TOPICAL REVIEW

Indoor location-aware medical systems for smart homecare and telehealth monitoring: state-of-the-art

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Indoor location-aware medical systems for smart homecare and telehealth monitoring: state-of-the-art

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Abstract
This paper presents a comprehensive literature review of current progress in the application of state-of-the-art indoor positioning systems for telecare and telehealth monitoring. This review is the first in the literature that provides a comprehensive discussion on how existing wireless indoor positioning systems can benefit the development of home-based care systems. More specifically, this review provides an in-depth comparative study of how both system users and medical practitioners can get benefit from indoor positioning technologies; e.g. for real-time monitoring of patients suffering chronic cardiovascular conditions, general monitoring of activities of daily living (ADLs), fall detection systems for the elderly as well as indoor navigation systems for those suffering from visual impairments. Furthermore, it also details various aspects worth considering when choosing a certain technology for a specific healthcare application; e.g. the spatial precision demanded by the application, trade-offs between unobtrusiveness and complexity, and issues surrounding compliance and adherence with the use of wearable tags. Beyond the current state-of-the-art, this review also rigorously discusses several research opportunities and the challenges associated with each.

Keywords: indoor location-aware medical systems, smart homecare, telehealth monitoring

(Some figures may appear in colour only in the online journal)
1. Introduction

Ageing populations and shifting global demographics have become common issues, especially in developed countries. These phenomena happen when the median age of the population rises due to an increase in life expectancy and/or a decline in birth rate. While this has initially been experienced predominantly by more economically-developed countries, more recently this trend has also gradually shifted towards less economically-developed countries (DESA 2013).

The impact of global population ageing is profound and enduring, and includes reduced economic growth and increased taxation of a relatively shrinking workforce in order to fund healthcare and pensions. As a result of recent transitions from high to low levels of fertility and mortality, these population trends show no immediate signs of reversing. According to a United Nations report on world population ageing (1950–2050), the population of older people globally will grow by 2% each year for the foreseeable future. Furthermore, without parallel in human history, it is also predicted that in the period from 2025–2030, the rate of increase will rise 2.8% annually (DESA 2013).

In addition, since the beginning of the 21st century, the number of people reaching 50 years and older has reached 600 million (a figure three times higher compared to the 50 years earlier) (DESA 2013). By the middle of this century, this figure will have increased three-fold, reaching a staggering figure of two billion elderly people out of a global population around 10 billion, which will be 20% of the world population.

While today the median age of the global population is 26 years, it is expected that in the next 50 years, the global median age will increase by 10 years to 36 years (DESA 2013). Since the health of older persons typically deteriorates with increasing age, this will induce greater demand for long-term care as the numbers of the oldest-old grow. Meanwhile, the number of seniors living alone, especially in developed countries, has significantly increased (DESA 2013). Given the aforementioned, the existence of reliable, accurate and yet affordable homecare systems, not only to assist the elderly in living independently but also to monitor the progress of their well-being, are desperately needed.

Since most people, especially older people, spend most of their time indoors and some of them are even living alone, it is not surprising that when it comes to incidents such as unintentional falls, according to report written by AIHW (2013), most falls (>75%) also occur within indoor environments, bathroom, bedroom, kitchen, laundry or other indoor living areas. Furthermore, as global populations are aging, this issue has become more critical. For instance, the same report details how the severity of injury associated significantly increases with the age of the faller. These figures will be discussed more comprehensively in section 3.3 and are graphically presented in figures 3 and 4. Therefore, it is essential to have powerful indoor-location-aware telehealth systems which are able to locate the positions of people indoor in the case of a medical emergency in order to summon immediate help.

Considering the advent of indoor positioning systems (IPS), the benefits of smart homecare or telehealth systems compared to conventional treatments are multifold. Firstly, these systems are specifically designed to better serve patients. Secondly, telehealth systems can also facilitate preventive measures and reduce healthcare costs while their long-term goal is to improve safety and quality of life. Accordingly, they can be used as an instrument to globally improve life expectancy and the quality of life.

In hospital environments, IPS can serve as reliable and accurate asset tracking systems, compared to their manual-tracking counterparts which are prone to human error and are labour-intensive. They also improve efficiency, as they can be used to improve productivity, save time, cost, energy and resources (e.g. significantly reduce paperwork) as well as to
simplifying tracking and stocktaking procedures. Finally, they can be used to locate the position of patients, care givers, and medical professionals in real-time with room-level accuracy.

IPS are enabling the development of highly-accurate location-aware healthcare systems in the form of smart homes, leveraging the benefits of ubiquitous sensor networks and smartphone applications of the modern world. With regards to smart home systems, there are two terms that are often used inconsistently. The term ‘telecare’ often refers to the use of sensors to mitigate risk in the home by providing care and reassurance to enable the elderly or physically disabled to live independently in their homes; a common instantiation of this concept is the pendant alarm, which is worn around the neck on a lanyard and can summon assistance when the user presses a panic button on the pendant. Meanwhile, the term ‘telehealth’ relates to the use of communication technology to transmit clinical information for the purpose of remote patient monitoring (e.g. blood pressure) and disease management (chronic disease in particular).

1.1. Contributions of this review

While in general this survey paper aims to provide the readers with a new perspective regarding location-aware healthcare systems which are largely based on the use of sensor technologies, our specific contributions in this review are three-fold. Firstly, this review compares and contrasts the current state-of-the-art telecare developments with their relative benefits for use within homecare systems. In contrast, previously published survey papers by Liu et al (2007), Fuchs et al (2011) as well as Harle (2013) and Dalce et al (2011) merely focus on indoor positioning techniques without considering their application for healthcare. Furthermore, Chan et al (2012) strongly focus on smart wearable systems, while Batistatos and Tsoulos (2012) discuss mobile telemedicine without considering its close relation to IPS. We also compare and contrast the potential benefits and technical challenges of some of the most widely-used IPS. In addition we also discuss the performance of each indoor positioning technology with regards to its lower bound of error, derived from first principles.

Secondly, this review also aims to highlight several perspectives beyond cost and accuracy, that are often neglected by designers, such as the level of obtrusiveness of the system. Hence, these issues should be carefully considered in order to enhance the acceptence and practicality of proposed systems.

Thirdly, we highlight several potential future research avenues with regards to unobtrusive location-aware medical systems. The authors hope that this paper will guide researchers, engineers, users, and developers to identify the potential research problems, solutions as well as benefits and limitations in this emerging area. We believe that this paper is the first in the literature that rigorously discuss the aforementioned issues.

1.2. Organisation of this paper

This paper is organised as follows. Section 2 depicts the current state-of-the-art of indoor positioning systems, while section 3 focuses on the current applications of indoor positioning systems for telehealth systems. Subsequently, section 4 presents a comprehensive discussion regarding state-of-the-art applications in this field and some potential research avenues. Finally, section 5 concludes the paper and presents possible future directions.

2. Indoor positioning systems (IPS)

As modern people spend most of their time indoors, one of the most promising technologies for fledgling smart buildings are IPS. While we can rely on satellite positioning systems (e.g.
Global Positioning System (GPS) or Global Navigation Satellite System (GNSS)) for outdoor activities, these systems generally do not work indoors since the received signals are generally unavailable, unreliable, corrupted or inaccurate because of the presence of many physical obstructions, such as concrete walls and buildings, which can significantly attenuate the signal on its path to indoor receivers. To overcome this issue, nowadays, many indoor localisation systems have been widely developed for extensive applications in both civilian and military domains, including robotics, sensor networks, search and rescue, security, and biomedical applications (Han et al. 2007, Eckert et al. 2007, Chavez et al. 2009, Holm 2009, Hijikata et al. 2009, Yue 2009, Gresmann et al. 2010, Withephanich et al. 2011, Jung et al. 2011, Dan and Luprano 2014, Higuchi et al. 2014). This section compares the pros and cons of the most widely-used IPS.

2.1. Comparative study of positioning technologies

In what follows, a discussion is presented on the pros and cons of various IPS represented in Table 1 and their potential benefits. These include not only radio frequency (RF) electromagnetic-based IPS but also optical and inertial systems.

2.1.1. Received signal strength (RSS): model-based and fingerprinting methods. Received signal strength (RSS) is the most commonly-used positioning technology for both indoor and outdoor environments. There are numerous reasons for considering this method, particularly for indoor positioning systems. The main reasons are its economical value and ease of implementation. This technique has been widely studied, spanning applications from robotics-related localisation to positioning for healthcare. Second, RSS has been widely accepted as a standard feature in most wireless devices due to its simplicity, as it does not require a highly accurate clock and time synchronisation techniques, unlike time of arrival (ToA) and time difference of arrival (TDoA) methods. Hence, there is no requirement for complex hardware (e.g. antenna arrays) as is required for the angle of arrival (AoA) technique.

However, RSSI measurements can be adversely affected by radio interference such as signal fading. In wireless communications, signal fading is a form of attenuation that affects the quality of the traveling waveform through a certain medium or channel. Fading interference is a random process and it may vary over the time, frequency or geometrical position. This can be due to multipath propagation, or shadowing from physical obstructions, e.g. walls or buildings.

Technically, there are two localisation techniques based on the use of RSS methods: model-based and fingerprinting-based. Unlike fingerprinting approaches, model-based techniques (e.g. path-loss propagation model) is considered substantially more practical since there is no requirement to conduct a training phase in which large amounts of data reflecting the characteristics of local fading environment need to be collected beforehand. Once the distance of a certain object with respect to at least three reference points can be obtained, its position can be mathematically determined by the well-known triangulation technique (Liu et al. 2007).

The lower bound of the positioning error of the model-based RSS technique, dictated by its Cramér–Rao lower bound (CRLB), can be mathematically expressed as follows (Santoso and Malaney 2011, Santos and Malaney 2011, Santos and Malaney 2011):

\[ \sigma_{\text{CRLB}}^2 \geq \frac{\sum_{i=1}^{N} \frac{1}{d_i^2}}{b \left( \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \sin^2(\theta_i - \theta_j) \right)} \]  

(1)
Table 1. Comparison of various IPS for homecare applications.

<table>
<thead>
<tr>
<th>No.</th>
<th>Methods</th>
<th>Pros</th>
<th>Cons</th>
<th>Cost</th>
<th>Resolution</th>
<th>Homecare applications and beyond</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Received signal strength (RSS)</td>
<td>Easy to implement, Widely used</td>
<td>Slow, unsuitable for rapid deployment. Typical standard deviation of the received signal is 10 dB</td>
<td>Low-cost</td>
<td>Typically several meters; depends on the geometrical configuration of base station and devices</td>
<td>Remote monitoring systems for patients with cardiac pacemakers (Rotariu et al 2012), patient-centric medical systems (Wu et al 2012), indoor tracking and navigation (Colombo et al 2011, Au et al 2013).</td>
</tr>
<tr>
<td>2</td>
<td>Time-of-arrival (ToA)</td>
<td>Provides high localisation accuracy</td>
<td>Highly synchronised nodes required, but accuracy limited by the bandwidth of radio signal hence high bandwidth requires to produce high accuracy in multipath environment, requires knowledge of hardware propagation delay</td>
<td>Low-cost</td>
<td>Room-level, bandwidth dependant</td>
<td>Athletes training, sport monitoring systems, underground mining tracking (Sathyan et al 2011).</td>
</tr>
<tr>
<td>3</td>
<td>Time difference of arrival (TDoA)</td>
<td>Low-cost</td>
<td>Requires highly accurate synchronisation clocks</td>
<td>Low-cost</td>
<td>Room-level and clock dependant</td>
<td>Mobile communication systems, marine location estimation by means of acoustic waves (Ahmed et al 2013).</td>
</tr>
<tr>
<td>4</td>
<td>Angle-of-arrival (AoA)</td>
<td>Allows the use of simple tags on the objects</td>
<td>Large directivity antenna with complex scanning mechanisms or array antenna required, expensive base station</td>
<td>Expensive</td>
<td>Room-level, poor in multipath fading environment</td>
<td>Mostly robotics applications, e.g. TripNav (Amudson et al 2011).</td>
</tr>
<tr>
<td>5</td>
<td>Ultra wide band (UWB)</td>
<td>Substantially reduce interference, it can coexist with Wi-Fi networks, inherent noise-like behavior makes it difficult to detect and have robustness against jamming</td>
<td>Inconsistent standard in most company, expensive hardware requirements, not scalable, illegal in some countries</td>
<td>Very expensive</td>
<td>Sub-millimetre accuracy</td>
<td>UWB-based wireless body area networks (Chavez et al 2009), orthopaedic surgical navigation (Mahfouz et al 2011).</td>
</tr>
</tbody>
</table>
Table 1. (Continued)

<table>
<thead>
<tr>
<th>No.</th>
<th>Methods</th>
<th>Pros</th>
<th>Cons</th>
<th>Cost</th>
<th>Resolution</th>
<th>Homecare applications and beyond</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Radio frequency identification (RFID)</td>
<td>Requires no line-of-sight condition, also suitable for inventory tracking</td>
<td>Requires multiple scanners to improve accuracy (one scanner/room only provides room-level accuracy), discrete tracking of objects, costly to scale, can cause interference to wireless networks nearby</td>
<td>Expensive</td>
<td>Room-level, highly dependent on the scanners’ positions</td>
<td>RFID-based for healthcare applications (Chen 2010).</td>
</tr>
<tr>
<td>7</td>
<td>Infrared</td>
<td>Operates at frequency well above wireless communication systems, immunity to interference unlike radio signals</td>
<td>Requires line-of-sight condition, IR signals do not penetrate opaque materials (walls and ceilings), frequent requirement of having several receivers in each room</td>
<td>Expensive</td>
<td>Room-level and sensor dependant</td>
<td>Real time breathing-rate monitoring (Boccanfuso and O’Kane 2012), fall detection systems (Ariani et al 2013).</td>
</tr>
<tr>
<td>8</td>
<td>Camera-based positioning systems</td>
<td>Free from signal masking problem due to communication channels</td>
<td>Privacy invasion, computational expensive hardware and image processing algorithms, requirement to have multiple cameras</td>
<td>Expensive</td>
<td>Centimeters</td>
<td>Behaviour monitoring for the elderly (Jansena et al 2009), fall detection systems (Lin and Ling 2007).</td>
</tr>
<tr>
<td>9</td>
<td>Inertial systems via dead reckoning</td>
<td>Free from signal masking problem due to communication channels, suitable for hybrid systems (to complement other systems, e.g. Wi-Fi or GPS)</td>
<td>Drift errors, unreliable for long-term use</td>
<td>Low-cost</td>
<td>Room-level but reliable for short-term use only</td>
<td>Indoor pedestrian tracking (Torres and Cha 2010, Colombo et al 2011).</td>
</tr>
</tbody>
</table>
where \( b = [10 \ln(\sigma_{\text{dB}} \ln 10)]^2 \), \( \sigma_{\text{dB}} \) indicates standard deviation of the noise, \( n \) denotes path loss exponential \( \sin \theta_i = \frac{x_i - x_0}{d_i} \). Moreover, \( d_i \) denotes the distance from the device located at an unknown position \((x_0, y_0)\) to the base stations of known positions \((x_i, y_i)\). Here, \( d_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} \). Also, the angle of any base station with respect to certain reported positions can be computed as follows: \( \tan \theta_i = \frac{x_i - x_0}{y_i - y_0} \).

CRLBs for location tracking provide a lower bound on the location error, and they are often used as a standard benchmark for the comparison of implemented sub-optimal filtering algorithms under an assumption of unbiased estimators. From (1) it is apparent that geometrical configuration of the transmitters and receivers plays an important role in minimising the lower error bound of the position estimates obtained by this system. Besides, the characteristics of fading environments (reflected by the value of the path-loss exponent \( n \)) and the standard deviation of the noise, \( \sigma_{\text{dB}} \), play a crucial role in determining the accuracy of the system. A more comprehensive illustration related to the error signal under RSS measurements can be found in figure 2. It is apparent that the error is determined by the geometrical configuration of base stations as well as the characteristics of the environment. Therefore, to accurately determine the accuracy of an RSS-based system, it is essential to acquire some \textit{a priori} knowledge about the characteristics of the fading environment.

Meanwhile, location fingerprinting is an RSS-based positioning technique which relies on a unique pattern of RSS values from multiple transmitters to build up its fingerprint database in order to compute the most likely location of the mobile device. Generally, it has two essential phases: training and positioning. In the training phase, the RSSs within the areas of interest are mapped to generate the fingerprint database, while during the positioning phase the likelihood of the location is computed. Hence, this method will require careful consideration of the transmitter reference points. One major drawback of this technique is the requirement of maintaining considerably large database for adequate accuracy. Any \textit{a priori} knowledge about the characteristics of the fading environment will assist the system in determining the position of the object relative to the transmitter reference points.

### 2.1.2. Time of arrival (ToA)

Relying on the time it takes the electromagnetic signal to propagate from the target to the measurement unit, also informally known as time-of-flight (which is directly proportional to distance in a homogeneous material), we can triangulate the position...
of the target. While two-dimensional positioning requires at least three base transmitting units, for three-dimensional positioning we require at least four measurement units.

The major advantage of ToA is its rapid and more accurate estimation compared to RSS positioning. However, to achieve accurate measurements, the transmitters and receivers in the system must be precisely synchronised. Furthermore, information is needed on the internal delays of the hardware. An example of ToA-based positioning is given by the Wireless Ad-hoc System for Positioning (WASP), which produces a reasonably accurate system for athlete or sport monitoring applications (Sathyan et al 2011).

Furthermore, the CRLB of the ToA positioning method is given as follows (Sathyan et al 2011):

\[ \sigma_{\text{CRLB}}^2 \geq \frac{1}{8n^2\gamma^2\beta^2} \]  \hspace{1cm} (2)

where \( \gamma \) denotes the signal-to-noise ratio at the receiver, while \( \beta \) denotes the bandwidth of the system. From (2), it is evident that the lower bound on the positioning error is in inverse relation to the bandwidth of the system. In other words, the error signal is bandwidth-dependent due to the requirement of having a very sharp impulse signal to determine an accurate propagation time between the transmitters and receiver, in the face of an adverse fading environment. This leads to the concept of UWB systems for accurate localisation.

2.1.3. Ultra-wideband (UWB) systems. UWB systems operate using very short (in the time domain) RF impulses. The short time duration of the impulse requires a very large channel bandwidth for the transmitted signal. UWB systems are intended for applications that require high levels of positioning accuracy (i.e. towards sub-millimetre accuracy). The positions of objects can be determined by employing a ToA method, instead of RSS, leading to high accuracy. UWB systems are also somewhat immune to RF interference and multipath propagation due to the very short duration of UWB pulses, on the order of several nanoseconds. Thus, any
reflections (in a fading environment) have an extremely small opportunity to collide and cause signal degradation.

This also makes it possible to coexist with local Wi-Fi networks. However, UWB systems are very costly and not scalable due to lack of consistency in standards among countries (i.e. it is even illegal in some countries).

According to Zhang et al (2004), the CRLB of a UWB system is given as follows:

$$\sigma_{CRLB}^2 \geq \frac{\int_{-\infty}^{\infty} |X(f, n, t_0)|^2 df}{N \int_{-\infty}^{\infty} f^2 |X(f, n, t_0)|^2 df}$$

where $f$ indicates frequency, $t_0$ denotes the scaling factor of time, $X(f, n, t_0)$ denotes the Fourier transform of $x(f, n, t_0)$, which is the representation of the UWB pulses as a series of Gaussian monocycles scaled with respect to Gaussian waveforms $x(t) = \exp(-2\pi t^2)$, i.e. $x(f, n, t_0) = x^{(n)}(t, t_0)$, while $n$ indicates the order of differentiation, $N$ denotes the number of symbols in the observation period given the pulse is restricted within a symbol period and $\gamma$ indicates the signal-to-noise ratio (SNR). It turns out that frequency and SNR play crucial roles in determining the upper bound on positioning accuracy (lower bound on positioning error).

2.1.4. Time difference of arrival (TDoA). TDoA works on the concept of relative positions among the mobile devices, determined by computing the difference in time where multiple signals arrive at different receivers. This problem can be mathematically solved using the concept of correlation between transmitted and received signals. Given the transmitted signal $x_i(t) = s(t - d_i) + n_i(t)$ and the received signal $x_j(t) = s(t) + n_j(t)$ corrupted by noise $n_i, j(t)$ and time delay $d_i$, the cross-correlation between two signals can be mathematically given

$$\hat{R}_{x_ix_j} = \frac{1}{T} \int x_i(t)x_j(t - \tau)dt.$$

From the aforementioned, it is clear that the purpose of TDoA is to estimate the time difference represented by the value of value $\tau$. In other words, we aim to work out the value of $\tau$ that shall maximise $\hat{R}_{x_ix_j}$. While this technique can give reasonably accurate position estimates, it requires a precise and synchronised time reference between transmitter and receiver to achieve this accuracy.

To investigate the bound on the positioning error, the CRLB can again be calculated, as clearly stated in So et al (2008), as follows:

$$\sigma_{CRLB}^2 \geq \frac{6(1 + L\gamma)}{\pi LN\gamma^2},$$

where $L$ denotes the number of sensors, $N$ is the length of the vector of measurements which ideally should be sufficiently large. From equation (4), it is clear that SNR (denoted $\gamma$) as well as the number of receivers ($L$) play important roles in the best achievable localisation accuracy.

2.1.5. Angle of arrival (AoA). The angulation technique, also known as the direction finding method, measuring the position of the target based on the intersection of several pairs of angled direction lines formed by the radii from the directional receivers with respect to the target. To determine the location of a certain target on a 2D plane, we need at least two known reference points (fixed receivers) (Liu et al 2007) and two measured angles, while 3D positioning requires three fixed receivers units. This will obviate the need for having an accurate time synchronisation between receivers, compared to ToA. Furthermore, this measurement can be performed by using directional antennae or antenna arrays. Interested readers may refer

While this can be considered as advantageous (suitability for rapid deployment compared to RSS and the absence of clock synchronisation compared to ToA), the disadvantage of this technique is clearly related to the requirement for having relatively large and complex antenna arrays leading to expensive systems.

The CRLB of an AoA system under line-of-sight conditions, as clearly stated in Ananthasubramaniam and Madhow (2012), is given as follows:

\[
\sigma^2_{\text{CRLB}} \geq \frac{NR^2 \sigma^2}{\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \sin^2(\phi_i - \phi_j)}
\]

where \((\phi_i - \phi_j)\) is the angle difference between the neighbouring receivers and \(R\) is the distance between the receiver and the estimated location, \(N\) is the number of the receivers and \(\sigma\) is the standard deviation of the received noise.

2.1.6. Radio frequency identification (RFID) systems. Radio frequency identification (RFID) systems locate the position of a certain object based on its physical presence within the sensing range of an RFID scanner. These systems comprise of active scanners which will interrogate tags containing certain electronic codes, either actively as radio transceivers, or passively as attached to objects. The main advantage of an RFID system is its simplicity, since it does not require complex computation to estimate position.

Nevertheless, the use of RFID for real-time tracking still faces several challenges, since it may be less cost-effective for many applications due to the requirement to install multiple scanners across the sensing area, as a result of the relatively short working range; especially for passive tags. In addition, the system itself is not adaptive nor is it scalable in the sense that once the floor plan of the environment changes, scanners must be repositioned. This may not be an effective solution, especially in frequently changing or complex indoor environments. In addition, given the nature of RFID systems, the accuracy of RFID systems is quite dependent on the position of the scanners; one scanner per room, or per entrance way, will only give room-level accuracy.

2.1.7. Infrared (IR) systems. Infrared (IR) radiation occupies the portion of the electromagnetic spectrum where the wavelength is typically in the range 700 nm–1 mm, which is longer than that of visible light. All solid bodies with temperatures greater than absolute zero (0 K) emit electromagnetic radiation. According to Wien’s displacement law, the relation between the temperature of the solid body and the peak wavelength of the emission spectrum is given as: \(\lambda = \frac{cT}{\text{peak}}\), where \(c\) is the speed of light, \(3 \times 10^8 \text{ m s}^{-1}\), \(T\) denotes temperature in K and \(\lambda\) indicates the wavelength in \(\mu\text{m}\). Using Wien’s law, the specific peak emission wavelength of any material or body can be calculated.

IR temperature sensors receive radiation from targets in the field. Subsequently, the IR energy is isolated and measured using photosensitive detectors. Moreover, the detectors convert the IR energy into an electrical signal which is then further translated into a temperature value based on the instrument’s internal algorithms and the target’s emissivity (a term referring to the emitting qualities of the target’s surface).

This method has been used in a wide range of applications for both military and civilian purposes, such as thermal-IR imaging, night vision, surveillance and tracking, weather forecasting, medical imaging, and thermography, to name a few. Some examples of IR-based tracking systems for telehealth applications can be found in Ariani et al (2013), Ariani et al
Hao et al (2009) and Zhang et al (2011), where the authors combine IR sensors and pressure mat sensors to develop unobtrusive fall-detection systems for the elderly.

The main advantage of IR systems is their immunity to interference from most man-made communication technologies and electronics, since the electromagnetic frequency spectrum of IR radiation sits far higher than the spectrum of most other wireless communication systems. Also, considering the nature of IR radiation emitted by the human body, there is no need to build a specific transmitter for the purpose of indoor tracking, as the human body naturally emits infrared radiation and hence it can be directly employed as a transmitter.

However, considering the fact that IR radiation does not penetrate opaque materials (walls or ceilings), multiple receivers in each room are required to avoid losing track of the target. In addition, the transmitted signals require line-of-sight to be maintained. Also, the systems are sensitive to the natural background variations such as temperature variation due to the presence of sunlight, heaters and pets.

The two main types of infrared detectors are thermoelectric-based sensors (e.g. thermocouples) and photonics-based sensors (e.g. photodiodes and pyroelectric sensors.) While photodiodes/phototransistors use a semiconductor PN junction, which work based on the variation of current in response to the number of photons received, pyroelectric sensors work based on the ability of the materials to generate a voltage in response to the temperature variation which results in polarization.

2.1.8. Camera-based systems. While camera-based positioning systems are well-suited for indoor applications and can give reasonably good accuracy, especially for real-time tracking applications, they may be less favourable due to perceptions that they invade privacy and due to their affordability, and since these systems require expensive and complex image processing systems leading to a potentially large hardware cost for large-scale implementations; this hardware cost reflects the need for at least one camera in every room in order to accurately localise objects.

Some typical camera-based applications incorporated within telehealth systems can be found in Jansena et al (2009), where Jansen et al. developed behaviour-based monitoring systems for older people with an increased risk of falling, proposing an automated timed up-and-go test as well as long-term physical activity monitoring. In Yu et al (2009), Yu et al developed a fall detection system based on 3D estimates of head velocity and human shape information, by means of two cameras whose optical axes are orthogonal to improve these 3D estimates. While these applications may have good accuracy, implementation cost and complexity may limit their practical usefulness as the system requires not only expensive hardware but also complex image processing algorithms.

2.1.9. Dead reckoning (DR) via inertial sensors. Inertial sensors, such as accelerometers, gyroscopes, and magnetometers, can be employed to develop self-contained positioning systems, which utilize dead-reckoning (DR) techniques to estimate position. Given an initial coordinate position and velocity of a certain object, DR systems work by estimating the accelerations experienced by the sensor within the world coordinate frame and integrating twice to estimate the distance traveled along each direction. Measurements can normally be performed by means of inertial sensors; e.g. accelerometers, gyroscopes and magnetometers. Besides being simple and self-contained, DR localisation systems theoretically require no external signal for positioning, and therefore do not suffer signal occlusion problems as GPS and Wi-Fi systems do.

However, in practice DR systems are not suitable as stand-alone positioning systems due to certain limitations of inertial sensors, such as output offsets, which introduce errors that
accumulate over time unless some external signal is periodically received to reset the estimated position; in other words, they are effective for a very short period of time (this time being dependent on the accuracy demanded by the application) before requiring external correction. To overcome this limitation, several error correction techniques have been proposed in the literature, such as using hybrid positioning systems or advanced filtering techniques (Xu et al. 2009).

DR systems, also widely known as self-positioning systems, have been widely used in some vehicles to improve the reliability of GPS navigation systems, especially in the absence of direct line-of-sight paths to external localisation beacons (such as in tunnels or urban canyons). For instance, Xu et al. (2009) proposed integrating a Wi-Fi network with embedded GPS and DR systems for tracking vehicles in an urban area to overcome the effects of non-line-of-sight and multipath propagation. Unscented Kalman filters are also extensively used to improve the precision of GPS when the signal from a GPS satellite is obstructed.

As an example of an indoor healthcare application, Colombo et al. (2011) developed a wearable embedded inertial platform with wireless connectivity for indoor position tracking, combining the benefits of both techniques. This system offers several advantages, such as reducing the required wireless communication rate with the external localisation system, which in turn reduces power consumption, and improves scalability when multiple targets must be tracked (by reducing network traffic).

### 2.2. Advanced location estimation techniques

State estimators have been extensively used in various engineering applications to estimate some hidden variables which may not be available by direct measurement. In particular, state estimators can also be employed to support the development of highly reliable indoor location-aware systems, to improve their accuracy and to replace or enhance the functionality of some sensors. In addition, state estimators can also be employed to mitigate adverse impacts of system noise or measurement noise. In what follows, a review is presented of the two most widely used state estimators: extended Kalman filters and particle filters.

#### 2.2.1. Kalman and Extended Kalman filters (EKFs)

Over the last 40 years, Kalman filters (KF) have proven capable of obtaining optimal solutions to a somewhat restricted class of linear Gaussian problems (Ristic et al. 2004). KF are also well-known because of their optimality in solving linear dynamical systems with Gaussian noise. As a nonlinear extension of the KF, based upon linear time invariant (LTI) systems, extended Kalman filters (EKFs) have received much attention and are considered the most widely-used version of the KF in the past few decades (Arumlaamplam et al. 2002, Ristic et al. 2004).

For healthcare applications such as indoor pedestrian tracking, a KF requires information from external sensors; e.g. gyroscope and accelerometer. Given the initial coordinate position of the object, the future position can be estimated through several iterative steps comprising of both time and measurement updates in line with the dynamics of the system. In the time update, we project the state and error covariance ahead using the mathematical model of the system represented by a state space model and the information related to noise covariance model, while in the measurement update we compute Kalman gain $L$ as well as performing an update of the states and covariance of the error. This process is iterative in nature and its convergence is determined by the eigen-values of the Kalman filter.
The EKF concept is based on the linearisation of nonlinear system models around an estimated solution point, and this estimated solution is obtained using a standard KF with a linear system model (Arumlamplam et al., 2002). KF have been extensively studied to improve the performance of location-aware medical systems. For instance, Torres and Cha (2010) developed the InertiaCube3, which is a wearable pedestrian indoor localisation system with dynamic position correction by means of an EKF. Meanwhile, Au et al. (2013) proposed indoor tracking and navigation assisted by map-adaptive KFs.

2.2.2. Particle filters (sequential monte carlo (SMC) methods). To overcome the technical limitations of KFs, there has been a surge of interest into nonlinear and non-Gaussian filtering methods. Sequential Monte Carlo estimation methods, collectively referred to as particle filters, have been the most popular method for stochastic dynamic estimation problems (see Arumlamplam et al., 2002, Danescu et al., 2009 and Ristic et al., 2004).

Compared to EKFs, particle filters offer an array of additional benefits, especially in the presence of non-linear components in the system model as well as uncertainty in the noise model. It handles non-Gaussian noise more effectively when compared to conventional Kalman filters (Gustafsson et al., 2002, Ristic et al., 2004, Gustafsson and Gunnarsson, 2005, Simon, 2006). In fact, the more non-linear the system and the more non-Gaussian the noise, greater are the benefits obtained by employing particle filters compared to its KF counterpart (Simon, 2006).

In addition, particle filters also ease the mathematical complexity of the algorithm, since there is no need to perform a local mathematical linearisation of the non-linear system. Although the initial disincentive for considering particle filters for real-time applications relates to their computational expense, due to the need to assign a large number of particles to achieve a reasonably good estimate, this issue is being progressively mitigated due to the increased speed of hardware processing systems nowadays. Yet another benefit of particle filters, compared to their EKF counterparts, especially for location-aware healthcare systems, is the ability to use a priori knowledge within the estimate, such as digital map information, to substantially enhance its accuracy. For instance, the authors assigned weights of zero to particles that cross a wall boundary leading to a significant improvement in accuracy (Harle, 2013).

Considering the nature of the particle filters which can be regarded as a statistical, brute-force approach of estimation theory, the cloud of particles is randomly allocated, at least for initial conditions. However, as time progresses, these particles will be gradually shifted in line with the motion of the objects. Particles that can better explain the true states will be more heavily weighted, while particles which are located far from the true states will lose weight. Thus, this random allocation may statistically lead to significant computational burden, as the accuracy of the system will be improved by having a reasonable number of points, although beyond a certain threshold, further increasing the number of particles may not significantly enhance the accuracy of the prediction.

Overall, we can consider the particle and the Kalman filters as virtually two opposite ends of the spectrum of Bayesian estimators. Under Gaussian noise conditions and for a linear system model, the Kalman filter is an optimal state estimator. However, in the face of non-linearity in the system model and non-Gaussian noise distributions, the EKF is no longer an optimal solution, and its tracking performance gradually degrades as the noise and system properties diverge from Gaussian and linear, respectively. Considering this issue, at some point, the particle filter can outperform the EKF, although it may introduce computational complexity as a trade-off. Nevertheless, considering current computer processor capabilities, this complexity is not a big issue; as it was in the past.
3. Current state-of-the-art applications of localisation for healthcare

This section discusses current state-of-the-art applications of IPS to support the development of indoor location-aware healthcare systems. Highlighted are the pros and cons of each application based on reported literature. Tables 2 and 3 summarise the discussion.

3.1. Tracking people with chronic illness

One of the leading causes of mortality, especially among the elderly, is chronic illness, such as cardiovascular disease. Cardiovascular disease refers to various medical conditions that affect the state of the heart and blood vessels, and include coronary artery diseases such as congestive heart failure (CHF), myocardial infarction (MI), angina, arterial sclerosis (i.e. hardening of the arterial walls), stroke, and peripheral vascular disease. Likewise, lung diseases (e.g. bronchitis, emphysema and chronic asthma), under the umbrella of chronic obstructive pulmonary diseases (COPD), which reduce lung function and prevent people from breathing normally (Maglogiannis and Hadjiefthymiades 2007) are also serious chronic medical conditions that require constant supervision. While those suffering from chronic disease are encouraged to stay active, the ability to locate such patients within reasonably short period of time is critical especially when a medical emergency has occurred.

Likewise, people suffering from degenerative cognitive impairments, such as Alzheimer’s disease or dementia, also require special attention for their safety and wellbeing. While they may be allowed to move freely, it is essential to have the ability to quickly locate and assist them should they need assistance due to unexpected medical circumstances.

In fact, there have been numerous benefits of employing IPS to remotely monitor people suffering from concerning medical conditions. The first benefit is to improve outcomes and the quality of care; see Cowie and Lobos (2012). Second, smart home systems can provide more convenient and comprehensive health monitoring, especially to out-of-hospital patients; however, developing well-integrated telemonitoring systems to address existing healthcare needs is a challenging problem, mainly due to trades-offs among numerous factors, such as accuracy, compliance, complexity, suitability, privacy and deployment costs. In what follows, several well-known health and wellbeing monitoring applications are described, followed by a discussion related on the pros and cons of each system. These systems are summarised in entries A1–A6 of table 2.

Leijdekkers and Gay (2006) developed a personalised heart monitoring system using a smartphone and wireless sensors which is capable of monitoring the health condition of those who are prone to heart attack. The system will alert emergency response personnel and caregivers when the patient experiences a critical cardiac event. The system is also capable of transmitting sensor data to a healthcare centre for remote monitoring by a cardiologist or nurse. The system employs the use of both Wi-Fi and GSM systems to determine the user’s location indoors and GPS when outdoor and in clear line-of-sight to GPS satellites. This will typically lead to an accuracy of several meters when using GPS and at least room-level accuracy when indoors.

This system allows for continuous longitudinal personalised heart monitoring. Local processing on the smartphone will enable remote monitoring without any need to be continuously connected to a healthcare centre. This will likely reduce the workload of the allied care team, and motivates the patient to engage in self-care. A drawback of this system is relates to the requirement to carry the smartphone at all times (Lee et al 2007, Bianchi et al 2010) which may lead to several compliance issues, especially for those also suffering certain cognitive
Table 2. Current state-of-the-art applications of localisation for healthcare: a comparative review. While group A depicts healthcare applications to assist people suffering from chronic illness, group B discusses applications related to the tracking of wellbeing.

<table>
<thead>
<tr>
<th>No</th>
<th>Telehealth systems/ projects</th>
<th>Benefits</th>
<th>Positioning methods</th>
<th>Cost</th>
<th>Resolution</th>
<th>Unobtrusiveness</th>
<th>Appropriateness</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Remote monitoring for cardiac patients (Leijdekkers and Gay 2006)</td>
<td>Remote monitoring during rehabilitation programs</td>
<td>RSS-based hybrid GPS-Wi-Fi system</td>
<td>Medium</td>
<td>Several meters outdoor or room-level indoor</td>
<td>High</td>
<td>Compliance issues; requires some computer skills to operate</td>
<td>Real-time experiment resulting in 99.42% sensitivity and 99.51% positive predictive value.</td>
</tr>
<tr>
<td>A2</td>
<td>Patient-centric medical system (Wu et al 2012)</td>
<td>Remote monitoring and emergency alarm for both patients and doctors; Save time; Reduce cost; Reduce mortality</td>
<td>GPS for outdoor and Wi-Fi for indoor</td>
<td>Expensive</td>
<td>Room-level</td>
<td>High</td>
<td>Unsuitable for those suffering cognitive impairment; Requires computer skills to operate</td>
<td>Prototype implementation resulting in 76% location accuracy.</td>
</tr>
<tr>
<td>A3</td>
<td>Real-time breathing rate monitoring (Boccanfuso and O’Kane 2012)</td>
<td>Rehabilitative robotic applications such as post-stroke and post-operative cardiac therapies</td>
<td>Single point infrared sensor</td>
<td>Low-cost system</td>
<td>Around 1% of the measured values</td>
<td>High</td>
<td>Not suitable for everyone; Compliance issues</td>
<td>Real-time experiment with 70% successful rate.</td>
</tr>
<tr>
<td>A4</td>
<td>Medical sensing, localisation, and communications (MELODY) (Chavez et al 2009)</td>
<td>Provides in-body tracking and imaging</td>
<td>Capsule endoscope camera on UWB platform</td>
<td>Expensive</td>
<td>Millimeter</td>
<td>High</td>
<td>Limited for use by medical practitioners only</td>
<td>Prototype development.</td>
</tr>
<tr>
<td>A5</td>
<td>Orthopedic surgical navigation (Mahfouz et al 2011)</td>
<td>Extremely accurate system for medical surgery</td>
<td>ToA-UWB</td>
<td>Expensive</td>
<td>Millimeter and smaller</td>
<td>High</td>
<td>Limited for use of medical practitioners only</td>
<td>Simulation study using 6 base stations and 8 tags.</td>
</tr>
</tbody>
</table>

(Continued)
### Table 2. (Continued)

<table>
<thead>
<tr>
<th>No</th>
<th>Telehealth systems/projects</th>
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<th>Appropriateness</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A6</td>
<td>Indoor wayfinding system for individuals with cognitive impairment (Chang et al 2008)</td>
<td>Increase workplace and life independence for cognitively impaired</td>
<td>RFID; Bluetooth</td>
<td>Low-cost</td>
<td>Room-level</td>
<td>Medium</td>
<td>It requires an ability to operate a personal digital assistant; Hardware is fragile and outdoor usefulness subject to weather conditions</td>
<td>12 cognitively impaired participants across 9 groups, each takes 4 routes. The percentage of deviation from the route is 7.3%.</td>
</tr>
<tr>
<td>B1</td>
<td>ARA (Automatic recogniser of ADLs) (Magherini et al 2013)</td>
<td>Classify and monitor ADLs</td>
<td>Stereo cameras</td>
<td>Expensive</td>
<td>Highly accurate</td>
<td>Medium</td>
<td>Privacy and compliance issues</td>
<td>3 subjects and 20 indoor objects, each subject performed a randomly selected subset of activities 12 times.</td>
</tr>
<tr>
<td>B2</td>
<td>ActionSLAM (Simultaneous Localisation And Mapping) (Hardegger et al 2012)</td>
<td>Indoor pedestrian tracking to support activity monitoring in the context of home assistance or rehabilitation</td>
<td>Wearable inertial sensors</td>
<td>Expensive</td>
<td>Several meters</td>
<td>High</td>
<td>Compliance issues for those suffering from cognitive impairment</td>
<td>Dataset of 1.69 km of walking in 3 rooms, with 241 location-related actions. Overall, the system achieves a mean tracking error of 1.2 m, with map error of 0.5 m.</td>
</tr>
<tr>
<td>B3</td>
<td>Context aware application (Hristova et al 2008)</td>
<td>Support development of ambient homecare system</td>
<td>RSS</td>
<td>Expensive</td>
<td>Room-level</td>
<td>High</td>
<td>Complicated; Not suitable for those suffering cognitive impairment</td>
<td>Unspecified.</td>
</tr>
</tbody>
</table>

(Continued)
### Table 2. (Continued)

<table>
<thead>
<tr>
<th>No</th>
<th>Telehealth systems/projects</th>
<th>Benefits</th>
<th>Positioning methods</th>
<th>Cost</th>
<th>Resolution</th>
<th>Unobtrusiveness</th>
<th>Appropriateness</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>B4</td>
<td>Indoor tracking system with special focus on energy minimisation (Köhler et al 2010)</td>
<td>Support ambient assisted living environments</td>
<td>TDoA-based hybrid ultrasound and RF systems</td>
<td>Low-cost</td>
<td>Sub-meter</td>
<td>High</td>
<td>Not suitable for those suffering from cognitive impairment</td>
<td>Unspecified.</td>
</tr>
<tr>
<td>B5</td>
<td>Ambient assisted living system (Nazemzadeh et al 2013)</td>
<td>To assist older people navigating indoor environments</td>
<td>EKF, two encoders, a gyroscope, a short-range RFID and a camera</td>
<td>Expensive</td>
<td>Several meters</td>
<td>High</td>
<td>Compliance issue for those suffering from cognitive impairment</td>
<td>Computer simulation of visually impaired people.</td>
</tr>
<tr>
<td>B6</td>
<td>ADL monitoring system (Krassnig et al 2010)</td>
<td>To classify postures and activities</td>
<td>Three-axis accelerometer supported with decision tree and neural network</td>
<td>Low-cost</td>
<td>Room-level</td>
<td>High</td>
<td>Compliance issues</td>
<td>2 female and 4 male, age: 28.7 ± 2.8 years performing 7 different postures and 4 different activities. Overall, the system achieves overall accuracy of 98.99%. Initially 6 participants, and then 24 within 1400 min of recorded data. Overall, the system achieves 98% accuracy.</td>
</tr>
<tr>
<td>B7</td>
<td>Smartphone-based ADLs (Gairy et al 2012)</td>
<td>Monitoring ADLs</td>
<td>Smartphone accelerometer with dedicated chest sensor</td>
<td>Low-cost</td>
<td>Room-level</td>
<td>High</td>
<td>Compliance issues</td>
<td></td>
</tr>
</tbody>
</table>

Note: We estimate the range of costs as follows. Low cost is defined as AUD 250 per person monitored. Medium cost fall within AUD 251—AUD 800 per person monitored. High-cost is more expensive than AUD 800 per person monitored.
Table 3. Current state-of-the-art applications of localisation for healthcare: a comparative review. While group C discusses cutting-edge fall detection systems, group D explicates indoor navigation systems for visually impaired people.

<table>
<thead>
<tr>
<th>No</th>
<th>Telehealth systems/projects</th>
<th>Benefits</th>
<th>Positioning methods</th>
<th>Cost</th>
<th>Resolution</th>
<th>Unobtrusiveness</th>
<th>Appropriateness</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Fall-detection systems (Lee et al 2007, Bianchi et al 2010)</td>
<td>Detect and locate fallers to summon immediate help</td>
<td>Wearable inertial sensors</td>
<td>Low-cost</td>
<td>Several meters</td>
<td>High</td>
<td>Compliance issue for those suffering from cognitive impairment</td>
<td>30 subjects, aged between: 26.9 ± 3.61 years old. They performed 4 activities repeated 3 times each, making up of 360 trials. Overall the system achieves 93.2% fall detection rate.</td>
</tr>
<tr>
<td>C2</td>
<td>Fall-detection systems (Lee and Mihailidis 2005, Yu et al 2009, Hazelhoff et al 2008)</td>
<td>Detect and locate fallers to summon immediate help</td>
<td>Camera-based head tracking (Rougier et al 2006, 2007)</td>
<td>Expensive</td>
<td>Room-level</td>
<td>Completely unobtrusive</td>
<td>Suitable for all, yet suffers from privacy issues</td>
<td>21 subjects aged 20–40 years old, with 1.52–1.9 m heights performing 5 scenarios, each repeated 3 times. The system achieves detection accuracy of 77%, missed falls 23%, and false alarm rate of 5%.</td>
</tr>
<tr>
<td>C3</td>
<td>Fall-detection system (FADE) (Popescu et al 2008)</td>
<td>Detect and locate fallers to summon immediate help</td>
<td>An array of acoustic sensors</td>
<td>Low-cost</td>
<td>Room-level</td>
<td>Completely unobtrusive</td>
<td>Suitable for all</td>
<td>A trained stunt actor to mimic an elderly faller, within 6 sessions of 15 min experiment, making up 1.3 h in total. The use of height information successfully reduces the hourly rate of false alarms from 32 to 5, with 100% sensitivity.</td>
</tr>
<tr>
<td>C4</td>
<td>Fall-detection systems (Zhang et al 2011, Ariani et al 2012, Ariani et al 2013)</td>
<td>Detect and locate fallers to summon immediate help</td>
<td>Infrared sensors and pressure mats</td>
<td>Low-cost</td>
<td>Room-level</td>
<td>Completely unobtrusive</td>
<td>Suitable for all</td>
<td>Multiple person simulation comprising of 15 scenarios (i.e. 3 ADLs and 12 different types of falls). Overall, it achieves sensitivity of 100%, specificity of 77.14%, and accuracy of 89.33%.</td>
</tr>
</tbody>
</table>

(Continued)
<table>
<thead>
<tr>
<th>No</th>
<th>Description</th>
<th>Benefits</th>
<th>Positioning methods</th>
<th>Cost</th>
<th>Resolution</th>
<th>Unobtrusiveness</th>
<th>Appropriateness</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Navigation for the blind (Cascalheira et al. 2012)</td>
<td>Helps visually impaired navigate indoors</td>
<td>Multiple antennas with very narrow radiation pattern mounted in every doorway</td>
<td>Expensive</td>
<td>Room-level</td>
<td>High</td>
<td>Suitable for most</td>
<td>Simulation and lab evaluations of the proposed antenna array.</td>
</tr>
<tr>
<td>D2</td>
<td>Waypoint navigation for the blind (Riehle et al. 2013)</td>
<td>Helps visually impaired navigate indoors</td>
<td>Inertial DR with real-time auditory feedback, supported with information from the mapped route</td>
<td>Low-cost</td>
<td>Decreased error compared to traditional DR approaches</td>
<td>Medium</td>
<td>May not be suitable those with cognitive deficits</td>
<td>Prototype development and pilot human trials aged between 18–59; comprising of 8 sighted individuals and 8 blind persons (total/partial).</td>
</tr>
<tr>
<td>D3</td>
<td>Navigation for the blind (Oktem and Aydin 2008)</td>
<td>Guiding visually disabled people in a store and helping access information</td>
<td>RFID and RSS</td>
<td>Moderate</td>
<td>Within range of tags</td>
<td>Medium</td>
<td>Unsuitable for those with cognitive deficits</td>
<td>It achieves overall height error of 2.7 m at 4%.</td>
</tr>
<tr>
<td>D4</td>
<td>Wayfinding for the visually impaired (Tjan et al. 2005)</td>
<td>Guiding visually disabled people to navigate indoor</td>
<td>Passive retro-reflective tags, hand-held camera and machine-vision system</td>
<td>Low-cost</td>
<td>Within the line-of-sight between tags and camera</td>
<td>Medium</td>
<td>Unsuitable for those with cognitive deficits</td>
<td>Prototype design of hand-held system.</td>
</tr>
</tbody>
</table>

Note: as with the previous table, we estimate the range of costs as follows. Low cost is defined as AUD 250 per person monitored. Medium cost fall within AUD 251—AUD 800 per person monitored. High-cost is more expensive than AUD 800 per person monitored.
deficits. In addition, it also requires the ability of the users to operate the smartphone which may become an obstacle for current older generations.

Wu et al (2012) developed a patient-centric medical system supported by a location tracking system; the latter based on a combination of GPS for outdoor positioning and Wi-Fi RSS-based fingerprinting for room-level indoor accuracy. The system aims to save time and money as well as to improve patients’ quality of life by providing remote monitoring and emergency alarming for both patients and doctors. The system can directly send a message to doctors’ mobile phones to alert them should an adverse event occurs.

The authors employed a $k$-nearest neighbour classifier to determine which room the patient was in. The training phase of this classifier requires the collection a large amount of AP (Access Point)-RSS readings from each room. Assigning a new $n$-dimensional vector of RSS values (from $n$ APs) is achieved by finding the $k$ closest training vectors to this test vector and choosing the room most often associated (a majority vote) with these $k$ vectors.

Supported by its extended coverage, via the use of a hybrid GPS/Wi-Fi location system, this system will also allow users to engage in outdoor activities. Data transfer is also performed via 3G/GPRS/Wi-Fi systems, sending medical and location information to a back-end cloud service. This system may also suffer from compliance issues due to the requirement for the user to carry and operate the smartphone. The Wi-Fi-based room-level detection accuracy of approximately 76% may not be sufficient to deal with events involving medical emergency.

In Chavez et al (2009) and Mahfouz et al (2011), the authors developed UWB-based in-body tracking systems to achieve sub-millimeter resolution. These systems can perform medical imaging to assist medical practitioners. Despite its accuracy, the proposed system may be costly, due to complex RF hardware requirements and processing algorithms. Another issue, as described in Chavez et al (2009), relates to the possibility of mutual interference with other systems when integrating medical devices into a single network based on the use of UWB, since this frequency band is shared with other narrow-band communication systems. Therefore, new interference avoidance techniques for spectrum sharing, such as cognitive radio, become important.

For tracking people with cognitive impairment, such as Alzheimer’s disease and dementia, Chang et al (2009), (2008) developed indoor wayfinding systems, based on passive RFID (Chang et al 2008). Using a personal digital assistant (PDA) or smartphone, the device will guide the user to navigate indoor using photographs (images of room layouts) and provide directions to certain locations.

The system employs passive RFID tags as a new traffic sign system to provide automatic guidance to the user, aiming to instill an increased sense of security. The major advantage of this system, compared to sensor network approaches, is its simplicity and immediate response. This system is also considered more economical, while also being reliable. However, depending on the severity of the user’s cognitive impairment, this system may not be suitable for those without the requisite skill or ability to operate the PDA or smartphone. Hence, this may limit the benefit of this system.

3.2. Tracking of wellbeing by monitoring activities of daily living (ADL)

One innovative solution to assist the elderly to live independently is by developing so-called ‘intelligent environments’. These systems can be used to continuously monitor activities of daily living (ADL) as well as ensure safety and support wellbeing. Researchers around the globe have developed various instantiations of such systems, aiming to facilitate a concept of care referred to as ‘ambient assisted living (AAL)’. In what follows, several state-of-the-art applications of intelligent environments for monitoring ADL are described.
Magherini et al (2013) developed a system, termed ARA (Automatic Recogniser of ADL), which employs propositional temporal logic and model checking to support automated real-time recognition of ADL within a smart environment. In this work, human behavioural patterns are categorized by means of formulae of propositional real-time and compared against the flow of events occurring within a smart system. The authors demonstrate that the logic they developed performed satisfactorily when managing observation streams obtained from stereo cameras to locate and identify the actions of single person. However, this method is somewhat complex in terms of processing required, and user acceptance of the system may be disadvantaged by its intrusive nature. As stated by the authors, the complexity of human activities may affect the complexity of the algorithm itself (e.g. a user may have two concurrent activities or switch from one to another). The system was also not designed to operate in an environment where there are multiple persons working together. It is also important to note that the poorer the resolution the harder it will be to infer specific activities, and some activities may be impossible to confirm using location information alone, such as whether a person is asleep or simply resting on a bed.

Subsequently, Hardegger et al (2012) proposed ActionSLAM (where SLAM denotes simultaneous localisation and mapping) for pedestrian indoor tracking that makes use of body-mounted sensors to support activity monitoring in the context of home assistance or rehabilitation. The system actively maps the environment and localises users. Furthermore, by means of foot-mounted inertial sensor, user trajectories through the environment can be identified. Meanwhile, drifting error accumulation within a particle filter framework can be directly compensated through observations of location-related actions (e.g. sitting on chair or standing) estimated using the body-mounted inertial sensors. One benefit of this system is the lack of requirement for external radio beacons, such as a Wi-Fi AP. Yet another benefit is the lower computational expense of the processing algorithms, as it only employs 1000 particles to achieve robust mapping, compared to 10 000 particles making it well-suited for real-time smartphone applications. Its lessened computational demand will make the algorithm suitable for systems with limited computational capabilities. However, this system may not be suitable for those suffering from cognitive impairment due to the requirement to carry several sensors, as such users may have difficulty adhering to this requirement due to memory and other cognitive deficits.

Hristova et al (2008) designed a context-aware application, known as ‘the Context Toolkit’ which was intended to support the development of an ambient homecare system. In other words, these systems aim to ease the burden of everyday life for elderly people who decide to live independently at home. The system employed RSS from beacons placed in different locations within the home, which serve as the source of location information. The main advantage of this system is its scalability, as it can be expanded to simultaneously monitor several users without modifying the algorithm. The main drawback is the requirement for the users to carry multiple devices (e.g. heart rate monitor, PDA, and mobile phone with RFID reader, and a sensor for measuring signal strength). This will increase its degree of obtrusiveness and limit its practical usefulness. In their future work, the authors state that they will try to integrate some devices to minimise the burden on end-users who must carry these many devices.

Köhler et al (2010) developed an IPS, placing special focus on energy minimisation in the context of AAL environments. The system employs a hybrid of ultrasound and RF technologies for three-dimensional indoor positioning by means of wall-mounted anchor beacons. Positioning is achieved through TDoA distance measurement via a multi-lateration algorithm. Furthermore, the authors employ a wake-up scheduling strategy for the wall nodes to reduce energy consumption; that is, to let the sensors enter a low-power sleeping state between positioning cycles and later activate them using a distinct ultrasonic pulse from the mobile device acting as a beacon. Besides being environmentally friendly in the sense of minimising energy
usage, another benefit of this system is its easy installation because there is no need for additional wiring. The system achieves room-level (sub-metre) accuracy. Again, as with all body-worn technologies, this method may not be suitable for those with cognitive impairment.

Nazemzadeh et al (2013) developed a smart rollator (rolling walking frame) by leveraging indoor position tracking to assist elderly people to navigate indoor environments (e.g. shopping malls, railway stations or airports). The system employs an EKF as a state estimator to filter data obtained from sensors (a gyroscope, a short-range RFID system and a camera). The system successfully achieved low-rate sampling and high-accuracy position estimation despite a large distance between RFID tags (within a few metres) hence minimising the number of RFID tags deployed. However, its practical usefulness may be limited by its complexity and obtrusiveness, due to the need to carry a device. The device may not be suitable for those suffering from cognitive impairment, while some people may be reluctant to use it as it becomes a public sign of their physical condition.

In Kautz et al (2002), developed an assisted cognition system to enhance the quality of life for those suffering from Alzheimer’s disease by assisting them with spatial orientation in indoor and outdoor environments. The system, known as ‘the activity compass’, which comprises of a hand-held device equipped with a large arrow (like a compass) to guide the person to reach their destination.

Based on a concept that artificial intelligence technology can support the failing memory and problem solving abilities caused by neurodegenerative disease, the system employs a client-server configuration, which means client devices handle interaction with the user while the server stores information from the sensors, constructed models as well as other background information. Furthermore, the system also needs to acquire a model of the person’s activity, such as favourite walks and destinations in order to comprehend the typical behaviour of the person.

The system works as follows. Assisted with GPS for outdoor positioning, the system can detect the current state of orientation of the user, especially if they have lost direction or appear to be wandering around for an extended period of time, and accordingly guide the user home by providing reliable visual guidance. Furthermore, when operating indoors, the system relies on the availability of indoor positioning systems to direct the person towards specific locations (e.g. to the kitchen at meal time or to the medicine cabinet). While considered to be reasonably accurate, with room-level resolution, its benefit may be limited by the ability of the user to operate and interpret the hand-held guidance device and by the requirement to carry the device at all times. The paper does not report any information related to the number of people studied or their demographics.

Giraldo et al (2002) developed a new platform to assist those suffering from moderate Alzheimer’s disease. The authors present a mobile system, known as a Mobile Patient Care-Giving Assistant (mPCA) comprising of local indoor positioning systems, Java-based smartphone applications, and other wireless and visual sensors. More specifically, the system aims to reduce the burden of care on the patient’s family. The system aims to leverage the ability of smartphones to effectively interact with multiple sensors, sending reminders for critical tasks, and orientating the patient, while monitoring their activity.

One important feature of the proposed algorithm is its attention capture feature, implemented using a state machine. If the patient’s attention wanes, the system will try to increase their attention levels through escalating interventions (e.g. by calling the patient’s name and requesting the user to perform a task). Furthermore, the system employs an ultrasonic subsystem to identify the posture or location of the patient, and to select a suitable monitor to play a video clip. The system can also release fragrances (e.g. artificial food) to stimulate patients. However, this system requires the user to mount tags on their shoulder, acting as active beacons, and may limit the usefulness of the proposed system (e.g. as users forget to wear it).
Similarly, to support person-centered care, Kanai (2002) introduced AwareRium, which can be regarded as an enhanced group home to provide care for Alzheimer’s and dementia patients. Using ultrasonic and active RFID localisation, the system aims to recognise danger in the environment, based on the location of the patient and their interaction with the environment, and sound cues. The audio cues are designed to closely resemble the sounds of tasks which the system believes the patient is engaged in. If the systems’ confidence in estimating this activity is low, it will mask the audio cue with a hissing noise to make it more difficult for the carer to interpret, reflecting this lack of confidence in the estimated situation. This system could potentially reduce the burden of care on caregivers in a large group home.

3.3. Fall detection systems

One of the leading causes of death and disability for those aged 65 years and over is accidental falls. Fall rates are worryingly high, with one in three people in this age category experiencing at least one fall per year (Tinetti 2003). Also, as people grow older, their risk of suffering an unintentional fall progressively increases, as illustrated in figure 3.

There are two main reasons for the occurrence of unintentional falls. The first is due to intrinsic factors related to ageing, such as neuro-degenerative disorders, Parkinson’s disease, decrease in muscle strength, balance, and vision, while the second reason relates to extrinsic risk factors, such as effects of medications, slippery floors, poor lighting, and obstacles in the environment (Tinetti 2003, AGS 2001). Interestingly, fear of falling is also a recognised risk factor for the occurrence of future falls (Tinetti 2003).

According to Abbate et al (2012), one primitive version of a fall detection system, known as personal emergency response system (PERS), in the form of compact battery-powered device, equipped with a help button, and worn with a belt or wrist band. Such systems have an embedded radio transmitter which transmits a signal to a base station (speaker phone), located within the user’s home, that can automatically dial to an emergency response center to summon assistance. However, the main problem with this system relates to a potential inability of fallers to press the button after a fall due to various reasons, such as injury, the final position of the body, and consciousness, and cognitive decline.
3.3.1. The cost of falls. There are three main possible adverse outcomes after a fall: no injury, but an increased fear of falling and subsequent limiting of activity; injury; and fatality. The associated medical costs to cover 10,300 fatal and 2.6 million non-fatal injuries in the US in the year 2000 was around $19.2 billion. Of that amount, direct medical costs for fatal injuries were around $200 million dollars while the non-fatal injuries accounted for the remaining $19 billion (Stevens et al 2006).

The same authors also found that among the cost components for non-fatal fall-related injury, hospitalisation took the biggest share of 63%, while emergency department visits, which constitute around 16%, was the joint second largest cost along with outpatient treatment (also 16%). Compared to men, medical expenditure for women was higher, costing 2–3 times more across all medical treatments. In addition, although fractures only constitute 35% of non-fatal injuries, their medical treatment is expensive, constituting 61% of the total costs, that is, the costs of treating non-fatal injurious falls.

3.3.2. Place of occurrence of falls and related activities. According to a report written by AIHW (2013), represented in figure 4, about 70% of falls occurred within indoor environments (e.g. at home or in aged care facilities).

Home and residential areas are places where falls occurred most frequently, as constituting around 6 in every 7 cases (85%), with outdoor areas around the home (e.g. garden) and the bathroom and the bedroom the most common places of occurrence. However, this level of detail was only available for about half the cases that occurred in the home. Meanwhile, aged
care facilities took second place, accounting for 10% of indoor falls involving people aged 65 years or older resulting in hospitalisation.

Most indoor falls occurred during unspecified activities, accounting for 35% of all cases. Resting, eating and sleeping are the three most common vital indoor activities during which falls most frequently occurred both in men and women, constituting around 49% of cases with a specified activity. Furthermore, work for income, sport and leisure activities only made up around 2.5% of all outdoor falls.

Considering the serious consequences associated with falls, we reinforce the importance of monitoring individuals at risk of falling using automatic detection systems to summon help should a fall occur.

### 3.3.3. Current state-of-the-art fall detection systems

To ease the burden of falls, especially among the elderly, fall detection systems have been extensively studied. The main research challenge in designing robust fall detection system is to accurately recognise fall events among other ADL which may have a high degree of similarity; e.g., jumping, sitting, lying down. Accordingly, the most challenging aspect of this research problem is to achieve a delicate balance between maximising detection rate and minimising false positive rate; while a system with a high false negative detection rate is clearly undesirable (failing to recognise true falls), a system with high false positive rate is equally undesirable due to repeated unnecessary false alarms.

We first discuss fall detection systems based on the use of cameras. Lee and Mihailidis (2005) employed a camera mounted on the ceiling to track the user’s movement and to detect the occurrence of falls by observing if there is a long period of inactivity beyond the normal zones of inactivity (e.g. chairs and sofas). Hazelhoff et al (2008) proposed a system with two uncalibrated cameras and employed a Gaussian multi-frame classifier. To recognise fall events, they employed the two features of the direction of the main axis of the body and the ratio of the variances of the motion in vertical and horizontal directions. Subsequently, Yu et al (2009) attempted to detect falls based on the use of the 3D horizontal and vertical velocity information of the head obtained by camera-based head tracking, using a variable state model particle filter. Furthermore, Rougier et al detect falls by means of head tracking (Rougier et al 2006) and human shape analysis (Rougier et al 2007).

The use of cameras could be considered by some users to invade their privacy. This may hinder the ultimate acceptance of cameras-based system (Zhang et al 2011). In addition, image processing algorithms can be costly due to their complexity and expensive hardware requirements. Furthermore, as stated in Lin and Ling (2007), one disadvantage of such a system is its inability to detect falls when the subject attempts to break the fall, falling more slowly, and that real-time transmission of video impedes system scalability (unless extensive local video processing is performed at the captured point, which would significantly reduce the battery life of the camera sensors).

An acoustic based-fall detection system using a vertical array of microphones was proposed by Popescu et al (2008). In an attempt to reduce the false alarm rate, they employed an array of acoustic sensors to obtain sound source height information. The main benefit of this system is its complete unobtrusiveness, as the subjects were not required to wear a sensor. While this system was able to achieve 100% sensitivity, its false positive rate was still reasonably high, at five false detection per hour (Popescu et al 2008). The system was tested on 23 real falls, performed by an actor trained to fall like an older person. The use of height information reduced the false alarm hourly rate from 32 to 5, at a 100% detection rate.

Likewise, to address the trade-offs between unobtrusiveness and complexity, Zhang et al (2011) developed a simple and yet reasonably accurate fall detection system using infrared
and pressure mat sensors. While this system could serve as a solution for unobtrusive fall detection, there were several issues which require improvement. Firstly, the sensitivity of the simulated PIR sensor was assumed to be uniform over the entire coverage area (Zhang et al. 2011) although in practice standard NaPiOn motion sensors from Panasonic Electric have a complicated 3D pattern of wedge-shape detection regions accompanied with some dead zones between sensors due to geometry of the sensor’s Fresnel lens. In addition, the sensitivity of PIR sensor decreases as the distance from the sensor grows, caused by reduced thermal energy. Nevertheless, this work has clearly proven that low complexity and complete unobtrusiveness can also go hand-in-hand, achieving a sensitivity of around 89% and a specificity of 100%.

To address the aforementioned issue, Ariani et al. (2013) and Ariani et al. (2012) proposed the use of heuristic-decision tree systems, based on dual technology sensors. The authors simulated patented microwave and passive infra red (PIR) technology to achieve better coverage and to minimise dead zones as well as to lessen directional sensitivity to movement (Ariani et al. 2012). The performance of the proposed systems was investigated for various fall types (e.g. falls with unconsciousness, falls with repeated failed attempts to recover, and falls with successful recovery). Overall, the system demonstrated reasonably good accuracy. There were 15 scenarios investigated with one and multiple persons and 12 different types of falls, each accompanied with different post-fall scenarios. They report a sensitivity of 100%, specificity about 77% and accuracy around 90%.

Motivated by the necessity to develop a reliable fall detection system that can also determine the direction of a fall, Tolkiehn et al. (2011) proposed a direction sensitive fall detection system using a waist-worn sensor comprising of a tri-axial accelerometer and a barometric pressure sensor. Besides being able to determine the direction of the fall, the proposed algorithm is relatively simple as it has linear complexity \( \mathcal{O}(n) \). The system demonstrated a reasonably good accuracy of 81.48%, a specificity of 83.33% and a sensitivity of 79.08%. The use of a barometric sensor combined with accelerometer increase the accuracy to 86.97%, specificity to 85.24% and sensitivity to 87.77%. However, the limitation of this study is related to the simulated fallers who comprised of young people instead of the elderly. Also, since falls took place on to a mattress, the impact may be different from falls on harder surfaces such as the floor.

Bianchi et al. (2010) proposed the use of a barometric air pressure sensor to improve the performance of inertial sensor-based falls detection systems. The authors incorporated the use of a barometric pressure sensor to obtain altitude measurements, which helped discriminate real fall events from normal ADLs. The wearable device recorded acceleration and air pressure data which was later analysed offline. Several simulated falls and ADLs were performed using 20 young adults, comprising of 12 men and 8 women aged between 23.7 ± 3.0 years. To label the suspected falls, the authors designed a heuristic decision tree classifier. Compared to standard accelerometer-based techniques, this method demonstrated a significant improvement as indicated by its accuracy, sensitivity, and specificity, that is, 96.9%, 97.5%, and 96.5%, respectively; compared to 85.3%, 75%, and 91.5% for systems using an accelerometer alone. However, one potential drawback of this system, as with all wearable sensor systems, is the requirement for the user to wear the sensors, making it less suitable for those with cognitive problems.

### 3.4. Indoor navigation systems for visually impaired people

array which allows for door identification and helps the person enter the room. Chumkamon
et al (2008) uses matrices of RFID tags which guide the person along the shortest path to their
destination.

However, the very short-range communication limits of the RFID tags will clearly disad-
vantage the usefulness of this technique in performing path-planning. Liu et al (2007), (2006)
used RFID, Bluetooth and fluorescent light communication to assist the blind or the visually
impaired people in navigating indoor environments. While the role of RFID tags are mainly
to identify objects, the fluorescent lights are intended to position the users or to assist them
to reach a certain indoor location, and the Bluetooth system is employed to map the indoor
lights.

Based on the use of a walking cane containing a camera, Ali and Nordin (2009) developed
a smart cane capable of identifying objects using 3D modelling and extensive image process-
ing. Unfortunately, the proposed system may not be cost-effective for most people due to
expensive hardware requirements to support its extensive image processing algorithms.

Hub et al (2005) proposed a sensor module combining the use of a direction sensor, a
stereo camera, and a small portable computer, in order to provide navigation guidance. The
main drawback of this technique is its complexity, leading to an expensive image processing
system, and high hardware cost.

To address this complexity, Cascalheira et al (2012) developed a simpler solution which
allows great precision in the entry or the exit of a room. The objective of their research was to
design an array of antennae which can provide a very narrow radiation pattern so as to max-
imise the power of the radiation pattern in the middle of the door entrance. This method offers
several advantages, such as ease of operation due to its simplicity, and is also very energy
efficient. Furthermore, the receiver is very compact (lightweight and small) and hence easy
to carry around. In addition, given the nature of the detection algorithm, the receiver does not
need an expensive processing system, as the decision is made based on the measurement of
the power levels emitted by the antenna array.

However, there are several issues that have not been properly addressed in this approach,
such as how to avoid collisions with multiple users entering the same doorway in busier envi-
ronments. Secondly, while this technique provides sufficient guidance for users to detect and
enter a door, it does not sufficiently help users to navigate in the space en route from one door
to the next.

4. Discussion

IPS have the potential to deliver a revolution in health monitoring, safety and productivity.
Automated IPS offer a potential technological solution that would have wide spread applica-
tions. However, there are some important factors that may limit the practical usefulness of
these systems. Along with current technical challenges, in what follows, we shall identify sev-
eral factors that should be carefully considered when designing smart homecare and telehealth
systems that leverage IPS and ubiquitous mobile sensor networks (Santoso 2010, Santoso
2011, Santoso 2015). Maximising the practical usefulness of location-aware health monitoring
systems is a matter of striking a balance among these various competing constraints.

4.1. Current technical challenges

While IPS specifically designed to support smart homes and telehealth systems have been
extensively studied, improving their accuracy remains an outstanding challenge. While
centimeter resolution is probably not necessary for way-point navigation for the blind or for fall detection systems, in many applications (such as for orthopaedic surgery, for instance) it would be quite essential. Although, several researchers have successfully mitigated the effects of multipath fading for indoor applications, they still end up with something less favourable, such as being obtrusive, expensive and complicated. This, in turn, may also limit the usefulness of the proposed systems. In what follows, we will discuss some research avenues worth considering to address these current technical limitations.

4.1.1. Hybrid positioning systems. Since wireless ranging alone cannot produce sufficiently reliable and robust tracking solutions to address many critical safety applications, one possible research avenue is to develop a framework and algorithms for robust tracking in mesh networks using multiple heterogeneous sensors; for example, to develop algorithms using a Bayesian framework for fusion of data from multiple heterogeneous sensors, such as combining inertial sensors via DR with other systems.

Initially intended to be used as a complement to address GPS-inaccessible spaces, DR has been extensively used indoor. Multiple sensing modalities, such as hybrid DR with other IPS will create competitive advantages, such as lower sampling rates and reduced communication traffic, while still maintaining reasonably good accuracy as well as increased energy efficiency. This could lead to the development of optimal data fusion of multi-modal sensors, specifically for health monitoring systems.

Despite their benefits, there are also several critical issues to be carefully considered for optimal fusion of multiple indoor positioning systems, such as calibration, quantisation and synchronisation. In addition, the designer should also carefully limit the cost and complexity of the system to maintain its practical usefulness of the proposed systems. The designer should examine each aspect equally and strike a practicable balance, avoiding designing a highly accurate system which is too costly and complex to ever be adopted.

4.1.2. Deriving a lower bound on positioning error from first principles. To fully understand the positioning accuracy of a given system, it is also essential to derive the lower bound on the position error from the first principles. The most widely used method for achieving this is via the well-known Cramér–Rao Lower Bound, which sets the lower bound of the covariant of the error for any unbiased estimator. It is derived from the Fisher information matrix. The beauty of this method is related to the fact that one can calculate the CRLB without ever considering any particular estimation method.

Having this knowledge in hand will give the designer some valuable insight to conduct a feasibility study when it comes to the suitability of any particular indoor positioning method in response to the requirements of any home care applications they develop. For instance, in most cases accuracy at room level is required for monitoring ADLs (including fall detection). Hence, designers can theoretically justify whether the system they design will meet this specification requirement given the information regarding all design constraints, such as bandwidth and the number of sensors deployed.

Second, this lower bound also gives thoughtful insight about what parameter should be considered to minimise the error signal. In other words, it highlights the importance of certain physical and/or signal parameters to the estimation problem relative to other parameters. In addition, this bound will also provide useful information as a judgement to evaluate the performance of the proposed systems. When it comes to developing telehealth applications, this will give sufficient insight for designers to optimise their systems without incurring extra costs, leading to increased benefits and effectiveness of their system.
In other words, one can always optimise the performance of a telehealth system without increasing cost and complexity. For instance, while bandwidth is the biggest constraint for ToA and would limit its accuracy, sampling rate limitations and system clock jitter and drift present formidable challenges for indoor UWB positioning systems. Meanwhile, the geometric configuration of the base stations play a crucial role in determining the lower bound of the error in RSS-based position estimation. Knowing all these affecting factors, the designers can perform fine-tuning to enhance the accuracy of location-aware healthcare systems at no additional cost. Therefore, acquiring this knowledge would present both challenges and opportunities to improve the performance of remote localisation and monitoring systems.

4.1.3. Hardware and network limitations. Yet another factor to consider are the constraints imposed by communication networks. Network constraints, such as bandwidth limitations and clock synchronisation, become very important considerations, particularly for ToA and TDoA-based positioning systems. Hence another possible research avenue relates to the question of how to minimise bandwidth requirements without sacrificing the accuracy of the system.

Sensor calibration is an integral factor in determining the accuracy of the proposed systems. Typical MEMS sensors will require proper calibration before being used, since their output may be affected by external factors such as temperature, humidity, scaling factors and other environmental factors that could bias their performance. It is also important to simplify the calibration procedure whenever possible (e.g. via automated calibration systems) to increase not only the value of simplicity but also the practical usefulness of the system. For instance, for typical foot-mounted inertial-based DR sensors, one can use zero velocity updates to continuously update the system (Torres and Cha 2010). Thus, another possible research avenue is to develop sophisticated signal processing techniques for automated calibration of various sensor configurations.

Power limitations and computational processing are other important issues impacting the usefulness of telehealth systems, especially for those based on sensor networks with large numbers of sensor nodes. One way of achieving an efficient system design is by improving the simplicity of the proposed algorithms; although this may not always be trivial due to accuracy requirements. Minimising the number of the active sensors to be used at a certain time is also an important research avenue to conserve power and reduce production costs. This can be achieved by developing on/off or wake-up/sleep scheduling algorithms. Yet another possible research avenue might consider the use of state estimators (e.g. EKF and particle filters) to minimize the number of sensors employed, by performing highly accurate estimation for some unmeasured variables as a substitute.

4.2. Accuracy versus cost and complexity

While cost and complexity often go hand-in-hand, it is not always the case with accuracy. The biggest challenge, therefore, is to design reasonably accurate systems while still making them simple and affordable. In other words, the direction is shifted towards designing low-cost and ‘sufficiently’ accurate unobtrusive health monitoring systems. However, there is no hard and fast rule about interpreting the word ‘sufficiently’ as it always refers back to the end users’ demands.

Nonetheless, the good news is that in most cases room-level accuracy is deemed sufficient; for instance, to track people with chronic illnesses or to detect night time falls as well as monitoring ADLs. Room-level localisation can be accomplished through various positioning techniques, including RSS, ToA, TDoA, RFID, and cameras; although some techniques may have
advantages over others. Meanwhile, for high-demand medical applications, such as surgery, one may need sub-millimeter accuracy, leading to very expensive systems. One well-suited method for this type of application is ToA-UWB. Meanwhile, for monitoring health and safety by tracking outdoor activities (e.g. monitoring outdoor activities of people with dementia) GPS-like accuracy (5–10 m) is reasonable.

4.3. Complexity, compliance and appropriateness

In an attempt to enhance accuracy, there have been frequent increases in system complexity. This will lead to a reduced degree of unobtrusiveness, which is indeed undesirable from a practical point of view. In addition, while many telehealth applications have been developed based on the use of electronic tags or portable devices, such as mobile phones and/or wearable inertial sensors, there are many people who are not compliant with wearing these tags (Ariani et al 2013, 2012), especially those suffering from various cognitive impairments (e.g. Alzheimer’s disease or dementia) who cannot be expected to carry and engage with portable electronic devices, even simple devices such as mobile phones or RFID tags.

To address this shortcoming, some efforts have been made to create special clothes purposefully designed for indoor tracking which emit certain radio signals, avoiding the use of an explicit portable device (Charlon et al 2013). However, this may not be suitable for some users, due to their reluctance to wear these types of clothes, since these ‘special uniforms’ may become a reflection of their ageing condition (Ariani et al 2012). Furthermore, designers should also take into account the target cohort’s ability to operate smartphones or other electronic devices, including computers, especially if these systems are purposefully designed for older people. Therefore, the proposed system should be have a simple user interface and require little maintenance and interaction to enhance its usefulness.

4.4. Security and privacy issues

There are at least two major security and privacy-related issues to be addressed for health monitoring systems. The first relates to security of medical information collected, to preserve patient privacy. Hence, it is essential that medical data is kept confidential (perhaps by means of encryption) during collection, transmission, distribution to, and access by, physicians to protect against any potential security threats.

Another issue regarding privacy relates to the nature of the monitoring system itself and the sensors used. Some location-aware health monitoring systems are more privacy-intrusive in nature. For instance, although the use of cameras for localisation can enable a reasonably accurate system, some people may have some objections due to personal concerns about privacy and the level of detail recorded by camera-based systems and the security of this information; while data may be processed locally at the sensor node to remove personal information, the user must trust that this is indeed the case and that they are not vulnerable to privacy intrusion if camera images are misused or intercepted. Therefore, addressing such shortcoming is also of priority to enhance acceptance.

4.5. Sensor networks and wearable inertial sensors for positioning

Wearable inertial sensors have been widely used in health and sport monitoring systems. There are several key advantages of considering wearable sensors compared to their fixed-mounted counterparts. Firstly, wearable inertial sensors are self-contained and hence do not suffer in performance when used in adverse fading environments since they do not use external RF
signals to localise objects. However, it should be noted that employing wearable inertial sensors for indoor telehealth monitoring may not be suitable for some people due to compliance. Thus, we envision that the future market for wearable inertial sensors in telehealth will gradually shift towards monitoring outdoor activities, such as outdoor rehabilitation, or sport monitoring, where the use of fixed-mounted wireless sensor networks may be considerably more difficult or impractical. Also, wearable systems can be easily integrated to complement GPS systems, especially in urban canyons where GPS signals may be blocked.

5. Conclusions and future trends

We envisage that unobtrusive, low-complexity and yet inexpensive smart-home technologies based on the use of wireless sensor networks will gradually become an integral part of modern homes, helping older people live at home, for longer, living more safely, and with reduced fear. Based on the availability of ubiquitous wireless networks, supported by various indoor positioning technologies, the role of smart home systems will become progressively more essential not only to decrease morbidity and disability, but also to suppress healthcare expenditure as societies age.

Since the future trend of location-aware healthcare systems will move towards unobtrusive, simple and yet inexpensive systems with high-levels of security and privacy, complex wearable systems will become of limited value to elderly people. Furthermore, there are several issues that may hinder widespread acceptance of wearable systems. The first relates to compliance with wearing devices, especially for individuals with cognitive impairment, such as Alzheimer’s disease or dementia, as they cannot be expected to carry or wear any tags or devices. Secondly, unobtrusive health monitoring systems may gain wider acceptance because they do not explicitly reflect a person’s ageing condition as a wearable sensor might.

Hybrid positioning systems, such as DR systems combined with other IPS have been extensively implemented in wearable sensors. Some areas, such as outdoor health rehabilitation and athletics and sport monitoring, will certainly be in higher demand for the development of high performance wearable sensor systems, since obtrusiveness is not an issue here, while cost and accuracy are of paramount importance. Also, there are opportunities here to aid the rehabilitation for young adults, where most of these users are more familiar with electronic devices and most of them have no specific age-related requirements or cognitive disabilities.

When it comes to positioning technology, we further envisage that hybrid systems will dominate future markets. As computing and MEMS sensor technology progressively advances, we can also expect to see smaller, lower-cost, highly-accurate and robust positioning systems supported by sophisticated computing algorithms, such as the particle filters, which once were considered computationally too expensive.

Considering the design trade-offs discussed earlier, to extend the potential benefits and the practical usefulness of future location-aware telehealth systems, the designer must carefully address the requirements of the system users. Since there are also various system requirements demanded by the market, due to various health and disease conditions as well as age, and personal preference, one must be realistic and not expect to satisfy all demands simultaneously—no one-size-fits-all.

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