FEATURE ARTICLE

Electronic Textile *Gaia:* Ubiquitous Computational Substrates Across Geometric Scales

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From in-body implantables to geotextiles and large-area spacecraft blankets, electronic fabric is now poised to operate across geometric scales that span many orders of magnitude, and thus across operational contexts with divergent material resiliency requirements, reaching far beyond the wearable device regime that is typically considered. This article reviews the key technical trends and lingering hurdles that are relevant to using functional fibers and e-textiles for operating at disparate scales—from microns to kilometers. We focus in particular on leveraging the unique material properties of a textile and the miniaturization of electronic devices in concert with the revolution in mass-manufacturing and digital fabrication technologies used to customize the device at the level of polymer, fiber, fabric, three-dimensional form, and system. We also offer a personal perspective on interdisciplinary collaboration between engineers, scientists, designers, and manufacturers for tackling some of the challenges in scaling and translation of electronic textiles.

Today, we have up to 39 000 km long deep-sea optical fibers supporting communication between four continents, and we have deployed up to 30-km-long electrodynamic tethers on orbit around Earth to harvest power from the magnetosphere. We have developed hundred micron-scale multisensory neural probes and millimeter-scale sensory meshes that can be injected into the body, alongside mesoscale fabrics with sensing, communication, and even locomotive capabilities. Functionalized fabrics now touch the full range of scales from microns to kilometers, with active and computational capability achieved at the level of fiber, yarn, fabric, and system. We consider our current place on the roadmap toward realizing an *electronic textile gaia* in which the living, nonliving, and increasingly the built environments operate as a single, harmonious, self-regulating organism, as imagined in Figure 1.

The textile has achieved ubiquity for its manufacturing scalability and myriad beneficial properties—protection, three-axis conformability, abrasion resilience, tensile strength, heat retention, high packing density, and aesthetic and cultural appeal all serve to motivate adoption of this material form.

While most textiles have remained electrically passive, one may still claim that computational textiles had an early start—the Apollo spacecraft guidance and control software developed in the 1960s at MIT was stored in a woven substrate called core rope memory.

Around the same time, a company called Woven Electronics was spawned to develop fabric circuit board prototypes that were evidently well ahead of their time. For a fleeting moment in these early days of printed circuit board (PCB) manufacturing, woven fabric circuits and core rope memory were competitive with silicon semiconductor technology.

Early fabric-based electronics hint at deep links between manufacturing processes used in the textile and electronics industries that in some cases continue into the present era: dies draw down both electrical wires and fibers, lithography, and screen-printing

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FIGURE 1. Imagined Electronic Textile *Gaia*, in which fabrics and fibers take on electrically active functions in-body, on-body, across the built environment, submerged within landscapes, seascapes, and extending out to our orbital and even our interplanetary infrastructure. (Illustrated with the help of Franny Xi Wu).

techniques pattern both printed circuits and fabric embellishments, and, as a historic example, punch-cards originally developed for the Jacquard loom found broad computational applications.

Still, large-scale deployment of functional fibers and textiles remain isolated, and application scopes for these devices highly specific. Bearing in mind Abelton, Knight, and Sussman's *Amorphous Computing Manifesto*,[1] which calls for ubiquitous, massively distributed computational bits with emergent order, what will it take to realize sensory, computational, and actuated elements that sink into fabric substrates across the in-body, on-body, and built environments? These substrates will be barely perceptible. In some cases they will be highly tuned for specialized environments and in other cases they will be highly multi-modal and generalizable across scale and application context.

A significant portion of prior art in the field of electronic textile (e-textile) design targets sensor-laden

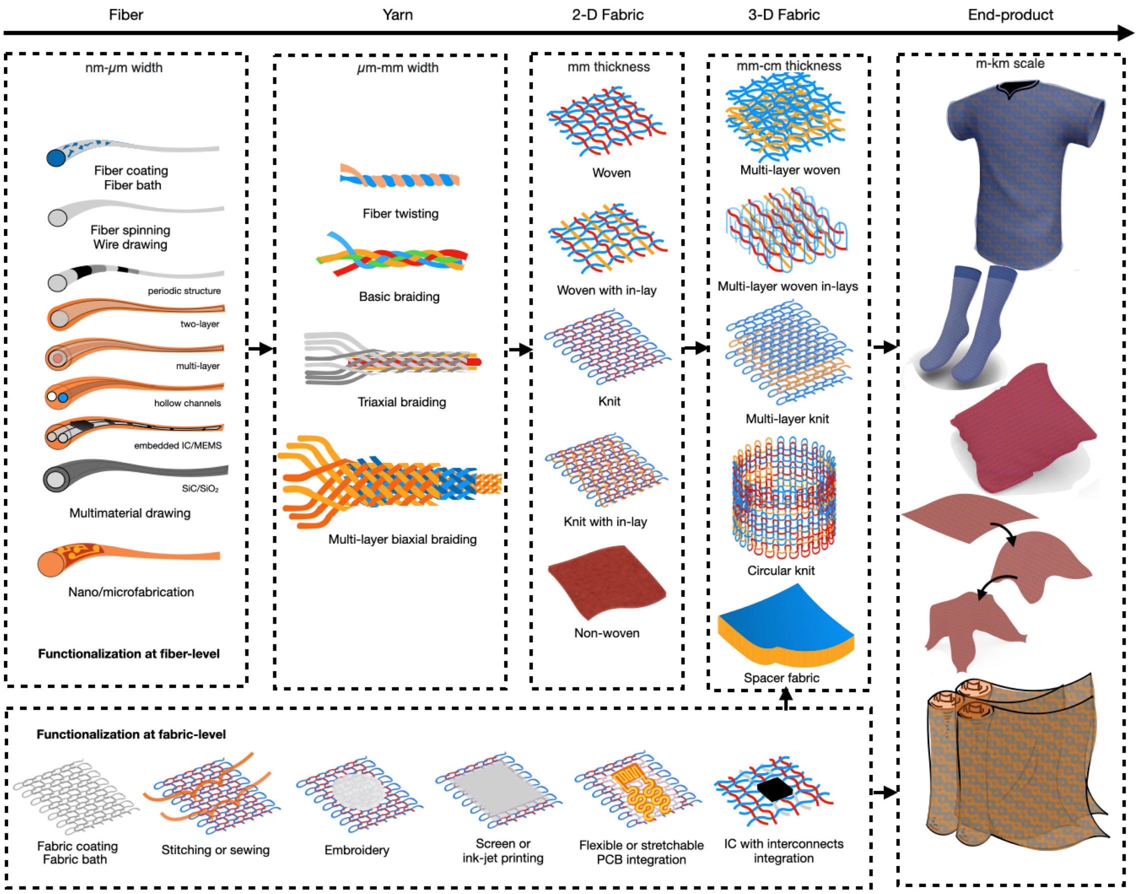

FIGURE 2. Hierarchical architecture and various structures of electronic textiles starting from fiber (1-D), yarn (1.5-D), fabric (2-D), fabric composite (3-D), to the end-product. Besides structural functionalization, we also show the material functionalization stage at the fiber or fabric-level.

wearables for health monitoring. Here, we focus on the breadth of scale and operational contexts appropriate for fiber-like and mesh-like architectures. We first review techniques for achieving electrical functionality at the level of fiber, yarn, and fabric. We then describe representative applications that cover the full range of geometric scales, highlighting in particular the importance of manufacturing partnerships in early research. Finally, we contextualize the textile as merely one ubiquitous medium among many more exotic substrates that are ripe for functionalization.

ELECTRONIC TEXTILE INTEGRATION: FROM MICRO, MESO, TO MACRO

As illustrated in Figure 2, the functionalization of textiles can take place at every dimension: 0-D (material), 1-D (fiber), 2-D (fabric), 3-D (complex structures), and finally the end-product or system. In this article, we will focus on electronic and electrically active materials, devices, and systems as means for integration and functionalization.

Generally speaking, there are three main approaches used to develop e-textiles, ranging in complexity from highly specialized to widely accessible. The first approach is to grow computational fibers by depositing electronic nanostructures on the surface or inside the fibers.

For additional progress in miniaturization, we require an advanced fabrication and manufacturing process that integrates microelectronics seamlessly within the 1-D fiber structure.

The second technique is to electrically functionalize textiles with solution-based coating or printing at either the fiber or fabric level. This technique can be quickly scaled using existing textile manufacturing and treatment processes. The third approach applies textile art practices such as knitting, embroidery, or sewing either by hand or machine.[13] Sewing, for example, can be used to attach microelectronic devices or circuits as appendages such as buttons, jewelry, pins, or embedded into textile pockets.[21] It can also pattern and integrate commercially available conductive or other electroactive fibers, yarns, or fabrics onto and into garments, footwear, and other end-products.[16]

Ultimately, it is the task of an engineer or system integrator to map the e-textile's requisite function to the forms achieved by these various textile manufacturing approaches.

Fiber

Spinning is one of the most frequently applied methods for manufacturing fibers. Raw materials in a fluid state, such as intrinsically conductive polymers, can be added to the spinning precursors. Depending on the spinning process, this base material is then melted or submerged in a chemical bath and pumped under pressure through a spinneret. The spinneret contains many small openings and a cooling mechanism to extrude and harden the polymers into long filaments. The output of this process is synthetic fiber with electrical functionality. Several efforts have blended fiber polymer with silver nanoparticles (AgNP), silicon nanowires (AgNW), carbon black, carbon nanotubes (CNT), graphene, polyaniline, polypyrrole, and poly polystyrene sulfonate (PEDOT:PSS) via wet or dry-spinning methods to develop conductive and resistive fibers as interconnects or sensors.[2] Their functional properties, morphology, and heterogeneity can be engineered to sensitively detect mechanical pressure, strain, temperature, humidity, pH, or specific chemical stimuli. Electrospinning, another approach that involves high-voltage polarization, has been demonstrated to produce piezoelectric nanogenerators by extrusion and beta enhanced, poled polyvinylidene fluoride (PVDF) fibers. It is also possible to coat conductive polymers onto nonfunctional, synthetic, or naturally spun fibers using postspinning processes such as *in situ* polymerization, dip-coating, electroless plating, vacuum plasma spraying, and physical vapor deposition.[3] In bundle drawing, a composite wire consisting of thousands of filaments from metal alloys or preforms such as stainless steel, titanium, nickel, ferrous, and aluminum and sacrificial fillers is pulled through a die multiple times until reaching the final desired diameter. The sacrificial fillers can then be dissolved through a chemical process. Even though metallic fibers have better electrical performance, polymeric fibers are more mechanically robust, lightweight, and flexible than metallic fibers. Therefore, they can be more easily integrated into standard textile manufacturing processes.

Preform drawing processes have also been explored to develop multimaterial and multifunctional electronic fibers (e-fibers) for a broad range of applications.[4] For instance, widely available copper wires, optical fibers, as well as shape-memory alloy (SMA) wires are each developed using fiber drawing methods. Before becoming advanced electrically functional fibers, a macroscopic preform is prepared by layering and distributing various polymers, electronic materials, and devices such as low-temperature metals, semiconductors, piezoelectric materials, and microchips. The preform is then melted and mechanically drawn through a temperature or laser-controlled drawing device. The method enables long fiber production with complex cross-sectional architectures for electrical signaling, optical networking, and microfluidic system.[5] This process can also be used to develop lengthwise distributed electronic devices such as transistors, diodes, and microelectromechanical systems (MEMS) together with interconnects using doped semiconductor materials or commercially available complementary metal-oxide-semiconductor (CMOS)-based dies.[4] A Si-coated silicon oxide glass and sintered silicon carbide (SiC) fiber has also been fabricated through this fiber extrusion method as a substrate for in or on-fiber integrated circuits.[6]

Finally, researchers have also leveraged nano and microfabrication techniques to fabricate fiber transistors using either inorganic or organic semiconducting material.[7] Even though the preform drawing method requires precision control of the melt flow and engineering of the preform material's viscosity and thermal expansion, it is more scalable and cost-efficient compared to nano and microfabrication procedures. A synergy between these two methods needs to be further explored to solve some of the technical challenges in developing a dense system-on-fiber.

Yarn

We can apply numerous yarn structures on our e-fibers to achieve further functionality and mechanical stability before they are integrated into e-textiles. Yarns can be assembled by twisting, twining, blending, or braiding many fibers across the axial direction. Twisted electroactive fibers such as CNT, for example, have been demonstrated to produce artificial muscle yarns, as well as energy-harvesting yarns that electrochemically or triboelectrically convert torsional mechanical to electrical energy.

As a traditional form of cultural practice that has existed for a thousand years, braiding techniques can be used to develop a more complex electronic yarn structure. The most common braiding architecture is a 2-D biaxial braid. This biaxial braid can create a textile skin that insulates a core conductive yarn, typically used for e-textile transmission lines. Multiple layers of biaxial braid can also yield a sandwich-type structure, useful for creating capacitive, piezoelectric, and piezoresistive yarns, with an active or dielectric layer in between two electrode layers. By orienting an additional yarn into the biaxial structure longitudinally, we can also construct a triaxial braid. A biaxial base in a triaxial braid, for instance, can be used as a structural reinforcement for multiple optical fibers.

Fabric

There are three common types of 2-D textile structure: knitted, woven, and nonwoven. Nonwoven textiles are fabricated by chemical, thermal, or mechanical bonding of staple or long fibers into a single continuous layer, while knit and woven textiles are formed by architecting multiple fibers into a specific structure and pattern.

Woven textiles consist of two sets of yarns that are orthogonal and alternately cross-over each other. Weaving generates dense textiles that are mostly found for upholstery, interior fabrics, and protective skins. Its 2-D array structure can be employed to develop e-textile sensors and interconnects that benefit a large-array of row-column contacts such as pressure sensors, transistor matrices, or IC routings. In-lay techniques in the weft direction have also been leveraged to distribute piezoelectric fibers and other sensors that are structurally larger than the rest of the fibers in a woven textile. Knitted textiles, on the other hand, are constructed through interlocking loops of one continuous yarn. Due to the loop formation and porosity, they are typically more stretchable and breathable than woven textiles. Apparel industries, including medical fabrics and sportswear, rely heavily on knitted textiles. The unique structural characteristics of knitted textiles have been explored in the design of strain sensors from conductive and piezoresistive yarns, as well as fabric-based actuators from shape-memory polymer (SMP) and muscle yarns.

Functionalization can also start at the fabric level. Like some of the processing steps at the fiber level, we can apply a solution-based coating and bath, as well as dry fabrication methods, to form an electroactive layer on the surface of a fabric. Solution-based methods such as screen or ink-jet printing of active materials provide a better commercial advantage, since it can be adapted for roll-to-roll (R2R) manufacturing. An example is their implementation for fabric-based energy storage.[39] Another technique is integrating a much more complex system-on-textile by attaching or embedding flexible or stretchable circuit board assemblies on or into fabrics.

Finally, in a technique that is similar to temperature-controlled wire drawing or electrospinning, 3-D printing can also be utilized to directly deposit electronics-integrated composites onto various soft 2-D to 3-D textile structures.[9]

Multidimensional Structures

The aforementioned 2-D textiles can be transformed into 3-D textiles by integrating multiple layers or adding another yarn dimension in the *z*-direction. 3-D structural textiles have desirable properties such as structural integrity and stability, large surface area, high protection, and warmth retention.

The significant advancements in textile manufacturing technologies enable mass-production of complex 3-D textile shapes and layers without requiring any post-processing. Using a flat-bed knitting machine, we can develop a 3-D warp-knitted fabric comprising two separate outer fabric layers integrated by intermediary in-lay yarns or knitted layers that can either interlock the fabrics into one substrate or create a hollow spacer structure. For e-textiles, we can use these multilayer woven and knitted textile configurations to form a sandwich structure. This layer structure is particularly suitable for pressure-sensitive e-textiles that require a spacer in between two fabric electrodes. Furthermore, by engineering the knitting pattern, we can control the spacers' compression characteristics.

Whole-garment 3-D knitting machines are becoming prolific in the textile manufacturing industry. These automated machines can produce geometrically complex 3-D textiles such as garments without any need for seams to piece the structure together. Using digital scanning and manufacturing, we will see more complex integration of e-fibers into advanced, customizable and personalized e-textiles, and their translation into various end-products.

ACTIVE TEXTILES AT THE HUMAN-SCALE

The ample selection of smart materials and the array of available manufacturing technologies ranging from fiber drawing to digital knitting and weaving enables e-fibers to be truly integrated into the fabric of everyday life. From stent implants and smart clothing to

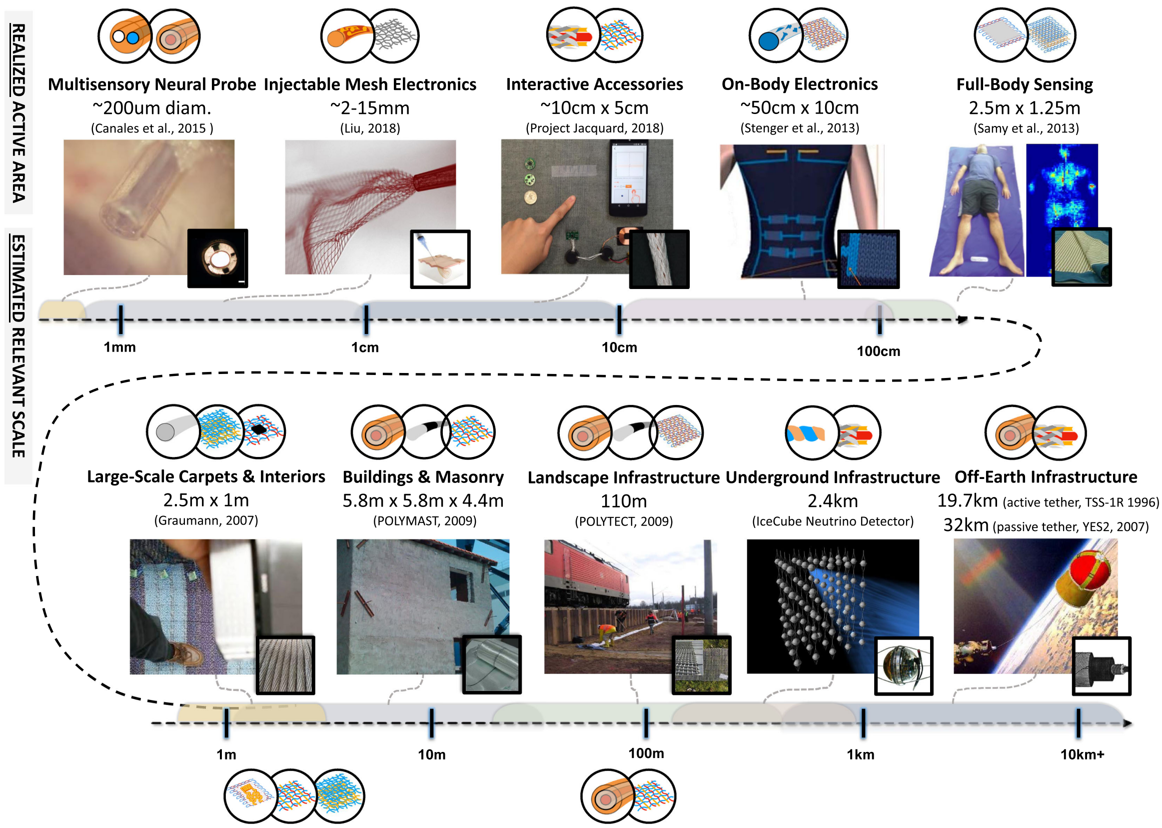

FIGURE 3. A sampling of representative electronic fiber and textile application areas that have been realized across geometric scales ranging from sub-micron to 10 km. Each project is approximately categorized by its fabric/fiber functionalization mechanism, using symbols from Figure 2.

interactive surfaces, e-textiles are galvanizing the future of personalized medicine and human–material interaction. Projects showcasing the range of existing applications at micron to meter scale are summarized in the top row of Figure 3.

Implantables and Surgical Devices

Through multimaterial fiber drawing, multimodal flexible and stretchable fibers that are biocompatible can be designed at less than the width of the human hair.[5] These fibers can elevate our understanding of the human brain and treat neurodegenerative diseases by performing simultaneous neural recording and stimulation through electrical, optical, and fluidic means with pinpoint accuracy. We can also achieve spatiotemporal resolution by developing mm-scale net-like mesh electronics that can be injected through a 100 μm thin needle and seamlessly flow through the 3-D space of the brain with minimal chronic immune response.[10] A mechanism like this is commonly used in angioplasty procedures with medical stents and catheters. Implantable fabric-net structures will be integrated with mobility, actuation, and sensing capabilities that allow them to independently manoeuvre and intervene through narrow vessels, ultimately without the help of guiding wires.[8]

Wearables and On-Body Devices

The textile is an ideal substrate for the interface between electronics and the human body since they are worn in daily life. Most research efforts in e-textiles thus focuses on the development of soft physiological and biomechanical sensors and their integration into clothing.[11] From the early development of embroidered electrodes for electrophysiology and muscle stimulation, optoelectronic textile circuits for blood-flow sensing and light therapy, to the acoustic fibers that can characterize tissue biomechanics and listen to the mechanical movements of our organs, e-textiles will permit continuous and long-term health monitoring and just-in-time interventions closer to our body, away from the hospital.

Knitted strain and pressure sensors have also found applications in activity recognition, sports, and gait analysis, prosthetics, rehabilitation, and virtual reality.[12] Combined with actuating fibers, we can achieve wearable haptic feedback for telepresence and entertainment, as well as active compression suits and exoskeletons that can be useful for rehabilitation, physical augmentation, and space exploration. Electrochemical and radiation-sensitive textiles may find use on personal protective equipment (PPE), to help protect workers ranging from miners and scientists to astronauts from possible hazards in their environments. E-textiles that are responsive can also adapt their mechanical properties such as texture and stiffness. These fabrics are useful for adaptive shoes or knee braces as well as for aesthetic properties such as clothing patterns and colors. They will redefine textiles not only as a medium for interaction and protection, but also for fashion and expression.

Objects and Interiors

Even though metallic yarns were found in tapestries and organza around the early modern period, their electrical properties were not commonly explored until the late 20th century. Initial applications of conductive textiles included electromagnetic shielding, antistatic, and antimicrobial surfaces. Conductive yarns and electrodes then started to be embroidered, sewn, or woven into fabrics to create interactive surfaces that respond to touch, pressure, and gesture.[13]

To achieve ubiquity, a large area, dense sensor, and actuator matrix can be manufactured and laminated everywhere as a floor, pillow, or wall sensate lining in the form of a carpet, sheet, or curtain. With this Internet of Things (IoT) ecosystem of e-textiles, we can track every object easily and realize a responsive, empathetic, and immersive environment that monitors our activity and reacts based on our context and intentions. An interior fabric, for example, can change its hue based on our preferences or mood or its form based on our needs. Endowing fabrics with mobility by integrating their structure with stiffness and shape-changing yarns would enable dynamic interaction between human and materials.[14]

ACTIVE TEXTILES AT THE ENVIRONMENTAL SCALE

From buildings and landscapes to vast structures in space and at sea, large-area technical fibers and textiles are taking on computation, actuation, and sensory function. Today's large-scale systems are typically composed of active cables that are either independently deployed or that are sparsely integrated within a semi-permeable textile for use in natural settings. Projects showcasing the range of existing applications for long fibers and large-scale fabrics are summarized in the bottom row of Figure 3. While passive, the artistic work of Christo Javacheff also bears mentioning—he is known for wrapping large structures like bridges and buildings with textiles.

Buildings and Vehicles

To save on the labor and cost associated with manufacturing infrastructure like bridges and buildings, e-textiles have been demonstrated as lightweight formwork—meshes onto which concrete is poured. These textiles are well suited for electrical functionalization, with particular emphasis to date on vibration and chemical sensing. Two of the most organized efforts to date to study this area have been the POLYTECT project (Polyfunctional Technical Textiles against Natural Hazards) and subsequent POLYMAST project (Polyfunctional Technical Textiles for Reinforcement of Masonry Structures), coordinated by a group of 27 companies across 13 countries to prototype functionalized e-textiles in the built environment for disaster response.[23] There is also a rich history of portable and/or deployable fabric-based architectures—from tents to inflatables—which, when functionalized, will find use in disaster zones, portable housing, and off-Earth infrastructure. Conductive meshes are also used for lightning protection on aircraft wings and as ground planes for antennas.

Landscapes and Seascapes

As the climate crisis worsens, natural disasters ranging from hurricane-related winds and flooding and widespread forest fire to the destruction of fragile deep sea ecosystems can threaten the lived environment. This looming existential threat is one explanation for growth in the geotextile market in recent years. Geotextiles are large, robust, and permeable fabrics that may be woven, knitted, or nonwoven, whereas woven fabrics are favored for strength and durability, the nonwoven form is chosen when filtration and separation is a priority. Geotextiles are used for such diverse applications as mitigating land erosion due to wind and flooding, operating as temporary roads in natural disaster zones, and as artificial coral reefs in the deep sea.[24] Increasingly, these textiles are also proposed as foundational infrastructure for distributed sensor networks that can assess the extent of any damage as well as detect environmental anomalies like landfill leakage.[25] In these systems, optical fiber-type sensors (e.g., time-of-flight reflectometers, and Bragg grating sensors among others) are currently the most commonly considered technology, owing to intrinsic mechanical robustness, RF noise immunity, and the ability to detect size and location of stress and deformation across scales up to hundreds of meters or more.[26]

Optical fiber-type sensors or other long cable elements can be deployed in bored tunnels or hard-to-reach areas for underground sensing and data transmission. For instance, km-scale cables with arrayed optical sensing elements are used in the IceCube physics experiment to detect neutrinos, rare particles with low scattering cross sections, by suspending multilayered strings with structural elements, conductive elements, and braided shielding elements inside an optically transparent ice block in Antarctica.

Space Webs, Tethers, and Blankets in Low Earth Orbit and Beyond

To date, e-textile technology has been leveraged only to a very limited extent in the space environment. Here, we highlighted some examples of existing ultra large tethers (1-D), meshes (2-D, sparse) and fabrics (2-D, dense) ripe for deeper functionalization.

First, nets and webs have been recognized as an effective means for deploying distributed aperture interferometers, phased array antennas, and solar arrays in orbit, and (in our own work) have been proposed as foundational infrastructure for sensors on low-gravity bodies,[27] among other potential application areas. Nets can be packaged in low volume containers during launch and deployed into stable configurations using carefully considered ejection, control, and grappling algorithms, often leveraging spin stabilization for long-term steadiness (see, e.g.[28]). The net itself is typically manufactured using high strength, abrasion, erosion, and fire resilient fibers including Kevlar, Vectran, Nomex, and Chromel-R, among other specialized soft materials.

Two attempts to realize in-space sensate meshes include the Suaineadh experiment in which a spinning space web was deployed off of a sounding rocket,[30] and the Furoshiki mission in which a deployed space web additionally contained three crawling robotic sensors.[29] While both missions encountered technical hurdles, some preliminary proof-of-concept data were still acquired. Further, in 2010, Japan successfully launched the 14 m IKAROS solar sail, which serves as an initial proof-of-concept for deployment of thin membranes in space.[31]

Furthermore, the exterior skin of both the International Space Station and next-generation inflatable habitats is composed of a densely woven protective fabric substrate that shields from overheating and atomic oxygen erosion, forming the outermost layer of the spacecraft's thermal blanket. This material is ripe for applications in structural health monitoring and large field-of-view environmental sensing (see our work in this area:[32,33])

Ultralong tethers scaling up to tens of km in length have been realized in the space environment, which can harvest energy from Earth's magnetic field When composed of an electrically conductive material.

PERSPECTIVES AND CONTRIBUTIONS FROM AUTHORS

Electronics and Manufacturing Challenges

With respect to fiber manufacturing, it remains a challenge to draw fibers with precise and complex internal structures at meaningful lengths. Interest is mounting in using machine learning and other predictive algorithms to optimize novel material designs suitable for different draw processes, as well as develop comprehensive and searchable materials database. In contrast, today, materials are often proposed based only on the evaluation of a small number of macroscale material properties and are then evaluated largely by trial-and-error.

Today's e-textiles can be wireless or data can be routed through traces in the fabric, either via peer-to-peer networks or via a centralized processor node embedded within or separate from the textile structure. Generally speaking, the design of sleek, robust, and machinable e-textile interconnects remains a core challenge. For complex and multilayered fiber structures, electrical connections are typically achieved by hand soldering, snaps, and other manual techniques. Microscale insulation piercing contact (IPC) connectors would be useful for interfacing with signal lines of multilayer fiber and fabric constructions, as would methods that are compatible with digital manufacturing in order to minimize touch labor. See, *e.g.,*[22] for more commentary. Regarding fabric development, electronic looms and digital knitting machines require significant training for researchers to operate. Substantial work is underway to develop open source and user-friendly design environments.

With respect to electronics and noise, RF pickup on long cables is a primary challenge when it comes to scaling out systems to large areas. Optical-fiber based sensors mitigate this concern, as do multilayer fiber manufacturing techniques that incorporate shielding around the active signal line. Generally, the use of differential signalling can also mitigate risk, in which two complementary signals with opposite polarities are transmitted, allowing for common-mode noise to be subtracted away.

Finally, as channel count scales, systems may become bandwidth limited, which, depending on the application, may be mitigated using clustering, algorithms, tracking algorithms, adaptive sampling schemes, and various decentralized networking topologies (including hybrid wired/wireless networks), which have been extensively reviewed elsewhere.

Industrial Partnership for Digital Manufacturing of Electronic Textiles

In the spirit of large-scale manufacturing, customization, and translation of e-textiles, we worked side-by-side with textile and printed circuit factories and adapted their manufacturing flow to accommodate our requirements and *vice versa*. As illustrated in Figure 4, several projects that were resulted from fruitful research and manufacturing collaborations included a knitted interactive surface for musical expression (KnittedKeyboard),[15] a distributed, large-area system-on-textile (SensorNets),[17] and an e-textile conformable suit for large-scale multimodal physiological monitoring (E-TeCS).[18]

In the KnittedKeyboard, by working together with manufacturers in a textile factory, we gained insights into operating a knitting machine to integrate various functional and nonfunctional yarns, such as conductive, thermochromic, thermoplastic, polyester, and spandex [see Figure 4(a)–(b)]. Initially, material scientists can consult textile manufacturers about developing an e-fiber that can pass design for manufacturability (DFM). These e-fibers or yarns should have certain mechanical characteristics or parameters, such as flexibility, density, and elasticity, to robustly go through the whole knitting process. We can adapt machine parameters such as knitting density, speed, and tension based on the stability and complexity of the e-fibers. System integrators can then use these fibers and design various knitted textile structures to make dense and/or large-scale e-textile system for the required application.

A modular, reconfigurable electronic network and integration framework could also be applied to standardize e-textile substrates for various commercial off-the-shelf ICs [see Figure 4(e)]. In the SensorNets project (see Figure 3), we combined a flexible PCB array with stretchable woven routings as self-aware, interactive textile with functionalities mimicking biological skin.[15] Further, by orchestrating both stretchable PCB fabrication and digital knitting, E-TeCS [see Figure 4 (c)–(d)] demonstrates a platform for embedding a large assortment of electronic components in a textile for multimodal, whole-body sensing.[18]

Industrial Partnerships for Augmenting Specialized Electronic Textile Technology

High-performance fabrics are manufactured at precise specification to meet the requirements of surgeons, firefighters, athletes, deep-sea divers, and spacecraft engineers, among others. As such, in order to augment existing specialized fabrics with sensory enhancements, it is beneficial to prepare research prototypes with the support of a manufacturer with specialized looms, knitting machines, and manufacturing expertise. This partnership can take different forms. Here, one example is provided related to the SpaceSkin project, summarized in Figure 4(f)–(h).[32]

In order to enhance Beta cloth fabric, which is traditionally used on the exterior of spacecraft and spacesuits, we first obtained small samples of this densely woven, Teflon-impregnated fiberglass material from Dunmore Aerospace. In initial prototypes, thin film and fiber sensors were laminated or epoxied onto the fabric backing. Following a series of experiment in which sufficient sensitivity to ballistic stimuli was confirmed, we were ready to directly weft-insert fiber sensors into this material. We worked with JPS Composite Materials R&D to minimally adapt NASA-approved manufacturing specifications to accommodate our fiber sensors while remaining compatible with the available prototyping loom. To do so required significant technical discussion between academic and industrial R&D researchers.

As one example, we identified a Teflon-coated yarn supplier as an alternative to bare fiberglass yarns, sidestepping the traditional step of inpregnating woven fiberglass in Teflon, which is a fabric-level coating process that requires high temperature heat treatment for strong adhesion and would have damaged our sensors.

By working closely with an industrial supplier, we as researchers are able to perform higher fidelity performance testing those baselines against heritage material. As specialized e-textiles take on more complex knit and weave patterns as in Figure 2, these academic and industrial manufacturing partnerships will grow in importance.

BEYOND FIBERS AND TEXTILES: UBIQUITOUS SENSATE SUBSTRATES AT SCALE

In some domains, the importance of balance between performance and function in textiles is of high priority—for example, the use of optical fiber sensor

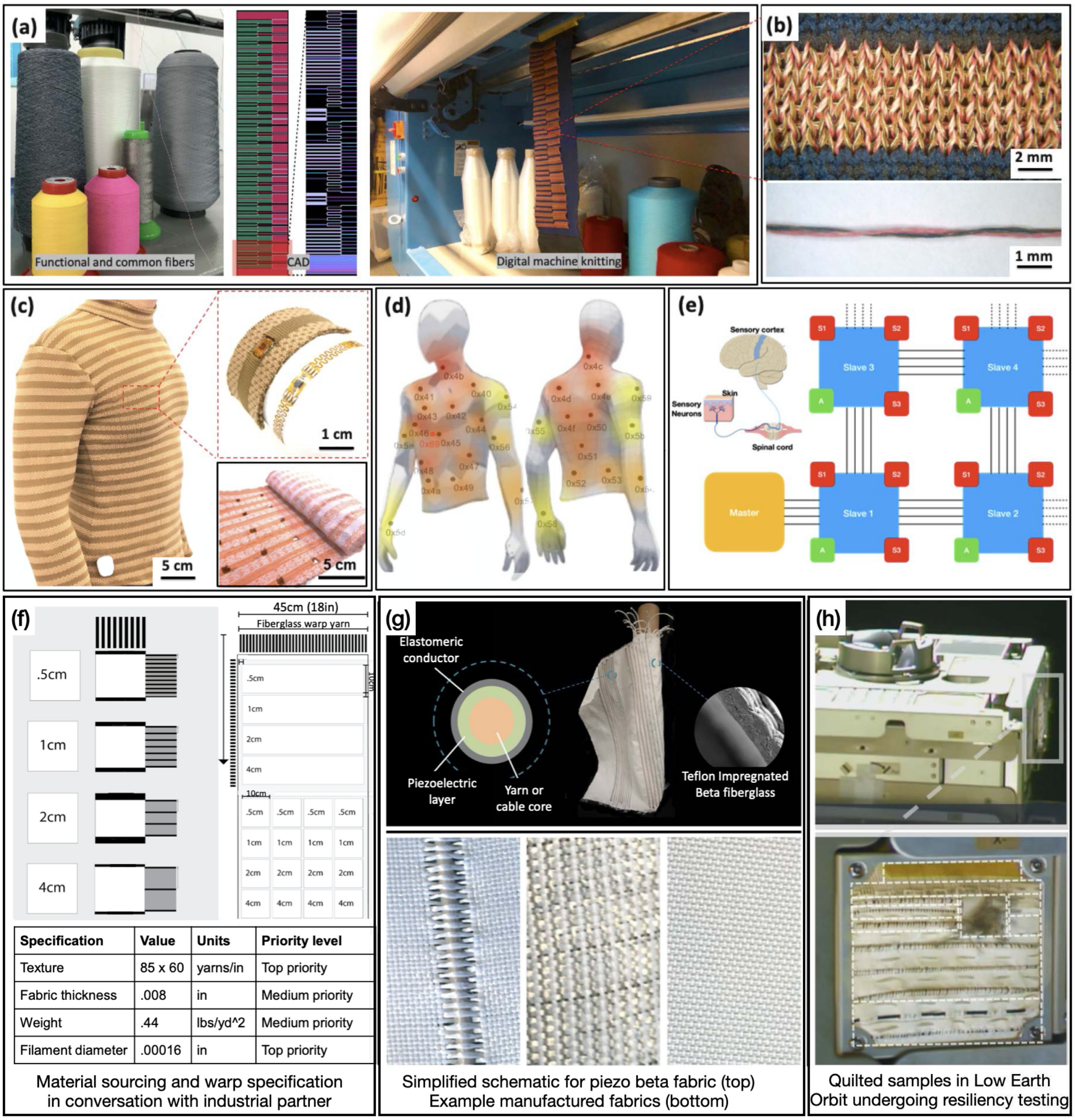

FIGURE 4. Integration techniques of functional fibers and devices into fabrics with knitting and weaving. (a) Digital customization of various fibers with machine knitting to produce KnittedKeyboard. (b) Microscope image of KnittedKeyboard pattern and twisted conductive and thermochromic yarn. (c) Stretchable PCB woven in a customized knitted clothing (E-TeCS) for (d) large-area body sensing. (e) SensorNets system architecture. (f-h) Sample manufacturing specification and testing stages for the SpaceSkin woven spacecraft sensor project.[32] (Weft design graphics in collaboration with Joao Wilbert; In-space images courtesy Space BD/JAXA).

technology in thermal or charged environments intrinsically achieves the requisite material resiliency requirements[36] and the use of fiber technology as an exterior skin in personal protective equipment can readily improve the system's protective function.[37]

However, in typical cases, the microscale fiber technology is incorporated at meso and macro-scale relative to the base fabric. What might it take to allow fabric sensors or other substrates for that matter, to more intrinsically adopt the materiality of the relevant environment?

We note, for example, the design of electrically conductive bacterial, mycelium (fungal), physarium (slime mold) networks,[34] as well as silicone elastomer, clay, glass, and concrete[35] as cases in which a baseline function is teased out of substrate. Broadly, the field of *Unconventional Computation* promises advances in the intrinsic substrates used to store memory, process data, sense, and actuate—from chemical, fluidic, and DNA computing techniques to even more exotic proposals, for instance—to reconfigure an asteroid as a mechanical automaton.[38]

At the extreme level, we foresee a shift from application-oriented sensate substrates to generic super-substrates with dense and intrinsic electronic integration for all applications.[19] Analogous to our envisioned systems, these substrates will be able to measure, learn, adapt, and respond to indirect, large-amount multimodal data from the environments and form self-organizing networks as a whole.[20]

CONCLUSION

The textile has long since established itself as ubiquitous in the built environment, and our growing ability to optimize and finetune manufacturing techniques will allow us to increase the sophistication, breadth of function, and scale of these substrates. Improved access to manufacturing tools can be achieved both through industrial partnerships as well as by increasing researcher access to mass manufacturing tools for prototyping at ultra-small and ultra-large scale and in large quantity. Interdisciplinary collaborations allow teams to extrapolate function from creatively engineering textiles that draw from heritage and cutting edge techniques. By broadening our outlook well beyond wearables, we grow to understand the fiber and fabric in more architectural terms as a *line*, as a *plane*, and as *surface*, the living and nonliving synergy of the e-textile *gaia* emerging.

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