Ubiquitous conformable systems for imperceptible computing

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Abstract

Purpose – *Although conformable devices are commonly designed to couple with the human body for personalized and localized medicine, their applications are expanding rapidly. This paper aims to delineate this expansion and predict greater implications in diverse fields.*

Design/methodology/approach – *Today's device technologies continue to face fundamental obstacles preventing their seamless integration with target objects to effectively access, evaluate and alter self-specific physical patterns, while still providing physical comfort and enabling continuous data collection. Due to their extreme mechanical compliance, conformable devices permit the query of signals occurring at interfaces so as to decode and encode biological, chemical and mechanical patterns with high resolution, precision and accuracy. These unique and versatile capabilities allow for a marked change in the approach to tackling scientific questions, with the ability to address societal challenges at large.*

Findings – *Here, this study highlights the current state of these devices in a wide range of fields, such as interactive teaching, textiles, robotics, buildings and infrastructure, agriculture, climate and space, and further forecasts essential features of these devices in the near future.*

Originality/value – *This study justifies conformable devices' growing utility through a novel quantitative analysis methodology that indexes peer-reviewed journal articles based on specific keywords, whereby this study tracks keyword frequency over time across specific fields in conjunction with conformability-like topics. The resulting trends' trajectories provide the foundation for this study's future projections. This study concludes with a perspective on the possible challenges concomitant with a ubiquitous presence of these technologies, including manufacturing, wireless communication, storage, compression, privacy and sharing of data, environmental sustainability, avoidance of inequality and bias and collaboration between stakeholders at all levels of impact.*

Keywords *Agriculture, Virtual reality, Health monitoring, Brain–computer interfaces, Climatology, Conformable devices*

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Introduction

Current efforts in miniaturization shrink all spatial dimensions of a device to achieve imperceptibility. Beyond a certain scale of reduction, devices almost entirely experience surface phenomena as the surface-area-to-volume ratio increases dramatically. As such, following Moore's law, it is becoming more difficult to manufacture and control the properties of heavily miniaturized, sensitive electronic systems with low tolerances. Conformable devices present an alternative way to create imperceptible devices by reducing only one spatial dimension (thickness). By additionally tailoring materials, their structures and the resultant mechanics so as to create mechanical adaptability, conformable devices can seamlessly laminate onto surfaces and decode or encode relevant information.

Conformable devices enable the translation of natural patterns occurring inside the human body (Tasnim, 2018) or in the surrounding environment into a language understandable by

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humans. These devices offer several technical advantages that can foreseeably give way to global ubiquity: mechanical adaptability allowing intimate contact with complex geometries; use of materials with elastic moduli comparable to those of target materials resulting in imperceptible meshing; surface properties that allow adhesion via van der Waals forces (Dagdeviren, 2017); flexibility and stretchability that aid in maintaining intimate adhesion under dynamic deformation conditions (Kim, 2011; Rogers *et al.*, 2010).

Highlighting recent advancements in such adaptive devices for personalized medicine, current perspectives forecast avenues by which conformable devices can revolutionize the field of healthcare (Tasnim, 2018). Despite recent focus towards health-care applications, conformable devices have the potential to expand their impact to various fields, ranging from agriculture to space exploration. Integration of such devices with virtual reality (VR), for instance, can assist those with disabilities to function beyond their capabilities or help simulate scenarios for more facile education and learning. Embedding electronics into fabrics in a conformable manner could also evolve the capabilities of fashion for bodily or environmental sensing or communication *in situ* (Wicaksono, 2020). The mechanical adaptability of such devices also allows for use on other organisms, such as plants and animals or nonliving objects, such as buildings and infrastructure, to continuously collect data for tracking ecological phenomena, agricultural performance or energy efficiency. Provided the use of proper materials suited to harsh conditions (Almuslem *et al.*, 2019) (e.g. tailoring encapsulation permeabilities, functional material sensitivities, thermal stabilities and chemical reactivities), such devices could be used across various ecosystems, including oceans at different depths, forests, jungles, tundra and even outer space. These devices can also enhance sensory input for fine robotic manipulation, provide means for ubiquitous sustainable energy harvesting and allow the creation of functional space suits and exploratory vehicles on earth and other planets.

In the upcoming sections, we predict technological advances in mechanically adaptive devices projected a few decades into the future based on recent advances in various fields, such as interactive teaching, textiles, robotics, buildings and infrastructure, agriculture, climate and space. In doing so, we introduce a methodology (see Online supplemental material) based on an analysis technique that tracks keyword frequency over time from peer-reviewed journals. Continuing trends' trajectories provides the foundation for our future projections and creates a link between current research. We conclude by forecasting key concerns and challenges of implementation for the future of conformable devices related to manufacturing, wireless communication, data, environmental sustainability, equality and collaboration between stakeholders at all levels of impact.

Human interaction and experience

Due to their mechanical adaptivity and the intimate contact they achieve with target substrates, conformable devices offer opportunities for enhanced interactions between humans, objects and abstractions. While traditional VR and augmented reality (AR) systems focus on creating novel visual and auditory stimuli, conformable devices allow access to the skin and other epithelia as sensory interfaces (Yu, 2019) and easily achieve spatiotemporal tracking and pattern recognition of touch signatures (Sundaram, 2019). Cutaneous pressure monitoring (Dagdeviren, 2014a) and soft tissue biomechanics characterization with high sensitivity *in situ* (Dagdeviren, 2015) could also facilitate system adaptivity to an individual's specific epidermal signatures and account for changing epithelial properties, such as hydration and elastic modulus. Designing VR and AR systems with conformable properties provides the potential to have broad impacts on interactive teaching, surgical modeling, assistive technology, psychological research and arts and entertainment.

Interactive teaching and surgical modeling

Training and skill development models benefit from embedded sensors used to track operator performance, and there exist several patents towards the development of such technologies (Mcwilliam *et al.*, 2019; Toly, 2012). Incorporating conformable sensors in VR systems for student or employee training can ameliorate interactive teaching efforts. Industries expecting fine motor skill, extensive practice and deep knowledge of physical systems in high-risk operations, such as those occurring in hospitals or nuclear power plants, could benefit from the real-time tactile, force-feedback information attainable in an imperceptible fashion via conformable systems.

The exchange and distribution of virtual surgical techniques is one area of teaching and communication poised for a revolution. Towards the improvement of anatomical models and training methodologies for surgeons, conformable sensors coupled with VR and AR will soon make the exchange of medical techniques more accessible. The documentation and virtual exchange of medical techniques to an entire classroom *en masse* could become a new paradigm in surgical teaching. Through the use of conformable sensors, instructors could develop lesson plans, detailing precise hand movements and techniques while documenting proper approaches, which could then be distributed to students on a large-scale. Such a classroom would use virtual simulation that is physically guided by haptic feedback and conformable sensors to communicate, document, teach and evaluate surgical technique beyond a small group of students. One study has demonstrated that mannequins embedded with conformable sensors can measure trainee performance in real-time and provide immediate feedback, enabling the creation of physical and virtual models of human anatomy for training medical students (Shen *et al.*, 2016). Extending this idea, surgical trainees could also be equipped with conformable sensors on their hands, in the form of a thin glove, or arms, in the form of a sleeve or tattoo-like patch, to receive force-feedback or haptic feedback (Okamura, 2009); coupled with glasses capable of displaying AR. This would circumvent the need for a physical mannequin altogether, potentially paving the way for precise "four-dimensional" teaching and learning experiences. The concept could be extended to teaching scenarios in non-high-risk situations, such as in a materials science or mechanical engineering classroom, where theoretical discussions could benefit from realistic virtual demonstrations. Additionally, measuring physiological signs such as heart rate and perspiration could allow for documentation of stress levels during a simulated procedure. Medical students could thus operate on what "feels" like real organs using environments that emulate not only visual and auditory sensations but also tactile ones.

Current methods in surgical planning can involve reconstructing a patient's anatomical features using computed tomography (CT) scans. Subsequent use of computer-based virtual surgical planning software (Cevidanes, 2010; Zhao *et al.*, 2012) allows for virtual manipulation of human anatomy to simulate surgery (Zheng *et al.*, 2019). Ongoing advancements in artificial intelligence coupled with virtual patient-specific anatomical models are increasingly aiding surgeons in becoming more equipped to predict and map the most efficient surgical strategies for custom treatments. Current medical navigation systems and surgery planning software, however, lack realistic physical feedback that could afford surgeons an added advantage during surgical planning. Coupling conformable devices with surgical simulation tools could make surgical planning more effective by closely representing the movement of the human body, allowing operators to develop a muscle memory for the forces and movements required for often delicate tissue deformations. Force sensing and actuation in a conformable form factor infers a future of physical feedback systems that mimic patient-specific anatomical profiles for seamless, kinesthetically accurate surgical planning.

Assistive technology

Given that various optical (Ko, 2008), mechanical (Dagdeviren, 2014a; Dagdeviren, 2015; Dagdeviren, 2014b; Daft, 2010), electrical (Fayyaz Shahandashti *et al.*, 2019; Oribe, 2019) and chemical (Dagdeviren, 2018) stimuli have been sensed or actuated in conformable or near-conformable form factors thus far, the use of conformable sensor readings interpretable via machine learning algorithms (Picard, 2000; Bernal *et al.*, 2018) could enable the decoding of human psychological states. As current mechanisms for interpreting psychological states involve direct measurement of a few weakly correlated signals (electrodermal activity [EDA], heart rate, breathing rate, epidermal temperature), the wealth of multisensory probing of both human and environmental factors made possible by conformable sensors expands the available phase space from which more accurate hyperplanes for distinguishing distinct psychological phenomena may be deduced. Such capabilities could potentially be implemented in a broader educational landscape to detect concentration, engagement, stress and mood (Marín-Morales, 2019); this ability to aggregate data in real-time could help a lecturer or speaker adapt to audience psychological states during their presentation.

There would likely be a greater impact of these technologies on distinctly affected populations. For example, autism affects perception, communication skills and interaction with the outside world (Marco *et al.*, 2011). Considering that people with autism often experience sensory overload and oversensitivity to stimuli such as light, sound and temperature, VR systems enabled by conformable devices could be used to induce calm and relaxation in children with autism by providing them with stable environments personalized to meet their needs when high-stress situations overstimulate their psychological states (Newbutt *et al.*, 2020). The extension to virtually-experienced cognitive behavioral therapy easily follows. These methods have an immense potential to help those with mental health afflictions, such as depression, anxiety or post-traumatic stress disorder. With conformable devices, such systems could become nearly imperceptible to users, allowing their experiences in the virtual world to feel more representative of real-world phenomena and thereby making the process of adaptation to such scenarios less daunting and more comfortable. Using physiological signals for recognition of psychological state is additionally advantageous because numerical results are difficult to fake or malinger, a front-facing camera is not required and external light and noise are irrelevant to measurements if the appropriate measurement modality is used. By interpreting the quantifiable patterns of human response to stimuli, researchers gain the ability to minimize distress by providing individuals with personalized virtual interactions.

Entertainment and culture

The ability to generate immersive experiences via tactile and force emulation into VR systems could dramatically alter entertainment and cultural experiences. For example, many video games (Woodard and Sukittanon, 2015) and museum installations (Meet The Enemy, 2021) are creating increasingly lifelike experiences, but are limited to generating visual and auditory stimuli. A recently created VR museum installation, “The Enemy,” allows users to immerse themselves in a conversation with a combatant or gang member involved in major conflicts stemming from three regions of the world: El Salvador, the Democratic Republic of the Congo and Israel and Palestine (Meet The Enemy, 2021). The creation of conformable kinesthetic emulators could better include the sense of touch into immersive experiences and allow for more realistic sensory feedback. Virtual experiences aim to provide spatially accurate views of simulated hands and objects in 3D and precise dynamic interactions with objects in 4D, using basic manipulation tasks such as selection, release, translation, rotation and scaling (Lu *et al.*, 2012). These functions, however, do not perfectly immerse users in the actions they perform as the games lack complex tactile feedback capabilities that reveal kinesthetic properties (such as surface topography, roughness, volume, hardness, elastic response) of a virtual object.

In an attempt to endow users with haptic feedback for a more natural in-game experience, Microsoft's TOuch Rigid Controller (TORC) provides an interface for the thumb, index and middle fingers to simulate the feeling of gripping and rotating virtual objects, with vibrational feedback intended to communicate object properties, such as size and elasticity, to the user (Lee *et al.*, 2019). The rigidity and bulkiness of the device combined with the use of only three large-area actuators limit the extent of immersion, allowing for simulation of only large objects with limited surface roughness. Object features with limited size scale, such as corners or roughness, cannot be emulated by the low spatiotemporal resolution available in TORC. Higher spatiotemporal resolution tactile feedback could be emulated via the use of actuated pins (∼10–100 nm thrust) for micro-roughness displays that simulate smooth bumps, roughness, or fine grating of a virtual object. This technology utilizes a two-dimensional (2D) array composed of pins, electrodes, air pressured chambers or voice coils to stimulate the operator's skin and thus forms a spatial force distribution that reflects the tactile properties of an object surface (Kim *et al.*, 2007). However, this method has limited force output and is currently limited to 2D implementations with rigid form factors. Friction modulation devices are another technology that simulate friction during virtual object manipulation. Such devices reproduce tactile information through the change of lateral force within a horizontal plane, using devices based on either the squeeze-film effect or electrostatic effect (Wang, 2019a).

Some efforts to achieve haptic feedback in a conformable form factor are underway. One recent result tackles two important challenges: achieving the vibrational power output necessary to simulate touch forces within a limited form factor (volumetric scaling of power output is a concern) and wireless power delivery and communication via near-field communication (NFC) to remove the burden of cables (Yu, 2019). Though this device uses electromagnets for vibratory force generation, new mechanisms of increasingly power-efficient actuation in smaller form factors will better facilitate the conformability of future VR systems and the applicability of conformable devices to smaller areas of the body, such as fingers. Incorporation of electronics that mesh more seamlessly with the skin (Miyamoto, 2017; Okutani *et al.*, 2020) could further facilitate the imperceptibility of skin-integrated VR systems.

Highly immersive VR experiences would further benefit from multimodal haptic actuators that simulate a wide range of properties, including hardness, warmness, variable roughness, friction and global and local shapes and sizes (Wang, 2019a). Such devices should be able to reproduce multi-properties of virtual objects and support multi-gestures of human digits, limbs and joints to perform fine manipulation and stimulate multi-receptors, including cutaneous kinesthetic and heat receptors, of the human haptic channel. Achieving accurate representations of the multi-properties of objects would additionally require machine understanding of the signatures of human touch and grasp (Sundaram, 2019) to recreate those experiences. As such, integrating accurate multimodal feedback within a soft, conformable structure with spatiotemporal resolution comparable to that of the skin's mechanoreceptors and thermoreceptors remains an open challenge. To accelerate the pace at which conformable devices unravel new channels for better immersive virtual experiences, human experience designers could enlist the help of researchers in the field of conformable devices to add new sensory dimensions to various formats of entertainment and culture.

Expression and creation: music, visual arts, cuisine, textiles and fashion

The mechanically imperceptible nature of conformable devices offers many novel avenues for enhancement of artistic expression and creation. Art seeks to enhance, explain or portray experiences and perspectives in novel formats. The arts tend to involve human sensory systems, such as the sound (music), sight (visual art), taste (culinary art), smell (perfumes, olfactory art) and touch (sculptures, tactile art) or combinations (theatre, dance, fashion). As conformable systems provide seamless coupling with the human body and its sensory systems, such devices offer unique capabilities to invigorate art forms by decoding and even encoding the body's patterns.

One artistic field ripe with opportunity for enrichment is music. Steps have already been taken to combine technology and music. For example, one class of technology seeks to use hand-worn devices (e.g. wrist-worn, palm-wrapped devices or gloves) to track gestures and map them to musical notes (Kwon and Gross, 2007; Serafin *et al.*, 2016). Conformable devices could be particularly useful in these contexts by providing a discreet way to measure movements of parts of the body, or even sync music to steady patterns such as heartbeat, respiration or brain waves measured via an electroencephalogram (EEG). Such devices could be used in the process of musical experimentation and performance by acting as invisible synthesizers (Jessop, 2010). Conformable devices could apply this mapping of bodily gestures and patterns to other forms of artistic mediums (such as color, brushes, lighting, odor release), thereby allowing for the creation of customizable artistic libraries for various creative explorations.

Two speculative methods of enhancing artistic expression involve altering the sensations of smell and taste. Conformable devices based on miniature pumps (Dagdeviren, 2018) or bioresorbable materials present approachable forms of altering taste. For example, electronic pills (Dagdeviren, 2017) or edible electronic strips that dissolve upon contact with bodily fluid (Hwang, 2014) could be used to detect biomarkers and collect data inside the body. A future extension of such technologies could load flavor chemicals in soft capsules and programmatically release them using data collected by conformable technology. Such a device could be used to experiment with combinations of tastes or enhance other artistic experiences by adding the dimension of taste. The same concept can be applied to create a miniaturized odor-releasing nose ring which responds dynamically to other bodily patterns or environmental cues.

Fashion is another easily accessible area in which conformable devices can mesh with art. Historically, the endeavor to infuse fashion and technology has been prominent. Dating back to the mid-18th century, conductive fibers were coated with metal to make metallic silk organza for traditional clothing (Uddin, 2010). By knitting or weaving different materials such as conductive yarns and optical fibers, fabric can become a vehicle for circuitry that creates a unique fashion experience while also providing useful features (Wicaksono, 2020; Service, 2003). Several existing projects seek to make interactive digital textiles that can dynamically alter their features in response to physiological signals or other inputs (Wicaksono, 2020; Poupyrev, 2016; Stoppa and Chiolerio, 2014). The development of such electronic textiles and their appearance in private markets (Wilson and Teverovsky, 2012) suggest vast potential for conformable electronics in textiles and fashion.

In the future, as clothing approaches the same level of sophistication as mobile devices and computers, fashion will face an upheaval as integrating electronics into clothing allows fashion designers to make dynamically adaptable clothing. Garments could be made to display personalized messages, bodily signals or even psychological states such as mood. These messages could be encrypted by customizable changes in a garment's shape, color or texture. Interest in such dynamic textiles is rapidly increasing and fashion studios are already experimenting with incorporating functional electronics into clothing (Freire *et al.*, 2018). The development of pH-sensitive or other chemo-sensitive textiles could also serve as a viable environmental analysis platform (Ghoneim, 2019a). Incorporation of conformable pH sensors into clothing could serve as a starting point for this venture. However, the creation of highly specific and accurate chemosensors for gases and particulates at ambient temperature and pressure (low density and low chemical potential) will be a predominant challenge for the development of environmentally-aware clothing. Further inventive uses of conformable devices in fashion coupled with novel technologies will facilitate a new standard of expression through clothing, making clothes more useful and versatile, adding a powerful set of tools to designers' and stylists' toolboxes. Combined with machine learning techniques (Sanakoyeu *et al.*, 2018), conformable electronics in clothing could lead to a realm of dynamic fashion which learns user preferences and evolves over time accordingly.

Personal garments also provide a platform by which bodily energy (in the form of heat, movement, or chemicals such as those in sweat) can be harvested to perform useful work (Lund, 2018). Currently, the amount of work that can be harvested from garments is on the order of hundreds of μW and is enough to power a host of ultra-low power sensors and electronics (Lund, 2018; Dagdeviren *et al.*, 2017). Both the low power electronics and energy harvesters based on piezoelectric or triboelectric materials can be integrated into fabrics in a conformable manner to enable seamless interactive textiles. Such materials, however, potentially suffer with regards to long-term reliability under dynamic deformation conditions and should thus be carefully engineered to avoid the possibility of negative environmental impact from fast electronic fashion. As the field of conformable clothing technology continues to grow, it is certain that fashion designers, companies and researchers will develop novel ways to use clothing. A future in which personal garments replace bulky, rigid mobile devices is foreseeable. The positive foreseeable trend is seen clearly in Supplementary Figure 1, wherein we check the count of articles published versus year for various fields. Particularly, research interest in AR, VR and haptic feedback has shown a dramatic increase in the recent past.

Robotics, prosthetics and brain–computer interfaces

On the frontier of augmenting human ability lies the race to interface seamlessly with the body's nervous system (Obidin *et al.*, 2019). Accurate measurement and modulation of neuronal signals from the peripheral nervous system (PNS) and the central nervous system (CNS) could enable markedly improved robotic and prosthetic technologies (Maimon, 2017; Clites, 2018; Srinivasan, 2017), as well as targeted drug delivery for enhanced treatment of neurological disorders (Dagdeviren, 2018).

Interfacing with sensorimotor nerves in the PNS directly responsible for a particular movement would allow a prosthetic limb to respond mechanically to its user's intention to make that movement. The ultimate goal of such a technology would be to not only synchronize the movements of human-like prosthetic limbs with the user's intended motion (by responding to signals from efferent nerves) but also send sensory information about the environment back to the user (by sending signals to afferent nerves). Highly concentrated efforts have resulted in achievements on both fronts, including the first artificial afferent nerve (Kim, 2018a), PNS-responsive leg (Clites, 2018) and arm (Kõiva *et al.*, 2015) prostheses and tactile sensing with high spatiotemporal resolution (Someya, 2004). However, the challenge remains to combine all three conformable technologies into one coherent mechanism while maintaining customizability to individual amputees. On a similar front, artificial efferent and afferent nerves, in tandem with high resolution pressure sensor arrays, can also be used to make more intelligent robotic systems. For example, robotic arms, though useful for many positional tasks, suffer in terms of force feedback control; this renders them too heavy-handed for delicate tasks. Conformable sensing of mechanical compliance has endowed robotic arms not only with the ability to sense the amplitude (Beker, 2020), but also the direction (Boutry, 2018) of subtle forces, allowing for the creation of robots capable of highly precise and gentle human-like movements.

Decoding and encoding the neurons of the CNS with high resolution and fidelity addresses one of the most sought-after challenges of modern-day technology. Such a technology would allow for a better understanding of structure-function relationships in the human brain; early diagnosis and treatment of neurological disorders and tumors; and the potential to augment the human capacity to store, process and create information. By combining conformable electronics with biocompatible materials, neuroimplantable devices can interface with humans to a degree formerly unattainable by rigid technologies (Obidin *et al.*, 2019). Such devices span a wide range of tools for recording brain activity (Rivnay *et al.*, 2017), stimulating neural networks (Penfield, 1936; Szostak *et al.*, 2017), chemosensing (Szostak *et al.*, 2017; Leiter *et al.*, 2013), optical sensing (Boyden, 2011) and pinpointing drug delivery with high spatial precision (Dagdeviren, 2018). While, historically, neuroimplantable devices have recorded neuronal local field potentials from single channel recordings for short periods of time, typically on the order of hours (Adrian, 1954), revolutionary progress in incorporating conformable mechanics and flexible substrates in novel form factors has enabled the creation of biocompatible, long-term neuroimplantable devices. New designs (Krüger *et al.*, 2010; BIOSTEC, 2015; Simeral *et al.*, 2011; Normann and Fernandez, 2016; Jones *et al.*, 1992) provide elevated standards for the materials and form factors for neural interfaces due to their durability, high recording density and relative biocompatibility. In the past few decades, these new standards have segued into a wide assortment of new conformable recording modalities, including polymer-based electrodes (Fattahi *et al.*, 2014), conducting nanostructures (Szostak *et al.*, 2017) and wireless sensing tools such as neural dust (Seo, 2016). In recent years, optical and chemical neuromodulation techniques have furthered our ability to interact with the human brain through optogenetics (Zhang *et al.*, 2006) and drug infusion (Dagdeviren, 2018; Ramadi, 2018). These tools have become increasingly less damaging to neural tissue via the incorporation of flexible substrates (Kim, 2018b). As new developments in conformable devices for neural interfacing both incorporate other forms of neuromodulation – such as mechanical, thermal and magnetic modalities – and improve upon current methods for decoding and encoding neuronal potentials with higher precision and fidelity, new frontiers open for augmenting brain function, elucidating pathways to the treatment of disease and broadening understanding of neural circuitry. The trend given in Supplementary Figure 2 shows that research interest in conformability, conformable and conformable devices yield a similar positive trend, which is expected.

Urban planning, buildings and infrastructure

Another area ripe for innovation in sensing technology is the study of human-made settlements. There remains a need to discover the underlying patterns and networks governing natural operation in these communities. Today's cities must be designed to minimize resource consumption, waste generation and pollution while also withstanding climate change (Masson-Delmotte, 2018). Expanding population, mass urbanization, rising inequality and climate change are some of the biggest challenges we face today regarding urbanization and urban planning. Conformable electronics can play an integral role at the micro level of an urban population, given that their conformal, light-weight and portable properties are conducive to widespread adaptation onto a wide range of irregular surfaces commonly found in urban cities. Such devices have potential to impact the fields of urban planning and design, and buildings and infrastructure. Urban planning could use conformable, remote sensors that achieve much higher spatial-temporal resolution than traditional bulky sensors to better inform urban designers and decision makers when simulating future development paths. Additionally, buildings and infrastructure can benefit from conformable electronics for energy efficiency to offset effects of changing climates and carbon footprint.

Urban planning

Studying a population's dynamics or resource usage at the individual, pedestrian level is one way conformable sensors can benefit the field of urban planning. Technology that can help planners measure the dynamics of urban society may enable better-informed decision-making. Spatial decision support systems, a type of decision-making tool used by urban planners, are computer-based systems that combine conventional data, spatially referenced data and information and decision logic (Carlson and Sprague, 1982). Data from geographical information systems, remote sensing and statistical data are used to simulate scenarios for future development paths. Conformable devices can provide an excellent opportunity to help improve simulation scenarios by realizing new strategies and applications aimed at gathering data at smaller spatial and temporal resolution in urban environments. From this, we can more deeply learn how individuals interact with their environments.

For example, measuring ridership on public transportation via conformable sensors embedded into irregular vehicle surfaces (such as hand poles, seats, or vehicle floors) could ascertain much about public facility usage – such as seating preferences, boarding patterns, and ridership capacities – at the individual level. Such data can be used to design better transit vehicles and stations, or inform urban planners of ridership dynamics and behaviors. With the recent surge of COVID-19 cases in 2020, real-time demand for information regarding current transit vehicle occupancy and usage patterns has piqued public interest, with public health officials interested in disseminating real-time ridership information to the general public to limit the number of passengers and encourage physical distancing (Crain's New York Business, 2020). One recent work by Kutschera *et al.* seeks to address this by creating flexible sensor-mats that automatically count passers-by (Kutschera *et al.*, 2011). The technology is based on distributed force sensing using flexible PCB electronics integrated into a rubber floor mat. The technology aims to register people traversing the mat through a network of sensor nodes distanced 30 mm apart. Although this working prototype is currently bulky with a relatively low spatial resolution, further development using higher spatial resolution sensor arrays with conformable electronics and materials could allow for coupling with irregular surfaces. For example, conformable pressure sensor arrays could accurately capture foot shape to track the direction that passengers face while standing on the mat. Through integration with artificial intelligence, foot traffic migration on-board transit vehicles relative to the present location or time can also be projected. As such conformable technologies do not rely on optical techniques, such as photo or video capture, they can be applied to continuously and anonymously measure usage of public transit, parks, benches, sidewalks and other areas or objects of interest. The integrability, anonymity and diversity of applicable conformable devices affords the technology a marked advantage for ubiquitous use in smart human settlements.

Buildings & infrastructure

Conformable devices can also be used to elucidate and alter another phenomenon occurring in urban cities: the microclimate, including weather pattern variation at small spatial scales, such as in a city block or neighborhood. Though the larger scale forces affecting urban climate are broadly understood, there lacks a quantifiable understanding of the components of urban form underlying the observable, highly dynamic patterns in the urban microclimate, particularly at the neighborhood scale and pedestrian level (Bodart and Evrard, 2011). Remote sensing can help gather more data at a lower spatial scale, and conformable devices can help further this concept by monitoring entire surfaces of irregularly shaped structures. The urban microclimate is one phenomenon that alters the environment at a relatively smaller scale. Cities have unintentionally created microclimates like urban heat islands (UHI) that cause adverse environmental and economic impacts on society (Rizwan *et al.*, 2008). For instance, UHI's have been associated with an increase in energy consumption (Konopacki and Akbari, 2002), mortality rates (Changnon *et al.*, 1996) and elevation of ground-level ozone (Rosenfeld *et al.*, 1998). Planners and architects are focusing on climatically responsive urban design to counter or eliminate undesirable microclimates and nurture conditions that provide a healthier environment. Today, buildings account for ∼40% of carbon dioxide (CO_2) emissions (Abergel *et al.*, 2017) and consume ∼40% of the electricity load in the USA (Environmental & Energy Study Institute (EESI), 2021; Doe, 2015). The following are some examples of how conformable devices can contribute to understanding the microclimate, and the ways we can design and build architecture to cut down on energy consumption.

Advances in remote sensing technology have the potential to enable future analyses of the urban climate at an appropriate spatial resolution required to examine the microclimate at the precinct and street scale, while at the same time supporting large sampling areas (Bodart and Evrard, 2011). For example, asphalt roads generate a large source load of heat in cities, yet their temperatures are not measured or accounted for at the local level. As another example, tall buildings and structures cast shadows that make some areas darker than others, or prevent wind from reaching some areas while concentrating it in others. Ubiquitous conformable sensors with remote sensing capabilities can help to better measure and understand the spatial distribution of the urban microclimate phenomenon. These sensors could be laminated onto irregular surfaces of interest. Recent work by Song *et al.* demonstrates an ultrasensitive multi-functional flexible sensor based on flexible polymers, capable of measuring multiple sensory inputs including heat, light, gas flow and touch Song *et al.* (2017). Such devices could also prove useful for building resource management. If these devices were made into conformable electronics rather than flexible, these sensors would be able to conform to arbitrary shapes of pipes, enabling the construction of networks of sensors that monitor and optimize management of resources such as water, heating and electricity. Increasing scope, similar sensors could also be deployed at the urban scale towards a future of smart cities.

Conformable devices can also play an active role in reducing energy consumption. For instance, rather than heating up entire volumes of empty space in buildings, which are responsible for most energy demands, thermal comfort could instead be implemented locally rather than atmospherically. Conformable electronics could be deployed as personal thermostats that conform to the body, allowing for the regulation of temperature on the surface of the skin. The energy required to run a personal thermostat is orders of magnitude below heating volumes of air, which could contribute to a massive reduction in carbon emissions. Conformable sensors could likewise be used to automatically and anonymously sense the occupancy of rooms in a building. If this information is incorporated into existing heating and cooling systems, it could enable higher energy efficiency by adjusting room-specific temperature regulation based on real-time usage. Energy harvesting is another approach by which conformable electronics can contribute to infrastructure efficiency. Rather than attaching solar panels to roofs, curtains can be tailored to incorporate energy harvesting in their fabric. Such an example of conformable energy-sustaining devices is a hybrid power textile (Chen, 2016). It is lightweight and has low-cost polymer fibers. With “mechanical excitation,” specifically wind blowing, and “ambient sunlight,” the device could be capable of producing enough energy for practical applications. The trend given in Supplementary Figure 3 shows a promising positive increase in research for solar cells and energy harvesting, suggesting that various energy sources yield similar trends.

Agriculture and veterinary care

The scalability and imperceptibility of conformable devices make them conducive to improving agriculture and veterinary care. While it might seem archaic to consider farming in an increasingly-digital world, these methods remain the primary source of food production. By the year 2050, demand for food from animal agriculture is anticipated to nearly double (DeSA and Others, 2013). To meet these food supply challenges, a better understanding of plant growth, animal welfare and waste production is imperative (Food and Agriculture Organization of the United Nations, 2018). Advances in conformable devices could provide insights for enhancing agricultural productivity in both the USA and the developing world. Moreover, these devices can offer insights into plant and animal health by monitoring physiological patterns and thus decoding status and wellness (El-Atab, 2020). Already, researchers have developed sensors that conformably adhere to plant leaves and subsequently read real-time data for various characteristics of a plant's environment and internal state. For example, Nasar and Hussain have developed a conformable sensor that adheres to plant leaves to detect experienced temperature, humidity and strain (Nassar, 2018). Similarly, conformable sensors can be used to detect qualities such as light intensity, soil composition and plant health. Applying these sensors on larger scales to areas in crop fields or gardens could likewise facilitate monitoring and regulation. Such conformable schemes would also inform farmers' decisions on fertilizer and water allocation in order to maximize yield and diminish waste and excess, reducing both environmental and economic costs. Furthermore, conformable devices could vastly improve agricultural quality control through automation. For instance, Kumar *et al.* have developed a conformable device that enhances the detection of harmful chemicals in aquaculture (Kumar *et al.*, 2017), and Tao *et al.* have created silk-based nanostructures that detect nutrient levels in apples (Xu *et al.*, 2019). Seeing conformable technology go further in the agricultural sector would give rise to better informed, more efficient and increasingly manageable agricultural processes, enhancing the quality and safety of produce, all while improving farmers' lives.

In a similar vein, animal health is essential, especially due to the vital role animals play in the earth's various food chains. Conformable devices could collect vital real-time data on livestock, further improving the agricultural industry, as well as quantifiably ensuring livestock health and high standard of living. Like humans, animals can wear conformable devices that collect data such as oxygen levels, heart rate, body temperature and limb movement. Researchers have already begun studies using conformable devices on livestock. For example, Sieber *et al.* studied the effectiveness of using inexpensive, human heart rate monitors to track the health condition of cattle. However, this study elucidates how animals present additional challenges to conformable sensing as surface elements (i.e. fur) complicate the design of a device that can be conformably laminated on animals while maintaining high accuracy (Sieber *et al.*, 2012). Nevertheless, if conformable devices overcome challenges associated with sensing livestock vitals, conformable devices could enable farmers to track animal health in detail, thereby preventing disease outbreaks, allowing for more accurate quality control and potentially providing insight for higher health standards and more humane treatment.

By extension, pets and other domesticated animals may also benefit from the same principles and sensor innovations described above. Conformable devices could provide insight into the mood and health of these animals, making caring for and understanding them easier. Accessing information on pets' mental states through easily accessible interfaces, such as mobile apps, would improve both the health and well-being of pets. In the veterinary sense, conformable devices can outperform traditional means of animal biological sensing. For instance, Susaki *et al.* demonstrated in a clinical trial that conformably fixing arterial catheters – devices used to monitor blood pressure – to dogs' paws better prevented blood vessel closure and resulted in more effective and continuous sensing compared to prior methods for affixing catheters to dogs (Sasaki *et al.*, 2019). The invention stands testament to the unique benefits that the incorporation of conformable devices lends to the field of veterinary care. Such benefits will soon be made possible as seen in trends given in Supplementary Figure 4 where there is a positive increase in research for both agriculture and veterinary care over time.

Environment

For the past century, the negative effects of technology on nature have proved increasingly detrimental, as evidenced by global warming, water contamination and decrease in air quality. As global temperatures continue to rise at unprecedented rates, not only are humans at risk, but wildlife and their natural habitats are greatly endangered, leading to the decline and eventual extinction of many animal and plant species. Conformable devices can help to study the impact of global climate change and even counter its consequences.

Climate

Conformable devices as remote environmental sensors can augment understanding of the microclimate and how it is impacted by changes to the overall climate system and vice-versa. As discussed in the previous section "Agriculture and veterinary care," recent studies (Nassar, 2018) have demonstrated a conformable sensor that seamlessly attaches to the soft surface of a plant leaf to measure its experienced temperature, humidity and leaf strain. Remote monitoring at such a local level can provide new possibilities for exploring the microclimate. For instance, climate data models can benefit by more accurately representing the range of microclimates that small organisms experience. To date, climate scientists typically rely on macroscale assumptions to estimate climate parameters at large spatial resolutions, often neglecting localized areas (Austin and Van Niel, 2011; Varner and Dearing, 2014). A widespread network of conformable devices across many localized areas – such as inside rain forests or other terrain with varying climate conditions – can potentially make climate data analysis more accurate and specialized. Aside from integration with stationary plants, further advancements in the field of conformable devices can realize the possibility of attachment onto the bodies of small creatures, such as amphibians. From this, we could potentially monitor the dynamic migration of these creatures. Such intimate data could help scientists develop more robust and accurate species distribution models while also studying their habitat, interactions, patterns, vital signs and population dispersion.

Renewable energy

The largest contribution to global warming is CO_2 from fossil fuel combustion. Widespread adaptation of renewable energy sources is seen as one method to reverse some of the damaging effects of existing technology. Conformable devices open new possibilities for renewable energy, due to advantages such as portability and seamless integration onto moving parts or non-planar substrates (Lipomi and Bao, 2011). In fact, as an attempt to improve existing renewable energy resources, conformability can be incorporated into the production of fuel cells, solar panels and textiles to produce more efficient and sustainable sources of energy. Beyond traditional applications that seek to replace fossil fuels as an energy source, these devices may find new uses in emerging fields such as textile electronics, or mainstream integration with consumer electronics. However, to compete with more established technologies for energy applications, conformable devices will require reduced manufacturing costs, improved performance and increased reliability.

Conformable photovoltaic and photoelectrochemical cells can be very convenient for the creation of power sources used in collapsible electronics, medical devices and the surfaces of automobiles and structures (Lipomi and Bao, 2011). In fact, introducing conformability to solar devices enables the emergence of novel applications currently unattainable by bulky, rigid semiconductors widely utilized in industry. Conformable devices can take advantage of the large surface area available on a target object (e.g. an automobile roof, door or window), whereas traditional bulky, rigid solar panels are limited to flat shapes and large planar surfaces. As outlined by Lipomi and Bao (2011), perhaps one of the most important applications of conformable devices can be in electrically-powered components that must change shape due to movement (e.g. robotic limbs). According to their research, another long-pursued application is the integration of solar panels into textiles. An example of this is integration into military uniforms, reducing the burden of batteries, or even military camps whose textile roofs must withstand harsh conditions.

Fuel cells are another technology that can help reduce CO_2 emissions. Unlike conventional combustion-based technologies in modern power plants and passenger vehicles, fuel cells do not produce CO_2 as a byproduct. Rather, fuel cells combine hydrogen and oxygen to produce electricity through an electrochemical reaction; this produces only water and heat as byproducts. Moreover, fuel cells boast a wide range of applications in various fields, including transportation, military, portable electronics, electric vehicles and energy storage units (Sørensen, 2012). To date, various types of fuel cells have been developed according to their electrolyte types, such as the polymer electrolyte membrane fuel cell (PEMFC), alkaline fuel cell, solid oxide fuel cell, molten carbonate fuel cell, phosphoric acid fuel cell and microfluidic fuel cell (Wang, 2019b). Indeed, conformability addresses a major issue that arises when integrating fuel cells into various devices; for a device to be powered by a fuel cell, it must have sufficient space to accommodate it, making the shape and size of fuel cells essential to their functionality. Thus, the conformable design of fuel cells facilitates their incorporation into a variety of devices. As a result, in devices powered by conformable fuel cells, spaces that would have otherwise been occupied with electrical power sources are freed for other purposes, increasing efficiency, reducing device size and allowing for integration with other technologies.

Ocean

Conformable devices can also help us better understand dynamic bodies of water. Monitoring the movement and communication of aquatic species by tagging sensors onto targets could illuminate changes in ocean temperature and composition. As an illustration, researchers have already produced lightweight conformable devices for tracking sea creatures (Shaikh, 2019). These devices are lighter than conventional tagging systems and enable understanding of a wider range of species (Shaikh, 2019). Beyond understanding migration patterns and lifestyles, the attachment of conformable devices to sea creatures enables the sensing of water quality and other environmental factors, providing a simple method for monitoring ocean health.

Additionally, conformable devices can aid underwater endeavors in research and beyond. Just as conformable devices can harvest biological movement on land to power electronics, they can also help power underwater scuba-diving sensing equipment. In fact, Zou *et al.*, inspired by eel skin, developed a flexible nanogenerator that can harness energy from water flowing over its surface to power aquatic electronics (Zou, 2019). Aquatic energy harvesting devices can vastly improve the ease with which people explore and analyze the ocean. Not only can conformable energy harvesters provide more immediate energy sources to scuba-divers and researchers, but they could also reduce the need for bulky batteries, thereby increasing sustainability. Additionally, conformable devices can provide added comfort and convenience to those performing underwater tasks. Scientists at RMIT University in Australia have designed waterproof conformable devices that can be fabricated using a lithographic printer (Thekkekara and Gu, 2019). Incorporating such devices into dive suits and scuba equipment could allow for more comfortable and functional underwater exploration. These devices could potentially be coupled with and powered by devices similar to those devised by Zou *et al.* (Zou, 2019). Conformable devices have the potential to provide a great deal of convenience and enrichment for humans traveling underwater as they systematically improve our understanding of the complex dynamic interactions occurring in the depths of the ocean. The trend given in Supplementary Figure 5 shows a dramatic positive increase in ocean exploration research while global warming research steadily increases.

Space

From lower earth orbit (LEO) to deep space exploration, conformable devices can offer lightweight alternatives to bulky systems while opening new possibilities of sensing and diagnosis. The sections above have already highlighted many potential technologies that can be further expanded to improve space exploration. For instance, conformable solar panels may provide large area coverage on the surface of spacecraft vehicles or satellite structures. Such devices could present advantages to flat solar panels, which are separate from the vehicle body. Due to their feather-light nature (Kaltenbrunner, 2013), conformable devices could potentially integrate with solar sail technologies (Johnson *et al.*, 2007) to provide ultra-lightweight payloads for space exploration. Described previously, conformable haptic feedback and human tactile touch sensors, if embedded into an astronaut's spacesuit or a robotic arm, could improve the sensation of grasping objects while wearing a spacesuit, or controlling a robotic manipulator, to a realistic level. In addition to technologies already discussed, space exploration beyond the earth's orbit will face newer challenges that require the adaptation of suitable technologies. Long-term space travel beyond Earth's orbit places flight crews at a disadvantage when it comes to receiving medical attention or addressing emergencies, such as unforeseen structural damage to spacecraft vehicles. Artificial intelligence algorithms that leverage data collected by conformable sensors could predict, monitor and diagnose these occurrences – such as disease onset or crack propagation on a vehicle structure – and would therefore offer invaluable resources as humans travel greater distances, such as to Mars and beyond. Of great interest for long-term space flight beyond LEO are the autonomous monitoring of flight crew vital signs, especially during mission-critical tasks (Hurlbert, 2012), and on-board, real-time monitoring for autonomous, non-destructive examination (NDE) of the spacecraft's structural integrity (Prosser, 2003). Conformable electronics may especially be suited for NDE over large curvilinear structures and around holes, bolts and other irregular and currently inaccessible surfaces. Beyond this, advancements in conformable sensors could mitigate the tradeoff between the payload and range of a launch vehicle due to decreased reliance on bulky, heavy stationary support infrastructure commonly needed to power, control or facilitate many modern devices.

For space travel, space suits control the pressure exerted on the body in vacuum environments to maintain safety and comfort. However, such suits are limited in their scope and properties, restricting (Waldie, 2005) natural motion. Recently, Bethke *et al*. fabricated a Bio-Suit that serves as a "second skin" space suit fabricated from shape memory alloy coils activated by an applied current (SAE Mobilus, 2014). This suit conforms to an astronaut's body while providing a thin yet hard exterior shell that provides rigid support to protect from the vacuum environment while avoiding the restriction of natural human biomechanics. Thus, the lightweight and conformal nature of the Bio-Suit maximizes mobility, comfort and safety.

On a related front, Wicaksono *et al*. have pioneered work on a tailored, electronic textile conformable suit for large-scale spatiotemporal physiological sensing, with capabilities of simultaneously measuring multi-modal and multi-nodal physiological and physical activity parameters (Wicaksono, 2020). Such modular concepts can be easily adapted and integrated into a space suit to measure vital signs of astronauts, particularly during mission-critical tasks. Continuous monitoring of physiological signals and physical activity is fundamental for an astronaut's well-being, as it would allow personnel on the ground to closely monitor an individual's health status, diagnose early and intervene when diseases are detected so that better-informed treatment decisions can be made. However, traditional medical instruments for long-term and continuous health monitoring of astronauts are still decentralized, cumbersome and obtrusive to wear. These traditionally bulky and rigid devices cannot conform to curvilinear regions of the body, nor can they offer a spatiotemporal mapping of physiological parameters to detail the full body status of an astronaut's health. The lengthy cables, sticky pads and form factors of these instruments cause discomfort and constrain mobility. In addition, since sensor placement and data interpretation are often dependent on the expertise of the operator, wearing and applying these conventional health monitoring instruments typically require the supervision of trained medical professionals. There is a strong need to develop effective and comprehensive physiological monitoring systems in order to accurately assess the capabilities and health of the crew members without relying on a trained operator (Hurlbert, 2012). Overcoming this challenge of automating health monitoring of the flight crew is a critical milestone to achieve before humans can travel for longer distances to Mars and beyond. The trend given in Supplementary Figure 6 shows dramatic positive increases in research both for space exploration and health monitoring, indicating a promising future of innovation.

There will come a point where further human migration is impossible, which means that automatons will be needed to further explore the depths of space. Technological advancements in making lunar expeditions more efficient provide insights into how conformable devices can be used. The Chang'e-3 probe's tele-operational communication, efficient landing and cautious locomotion are recent innovations, but conformable devices can be used to improve efficiency even further (Sun *et al.*, 2013). For instance, although extravehicular isotropic heat with the aid of a two-phase fluid is currently used for thermoregulation, conformable devices can be implemented instead to inform heat flow over complex or irregular shapes by gathering better data to optimize temperature (Sun *et al.*, 2013).

Researchers further explain the possible use of tactile sensing technology adapted from natural human sensing capabilities (Park *et al.*, 2018). These critical requirements for tactile sensing as described by Park *et al.* include sensitivity, sensor-addressing and shear (or slip) sensing (Park *et al.*, 2018). In addition to sensing, perhaps robots (specifically rovers) can be given a kinesthetic sense to help them understand their location in space and, in conjunction with the sense of touch, readjust themselves to more efficiently travel on lunar terrain and adapt to potential obstructions. Technologies similar to those discussed in the section, "Robotics, prosthetics, and brain-computer interfaces" can thus be similarly applicable to space-related travel, provided the proper materials are used to prevent space radiation from damaging the conformable electronics.

Conclusion, challenges and perspectives

Although the application of conformable devices in various fields has grown rapidly for the past two decades, there remain many avenues for further research. In the pursuit of ubiquity in the future of these conformable technologies, certain crucial factors must be considered from the start of the design phase such that today's social, economic and environmental issues may be addressed in a positively impactful manner. Such challenges include manufacturing, wireless communication, storage, compression, privacy and sharing of data, environmental sustainability, avoidance of inequality and bias and collaboration between stakeholders at all levels of impact.

Mass production and high-volume manufacturing will be key to enabling wide-scale availability of conformable electronics. Yet, current semiconductor capital equipment tools for mass production are geared towards the manufacturing of rigid, silicon-based technologies. One solution is to adapt conformable electronics fabrication steps to those of already-established silicon-based processing methodologies. For example, if conformable devices can be designed to be compliant with complementary metal oxide semiconductor (CMOS) fabrication flow, mass manufacturability may be possible (Sun *et al.*, 2020). Another solution may entail the development of a new class of equipment and technology to mass produce conformable devices. Regardless, standardization regarding process flow for fabricating conformable electronics is imperative. There exist multiple viable avenues for fabrication of similar styles of conformable devices; e.g. transfer printing (Ahmed *et al.*, 2015) and anodization (Sun *et al.*, 2020) can both be used to incorporate soft substrates into conformable designs. Moving forward, efforts should be made towards establishing a standard system by which capital equipment can be designed to handle different processing requests to realize ubiquity in conformability.

Wireless data transfer should be integrated within conformable devices in order to realize the true potential of real-time continuous monitoring. Existing solutions use radio frequency signals transmitted through flexible antennas following NFC protocols (Yu, 2019); however, the requirement for large-area antennas and the limited spatial range and communication speed of NFC presents difficulties for use in long-range, high speed data transfer scenarios with the need for small-area, highly imperceptible devices. Therefore, it is necessary to incorporate the high-bandwidth, large spatial range and small-area configurations of Bluetooth and Wi-Fi communication protocols into conformable form factors without loss of reliability (Niu, 2019). In this direction, researchers have integrated the die of a Bluetooth chip into silicon-based devices with polymer substrates (Xu, 2014). Going forward, commercial off-the-shelf integrated circuits (ICs) such as Bluetooth or Wi-Fi chips, could be designed as a product that incorporates conformability into its design, i.e. with bridge–island structures (Rogers *et al.*, 2010), thin polymer encapsulations and soft stretchable substrates (Kim, 2011). Thus, rather than individual developers customizing solutions for conformable wireless data transfer, existing IC chip vendors could sell these premade, conformable ICs in bulk, thereby spurring the rapid adaptation of conformable devices, lowering the cost of entry and shortening the assimilation period of conformable devices into the market.

The continuous, real-time monitoring capabilities afforded by wirelessly-enabled conformable devices generate new concerns related to the creation of large swaths of data. Issues of data compression, storage, privacy and sharing are paramount. Widely adoptable methods to reduce the size of collected data, especially with implementation of compressed sensing methods (Eldar and Kutyniok, 2012), will prove crucial to reducing the demands placed on data servers. If open access to data for a particular case is desirable, standardizing regulations by which non-confidential data is shared with the public would facilitate safe and transparent dissemination (Litchman, 2018; Sydes, 2015; Beaulieu-Jones, 2019). In the case that generated data is private (i.e. personal medical data), standardized protocols for encryption (Thompson, 2003) should be developed.

With the potential to become ubiquitous, conformable devices could greatly benefit the ecological outlook of the earth by incorporating measures to ensure environmental sustainability. If thorough life cycle assessments (Kirchain *et al.*, 2017) of conformable devices are conducted during the design phase so as to drive better holistic decisions regarding materials choices, fabrication steps, power demand, waste management and end-of-life protocols, this device paradigm could maximally reduce its negative impact on the environment. For example, self-powered (Dagdeviren *et al.*, 2017) or bioresorbable (Kim, 2010; Yu, 2016) conformable devices reduce power demand and end-of-life impact, respectively. However, many conformable devices rely on the usage of toxic chemicals, for which waste management protocols would have to be strictly enforced for manufacturing industries. Furthermore, though bioresorbability provides a method by which sensor disposal is minimally harmful to the environment, some designs, such as those involving standard piezoelectric materials (Dagdeviren, 2017), cannot yet be realized with bioresorbable properties. As such, strong efforts towards materials and fabrication innovation, as well as the creation of standardized protocols to regulate power usage and waste handling, will be necessary to ensure reduced environmental impact.

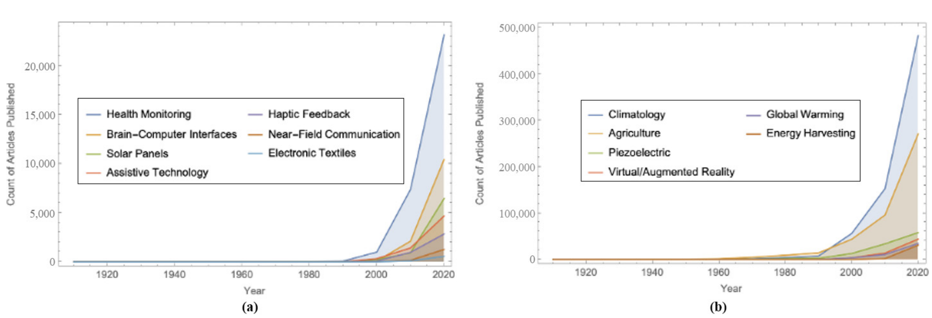
The increasing demand for surface-sensitive decoding and encoding in various applications necessitates continuous innovation in conformable electronics. Although great progress has been achieved, many studies have failed to report key parameters for reproducibility and accurate benchmarking of materials and fabrication steps. To this end, widely accepted conventions for determining materials, processes and manufacturing steps would be helpful to compose global protocols (Obidin *et al.*, 2019; Ghoneim, 2019b). Widespread use of such protocols would help to sustain continuous advancement in the field of conformable devices and enable rapid progress in commercialization.

A collaborative environment is certainly needed to foster progress in any field, and it is definitely the case for conformable devices. Stakeholders such as individual scientists, institutions, governments and companies should work closely with their intended user base to truly understand the needs and further develop timely policies to support prospective improvements and alter potential disruptions. This necessitates continuous dialogue among stakeholders with regular checks and balances between them. One potential scenario would be to establish mutually beneficial areas for stakeholders to build short- and long- term goals with progress reports made publicly available as a reference for others to implement. Such databases might start as specific, local efforts, with the potential to transform into a global understanding once progress is more widely documented. Transparent and regular dialogues with associated reporting among stakeholders, therefore, would be vitally important for initiating productive and collaborative environments. As witnessed during the COVID-19 pandemic, a system for crisis management is crucial to provide checks and balances at multiple levels of organization such that further development can proceed whilst maintaining collaboration. The MIT Media Lab and its membership consortia with dozens of companies is a profound example to highlight. Interactions with member companies during annual Member's Week events at the Media Lab provide a fruitful and unusual opportunity to dive into unanswered questions that can fundamentally change the way people live, communicate and engage with the world. Rapid transition to a virtual platform for the 2020 Media Lab Member's Week, called Out of Lab Experience, exemplifies the efficiency possible in crisis management wrought by avoiding disruptions to existing relationships and collaborations.

Equality across all levels of collaboration is similarly important to ensure the creation of ubiquitous conformable devices. Eliminating inequality in terms of gender, race, ethnicity, sexual orientation and socio-economic background in human subject selection will certainly bring new dimensions to conformable device design and enable a wide range of scientific findings to advance the field and encourage societal awareness of injustice. Furthermore, from a device perspective, conformable devices that attach to human skin should be designed such that their functionality remains constant across all skin types.

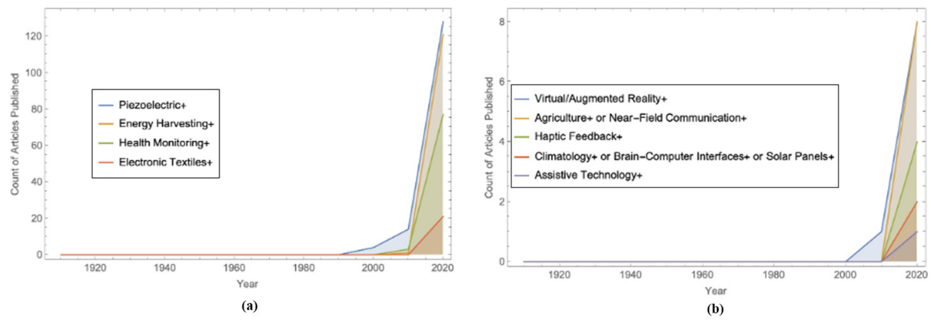
This paper summarizes our perspective on how conformable devices will advance numerous fields beyond healthcare technologies. As can be seen in our analysis (Figure 1), interest in "piezoelectric", "virtual reality", "augmented reality", "assistive technology", "near-field communication", "haptic feedback", "electronic textiles", "energy harvesting", "brain-computer interfaces", "global warming", "solar panels", "health monitoring", "agriculture" and "climatology" topics is growing rapidly (see Supplementary Information). Starting from the first keyword-containing publication, the usage of these particular keywords has increased tremendously in only a few decades. The positive trends and the lines' steepening slopes indicate that the continual increase in publications containing these keywords will become more apparent as time progresses. Additionally, increasing interest in adopting conformability-like topics into these disparate fields is beginning to take effect (Figure 2). Here too, there is an increasing positive

Figure 1 Trends in discipline-specific keywords from Web of Science



Notes: Count of articles published versus year for: a) health monitoring, brain–computer interfaces, solar panels, assistive technology, haptic feedback, near-field communication, electronic textiles; b) climatology, agriculture, piezoelectric, virtual/augmented reality, global warming, energy harvesting. These upward trends indicate that research interest in and development of our selected keywords will continue to advance over time

Figure 2 Trends in discipline-specific keywords and conformability from Web of Science



Notes: Count of articles published versus year for: a) piezoelectric, energy harvesting, health monitoring, electronic textile, in conjunction with conformability; b) virtual/augmented reality, agriculture or near-field communication, haptic feedback, climatology or solar panels, brain–computer interfaces, assistive technology, in conjunction with conformability. These upward trends indicate that conformable devices will continue to advance numerous fields beyond just health-care technologies

relationship between the count of articles published and the passage of time. Thus, we conclude that there will be an imminent ramp-up in research and subsequent innovation regarding conformability-like topics.

Although still in its infancy, the field of conformable devices is poised to play a major role in addressing societal challenges, due to their ability to seamlessly integrate with target objects. The surface sensitivity of conformable devices allows for effective decoding and encoding of self-specific physical patterns, while providing physical comfort and enabling continuous data collection. While such benefits will facilitate adaptation of conformable devices into new realms and applications mentioned in this paper, there still exist key challenges and opportunities to address before this technology can become ubiquitous. We forecast essential features of these devices in the near future, and the steps that can be taken to ensure the longevity and sustainability of these devices for wide-spread, practical use on a global level.

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Supplementary materials

Supplementary files are available online for this article.

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