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Review

Healthcare in the Smart Home: A Study of Past, Present and Future

Jamie Bennett *, Osvaldas Rokas and Liming Chen

School of Computer Science and Informatics, De Montfort University, Leicester LE1 9BH, UK; osvaldasrokas@gmail.com (O.R.); liming.chen@dmu.ac.uk (L.C.)
* Correspondence: jamie.bennett@gmail.com; Tel.: +44-796-225-9437

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Abstract: Ubiquitous or Pervasive Computing is an increasingly used term throughout the technology industry and is beginning to enter the consumer electronics space in its most recent form under the umbrella term: "Internet of Things". One area of focus is in augmenting the home with intelligent, networked sensors and computers to create a Smart Home which opens a host of possibilities for the role of tomorrow's dwelling. As the world's population continues to live longer and consequently experience more medical-related ailments, at the same time institutional healthcare is struggling to cope, the role of the Smart Home becomes paramount to monitoring a dweller's health and providing any necessary intervention. This study looks at the history of Smart Home Healthcare, current research areas, and potential areas of future investigation. Unique categorisations are presented in Activities of Daily Living (ADL) and Personal Sensors, and a thorough look at the application of Smart Home Healthcare is presented. Technology can augment traditional methods of healthcare delivery and in some cases completely replace it. Costs can be reduced and medical adherence can be increased, all of which contribute to a more sustainable and effective model of care.

Keywords: healthcare; smart home; sensors; IoT; ADL; automation; augmented reality; implantable medical devices; wearables; telemonitoring

1. Introduction

From smartphones to smart homes, many of today's developed and developing countries rely heavily on technology to assist in day-to-day living. As technology advances it brings with it new opportunities to enhance the wellbeing and quality of life of its users but far from being a nice-to-have, technology is becoming a necessity especially in the field of healthcare. According to the World Health Organisation (WHO), the world's elderly population is on the rise and with it the incidence of age-related illnesses such as Parkinson's disease and Dementia. The consequences of thes phenomena are an increased strain on healthcare and medical resources as well as more reliance on caregivers, families, and society. To combat this, emphasis should be given to supporting independence with technologies, especially those found in the home.

Much attention has been given to so-called "Smart Homes" over the past several decades especially in the research community who have looked at the benefits of enhanced monitoring and automation using sensors and actuators to provide ambient assistance. The combination of healthcare and Smart Homes creates the term: Smart Home Healthcare and is the subject of this paper. What follows in an introductory review of the most pertinent topics around healthcare in the Smart Home. Starting with a more up-to-date definition and background information in Section 1, we continue by looking at the important technologies in Section 2, applications of these technologies in Section 3, emerging trends in Section 4, and future discussion points in Section 5.

1.1. Smart Home Healthcare Definition

First, we need to tackle the question, what is a Smart Home and what does healthcare in the smart home mean? These two terms are somewhat nebulous and, over the years, there have been many attempts to define, and redefine, what they mean. What follows is a short exploration of the definitions given by various authors.

When the main purpose of the Smart Home is to help deliver care to that of its occupants we can further refine the definition. Chen et al. [1] concentrate on how a Smart Home (SH) can assist its inhabitants with their Activities of Daily Living (ADL), looking at how monitoring, prediction, and inference supports independent living. Chen et al., state that "*By monitoring environmental changes and inhabitant's activities, an assistive system in an SH can process perceived sensor data, make timely decisions, and take appropriate actions to assist an inhabitant perform activities of daily living (ADL)*" but a more general definition is needed to cover all the aspects of Healthcare in the Smart Home. The Smart Home becomes an extension of the traditional healthcare services and encompasses not only treatment but also prevention. This application of decentralised healthcare is made possible by technological advancement and a more open stance towards technology in general. We can extend our original definition of a Smart Home to come to a final definition for Smart Healthcare in the Home:

> A home or dwelling with a set of networked sensors and devices that extend the functionality of the home by adding intelligence, automation, control, contextual awareness, adaptability and functionality both remotely and locally, in the pursuit of improving the health and wellbeing of its occupants and assisting in the delivery of healthcare services.

1.2. Background

The term Smart Home itself was first introduced in 1984 but efforts to augment the home with technology stretch back to earlier in the 20th century. With the introduction of the first microprocessors in the early 1970s came a new wave of devices that could be adapted for assisting homeowners. It was not long before the first Smart Home use cases for this technology began to appear and in 1975 Pico Electronics, a company based in Glenrothes, Scotland, created the first network protocol directed solely at the Home Automation market: X10. Several alternatives exist including wireless protocols such as Zigbee and Z-Wave but the low-cost powerline devices implementing X10 have gained traction, especially for the home automation use case that continues to be the main driver for consumer adoption. Automating tasks, especially those that assist with Activities of Daily Living (ADL) are the focus of much research; several examples can be found in Section 3.

Smart Home Healthcare centres on providing care in the home for outpatients, the elderly, and those with disabilities. An increasing trend is to also cater for healthy individuals by monitoring the health and wellness of occupants using sensors either worn or embedded in the surrounding environment. The former group of sensors have garnered a lot of attention recently as the consumer market has been flooded with devices from Fitbit, Jawbone, Apple and others and form the basis of a new emphasis on health and lifestyle awareness. Other sensors in the home, such as those used in video surveillance, movement detection, and activity elucidation, can be augmented with more traditional facilities such as access to a medical practitioner, albeit in the updated form used in telesupport and telemonitoring solutions. As advances in healthcare and medicine continue to result in a lower mortality rate, the strain of traditional medical resources will dictate the need for alternative solutions.

Smart Homes can prove cost-effective in aiding the elderly and disabled to remain in the home for longer in a non-obtrusive way. This can allow greater independence and quality of life while reducing the chance of social-isolation. The use of Smart Home components such as sensors, actuators, controllers, and appliances allow occupant monitoring and interaction and when fused with biomedical devices, adds personal information to the potential plethora of collectable contextual data. These technologies can create 24 h/7 days a week healthcare solutions for the most vulnerable.

Analysing the data either internally within the Smart Home or externally by a data processing entity can lead to early diagnosis of potential problems as well as emergency support if necessary, although all this functionality must come with a warning. To fuel assisted healthcare analysis and support, an occupants' most personal data need to be shared such as bio-medical, lifestyle, and behavioural information which raises concerns over privacy. This is explored further in Section 2, albeit at a high-level as this topic is the subject of many papers itself.

An increasingly elderly population brings with it an increase in healthcare costs. For example, the cost associated with the failure to stick to a medication regime in the US is measured in the billions of dollars with forgetfulness the leading cause, either through general carelessness or age-related memory difficulties. Addressing this and other causes of preventable healthcare costs, especially in the home, continues to fuel a plethora of new and valuable research.

While people are living longer and dealing with age-related illnesses there has been, and continues to be, a technological revolution. Within the next 20 years the amount of people over the age of 65 will substantially increase, Figure 1 shows this projection for the UK alone, and this is where technology can help. Devices are getting smaller and more powerful, software methodologies are maturing, and the populations' adoption of technology is ever increasing. It is now common to see people carry around several devices at once, all of which are more powerful than their predecessors of 20 years ago. Smart phones, tablets, smart watches, fitness trackers, and even smart eyewear to name a few are often part of a person's regular carry-around items and each are embedded with powerful processing capabilities, sensors, and software. In addition, our surroundings are becoming smarter. From washing machines to coffee-makers, wireless access points to door-bells, each has a part to play in the smart home revolution and each can contribute to making a person's life better, especially those with healthcare problems.

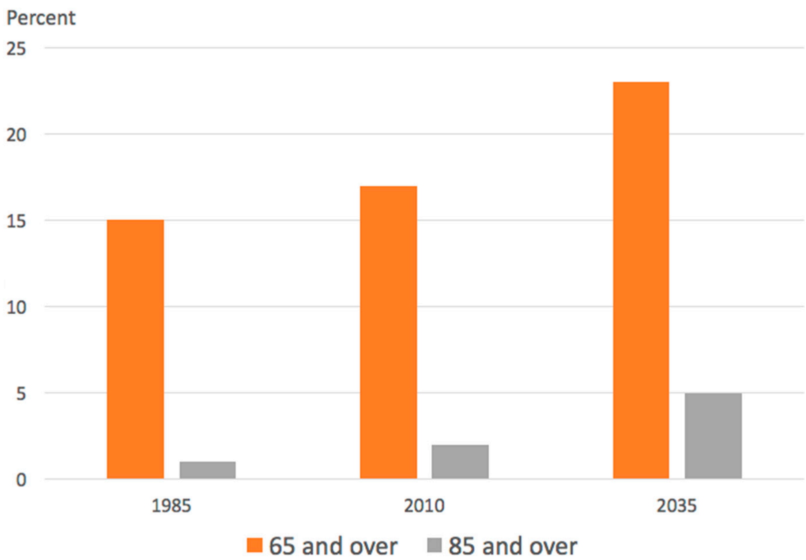

Figure 1. Percentage of older people in the UK according to the Office for National Statistics, National Records of Scotland, Northern Ireland Statistics and Research Agency 1985 to 2010 estimates.

It may not be immediately apparent when thinking about how a smart doorbell could improve the life of a dementia sufferer, but look more closely and the benefits are profound. Take for example the hypothetical case of Bob who suffers from dementia. He is at home when his doorbell is pressed as a visitor arrives. Bob's smart doorbell is equipped with a video camera which quickly analyses the face of the visitor and, using facial recognition software, determines that this is Alice, Bob's daughter. Bob is in the kitchen making dinner and is made aware of the visitor by a vibration on his smart wearable bracelet that has a text-based user interface reminding him to look at his phone. He glances at the video feed that is relayed directly to his smart mobile phone but does not immediately recognise the person at the door. The smartphone software uses Bob's contact database and the positive match of Alice's face to bring up her personal details. Bob then reads the information, realises this is his daughter and lets Alice in remotely by clicking a button on the phone. Although Bob's dementia meant that he did not immediately recognise his daughter the technology embedded in his house and on his person meant that Bob had the required information in his hands to quickly enable him to welcome Alice when she visited. This and many other use cases become possible with Smart Home technologies.

It is now clearer than ever that the field of healthcare is ripe for technological improvements and that the home is a key to successful delivery.

2. Technologies Used in the Smart Home

Smart Homes and Smart Healthcare rely on the ability to gather data from a variety of sources including the environment, the home and the patient themselves. Hardware coupled with software can create an environment with Ambient Intelligence and autonomous capabilities which is particularly interesting for people who rely on assistive care. Sensors form the backbone of any Smart Home and are the main input for data-driven and knowledge-driven approaches, the selection of which and their combinatory value are a key decision point for any solution developer.

What follows is a short introduction to the technologies commonly used in Smart Homes and how they can apply to the healthcare sector.

2.1. Environmental Sensors

A network of sensors can be used to capture environmental parameters applicable to the Smart Home and its occupants such as light, temperature, air quality, weather conditions, pressure and other data. This information can then be used to make intelligent decisions on behalf of the home-owner. For example, a light sensor can detect low levels of light in a room and turn on lights should the occupant be considered present. The decision on whether the occupant is present can be determined using a variety of means such as infrared (IR) movement, furniture and surrounding pressure sensors, video capture, and so on. In addition, sensors are often used in conjunction with actuators to perform physical world responses to ambient information and provide a complete event-react system. Systems such as Care-O-bot, used to assist elderly or disabled persons in the home rely heavily on such sensors. Care-O-bot is looked at Section 3.

Environmental sensors are often hidden in the surroundings of the home, physically located within doors, chairs, walls, floors, and a variety of other places where they gather contextual information via a wired or wireless protocol. Localised sensor data can then be combined with external data such as that from a Smart City to provide a more holistic solution. For this to happen a cloud element is often needed; a place where the data can be gathered, combined, and mined to expose relevant information for the occupant.

2.2. Personal Sensors

When looking at personal sensors it is important to review devices that are often used on or around a person, a so-called accessory. According to the Oxford dictionary, an "accessory" is "a small article or item of clothing carried or worn to complement a garment or outfit" [2]. Their advantage is a publically acceptable design, which could be worn for both tracking and fashion reasons. Another benefit is larger dimensions, which is sufficient to fit currently available sensors. On the other hand, most wearables require frequent recharge and should be mounted for recharging each day.

Various wristband sensors have been introduced in previous years. To start with, Fitbit was designed as an activity tracker, which provides a broad range of models to fit. Interestingly, the market provides a great selection of wristbands and some of the most popular are produced by Jawbone, Garmin, Wego, Microsoft and Sony, which typically provide similar functionalities to track steps, floors climbed, sleep, heart rate and sometimes location.

Many eye-wearing smart glasses exist including Google Glass, EyeTap, Golden-I, Jins MEME ES, Vuzix and Microsoft HoloLens. Most glasses provide similar functionality such as navigating, viewpoint camera and speech recognition. Although, a Japanese company introduced a glasses product called "Jins MEME ES", which could measure mental state and display in categories for example focus and posture [3].

Interestingly, wearable sensing devices can be implemented into almost any accessory. In this section, we introduce smart belts, earrings, earphones, headphones, gloves, shoes, baseball caps, bras, arm bands, straps, helmets and scarfs. The list of examples will begin with Samsung, who introduced a smart belt to measure waist, sitting times and steps [4]. Smart earring called ear-o-smart is another activity tracker [5]. Another interesting device is earphones that could be placed inside an ear to measure heart rate [6], although a company named Cosinuss added an extra feature to calculate the temperature in their device [7]. Smart gloves are devices that translate sign language into speech [8]. Body sensing shoes were presented as well [9]. Moreover, baseball caps are also receiving part of the wearable sensors market, for example, a radiation detecting hat has been invented and patented [10]. Several companies created another baseball cap for fitness and monitors attributes includes heart rate, movement and body temperature [11,12]. Furthermore, armbands to monitor blood pressure were introduced by a firm called Withings [13]. Another armband by a Swiss company Biovotion claimed to produce medically accurate measurements of vital signs: skin blood perfusion, blood oxygenation, skin temperature and heart rate [14]. Consequently, a pulse strap on the chest is a commonly utilised wearable device for athletic activities. Various implementations are available [15]. Another type of wearable sensing device is smart bra which tracks respiration, heart beats and steps while being a comfortable and stable item on its own [16].

In addition to the class of wearable personal sensors, more recent developments have been focused on implantable medical devices (IMD). Although early examples include insulin pumps and artificial cardiac pacemakers, the use of smart pills and internal sensors are being used to explore the body in ways not possible before. These sensors can be implanted into a human or attached to internal organs and are often very small, Figure 2 shows one such example. Radio-frequency identification (RFID) has been used previously to identify and trace objects (for example cash, clothing, and other personal belongings) although there is no legal or technical reason why this type of technology could not be injected into humans for tracking purposes [17]. However, some ethical reasons do exist as to why RFID should not be implanted into people [18]. Nevertheless, it has been forecasted that the RFID market would grow from $10.1 billion in 2015 to $13.2 billion in 2020 [19]. IMD are the subject of much research and are explored further in Section 4.

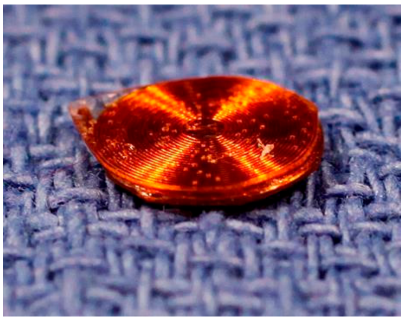

Figure 2. An example implantable sensor.

2.3. Controllers and Gateways

Patient data gathered by the Smart Home are often aggregated at a central hub or gateway, a key component in the telemonitoring system. Controllers and Gateways serve a dual purpose in the Smart Home; they are the aggregators of distributed data coming from the various sensors around the home and the provider of external services to the home and its occupants. These devices are often called the heart of the Smart Home and typically make decisions on the data they collect [20–22]; an alternative approach is for the Gateway to off-load the data analysis and decision making to a cloud-based service but this can be problematic for decisions that need to be made with low latency.

Gateways can be dedicated hardware devices or part of a multiuse device such as a smart phone or network router. In the reference system proposed by Zhang et al. [23], an off-the-shelf Windows XP desktop computer was used and combined with several ambient medical devices such as a glucose meter and a heart rate monitor. The trend of using commodity hardware was continued by others such as the Intel Home Health Gateway demo [24] (Intel Atom PC with Windows) and the Home Health System [25] which used a traditional Windows XP desktop PC.

2.4. Actuators and Smart Appliances

Actuators enable physical manifestations based on digital sensor and control data or, more specifically, they are responsible for taking actions based on input control signals. The term itself is applicable to a wide range of devices in the Smart Home, from simple switches to complex systems with early research centring more on basic reactive actions based on modal sensor input. Later, others, such as Dengler et al., broaden the Actuator term by including more advanced systems such as mobile robots into the classification [26]. Today, anything that can be controlled via an electrical signal can be considered an actuator such as a lamp, speaker, or TV [27].

Often Home Automation systems will use actuators to control heating, lighting, and turn on/off appliances in the home for the sake of convenience but in some cases, especially when the patient is physically impaired, the ability to use appliances without fiddling with small buttons and knobs is of great advantage. Furthermore, actuators can be used to assist people who suffer from cognitive disorders such as those employed in the ENABLE project [28] or more recently in the design proposed by Amiribesheli et al. In their 2016 research, Amiribeseli and Bouchachia propose the way to find out a user's requirements is to elicit them using a User-Centred Design (USD) approach [29]. Providing a model to potential users of the system and interviewing them resulted in several scenarios a patient feels most concerned about being elicited. Their dementia-focused research determined that there are 11 main areas that could be monitored and automated to bring about the biggest impact and using off-the-shelf software and hardware they implemented a system using sensors, actuators, and a gateway. The results show that introducing Smart Home technologies decreases the difficulty of performing some tasks whilst increasing the effectiveness of the outcome. For example, the risk of dehydration was a concern to participants and when asked how difficult it was for caregivers to remind them to drink enough water all participants felt that the given Smart Home solution would decrease the complexity by over 50%.

Often, actuators need sensors to perform the required function. Dengler et al. refer to this marriage of sensors and actuators as SANETs (Sensor/Actuator Networks) [26]. However, when these sensors and actuators are incorporated into appliances, they bring about a new class of devices known as Smart Appliances.

Smart Appliances are also becoming commonplace as manufacturers increasingly embedded them in their product. From the smart washing machine that has functionality to enable the owner to monitor the wash cycle via Wi-Fi [30] to the smart to the Egg Minder that tries to determine if the eggs it is holding are fresh enough to eat [31], it seems that everything is getting "Smart" but when it comes to healthcare some appliances could actually make a real difference.

2.5. Software

Combining home automation and healthcare systems can result in unique assistive solutions. For example, a patient may be able to control home automation devices based on health sensor data such as the use case to reduce a room's thermostat if the patient's wearable device indicates an elevated body temperature. This fusion of healthcare data and home automation is only possible if a unified and heterogeneous approach is taken when designing devices and software but today this is often implemented as a closed ecosystems or single-purpose solution due to a lack of adopted standards in this area.

3. The Application of Smart Healthcare in the Home

Integrating smart technologies into the home for assistive purposes has garnered much research over the years. Some, such as MavHome, combine several technologies together to provide a more homogeneous solution whilst others concentrate on one aspect such as patient requirements during the nighttime or Activities of Daily Living recognition.

What follows is a look at several applications of Smart Healthcare systems grouped into a classification based on their technological approach.

3.1. Smart Homes

Although the technologies involved in Smart Homes have evolved rapidly over the last three decades, the principals and techniques have remained surprisingly consistent. A Smart Home is a collection of sensors and actors, and in some cases an intelligence, whose aim is to provide autonomous services to its inhabitants. There are many degrees of intelligence, or "smart", when it comes to the Smart Home which can range from simple reactive actions based on predefined rules right through to adaptable and self-learning systems able to learn what the occupant needs and act upon it.

For completeness, a look at three key early systems is offered to give an insight into the evolution of the Smart Home. These three projects, all with research published in 1998, show different approaches to information gathering and dissemination: video surveillance and local processing, simple sensors and PSTN network communication, and ambulatory monitoring with automatic emergency recognition. By considering these systems as well as modern approaches a more complete picture can be given.

Microsoft's EasyLiving project [32] showcases the early investigations into context aware computing using an array of video capture devices instead of more traditional physical sensors. Using several vision modules in each room, the system can identify motion, people, gestures, and even the surrounding environment including room fixtures and fittings. Individuals are identified by use of an active badge system and data from the video feeds are processed using a distributed computer network. One unique aspect of the EasyLiving project, especially at the time of its creation, was the focus of geometric relationships between people, places, and things. These relationships, or mappings, enable the EasyLiving system to form interaction information that would associate objects with their likely use, which could later be used in a more intelligent system for behaviour prediction.

Another early system targeted specifically at the elderly was developed in the UK by British Telecom (BT) and the Anchor Trust [33]. To address the ever-increasing demand for community care, the Smart Home system was designed to monitor and report on the lifestyle of its elderly inhabitants. This was achieved using a low-cost sensor network comprised of PIR, door, and temperature sensors. This data was stored along with a timestamp to compile a lifestyle database as a reference pattern. Significant deviations from this pattern, such as long periods of inactivity, are used to detect anomalies whereby an alert message via the telephone system was sent to the patient's designated carer.

CarerNet [34], another UK-based system, takes the approach of combining several environmental and personal sensors to provide an after-care system in the home. Centring on the hypothetical scenario of a patient returning home following hospitalisation, CareNet tries to address the aging population and "hospital-at-home" market. A key feature of the system is to provide emergency support by incorporating environmental and ambulatory monitoring with analytical capabilities to facilitate automatic recognition of alarm conditions, taking the onus away from the client to instigate the call for help. CarerNet achieves this using a distributed sensor network and various wearable devices.

Fast-forward 5 years and we begin to see more powerful hardware combined with sophisticated software able to offer more than just reactive functionality. MavHome (Managing an Intelligent Versatile Home) [35] aims to provide an agent-based rational intelligence able to gather, process, and make decisions upon a multitude of data streams. What makes this system particularly interesting for a healthcare application is its use of a probabilistic model to estimate the inhabitants' movements. This functionality is constructed by sampling events and comparing them to known sequences or sequence matching. If an event is followed by another that is part of a known chain, there can be a confidence factor associated with the prediction of the next event. The more events occur in sequence, the greater the level of predictability. Once events are detected or predicted, the appropriate action can be instigated. Over time, the system can become more accurate through use of a data-mining algorithm named Episode Discovery, operating on the larger set of data. The work on MavHome was later extended at the Washington State University in a project named CASAS [36].

The GatorTech Smart House [37] from researchers at the University of Florida takes a whole-home approach to provide a "programmable pervasive space". The team tries to address the problem of closed ecosystems and fixed installations by designing an extensible framework for software and hardware made possible by a generic abstraction middleware. Using a multi-tiered approach incorporating the physical, sensor platform, service, knowledge, context management, and application layers, the system can interpret sensory data and combine it with contextual information about the home, its environment, and its inhabitants to provide assistive living functionality. This "smart house in a box" was aimed at the aging population market providing a system that the "average user can buy, install, and monitor without the aid of engineers".

Stratogiannis et al. take a different approach, which they term SandS or Social and Smart. They argue that "Filling a home with sensors and controlling devices by a computer is nowadays not only possible, but it is commonly found in homes" [38]. In their system, users are modelled using persona stereotypes which are a source of information about users and their characteristics. Contextual information is gathered using wireless ambient sensors (temperature, humidity, etc.) and is combined with external smart city data such as weather conditions, people movements, and social interactions. Rules are expressed in a high-level language and knowledge is represented through semantic web technologies such as OWL 2 Web Ontology Language to ensure actor interoperability. The collected contextual information can be used to characterize an entity, i.e., people, place, or thing. Although this system is in its infancy it does shows promise as a flexible and extensible framework for modelling context aware environments.

There are several examples of intelligent smart homes capable of adapting to the occupants needs through a variety of approaches but the system proposed by Pradeep et al., is somewhat unique [39]. When it comes to more advanced ways of controlling a smart home using brain waves is an approach that not many smart home researchers have investigated let alone produced a prototype to demonstrate its effectiveness. The field of Human Computer Interaction (HCI) has been explored for several decades and often revolves around the use of computer input peripherals and visual/tactile feedback mechanisms but using the Brain Computer Interface (BCI) is relatively new. Table 1 lists some characteristics of the given systems. Columns marked with a '●' indicate that the system does exhibit that particular characteristic.

Table 1. A comparison of the given Smart Home systems.

System	Type	Contextual Awareness	ADL	Reasoning	Prediction Capability	Actors	Vital Sign Monitoring
BT and Anchor	Telecare	●	●	●			
MavHome	ADL Automation	●	●	●	●	●	
CASAS	ADL Automation	●	●	●	●	●	
GatorTech							
Microsoft EasyLiving	ADL Automation	●	●	●		●	
House_n	ADL Detection	●	●		●		
CarerNet	Telecare	●	●	●		●	●
SandS		●	●	●			
Pradeep et al.	Automation with BCI						●

3.2. Robotic Assistants

In contrast to medical intervention which is primarily given by caregivers, doctors, nurses, and other medical professionals, it is now possible for many day-to-day tasks can be performed by Robotic Assistants. These activities really can make a difference to the health of the patient and can be essential to delivering a holistic approach to care.

Robotic Assistants can perform a whole gamut of operations but often it is the simplest tasks that lead to a patient giving up their independence in the first place. For example, tasks such as forgetting to eat, take medication, or go to the bathroom are real problems that can be addressed by providing intelligent reminders. A wearable device could perform this function but there is a danger that the patient simply forgets to wear the device. Instead, a Robotic Assistant could be aware of exactly where the patient is in the home and proceed to "meet" with them to deliver the reminder.

Robots have often been the antagonist in popular culture made famous by authors such as Isaac Asimov and Philip K. Dick, enough so that many studies have been performed exploring attitudes towards robots using the "Negative Attitudes toward Robots Scale" (NARS). Differing cultural perceptions may play a part in the introduction of robots in the home. Although many reports indicate a positive attitude to the companionship of an electronic aid, a survey of the available case studies involving robots and the elderly shows that a large proportion were undertaken in Japan where attitudes to technology and robotics may not be reflective of other countries. Despite this bias towards one culture Robotics is an area that has merits in the field of home assistance. More research is needed with a broader and more diverse audience, ideally with the same techniques and technologies, to make a more general acceptance statement but as the technology to enable robotic assistance matures the inevitability of their use becomes more apparent.

The biggest barrier to entry today is the prohibitive cost-to-functionality of these devices. Outside of the often single-function robots such as the Roomba (which may also be considered expensive to most), more general-purpose assistive devices are currently the domain of the research community.

3.3. Telemonitoring and Telesupport

There are four key areas of concern in Telemonitoring:

1. Vital-sign monitoring
2. Activities of daily living (ADL) monitoring
3. Emergency assistance monitoring
4. Social interaction

When it comes to vital-sign monitoring data in the Smart Home comes from various devices and sensors placed on or in the patient (in the case of wearables/implantables) or around the home itself (environmental sensors). Often these sensors relay data back to a central hub or gateway that can process the information or send it on to a remote server where it can be combined with patient information for automatic and/or manual interpretation. When dealing with patients that have potential life-threatening conditions such as respiratory congestion or a heart condition, this information can literally be used to save lives through fast medical intervention.

Various systems have been proposed that monitor patient vital signs to provide Real Time Health Advice and Action (ReTiHA) [40]. One such system, used to monitor paediatric neuroblastoma patients at home, concentrates on a wide range of vital signs including "*blood pressure, heart rate, temperature, body weight, C-reactive protein, white blood cell count, wellbeing, pain level, nausea level, skin alterations*" using a smartphone application and a set of sensors [41]. What is particularly interesting with this solution is the fusion of sensor data with subjective feedback to build an overall picture of the patient's wellbeing. Using a mobile device (or tablet) the patient is presented with a user interface tailored specifically for children. An Android application named *MobileMonitor* collects data from the measurement devices and transmits it to a backend system over the HTTPS protocol for added security. In addition, the Near-Field Communications (NFC) protocol is used in conjunction with an A4 graphical representation of patient wellbeing (good, medium, bad) to capture subjective data. Together, the sensors and wellness data can be used by healthcare professionals that in turn allow the patient to remain at home longer between hospital visits. Alerts are given to the corresponding oncologist if deteriorating conditions are observed.

One of the biggest hazards confronting the elderly at home is the potential of falling. Elderly falls cause around 8 billion dollars of direct medical costs per year in the US alone and are the leading cause of accidental injury and death in the elderly with 68% of all elderly hospitalisations [42]. This figure increases to 86% in patients over 85 years old. Li et al. propose a wristlet device with accompanying mobile interface for real-time fall detect in the elderly. Current wearables can employ sensors such as accelerometers to detect if a human is falling using either fixed threshold methods, pattern recognition strategies, conventional or fuzzy logic, or artificial neural networks. The problem is that detection accuracy is usually low with traditional software methods leading to medical negligence. In addition, such algorithms often require complex computing resources, draining embedded batteries. Li et al., propose a smart wristlet, giving 24 h of fall detection service with a detection rate of up to 93% with a simplified solution that saves battery life. This can then be coupled with a wearable airbag system to deploy when a fall is detected. The wristlet has a three-layer architectural design: Application layer (software and statistics), Network layer (communications), and Sensing layer (3-axis accelerometer, 3-axis gyroscope, 3-axis compass, and pulse sensor). Sensor data are sent to a mobile phone via Wi-Fi or Bluetooth where they are analysed further. It should be noted that although this research concentrates on fall detection the technology and approach can be extended to heart-related diagnosis, activity monitoring, and even to non-traditional approaches such as those seen in Chinese traditional medicine. The system learns by mining training data to effectively learn what a fall looks like and use this to compare to real-time data while the algorithm used looks at occurrence, or most notably recurrence, where the most relevant data are often seen multiple times, whereas irrelevant data often occur only rarely. Using Term Frequency Inverse Document Frequency (TF-IDF), the process can discard irrelevant data whilst surfacing only the most important features which results in a higher accuracy. Despite some success in a trial of 246 aging people in Beijing (all aged between 59 and 63 years old) this system, similar to others of this kind, does have its limitations. Most notably, ordering and time-sequential problems are present which can be of concern for a real-time critical system like this. The authors of this research are looking at ways of addressing this in the future. Furthermore, battery life of the wristlet is still only 24 h which is limiting for some situations where the user may forget to charge the device or charging is just not possible each day. This is also present in more commercial solutions such as those from Fitbit, Apple, and Garmin, whose tracking devices are all limited by battery life measured in hours rather than weeks.

One of the hottest areas of Smart Home research now is that of determining what a home occupant is doing at a given point in time. Activities of Daily Living (ADL) is the term given to everyday activities that people perform such as washing, eating, and sleeping. For most people these activities form patterns which, when monitored, can be very useful in identifying abnormalities that may be a precursor to patient intervention. Many elderly people, the demographic most susceptible to degenerative diseases, live alone at some point in their lives which puts them at risk not only from their afflictions, but from accidents. According to the most recent Office of National Statistics report on injury and poisoning mortality in England and Wales [43], published 2013, those over 65 years of age are most at risk, suffering the highest mortality rates and highest accident severity. Falls were the leading cause of accidental death with 30% of male and 39% of female mortalities attributed to this. Another disease that ADL and other Smart Home technologies tries to address is dementia which has seen a threefold increase in mortality in the decade 2004–2014. Overall, people are generally living longer, which poses a challenge for traditional healthcare services.

A list of common ADLs is shown in Table 2:

Table 2. Common Activities of Daily Living (ADL).

Popular ADLs	
Eating	
Sleeping	Cleaning the house
Washing	Reading
Brushing teeth	Walking
Cooking	Running
Getting dressed	Riding a bike
Watching TV	Meeting friends and family
Making telephone calls	Video conferencing
Using the internet	Grooming
Taking medication	Drinking
Shopping	

According to research by Ni et al. [44], there are two major types of ADL: essential basic or personal self-care activities (BADL) such as bathing, grooming, toileting and consuming food and drink, and non-essential instrumented or domestic activities (IADL) such as shopping, watching TV and reading. Additionally, although not formally defined, a third ADL can be extrapolated from the text and defined as ambulatory or movement related activities (AADL) such as walking, running and bike riding. To extend this categorisation we can propose that a fourth ADL group be defined: Social interactions ADL (SADL) that would include activities such as email communication with friends and family, video conferencing with tools such as Skype, telephone calls and in-person visitors. Grouping ADLs into these four categories allows a general wellbeing assessment of the patient rather than concentrating on one aspect such as physical health that provides only a limited view.

Using the extended Ni et al. groups, we can reclassify the ADL activities in Table 2 as shown in Table 3.

Table 3. Reclassified common Activities of Daily Living (ADL).

Classification	**ADL**
Basic activities (BADL)	Eating, drinking, sleeping, washing, brushing teeth, cooking, taking medication, getting dressed, grooming
Non-essential instrumented activities (IADL)	Watching TV, using the internet, reading, shopping
Ambulatory activities (AADL)	Walking, running, riding a bike, cleaning the house
Social activities (SADL)	Making telephone calls, meeting friends and family, Video conferencing

The actual identification of activities is often difficult as the accuracy of existing indoor tracking sensors and the corresponding analysis software is still in its infancy. Movement tracking, the fundamental foundation of ADL studies, is not always easy to accurately detect, especially in the indoor setting of the home. To overcome this some attempts have been made to combine technologies such as those found in common smart phones such as the iPhone 6S (accelerometer and gyroscope) with software filters to detect occupant movement. In trials, one solution using the software Monte Carlo and Kalman filtering methods managed to get accuracy down to an average 0.47 meter resolution at a 95% confidence level from using a Bluetooth LE sensor network and an off-the-shelf Apple iPhone device [45]. What makes this research so compelling is the fact that only one form of sensor data was used, which opens the possibility of further improvements by combining sensor technologies. In fact, the authors plan to extend this work by adding other sensor data from force sensitive resistors around the location but this could easily be extended further with Wi-Fi, IR, sound, and video data. This work was part of a larger project to implement a patient telemonitoring solution.

One recent effort to combine sensor data is Google's Project Tango [46], announced 5 June 2014, and is an attempt to solve the issue of movement tracking using video, accelerometer and gyroscope data from a mobile device. Using such a device, researchers in Germany, again using Kalman filtering and Monte Carlo localisation combined with simple 2d floor plans, discovered that it is possible to track people indoors even in an environment that was not previously mapped, and to do so with accuracy [47]. Although the authors do not offer insights into future enhancements, research such as this is not only applicable to tracking people through their environment but can be used by robotic assistants both for movement and tracking their owners. In the future, it is conceivable that this technology could be used to gather similar movement data. Once location data can be accurately determined there needs to be some way to detect activities themselves.

A high-level taxonomy of Activities of Daily Living (ADL) and their applications in healthcare and wellness in the home is proposed in Table 4.

Table 4. Classification of applications of Activities of Daily Living (ADL).

Application	ADL Example
Cognitive Orthotics and Mental Augmentation	Reminders, Navigation Assistance, Reasoning Assistance, Planning Tools, Multimedia Coaching, Information Retrieval
Continuous Vital-Sign Monitoring	Vital Sign Monitoring (Blood Pressure, Heart Rate, . . .), Sleep Monitoring, ADL Monitoring, Habit Monitoring, Movement Detection
Social Assistance	Telephone Calls, Human Interaction, On-Line Interaction
Medical Intervention	Telesupport, Remote Health Assistance, Online Medical Tools
Medical Emergency Detection	Fall Detection, Abnormal Behaviour Detection, Hazard Detection
Physical Assistance	Home Automation, Assistive Tools, Predictive Software

Activity detection is not only limited to the waking hours of a patient, in fact monitoring a patient's sleep can be used to detect alert conditions as well as be an indicator for general wellness.

The NOCTURNAL system [48] attempts to cater for the specific needs of individuals during the night-time period. Monitoring the sleep patterns of house occupants, specifically for restlessness, occupancy, and wandering, this system uses X10 technology for affordable yet flexible functionality. The system is comprised of pressure mats, lighting control, and actuators to assess and then intervene if abnormal sleep behaviour is detected; interventions include playing soothing music and dimming lighting. This information is fed back to a listening agent that can be used to monitor the occupant. In cases such as Obstructive Sleep Apnoea (OSA), sleep walking, and other sleep disorders, the real-time feedback given by such as system can alert carers to potential problems as they occur.

Another area of intense research is the delivery of healthcare remotely using technology as an enabler. Elderly people are the fastest growing segment of the population in developed countries but independent living comes with risks and challenges. In France alone it is predicted that the current 1:5 ratio of people over 60 years old will rise to 1:3 by 2050 bringing with it an increased demand on healthcare services and medical intervention. Telemonitoring and Telesupport are two ways to address this demand using technology. Solutions tend to use a multi-modal approach, employing several sensors to detect patient behavioural patterns and environmental conditions with the aim of providing intervention only when it is needed. Furthermore, solutions may be holistic, trying to encompass a wide range of monitoring and support functionality or conversely may be targeted specifically at one aspect of support, such as medication reminders, the actual implementation is often dictated by the patient's condition.

First tested in lab conditions and followed up by application in the Broca Hospital in Paris, the system produced accurate data in 10 adults aged from 65 to 75 years old. Four parameters were used, sensitivity, specificity, error rate, and perfect classification when detecting abnormal situations with a 96% or above accuracy in sensitivity specificity and perfect classification, and only a 3% error rate. The 3% error rate could be reduced using these anomalous data to teach the system further. The system needs further trials on a larger population to improve accuracy and validate this approach but initial results are impressive.

Five main services are offered by the system: (1) caregiver Intervention i.e., to give the patient a required medication or respond to a non-emergency alarm; (2) cloud Storage to securely store medical data for data mining; (3) Emergency Response Services (ERS) in the case where immediate assistance is required; (4) real-time health advice and action to advise anyone present during an emergency situation the required response based on medical reports and past history; and (5) Patient Monitoring Service (PMS) to enable more independent living providing peace-of-mind to caregivers and relatives.

Although similar to [49–51], the extension to include an extensible services framework and emergency response capabilities as well as caregiver and patient advice is unique. Implementing such a system will require a lot of further research into software and hardware solutions.

4. Emerging Trends in Smart Healthcare Technologies

4.1. Automation

The use of automation technology in the home is not new. From humble beginnings in the 1960s as hobbyists attempted to automate simple functionality, the term Smart Home was first coined in 1984 (almost ironic given the content of George Orwell's novel of the same name) by the American Association of House Builders [52]. Automation has been a key driver of consumer smart device uptake for the home but its use is not as widespread as some may have predicted. However, with the advent of low-cost computing platforms such as the Raspberry Pi Zero it is now more likely than ever that Mark Weiser's vision of "*integrating computers seamlessly into the world at large*" will be realised [53]. This increase in computing power integrated into today's "dumb" appliances allows for control of functionality such as lighting, heating, and security among others. In the context of healthcare, this automation can be a key enabler for people with physical and cognitive disabilities or impairments such as those experienced with age. The ability to automate common tasks relieves the burden of being able to operate knobs, switches, and various appliances around the home and can be the difference between a patient receiving care in their own home or in a specialised care setting. Initiatives such as Health Mart Home (HSM) use off-the-shelf, low-cost components to issue warnings to people with physical disabilities, such as visual or hearing impediments, to avoid potential hazards allowing them to stay at home longer [54]. Similarly, the system proposed by Ramlee et al. uses commodity components and the prevalent Bluetooth communication protocol to allow people with physical disabilities to control appliances by using only their smartphone or tablet [55].

4.2. Augmented Reality

Augmented Reality (AR) is the field of study concerned with meshing the real world with computer generated data and images to provide an enhanced view of reality. AR has been used in rehabilitation to encourage movement in patients suffering with akinesia, which is a disorder that is characterised as a loss or absence of voluntary movement. Coiera looked at one study that "*projected virtual objects on to the patients' physical world to give them the impression that they were walking through them, therefore restoring their mobility*" [56]. Coiera cites issues with the current (as of 1996) hardware displays in addition to ethical considerations as the major limiting factors to AR adoption in healthcare. Coiera also notes that AR can have a detrimental effect on some people, stating that, "*undesirable side effects such as equipment failure, fatigue, or motion sickness*" were experienced in some trials.

4.3. Implantable Medical Devices (IMD)

Challenges remain to design devices that can operate in the somewhat harsh environment of the body. Using the Medical Implant Communication Service (MICS), low powered antennas, and programmable and configurable components such as the one proposed by [57] allow for changes after the implant has been made but this of course comes with risks thus one area of intense scrutiny is security in medical devices. Hacking the computer of mobile phone is one thing, hacking an implantable medical device is entirely another. Security applies across the board with medical equipment but is particularly important in implantable devices due to the importance and control they have over their wearer. Much has been written in the press about compromised medical devices [58,59] so one area of future focus will be in securing these types of devices.

Another field that is gaining in popularity, albeit in a somewhat niche market, are implants for convenience. Kevin Warwick has been a long-term proponent of augmenting the human body and his 2006 paper details his experimentation with a surgically implanted RFID (Radio Frequency Identification) device [60]. This implant allows for user identification, movement detection, and automation, and enables the Smart Environment to react to the presence of the user. While being an extreme example, it can be argued that Warwick's research in this area has broken new ground. It is now common to see transitory implantables in the form of ingestible devices that can measure everything from the level of acid in the stomach to blood alcohol level. This latter information could, for example, be used to enable or deny access to a vehicle by the home owner. Implantable devices will continue to be the focus of attention in the coming decades. Figure 3 shows a number of implantable sensors and where they are located in the body.

Much more likely, in the short-term at least, is to see an increase in the use of wearable devices.

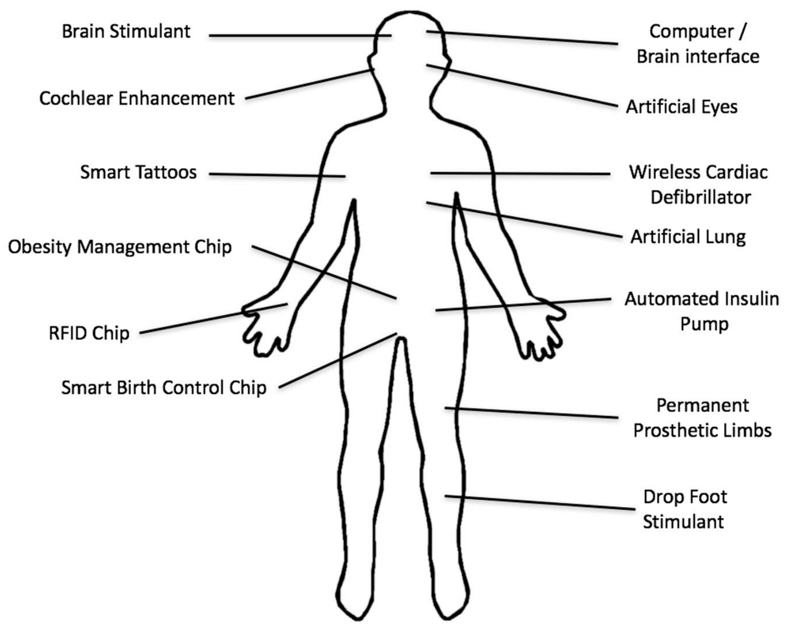

Figure 3. A selection of implantable devices released and in development.

4.4. Wearables

Wearable sensors provide an excellent solution to monitor a person continuously and provide instant results. Probably, this could not be achieved using any other technology. Mukhopadhyay [61] forecasts that wearable sensors might revolutionise exercising, communication and our life, similarly as personal computers did. Another advantage noted by Paolo Bonato [62] more than decade ago that wearable sensor platforms have progressed to produce medically accurate signals and the gadgets allow measuring a patient for an extended period, which could last even few month, and it is a great advantage in contrast to a stationary technology.

The demand for wearable devices has increased dramatically over the last decade and, according to Juniper Research in 2014 [63], the wearable market is set for a more than 10-fold increase in hardware revenue alone by 2019. Wearables cover a wide range of uses such as lifestyle, sports and fitness, entertainment, healthcare, and enterprise, with the current surge in awareness particularly focused on the former two, spearheaded by companies such as Fitbit, Apple, and Jawbone. While originally these devices performed simple operations, such as tracking the number of steps a wearer performed throughout the day they are now becoming more sophisticated. Most consumer wearables do not employ medical-grade sensors but devices such as the Apple iWatch can interoperate with medical-grade add-ons such as the Kardia Band [64] which can be used to detect Atrial fibrillation, the leading cause of strokes. It is expected that the lines between traditional medial-grade devices and consumer health and fitness devices will continue to blur especially for use-cases including monitoring heart- and blood-related data. Fitness trackers will also continue to be the subject of clinical trials focused on weight-management, obesity, diabetes, cancer, and more [65].

The work by Zhu et al. on correlating physical activity with mood [66] is particularly interesting. The researchers use only off-the-shelf components, in this case the Pebble Smart Watch and an Android Smart Phone, to advise the wearer based on predicted mood. What makes this research unique is the fusion of activity tracking detection and mood inference engine that can use perceived mood such as "stressed" to try counter that by suggesting an anti-stress activity such as exercise based on heuristic data. Similarly, the software can correlate the activity with the mood so if "shopping" results in the wearer being in a bad mood this data can be used to predict future moods based on activity and advise accordingly. This fusion of data and interpretation holds promise for future research.

The environment could provide energy for wearables as well, for instance, it was reported that circularly polarised textile antennas could transmit power [67]. Furthermore, sensors, which harvest energy from nearby health monitoring bands has been implemented [68]. Moreover, radiofrequency (RF) energy harvesting antenna in a wearable sensor was introduced by researchers at the Massachusetts Institute of Technology [69]. Current devices can generate energy from both a body and environment, but further development is required to harvest more power.

Research opportunities are present in data-mining the vast quantities of information that wearables generate, especially when it comes to detecting anomalies in individuals and in statistically-relevant groups. Apples initiative here with their ResearchKit and CareKit hint at innovation at a massive scale, enabling field trials with millions of individuals. There will be further research opportunities around combining data from several sensors to form a holistic picture or a wearers health and how that is affected by external factors such as weather (seasonal affective disorder (SAD) detection), amount of exercise (exercise-related endorphin boost), social interactions (GPS, Bluetooth, proximity data, and social media), TV viewing habits, or even a person's income level. Hardware sensors will continue to be miniaturised and become more viable as they are embedded into all-day, every day accessories but research needs to done to improve the battery life of these devices. Typically, something such as an Apple iWatch lasts around a day of normal usage, a Fitbit Charge up to 5 days, but this will have to improve especially when consumers are used to watch-like devices lasting much longer.

4.5. Robotics and Personal Assistants

While robots and personal assistants will undoubtedly become more popular over the coming decade, current technologies will have to overcome the unique issues around operating in domestic environments. The very unstructured and dynamic properties of a home make navigation difficult and interacting with unpredictable humans increases the complexity still further. Robots need to be "smarter" and have the capabilities of self-learning, adaptability, proactiveness, and logical reasoning to effectively assist people in their home. Both hardware and software will need to advance further to realise the full potential of robotics in the home but today's solutions are progressing rapidly. For instance, Cao et al., proposed self-learning robotic solution for the domestic environment used the popular ROS (Robotic Operating System) software and Care-O-bot 3 (COB) hardware [70] but already Care-O-bot 4 is close to release with many improved features that will further this solution [71]. Features such as full modularisation and adaptability would improve the robot's ability to adapt physically to any environment by configuring things such as hip and neck joints that swivel through 360 degrees or adding tray-like hands instead of grippers for carrying and serving items such as medication. As the software is fully open-source it is possible to extend the software still further. The use of open source allows hobbyists and experts alike to get involved and innovate faster in this highly evolving area.

4.6. Micro-Sensors

In this section, body patches (also referred as stamps, stickers and tattoos) are described. The name micro-patches come from having less than one-millimetre thickness. Another advantage is that they could receive energy from the internal source, such as pressure [72] or body heat [73], thus eliminating recharging procedure and expand wearing time. Recently, researchers developed battery which is stretchable up to three times of its length and rechargeable wirelessly [74].

Micro-patches are less than one millimetres thickness, and they are classified in this paragraph as labels, tattoos, and electric skin. A company named Thinfilm produced a unique sensing label for reading temperature called Smart Labels [75]. Another wearable sensor measures oxygen, have a thickness of 84 µm and are placed on forearm [76]. The extensive research was done to bio-stamps which look like stickers or temporary tattoos, nonetheless, they can monitor sun's ultraviolet (UV) rays, chemicals in sweat or even measure blood pressure, as displayed in Figure 4 [77]. One more group is electric skin that could sense an external stimulus similarly as human skin does. The technology implements flexible pressure sensors [78–80] and it would be beneficial to humanoid robotics, prosthetics and flexible displays [81]. Hayward and Chansin forecasted that this type of stretchable and pressure sensors growth rate would be greatest in comparison to other wearable sensors, and will increase by 40% in the next ten years [82]. The smallest type of micro-patches are tattoos which could be directly printed on the skin sensors (as seen in Figure 5c) and could measure "skin hydration, temperature, and any electric signals from muscle and brain activity" [83]. They could also be ultrathin, stretchable and is not irritable to a user [84].

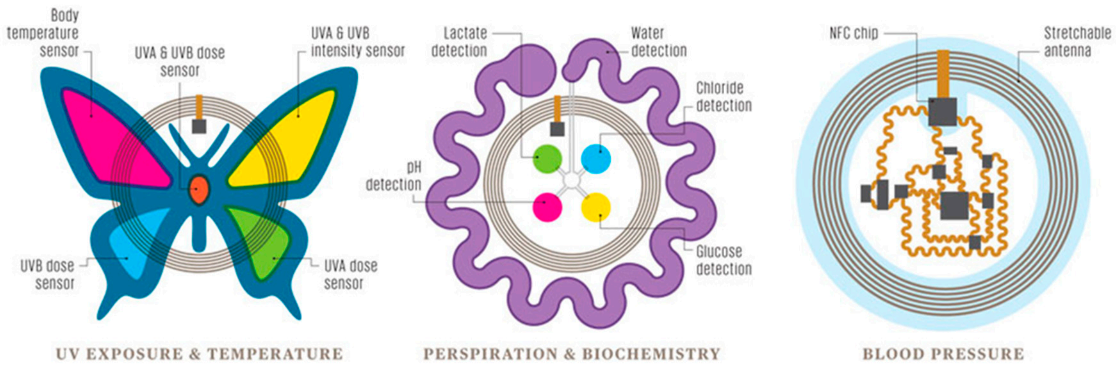

Figure 4. Biostamps [77].

Figure 5. Comparison of micro-thin sensors. (**a**) Smart Label composition (**b**) Sensors embedded in stickers; (**c**) Sensor directly printed on the skin [76,78,84].

4.7. E-Textile

E-textile could measure various stimulus including temperature, chemicals, humidity, force and pressure variations [85], but the sensing stimulus was reviewed in detail in previous sections, hence this chapter this be concentrated on implementing materials and produced platforms.

Sensing clothing has a wide-ranging list of advantages in comparison over accessory based and micro-sensors wearables. First, a garment allows extended measurement of movement and electro-stimulus. For instance, body positioning monitoring, for example, accurateness of action performing in athletic exercise to avoid injury and target selected muscle groups [84,86]. Snug clothes are usually close to the body; therefore they could be used to monitor posture [87,88], perform an Electromyography (EMG) technique, and detecting fatigue for vehicular drivers [89]. The second principal benefit is that E-textile permits modification of clothing, therefore smart textile can act as camouflage, or even heal wounded soldiers [90]. Performance enhancing e-textile "are fabrics that help regulate body temperature, reduce wind resistance and control muscle vibration—all of which help improve athletic performance" [91]. Moreover, fashion field also benefits from smart textile to create transforming, environment aware and flashy designs. The third benefit is permitting an extensive access to skin permits greater energy generation, and it occurred after employment of conductive polymers, which could be used as a power source. It is profitable to various fields including military [92]. Another advantage is greater variety and larger sensors on a single wearable, although in some cases weight could be noticeable higher allowing, for example, observing hazardous chemical materials [93]. The final advantage is that most smart-textiles are machine washable, which is highly beneficial to professional and amateur athletes.

Fabric technologies could be more adaptable and flexible, although, on the other hand, they are not as tough as accessory based wearables [94].

Lina M. Castano and Alison B. Flatau described extrinsically altered textile as a "*modifications to enable sensing features can be introduced at any level of the fabric structure*". It includes self-containing sensors attached to clothing, which examples could be the popular Lumo Lift appended to t-shirts, shirts or bra using a magnetic plate and is placed on below collarbone to measure slouching of a user. The Wearable Motherboard™ was introduced back in 1999 and contained a thermometer and ECG applied for medical applications [95]. Another example could be that company called Owlet implemented oxygen level and heart rate monitor sensor into a smart sock extrinsically [96]. Various other devices monitoring respiration and attached to clothing exists both for adults and infants [97,98].

Intrinsically modified textile contains yarns and fibres which could sense chemical or mechanical stimuli, and changes were done intrinsically in comparison to extrinsic modifications which usually contains attached device and was introduced in the previous section. For the development of yarn fabrics, several techniques exist including core spun yarn, cotton-wrapped nichrome yarn, copper core yarn, plastic optical fibre (POF) yarn and yarn for teleintimation faction. Recently a conductive fabric was developed to replace wires [99]. It was perhaps a reason for a revolution of e-textile and growing interest in previous years.

5. Discussion

The technology behind what many people envisage as "The Smart Home of Tomorrow" is mostly available today with the home automation and sensors markets maturing over the last few decades. What needs to happen now is acceptance and adoption by the public, integrating these devices into the home and allowing the data to be gathered. Research into what will trigger a more widespread acceptance and adoption of smart technologies in the home needs to look at user-friendliness, ease of installation, and cost vs. benefit for the homeowner but it may be government legislation that starts the ball rolling. Similar to the mandate from the British Government to have a Smart Meter installed in every home in the UK by 2020 it may be this kind of initiative that paves the way for other smartness in the home. Similarly, the big energy and utility companies can play a part here, offering cheaper services in exchange for more sensors and meters in the home. Once these are in place, it is easier to connect them together to create new and interesting use cases. Finally, just as governments around the world have pushed for energy-saving initiatives such as phasing out incandescent bulbs, especially above a certain wattage, they too could push for higher tariffs on certain unhealthy foods, rewards for healthy eaters (monitored through a smart fridge) or increased exercise (monitored through a fitness tracker). In this way, governments could potentially relieve some of the strain on traditional healthcare services while subsidising more health-related technological initiatives in the home.

Implantable devices will continue to be an interesting area for research. As technology is miniaturised it enables new and interesting uses cases. From simple RFID chips embedded just under the skin to the more sophisticated smart pills that target specific illnesses it will become more common to have non-organic material added to the body. The latter is of interest as designer drugs can be created to target an individual's ailments but in the home, it is technologies that consume the data of implantable devices that will lead to a Smarter Home. Appliances such as the smart fridge that helps control glucose based on data from an implantable Wi-Fi-enabled gastric-band will be the source of some research but with this, and other data sources it will be all about how the vast quantities of data these sensors generated is mined, interpreted, and then used to improve the health of the patient. This will drive software innovation in big-data and data modelling and will be the subject of future research.

In robotics, there are opportunities to not only improve hardware and software, but to also study the acceptance of robots from a social perspective. Bringing a robot into the most intimate setting of the home and having it help with the deliverance of healthcare will be a challenge especially on ethical and liability topics but the benefits of this technology to not only free up scarce healthcare resources but to allow people to live with health conditions in their home longer are apparent. This will be especially important as the world's population continues to age and with people having less children in developed nations contributing to a shortage of family carers, robots may help to fill the gap.

The home of tomorrow will be substantially different; technological advances continue to make our lives easier, while, at the same time, the cost of delivering healthcare is increasing around the world. Life expectancy is increasing and people are living with chronic illnesses for longer, increasingly relying on family, friends, and the healthcare system to survive. The healthcare service needs to improve but ploughing more money into a centralised health delivery system may not be the most optimal use of resources. Technology can help to decentralise health care, bringing treatments and health management into the home. This not only benefits the patient but also the people delivering the care. As this article has shown, the field of Smart Home Healthcare has come a long way but is ripe for improvements across the board. Various building blocks of technology must all come together to provide a successful and holistic solution; from sensors to actuators, wearable devices to software, when applied in a standard and modularised way the Smart Home of the future can really improve the health and longevity of its occupants.

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