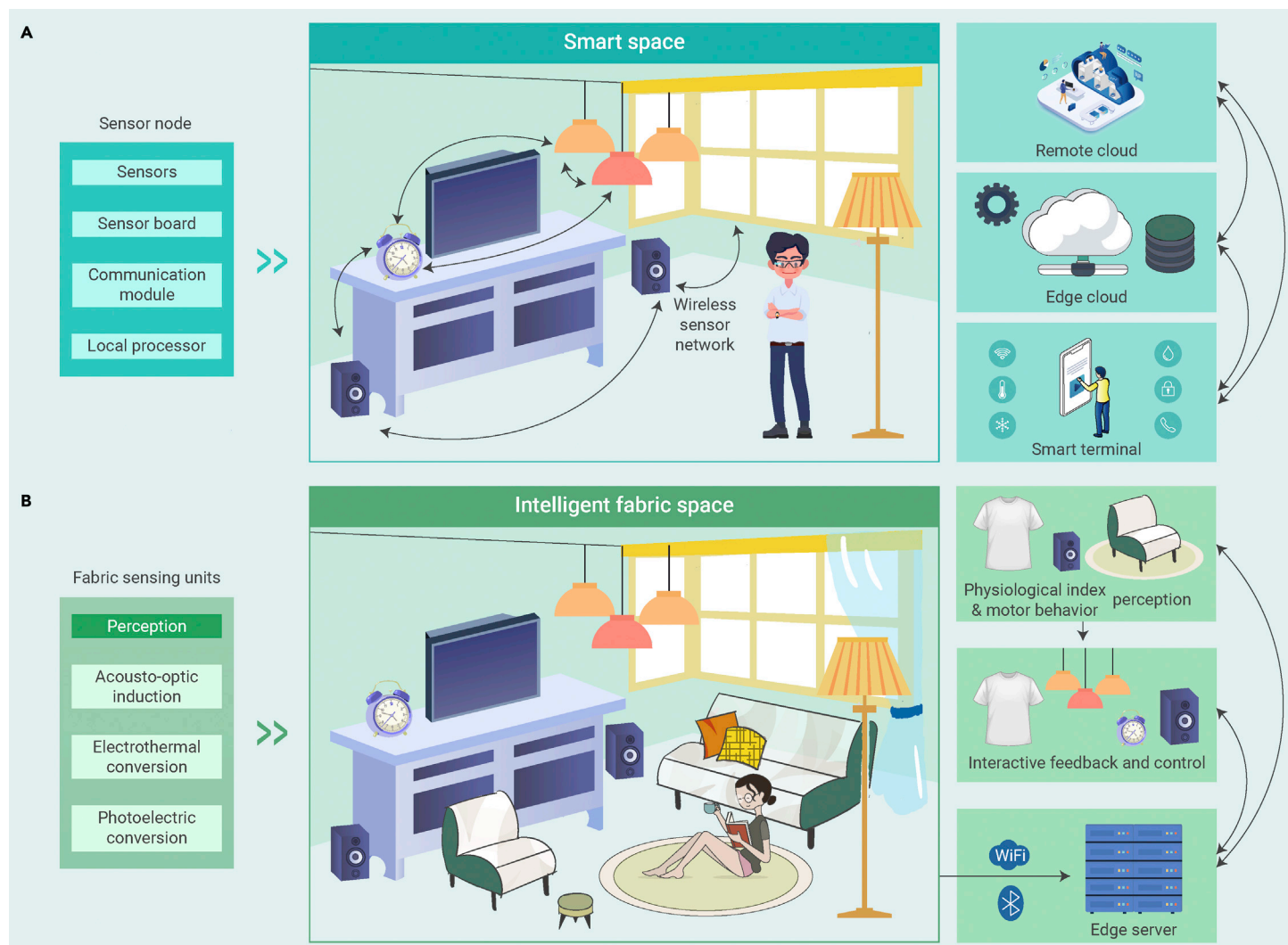


Figure 4. Comparison between pervasive computing and fabric computing (A) Smart space in pervasive computing. It cannot eliminate the interference of hardware devices for users, and it is also difficult to solve security and privacy issues. (B) The intelligent fabric space. This refers to a typical fabric computing environment built around human centrality using a variety of heterogeneous intelligent fabric agents in the living space and can meet people's requirements for esthetics and comfort to the greatest extent, while meeting the functional requirements of information services.

intelligent fabric agents are distributed in all corners of the living space and can perform data collection without disturbing users. (3) *Diversity of the services*. This refers to providing customized and empathetic services for a variety of different groups of people. (4) *Transparency of the computing*. The intelligent fabric agent is highly integrated with the living environment, realizing interactions that can access any information anywhere and at any time. (5) *Comfort of the interaction*. The application interaction provided by the intelligent fabric agent does not require complex user instructions.

RESEARCH CHALLENGES

The changes in the computing mode of fabric computing will bring some new research hotspots and challenges, as shown in Figure 5. For example, from a global perspective, consider the architecture design of intelligent fabric space for different application scenarios; from the perspective of algorithm design, such as completing data fusion of multiple fabric agents and complete human-centered life modeling from the perspective of time and spatial coherence; in addition, from the perspective of devices, energy harvesting via fabric devices worth researching.

Automatic system-based architectural design

The intelligent automatic systems have four main features, which are autonomy, activeness, intelligence, and perceptibility. Based on advances in the textile and materials disciplines, multifunctional fibers bring computing technology closer to the human body for multimodal data collection under long-term imper-

ceptible interaction. Therefore, automatic systems based on the intelligent fabric space with multiple forms of appearance, deployment methods, and multitechnological cores, have been proposed to satisfy the needs of intelligent human-computer interaction.

Modeling the intelligent fabric space is the primary premise for constructing the intelligent fabric space. It specifies the organizational structure and management method among the heterogeneous devices and defines the dynamic and static combination of the intelligent fabric space. It also describes how each service and application is constructed.

To allow users to seamlessly engage with multiple services in the intelligent fabric space, the systems should be carefully designed to meet the requirements of different real-life applications (Figure 5A). On the other hand, given the limited software and hardware resources, the requirements of different systems cannot always be satisfied. This poses a pressing need to maximize the usage of computational resources at hand, including the dynamic allocation of system resources, connection between various fabric agents, and the scheduling of workflow, such that the state of each component in the system can be effectively adapted to the dynamically changing environment. Specifically, smart spaces can simplify application and service development to provide a unified interface for each access device. Intelligent application services need to comprehensively consider a large amount of multimodal perception information within a certain period and spatial range. Every agent in an intelligent space has the ability to perceive and process, as well as automatically schedule tasks according to the needs of the environment.

Table 1. The comparison table of pervasive computing and fabric computing

	Pervasive computing	Fabric computing
Data scale	small-scale and single-point data collection	large-density data acquisition of wide-scale and multifunctional fibers
Location of tech entities	exposed to the forefront of the living space	can be pushed to the farthest end of the fabric without disturbing the user
Comfort and beauty	rigid silicon-based electronics disrupt living space design	intelligent fabric agents are consistent with traditional textiles in terms of users' experience
Privacy	audio and video contain sensitive information about user identity	use fabric to sense user behavior without fear of privacy leakage risk
Synergy	it is difficult to spontaneously and effectively collaborate among large-scale heterogeneous devices	significantly reduce the amount of devices thus reducing the difficulty of collaboration
Design space	limited to traditional IoT devices	push the perception boundary to the forefront of human-computer interaction, and incorporate clothing, sheets, carpets, etc. into the creative designing space

Data fusion of multiple fabric agents

As an intelligent fabric space, the perception of human activities, behavior, health, and life, by intelligent fibers, requires the use of large-scale, multimodal data for fine-grained and all-around perception and interaction. Therefore, distributed data fusion is a necessary technology for an intelligent fabric space. Traditional multisensor data fusion technology usually needs to consider the fusion of scattered and heterogeneous data,³⁸ but in the intelligent fabric space it is also

necessary to consider long-term, large-scale, human behavior modeling analysis, as well as data errors, and long-term ineffectiveness.

Common data fusion categories include probabilistic methods, intelligent aggregation methods (e.g., neural networks, genetic algorithms, fuzzy logic),³⁹ and evidence-reasoning methods. According to the timing of the data fusion, it can be further divided into data fusion at the data layer, feature layer, and decision layer⁴⁰ (Figure 5B). (1) *Data layer*. This refers to the processing and integration of

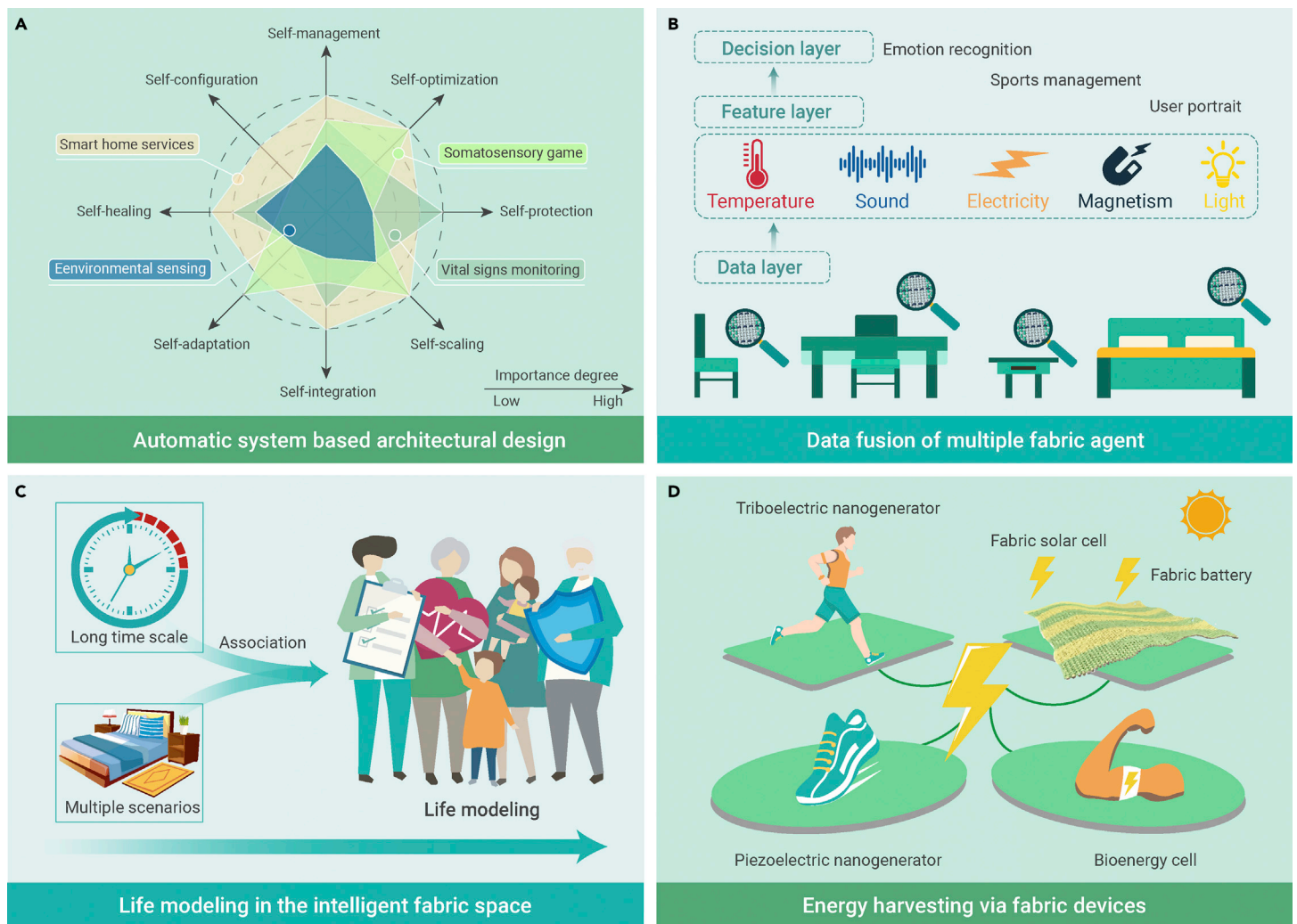


Figure 5. Challenges arise when the computing mode changes (A) Automatic system-based architectural design. The different requirements for the eight features of the autonomic system in the four scenarios of smart home service, somatosensory game, environmental sensing, and vital signs monitoring were exemplified. (B) Data fusion of multiple fabric agents. The perception of human activities, behavior, life, health, etc., by intelligent fibers, requires the use of large-scale and multimodal data for fine-grained and all-around perception and interaction. (C) Life modeling in the intelligent fabric space. An intelligent fabric space should have the ability to analyze the relationship between the contexts of multiple objects (devices, users, physical environment) in real time and respond in a timely manner. (D) Energy harvesting via fabric devices. Power supply issues of tiny sensing devices cannot be ignored, and the use of fabric devices to harvest energy is an approach to ensure battery power.

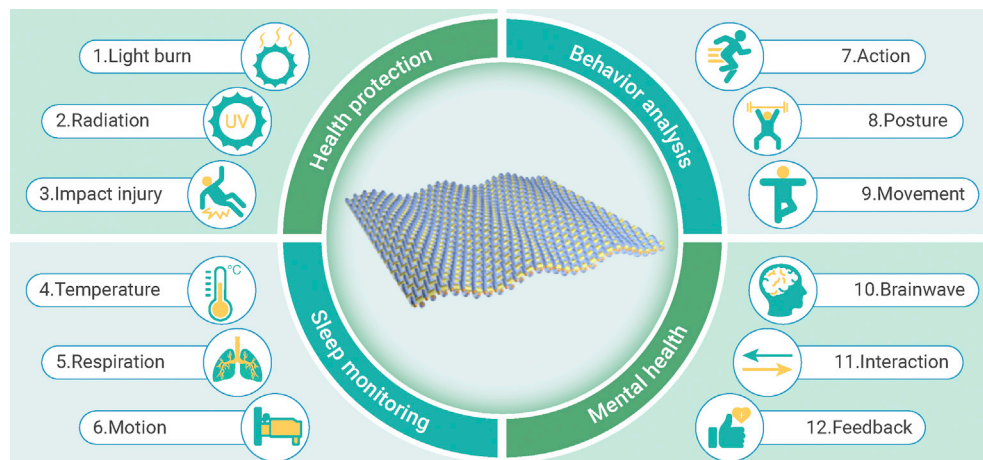


Figure 6. Application scenarios Potential application scenarios, such as health protection, behavior analysis, sleep monitoring, and mental health, can be enhanced by focusing on the fundamental changes that can be brought by the fabric computing framework.

generation.²³ However, many more research efforts are highly desired to improve energy conversion efficiency, output stability, robustness.

APPLICATION SCENARIOS

Intelligent fabrics can receive many multidimensional and multimodal perception signals and respond to changes in the environment and objects in real time.⁶¹ With the support of AI and advanced digital computing, fabric computing can target a variety of characteristic

edge-aware, multichannel signals within the intelligent fabric agent. De-noising and feature extraction are required in multichannel data with noise, conflict, and redundancy. Normally, data layer fusion methods contain Bayesian analysis,⁴¹ state-space modeling,⁴² Kalman filter,⁴³ and other methods. (2) *Feature layer*. This refers to the integration of heterogeneous data, which takes place within a multiple fabric agent system. The multimodal feature dataset³⁹ extracted from multiple data sources needs to be combined with high-dimensional features for simple modeling and analysis. Some knowledge-based reasoning methods (e.g., artificial neural networks, genetic algorithms, knowledge graphs) are often used. (3) *Decision layer*. This refers to the hypothesis set for the decision generation of multiple fabric agents in the intelligent fabric space, and a unique decision is generated from the local decision. Common decision fusion methods include Bayesian inference, fuzzy logic, heuristic search, etc.

Life modeling in the intelligent fabric space

In the intelligent fabric space we need to consider how to implement AI-enabled, personalized, long-term deep modeling (Figure 5C). In many application scenarios, it is often impossible to obtain accurate judgments based only on spatiotemporal single-point information.⁴⁴ An intelligent fabric space should have the ability to analyze the relationship between the contexts of multiple objects (devices, users, physical environment) in real time and respond promptly. Specifically, the intelligent fabric application system that realizes efficient and accurate human-computer interaction needs to have the following capabilities: (1) enable comprehensive and continuous monitoring⁴⁵; (2) accurately determine the identity characteristics of different users; (3) realize multisensory information integration and internal information mining.⁴⁶

Energy harvesting via fabric devices

While intelligent fabric space can lead to pervasive and personalized service for users, for wearable devices, conventional rigid batteries are not conducive to maintaining their wearable performance, and battery cells based on toxic chemical materials have huge drawbacks in terms of bioelectronic applicability and environmental protection. The human body, including its surroundings, such as biomechanical movement, biothermal energy, biofluids, and sunlight, is a sustainable source of energy.⁴⁷ In recent years, the rise of multiple working mechanisms and wearable device designs has provided multiple avenues for harvesting these types of energy^{48,49} (Figure 5D), such as triboelectric nanogenerators,^{50,51} piezoelectric nanogenerators,⁵² thermoelectric generators,⁵³ bioenergy cells,⁵⁴ solar cells,⁵⁵ and other hybrid generators.⁵⁶ However, these designs have some drawbacks in wearable applications. Most wearable energy harvesting devices are based on polymer films. These materials have poor air permeability and mechanical fatigue properties, and the thick structure makes it less comfortable to wear and hinders human movement.^{57,58} Rapid advances in materials science and chemistry have provided room for revolutionary advancements in intelligent fabrics for energy harvesting. For example, electro-active materials and electrodes have been integrated via thermal drawing,⁵⁹ solution-extrusion,⁶⁰ and continuous coating²⁵ to form ultra-long flexible battery fibers that provide universal energy to the arbitrary geometrical electronic systems. Ferromagnetic fabrics and coils have been sewn on both sides of a garment for swinging motion-based electricity

groups and build a variety of application scenarios (Figure 6).^{14,44} It will accompany people during their entire lifetime and will be committed to maintaining life and health in a non-interference fashion.

Health protection: the human body is influenced by light, heat, force, germs, dust, etc., when exposed to external environments. So, how do we detect and receive warnings related to these factors? Most existing solutions involve monitors and other equipment. However, such equipment is rigid electronic testing devices, the monitoring range is incomplete, the generated data are inaccurate, and it cannot play a reliable, early-warning role. Fabric computing with autonomy, perceptibility, intelligence, and adaptability empower medical protective garment upgrades.^{62–64} Wearable fabrics with sensing ability are adopted to perceive external physical quantities, such as light, heat, and force, in real time, and the status of the user is transmitted to the cloud server automatically. The predictions and warnings are executed to prevent the occurrence of potential dangers.

Behavior analysis: fabric computing can analyze movement, detect movement indicators, and provide feedback.^{27,65} This is equivalent to a personal trainer accompanying the user on an exercise session. For example, during sports training, athlete's swing range, stride length, stride frequency, valgus range, touch-down time, and impact on the ground can be monitored and analyzed in real time. When the user performs sports, such as boxing, the interaction strength and speed of the human body and the smart fabric can be used to identify the action and evaluate the action's specification and athlete's strength. This gives the athlete an accurate feedback and the assistance they need to receive better training.

Sleep monitoring: about one-third of life is in a state of sleep, and the human body needs sleep to eliminate fatigue and maintain normal body functions.^{66,67} Prolonged insomnia and poor quality of sleep will weaken the human immune system and increase the incidence of various diseases, such as hypertension and cardiovascular diseases.^{68,69} Using intelligent, interactive fabrics to create invisible sensors, we can monitor vital-signs data, such as heart rate, breathing rate, snoring, fretting, tossing, getting out of bed, and daily behavior in real time, to make predictions about the health trends of users, and provide sleep quality reports and sleep health suggestions.^{70,71} Then we can analyze, warn, and establish an interactive remote diagnosis and treatment model to reduce the risk of disease.²⁷

Mental health: smart fabrics can also combine neural network kernel algorithms to realize multichannel, signal-sensing analysis feedback for mental health analysis. We can collect electroencephalogram signals through brain wearable devices to analyze the user's mental state based on brainwaves, analyze user behavior through smart touch and other devices, and build an intelligent emotional interaction robot to interact with users in real time to relieve a user's nervous state.^{72,73} We can also use multidimensional and multimodal physiological, psychological, and environmental information collection plus multisource heterogeneous data analysis and interactive feedback to monitor and possibly evaluate the user's mental health.^{74,75}

CONCLUSIONS

As fibers are gradually endowed with the ability of perception and interaction, multifunctional fabrics composed of multifunctional fibers have become an

efficient carrier of multimodal physical-quantity information. Meanwhile, the concept of computing is constantly expanding, gradually separated from the computer and abstracted into the processing of information. Therefore, we propose fabric computing, which constructs an ultra-dense sensing and interaction channel array that is not limited by chip density. Fabric computing uses functional fibers to obtain first-hand data to realize cognitive intelligence, which can be seamlessly integrated with daily life.

Although we have seen many advances in the intelligent fabric industry in recent years, research prospects in multifunctional fibers preparation, integrated circuit design, automatic system implementation, and interdisciplinary system integration are still broad. We explore several open research challenges in the hope that potential application scenarios can be enhanced by focusing on the fundamental changes that can be brought by the fabric computing framework. For example, the rise of fiber electronics and AI enables health-monitoring agents derived on multifunctional fibers to direct future medical and health management to intelligent health.

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AUTHOR CONTRIBUTIONS

G.T., G.-Z.Y., and M.C. developed the idea for the study. All authors contributed to the writing and revisions.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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