Transforming Health Care

Body sensor networks, wearables, and the Internet of Things.

By Benny P. L. Lo, Henry Ip, and Guang-Zhong Yang

Despite the myriad assistive technologies that have been developed over the years, high installation costs and limited functionalities have prevented their widespread adoption. To overcome these barriers, the concept of body sensor networks (BSNs) was introduced, which proposes the development of miniaturized wireless sensing systems to continuously capture physiological signals and context information. Many novel sensing platforms have since been introduced, enabling pervasive monitoring of blood pressure, Galvanic skin response, electrocardiogram (EKG), gait, photoplethysmogram (PPG), and other vital signs.

Extensive research also has been conducted on ambient intelligence and its applications in health and well-being. By

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using low-cost ambient sensors installed in patients' homes, patient behavioral and activity patterns can be captured to detect anomalies and infer the user's health. Recent developments in low-power wireless connectivity have greatly simplified the installation, reduced costs, and enabled large-scale commercial deployments.

Combined with advances in low-power wireless network technologies and the migration from IPv4 to IPv6, every object will soon be connected to the Internet and become part of the Internet of Things (IoT), as first proposed by Kevin Ashton in 1999 [1]. Instead of ambient sensors scattered around a household, every object in the household could become sensor-enabled, forming a smart living environment. The context-rich information gathered by these smart objects could provide much more accurate and timely detection of incidents in home care applications.

Wearable, BSN, ambient, and IoT technologies have already been widely adopted in health-related research. For instance, an extensive study was conducted by the U.K. Biobank using wearable sensors to quantify activities of a large cohort of patients [2]. The National Health and Nutrition Examination Survey used a similar wearable device to survey the physical activity, sleep, and strength of a large population [3]. These emerging technologies will soon be incorporated into clinical practice, reshaping our future health care services.

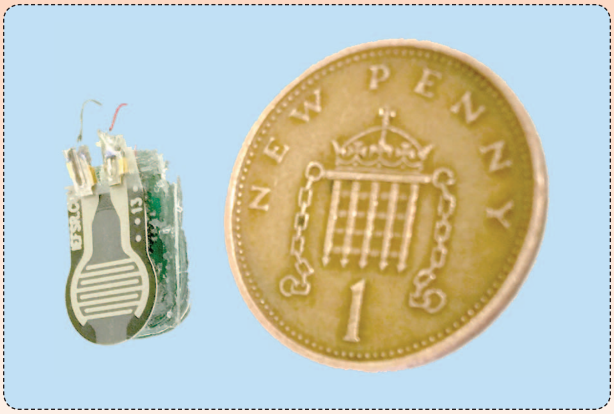

FIGURE 1 Wireless inductive powering and telemetry—a pressure sensor incorporates a ~1.2-cm x 0.8-cm coil for receiving wireless power and data uplink. (Image courtesy of the Hamlyn Centre, Imperial College London.)

Toward Zero Power, Zero Drift, and Zero Ambiguity

Although sensor electronics and microcontrollers in millimeter-sized packages are readily available, the miniaturization of wearable and IoT devices is often limited by the size and shape of the power source. As the battery life of a device largely determines its usability, it is crucial to bring down the power consumption of the sensor electronics. With the steady reduction in power consumption of integrated circuits and improved efficiency in energy scavenging technologies, it is possible to realize "zero-power" batteryless sensors. Among these platforms are ones that are wirelessly powered by dedicated sources (e.g., inductive powering; see Figure 1) or ones that harvest energy from movement and the environment, such as capturing ambient radio-frequency energy and solar power.

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While relatively bulky batteries limit the miniaturization of wireless sensors, another major challenge for ubiquitous sensing is imperfect sensor data acquisition. Sensor drift and measurement ambiguity greatly hinder the robustness and usability of sensors, with biochemical sensors exhibiting drift due to their chemically reactive nature; physical sensors such as gyroscopes can also exhibit considerable drift in the measured signal. The imperfection of sensors is often seen in the form of sensitivity degradation, nonlinearity, output noise, and environmentally dependent responses, such as variation with temperature and humidity, as well as dependencies on electrical parameters (bias). These are traditionally tackled by bench-top systems through automatic, closed-loop measurement and correction facilitated by the sensing and electronic hardware.

For miniaturized wearable sensors, drift and ambiguity can be mitigated by built-in redundancy using a large number of microfabricated sensors and reference electrodes. The close proximity of the sensors, transducers, and readout electronics as a result of microfabrication in many cases virtually eliminates the effect of interference pick up via the antenna effect. Multimodal sensing can be deployed to improve context awareness. This is particularly useful for nonspecific biochemical markers for certain sensing targets, such as sweat sensing and energy expenditure estimation. Inertial sensors can be used to correct the motion artifacts found in EKG and PPG data acquisitions. On-node processing methods, such as baseline readjustment and frequency-selective filtering, as well as statistical estimation techniques, such as Kalman filtering and Markov chain Monte Carlo estimation, have been used to improve signal integrity. A key example of on-node drift correction is that for attitude estimation from integrated inertial measurements. Attitude measurements are important inputs for gait and posture analysis in biomechanical studies and gait-related pathology profiling and rehabilitation quantification.

Smart Environment and the IoT

As wearable technologies have only become accessible to most people in the last couple of years, the majority of current assistive and telehealth systems are constructed based on ambient sensors. The high installation cost and the lack of ability to collect and store information have hindered the use of ambient sensors for home care applications until recently. The emergence of the Zigbee and Z-Wave standards has enabled the wide adoption of low-cost wireless sensing systems for home care. For instance, the Connecting Assistive Solutions to Aspirations, an Innovate U.K.-funded project, demonstrated the feasibility of using low-cost Z-Wave sensors to construct a home care system for long-term care applications.

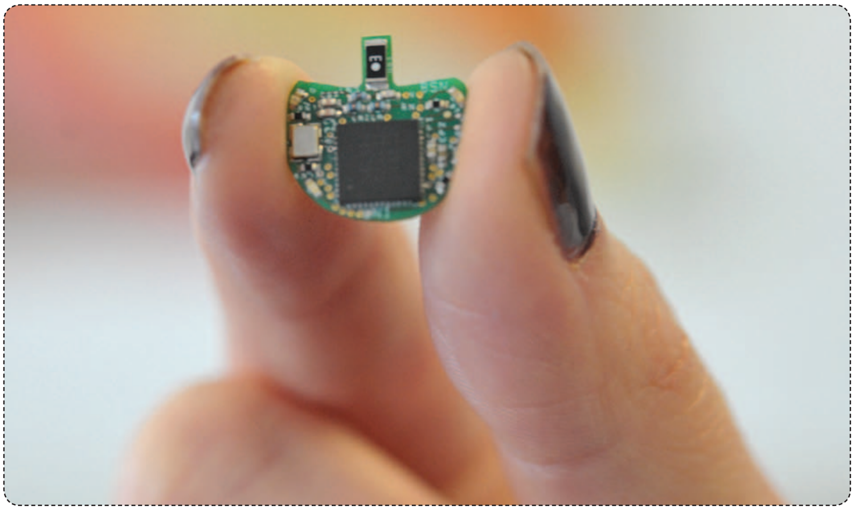

FIGURE 2 A miniaturized BLE sensor tag. (Image courtesy of the Hamlyn Centre, Imperial College London.)

Apart from ambient sensing, the concept of iBeacon was recently introduced for indoor localization and object identification. Based on the Bluetooth Smart [or Bluetooth low energy (BLE)] proximity-sensing function, objects can be tagged and identified by a mobile application. A range of applications have been proposed for location-based mobile marketing. Figure 2 shows a new miniaturized BLE sensor tag developed by the Hamlyn Centre for context-aware sensing in home-care applications. The tiny sensor tag can be attached to any household object, such as cutlery, and the interactions between the objects and the user can be quantified, for example, to monitor food intake and detect malnutrition. Such low-cost wireless technology is considered one of the enabling technologies supporting the realization of the IoT.

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As many household appliances such as televisions and refrigerators already have built-in Wi-Fi and Internet connectivity, the new era of the IoT has already begun. The new wearable technologies, low-cost ambient sensors, and ubiquitous beacons will expedite the adoption of the IoT. Just as the Internet and smartphone have revolutionized our lives, it is anticipated that the IoT will soon transform our lives and the health care system [4]. Despite capturing dense, detailed, and contextualized information, the Internet-connected sensing objects together with the smart infrastructure could be integrated into smart environments to improve comfort and health and enable intervention to prevent adverse events. For instance, by profiling the activity patterns of users of wearable and ambient sensors, heating systems could be optimized to maintain a comfortable temperature in an occupied room and so prevent hypothermia while minimizing energy costs, resolving a major health issue for the elderly in the United Kingdom [5].

Challenges and Opportunities

Since the introduction of the concept of the BSN and pervasive health monitoring, extensive studies have been conducted assessing the feasibility of using wearable sensors to enable long-term health monitoring. However, because of the limited access to the new wearable technologies and the high cost of deploying and supporting the not-yet-mature technologies, most studies are limited, with a small cohort of patients. Following the recent explosion of new products launched on the market, wearable devices have become much more accessible. One in five Americans now owns a wearable, and the adoption rate of wearable technology in 2014 was about the same rate as for tablets in 2012 [6].

Although most wearable technologies are designed mainly for quantified-self applications—allowing the user to collect his or her own data—an increasing number of manufacturers have opened up their application program interfaces, enabling developers to build their own applications and gather data from a large number of users. Like smartphones, wearable technologies will open up new opportunities in health research, and new services could be developed to improve health and well-being. For example, Figure 3 depicts a new wrist-worn sensor, developed by the Innovate U.K.-funded project Care for Adaptive Living and Learning with Interactive Sensing for Children and Adults with Learning Difficulties, for use by people with learning disabilities to monitor challenging behaviors such as teeth-brushing, assist in tackling personal hygiene and other behavioral matters, and enable independence.

Wearable technologies are often considered part of the IoT. In parallel to the exponential growth in wearable technologies, the number and variety of other smart IoT devices have also increased rapidly. Apart from household appliances, cars, environmental controls, and even plants and pets can be Internet-connected and -monitored. Similar to social networks, the IoT is reshaping society and enabling potential new discoveries in health and well-being. Although most wearable and IoT technologies are fairly mature, there are still many major challenges hindering their adoption and impacting health care.

User Compliance and Adoption

More than half of people in the United States who own an activity tracker have already lost interest and stopped using it. As most devices can only capture superficial information, the novelty of the devices wears off very quickly, especially for young and healthy users. On the other hand, people with chronic conditions tend to be more committed; 65% of adults in the United States with two or more chronic conditions are constantly using their activity trackers to monitor their well-being [7]. Although patients and insurance companies are already embracing the technologies, most health care services have yet to adopt them into their practices.

Regulations

Although many of the devices can potentially be used clinically, the majority of wearable and IoT devices are designed as consumer products to avoid the long and expensive process of regulatory approval for clinical deployment. This could be the reason such technologies still cannot penetrate the health care market and be used in clinical practice.

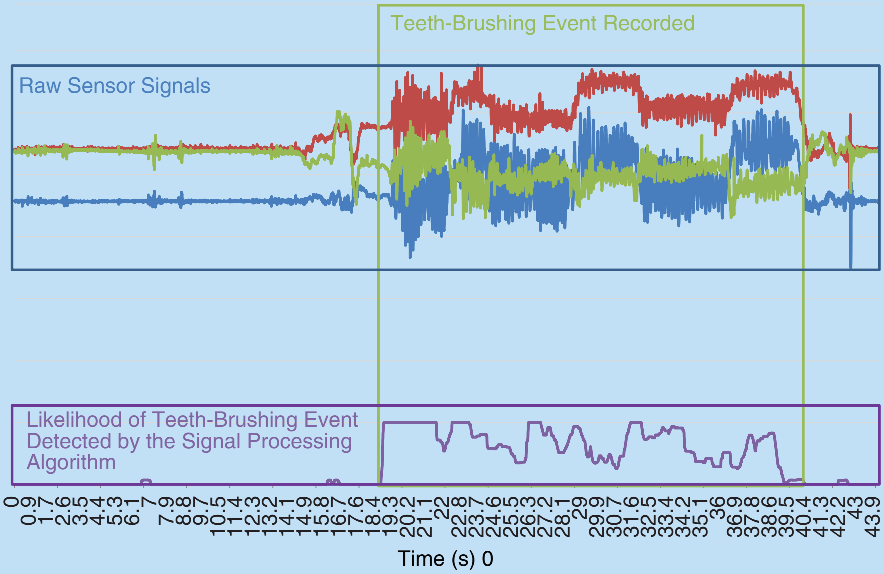
Security and Privacy

Personal health, well-being, and activity information can be captured by the IoT and wearable devices. Although most users may not be aware of the importance of such data, it is crucial that the privacy of the user is protected and the system is secured. A user's activity information could reveal his or her lifestyle, routine, and personal preferences, which could be of great value for targeted marketing and, worse, surveillance having malicious intentions. Apart from eavesdropping, corrupting the data stream could damage the devices, cause malfunctions, or even bring harm to the user.

Big-Data Analytics

The countless number of IoT devices could generate an unprecedentedly large volume of data. In addition to the issues related to storing and archiving such massive amounts of data, it is a great challenge to comb through vast, multidimensional data and to mine context from highly unstructured data. On the other hand, long-term data could reveal previously unknown information regarding health and lead to new discoveries.

(a)



(b)

$$v(t) = \frac{1}{NM} \sum_{j=-N/2}^{(N/2)-1} \sum_{i=0}^{M} (a_{ij}(t+j) - \mu(t))^2,$$

where $N = 11$, $M = 3$,

$$\mu(t) = \frac{1}{NM} \sum_{j=-N/2}^{(N/2)-1} \sum_{i=0}^{M} (a_{ij}(t+j)),$$

and $a_i(t)$ represents the sensor data of axis i at time t

$$u(t) = v(t) - \frac{1}{11} \sum_{i=-5}^{5} v(t+i)$$

$$w(t) = \exp\left(-\frac{(u(t) - u(t-1) - \varepsilon)^2}{2v^2}\right),$$

where $\varepsilon = 1{,}000$, $v = 200$

$$\text{likelihood}\,(w(t)) = \frac{\sum_{i=0}^{20} w(t)\exp\left(-\frac{(i-10)^2}{2\sigma^2}\right)}{\sum_{i=0}^{20} w(t)\exp\left(-\frac{(i-10)^2}{2\sigma^2}\right)},$$

where $\sigma = 3$

(c)

FIGURE 3 (a) A wearable sensor developed for people with learning disabilities, (b) the detection of teeth-brushing events, and (c) the associated equations for calculating the likelihood measurements. (Image courtesy of the Hamlyn Centre, Imperial College London.)

Power Source and Energy Scavenging

Because advances in battery capacity are lagging behind the rapid growth of wearables and the IoT, battery technologies are still catching up with the increasing demand from these new devices. Although energy scavenging technologies are promising, it is not yet possible to rely solely on energy scavenging to power up wearable devices due to the low power throughput.

Network Capacity

Although most IoT devices use spread spectrum for communication, network congestion could still be a problem for the IoT because most wireless communications channel through the 2.4-GHz band, including Wi-Fi, Bluetooth, and Zigbee or various industrial, scientific, and medical bands. Although most devices sample and send data at very low frequency and most IoT devices do not stream any data, a vast number of devices crowded in a small smart environment could lead to collision and network instability.

System Administration

Because of the growing number of IoT devices and sensors with limited computation power, managing and configuring the systems could become an impossible task. IT companies are already facing many challenges in administrating and supporting their servers and Internet services. Unlike computer servers, IoT devices have much lower computational power, scattered everywhere, running mainly on batteries, and could be worn by people traveling around the world. The conventional IT administration and support approaches will not be able to cope with such a diversified and dynamic system. To tackle this challenge, the concept of autonomic sensing was introduced, aiming to adapt the characteristic of our biological autonomic system into a self-management system for a network of sensing devices [8].

Interoperability

Although most of the IoT and wearable devices adopt standardized wireless protocols, such as BLE or Wi-Fi, the devices are all designed to operate alone and mainly interact with a smartphone or a home hub. Most devices lack the functionality and capability to communicate and interact with each other. For instance, a wearable wristband cannot link up with a smart refrigerator or smart TV, unless a dedicated application or interface is built. To create a smart environment, it is essential to link the devices together to provide basic functions and services. There are some initiatives aiming to standardize the architecture and communication of IoT systems, but it is yet to be seen how widely the standards will be adopted by industry.

A New Era of Proactive and Preventative Care

We are already in the new era of BSNs, wearables, and the IoT. Like the Internet, smartphone, and social networks, these new technologies are transforming our lives. People are now relying on their wristbands to wake them up rather than using an alarm clock. Instead of sharing photographs, people are sharing their exercising information captured by wearable gadgets. Such ubiquitous technologies could be translated for clinical use. The continuous and long-term measurement of physiological, activity, behavioral, and contextual information could help unveil the underlying causes of symptoms and diseases. Personalized targeted treatments and proactive strategies could be designed accordingly to improve the health of the growing older population with much less cost. With strong support from the health services and backing from industry, these new technologies could soon transform health care services and enable proactive and preventative care.

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