



# Grand Challenges in Wearable Electronics

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## OVERVIEW

Wearable technology has deep roots in history, with eyeglasses and wrist and pocket watches being two of the most prolific technologies still being in use today. These technologies developed and evolved over the centuries. For example, watches started as decorative pieces based on an oscillating wheel and gear mechanism, later acquiring a primitive form of energy harvesting (self-winding), progressing to electromechanical and then to fully electronic devices (McCrosen, 2013). Future watches may integrate sophisticated electronics, solar or thermal energy harvesting, carry a huge variety of functions beyond timekeeping and still be a decoration and a fashion statement. Eyeglasses is another vivid example, starting as assistive technology (Letocha and Dreyfus, 2002), also evolving to become a fashion accessory, frequently used by individuals who do not need vision correction. Eyeglasses are rapidly becoming a high-tech electronic device, with Google Glass, Alexa Frames, and the likes paving the way to everyday use of augmented reality. The long-term success of these two technologies is based on their utility, deep integration with daily activities, and social acceptance by the population (Degerli and Ozkan Yildirim, 2020). These examples are very valuable when we consider the challenges facing wearable electronics today.

Future growth in wearable devices is tightly coupled with advances in semiconductor technology and electronics. Wearables integrate a power source, sensors, data processing and storage core, actuators and displays, and a communication interface, packaged in a small, lightweight device that is worn on the body or integrated with everyday wear items, such as clothing, footwear, or accessories. Such wearables exemplify the cutting edge of the electronics, demanding the highest performance for the least amount of power, in the least amount of space, and in a challenging operating environment. Here wearables may gain a valuable lesson from a recent success story—the emergence of the smartphone as a ubiquitous communication device. The demands of modern smartphones closely match those of wearable devices, albeit in a larger package. The driving force behind the innovation and miniaturization of smartphones is high acceptability and demand across different cultures, generations, and societies. Resonating with the success of watches and eyeglasses, smartphones have a great utility that is tightly integrated into our life. Wearables may just as well become the next success story if they find an application that is demanded by the masses and if the electronic technology can support the effortless integration of wearables into the daily routine.

Looking into the electronic technologies that form the foundation of wearable devices, we can highlight several distinct areas:

- Edge and Fog Computing (Bonomi et al., 2012; Shi et al., 2016): First and foremost, a wearable device is a computer with real-time processing capabilities, operating in extremely power-restricted environment. Modern wearables wield hefty computing power to execute signal processing and machine learning algorithms to process the information provided by the sensors (Witt et al., 2019). The advances in low-power digital electronics drive the capabilities of wearables.

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- Sensing: Sensors are the eyes and ears of wearable devices, measuring mechanical, electrical, chemical, optical, and other signals originating from the body and thus largely defining the utility available from a given device (Bandodkar and Wang, 2014; Nag et al., 2017; Ahmad Tarar et al., 2020; Shi et al., 2020). In the area of sensors, most of the recent progress is driven by advances in Micro-Electro-Mechanical Systems (MEMS) and Nanotechnologies (Jayathilaka et al., 2019).
  - Storage: The wearables generate huge amounts of data, especially if raw sensor signals are required for a given application or communication capability is limited. Advances in solid-state storage are propelling the utilization of wearables in the collection of versatile, large datasets (Rajan et al., 2018).
  - Communications and Internet of Things: In today's connected world, device-to-device communication is mandatory in the data processing pipeline. A wearable may be one of the many sources of information that are integrated into the "cloud" (Atzori et al., 2010). The expectation for a future wearable is that it is capable of communicating with other electronic devices, such as smartphones and tablets, where the human body itself may be considered as the communication medium to exchange information with other wearables. Progress in wireless and human body communications methods and related electronic devices will be continuously demanded (Cotton et al., 2014).
  - Displays and actuators: Wearables may involve a variety of modalities in interfacing with the user, including tactile, haptic, visual, and audible information exchange (Pacchierotti et al., 2017; Gonçalves et al., 2018). These could be implemented as electronic or MEMS devices, facing the challenge of limited size and restricted power consumption.
  - Battery technology and energy harvesting: Availability of power is the single, most important limiting factor in modern wearables. Developments in battery technology, electronic devices for efficient power conversion, and energy harvesting enable longer operation and richer functionality (Yang and Daoud, 2016; Kim J. et al., 2017; Dubal et al., 2018; Chong et al., 2019; Wang and Daoud, 2019a).
- provide. The challenge of modern wearable electronics in discovering ubiquitous applications, as its future growth is contingent on emerging applications in health, wellness, and other personal needs. Novel applications of wearables may need to be supported by extensions of sensing and data analytics capabilities, thus presenting a compelling use case (Patel et al., 2012; Mukhopadhyay, 2015; Ahn et al., 2019; Degerli and Ozkan Yildirim, 2020).
- (b) Minimization of user burden and integration with everyday wear items. The illustrations of wearable devices frequently include pictures of individuals instrumented at every possible location on the body, such as arms, legs, torso, etc. Practically, such a scenario represents an unrealistically high user burden and is unfeasible. A related challenge is the seamless integration of wearable electronics in everyday wear items, such as textiles (Heo et al., 2018), clothing, footwear (Hegde et al., 2016), and accessories.
  - (c) Efficient and informative interpretation of data generated by wearable devices. Wearable devices may generate an abundance of data, for e.g., health-related sensor signals (Redmond et al., 2014). The challenge lies in the interpretation of such data streams and connection with health outcomes, using sensor data to guide behavioral interventions and health education. Emerging methods of artificial intelligence carry a promise of solution to the problem of data analysis and interpretation.
  - (d) Ultra-low power operation. A wearable device should ideally sustain a lifetime operation without or minimal user interference. In terms of power, this implies operation on a battery, energy harvested from the body, or a combination thereof (Chong et al., 2019; Wang and Daoud, 2019b; Wu et al., 2019). This requires low-power operation both for analog and digital electronics of a wearable. Wireless power delivery (Kim H. et al., 2017) may be explored to seamlessly charge many devices without need to connect each individual device to a charging circuit (for e.g., charging all socks in a drawer), biofuel cells and supercapacitors may need to be utilized in the power subsystems (Bandodkar and Wang, 2016; Dubal et al., 2018).
  - (e) Flexible and stretchable electronics. Epidermal and body compliant electronic devices (Yeo et al., 2013) may be considered a subset of wearables with additional requirements of allowing shape changes in response to body movement, making such devices especially sensitive to motion artifacts, demanding high biocompatibility and adaptability to variation in human body shapes, sizes, and characteristics (Ray et al., 2019).
  - (f) Biocompatible communications. Communications from the body (to the outside world) and on the body (between multiple wearables) demand new solutions, as traditional radio methods experience challenges due to absorption by body tissue (Cotton et al., 2014; Paracha et al., 2019). The related challenges include

The technological advances in these areas were critical for the initial proliferation of wearable devices. The future of wearables will depend on the continuing progress and development of new solutions that provide high performance under power and space constraints.

## GRAND CHALLENGES

Wearable devices and electronics present a unique interface of technology and humanity, thus producing unique challenges that need to account both for technological and human aspects of the problem. Human behavior may affect the operation of wearable as much as the technology advance. The following aspects may be considered as some of the challenges facing the field of wearables:

- (a) Break-through applications of wearable electronics. From the dawn of history, the evolution of wearables is driven by the practicality, utility, and convenience they

development of efficient methods for communicating through or on the body (Seyedi et al., 2013), including the organization of wearables in body sensor networks and their integration into the Internet of Things (Cirani and Picone, 2015).

- (g) Biodegradable Electronics. If wearable electronics are to become the true mainstream, the challenge of sustainable, ecologically viable manufacturing, and disposal needs to be addressed (Irimia-Vladu, 2014; Li et al., 2020).
- (h) Privacy and Security. By definition, a wearable is an electronic device that resides on or close to a person and is present in a variety of life situations. The challenges include protection of personal information, preventing the unauthorized use of wearables for biometric identification, and ownership of the data produced by wearables (Arias et al., 2015; Cirani and Picone, 2015).

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## CONCLUDING REMARKS

Wearable electronic technology has immensely stepped into our daily life, being interactive with people in every aspect, and shaping the new lifestyle that technology brings. The development and advances in electronic technology toward further tackling the challenges of wearable devices hold great potential for applications in wearable devices. The impacts on both human conditions and technological properties of the devices need to be considered for realizing interfaces between human and wearable electronics.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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