Transforming Healthcare:

Body Sensor Networks, Wearables, and the Internet of Things

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Despite the myriad of assistive technologies that have been developed over the years, high costs of installation and limited functionalities have prevented widespread adoption of these technologies. To overcome these barriers, the concept of Body Sensor Networks (BSN) was introduced, which proposes the development of miniaturized wireless sensing systems for continuous capturing of physiological signals and context information. Many novel sensing platforms have since been introduced, enabling pervasive monitoring of blood pressure, Galvanic skin response (GSR), electrocardiogram (EKG), gait, photoplethysmogram (PPG), and other vital signs.

Extensive research also has been conducted on ambient intelligence, and its applications in health and wellbeing. By using low cost ambient sensors installed in patients' homes, behavioral and activity patterns of the patient can be captured to detect anomalies and infer the user's health. The recent developments in low power wireless connectivity have greatly simplified the installation, reduced costs, and enabled large scale commercial deployments.

Combined with the 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 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 homecare applications.

Wearable, BSN, ambient, and IoT technologies have already been widely adopted in health related research. For instance, an extensive study has been conducted by the UK Biobank using wearable sensors to quantify activities of a large cohort of patients [2]. Similarly, the National Health and Nutrition Examination Survey (NHANES) 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 healthcare services.

TOWARDS ZERO POWER, ZERO DRIFT, AND ZERO AMBIGUITY

Although sensor electronics and microcontrollers in millimeter sized packages are readily available, miniaturization of wearable and IoT devices are 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 ever-reducing power consumption of integrated circuits and improved efficiency in energy scavenging technologies, it is possible to realize "zero power" battery-less sensors. Amongst these platforms are ones that are wirelessly powered by dedicated sources (e.g., inductive powering, see Fig. 1) or ones that harvests energy from movement and the environment, such

as capturing ambient RF energy and solar powering.

While relatively bulky batteries are limiting the miniaturization of wireless sensors, another major challenge towards 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 whereas 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 benchtop 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 with a large number of micro-fabricated 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 non-specific 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 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 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.

Fig. 1. Wireless inductive powering and telemetry - a pressure sensor incorporates a $\sim 1.2\text{cm} \times 0.8\text{cm}$ coil for receiving wireless power and data unlink. (Image courtesy of the Hamlyn Centre)

SMART ENVIRONMENT AND INTERNET OF THINGS

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 homecare applications until recently. The emergence of Zigbee and Z-Wave standards has enabled the wide adoption of low cost wireless sensing system for homecare. For instance, the Connecting Assistive Solutions to Aspirations (CASA), Innovate UK funded project, demonstrated the feasibility of using a low cost Z-wave sensors to construct a homecare system for long term care applications.

Apart from ambient sensing, the concept of iBeacon was recently introduced for indoor localization and object identification. Based on Bluetooth Smart’s (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 for homecare applications. The tiny sensor tag

can be attached to any household objects, 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 very low cost wireless technology is considered as one of the enabling technologies supporting the realization of the concept of Internet of Things (IoT).

As many household appliances, such as televisions, fridges, kettle, etc., already have built-in Wifi and internet connectivity, the new era of Internet of Things (IoT) has already begun. The new wearable technologies, the low cost ambient sensors, and the ubiquitous beacons will expedite the adoption of IoT. Like the Internet and smartphone have revolutionized our lives, it is anticipated that IoT will soon transform our lives and the healthcare system [4]. Despite capturing dense, detailed, and context 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 pattern of the user using wearable and ambient sensors, the heating system could be optimized to maintain comfortable temperature in an occupied room to prevent hypothermia meanwhile minimize the energy cost, resolving a major health issue for the elderly in the UK [5].

Fig. 2. A miniaturized BLE sensor tag (Image courtesy of the Hamlyn Centre)

CHALLENGES AND OPPORTUNITIES

Since the introduction of the concept of BSN and pervasive health monitoring, extensive studies have been conducted on assessing the feasibility of using wearable sensors to enable long term health monitoring. However, due to the limited access to the new wearable technologies and the high cost of deploying and supporting the premature technologies, most studies are limited with a small cohort of patients. Following the recent explosion of new wearable products launched into the market, the wearable devices have become much more accessible. One in five Americans now owns a wearable and the adoption rate of the wearable technology in 2014 was about the same rate as per tablet in 2012 [6].

Although most of the wearable technologies are designed more for quantified-self applications—allowing the user to collect his/her own data—an increasing number of manufacturers have opened up their Application Program Interface (API), 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 wellbeing. For example, Figure 3 depicts a new wrist worn sensor developed (by the Innovate UK funded project Care for Adaptive Living and Learning with Interactive Sensing for Children and Adults with Learning Difficulties) for people with learning disabilities to monitor their challenging behaviors, such as teeth-brushing, assist them to tackle personal hygiene and other behavioral issues, and enable independence.

Wearable technologies are often considered as part of the Internet of Things (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, etc., now even plants and pets can be Internet connected and monitored. Similar to social networks, the IoT is reshaping our societies, and enabling potential new discoveries in health and wellbeing.

Although most wearable and IoT technologies are fairly mature, there are still many major challenges hindering their adoption and impacts on healthcare:

- **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 those young and healthy users. On the other hand, people with chronic conditions tend to be more committed, where 65% of adults in the United States with two or more chronic conditions are constantly using their activity trackers to monitor their wellbeing [7]. Although patients and insurance companies are already embracing the technologies, healthcare services are yet to adopt them into 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 why such technologies still cannot penetrate into the healthcare market and be used in clinical practice.
- **Security and privacy:** Personal health, wellbeing, and activity information can be captured by the IoT and wearable devices. Although most users may not aware importance of such data, it is crucial that the privacy of the user is protected and the system is secured. The activity information of a user could reveal his lifestyle, routine, and personal preferences, which could be of great value for target marketing and 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 unprecedented large volume of data. Despite the issues in storing and archiving such massive data, it is a great challenge to comb through the vast multidimensional data and mine the context out from the highly unstructured data. On the other hand, the huge long term data could reveal previously unknown information on health and lead to new discoveries.
- **Power source and energy scavenging:** As the advances in battery capacity are lagging behind the rapid growth of wearable and IoT, battery technologies are still catching up with the increasing demand from these new devices. Although energy scavenging technologies are promising, it is yet to

be able 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 congestions could still be a problem for IoT, as a majority of the wireless communications channel through the 2.4GHz band, including Wifi, Bluetooth, and Zigbee, or other ISM bands. Although most devices sample and send data at very low frequency and most IoT devices do not stream any data, the vast number of devices crowded in a small smart environment could lead to collision and network instability.
- System Administration: Due to the growing number of IoT devices and sensors with limited computation power, managing and configuring the system could become a humanly 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 travelling 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 Wifi, the devices are all designed to operate alone and mainly interact with a smartphone or a home hub. Most devices lack the function and capability to communicate and interact amongst each other. For instance, a wearable wristband cannot link up with a smart fridge or smart TV, unless a dedicated application or interface is built. To create a smart environment, it is essential to link up the devices together to provide the basic functions and services. There are some initiatives aiming to standardize the architecture and communication of the IoT systems, but it is yet to see how well the standards will be adopted by the industries.

We are already in the new era of BSN, wearables, and IoT. Like the Internet, smartphone, and social network technologies, the new technologies are transforming our lives. People are now relying on their wrist bands to wake them up rather than using an alarm clock. Instead of sharing photographs, people are sharing their exercising information captured by the new wearable gadgets. Such new ubiquitous technologies could be translated for clinical use. The continuous and long term measurement of physiological, activity, behavioral, and context information could help unveil the underlining 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 the strong support from the health services and backing from the industries, these new technologies could soon transform the health care services and enable proactive and preventative care.

REFERENCES

1. Wood, A., *The internet of things is revolutionising our lives, but standards are a must*, in the *Guardian* 2015, Guardian News and Media Limited
2. Watts, G., *UK Biobank opens its data vaults to researchers*. BMJ, 2012. **344**.
3. Troiano, R. and J. Mc Clain. *Objective measures of physical activity, sleep, and strength in US National Health and Nutrition Examination Survey (NHANES) 2011–2014*. in *Proceedings of the 8th International Conference on Diet and Activity Methods*. 2012.

4. *The 'Internet of Things' is revolutionising healthcare – Jeroen Tas*. 2015 20 July 2015 20 July 2015]; Available from: <https://www.england.nhs.uk/expo/2015/07/20/the-internet-of-things-is-revolutionising-healthcare-jeroen-tas/>.
5. *Hypotheria deaths double over five years*, in *The Telegraph* 2011.
6. Comstock, J., *PwC: 1 in 5 Americans owns a wearable, 1 in 10 wears them daily*, 2014, mobihealthnews.
7. Herz, J.C., *Wearables Are Totally Failing the People Who Need Them Most*, in *Wired* 2014, Wired.
8. Yang, G.-Z. and M. Yacoub, *Body sensor networks*. 2006.