Hassle-Free Vitals

ARTICLE *in* IEEE MICROWAVE MAGAZINE · DECEMBER 2014

Impact Factor: 1.13

1 AUTHOR:

Mohamed R Mahfouz

University of Tennessee

Hassle-Free Vitals

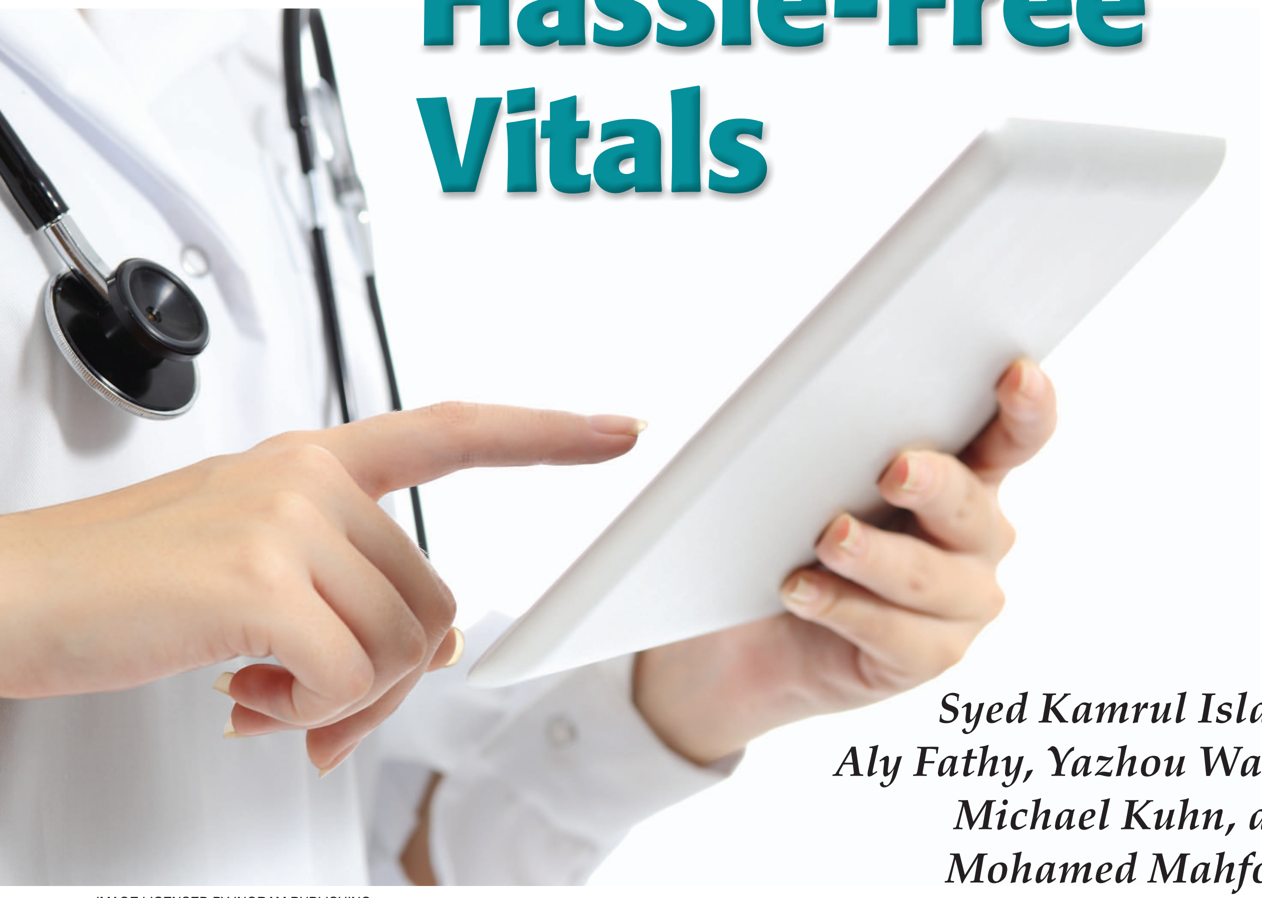

IMAGE LICENSED BY INGRAM PUBLISHING

Syed Kamrul Islam, Aly Fathy, Yazhou Wang, Michael Kuhn, and Mohamed Mahfouz

Continuous monitoring of vital information via a wireless medium has become an integral part of next-generation health-care technologies. The benefits of a wireless monitoring technique include facilitating in-home care services, reduction of the cost of frequent visits to hospitals, and lightening of the burden to the elderly persons. The development of miniature, lightweight, and energy-efficient circuit solutions for biomedical sensor applications has been made possible by the tremendous recent advancements in health-care monitoring technologies, micro- and nanofabrication processes, and wireless communications. Exuberant growth of the wireless sensor networks has opened up a new and innovative application of wireless technology in health care. The advancement of wireless technology has led to the development of the recently proposed comprehensive patient monitoring systems such as wireless body area network (WBAN) and body sensor network (BSN). Implantable and wearable sensors are integral components of these networks and are employed for monitoring various levels of physiological activities. Wireless sensor technology provides an effective tool for instant access to patient data, laboratory test results, and clinical histories as well as insurance information, thereby ensuring immediate health care in case of emergency, eliminating the lengthy clinical decision. This biomedical wireless technology has resulted in a new health-care concept known as telemedicine, which facilitates the monitoring of in-home patient care by incorporating smart medical devices and WBANs. In this scheme, implantable and wearable sensors are placed within the vicinity of the patient's body and

Syed Kamrul Islam (sislam@utk.edu), Aly Fathy, and Yazhou Wang are with the Department of Electrical Engineering and Computer Science, and Michael Kuhn and Mohamed Mahfouz are with the Department of Mechanical, Aerospace, and Biomedical Engineering, all at the University of Tennessee, Knoxville, United States.

Digital Object Identifier 10.1109/MMM.2014.2356148
Date of publication: 12 November 2014

various physiological parameters are monitored and transmitted wirelessly to a nearby hub station and subsequently to the remote health-care provider via a secure wireless communication network. The telemedicine platform can also be configured for identification of the object location, medicine reminder, or emergency alert in case of any sign of fatal disease. As a result of the recent developments in biomedical wireless technologies, the traditional clinic-centric health care is giving way to a patient-care centric health-care concept. This translational health-care concept facilitates the multidirectional integration of basic research, patient-oriented research, and population-based research, with the long-term aim of improving the health of the public. However, the successful integration of this new health-care paradigm hinges on the proper interpretation, storage, and dissemination of the large data sets generated by the all implantable and wearable devices within the wireless network.

Wireless Sensor Network Technologies for Medical Applications

The health-care systems such as in-home assistance, smart home care, and remote patient monitoring are greatly enriched by the adoption of the wireless sensor network technologies. Figure 1 illustrates a broad range of applications of wireless networks in the medical field [1].

Biomedical wireless technology, networks and sensing systems (BiowireleSS), is rapidly becoming an integral component of health-care delivery [2]. A wide range of wireless technologies is being brought to bear on a long list of health-care and pharmaceutical applications with the promise of utterly transforming health care as we know it today. From a recent biowireless research health-care market study [2], it was clear that BiowireleSS will bring unprecedented efficiencies and productivity to health-care delivery while lowering costs and improving patient outcomes. More importantly, many patients and their health-care providers will experience far more freedom and flexibility. Where once a patient would have been confined to a hospital bed for extensive tests, to be monitored post-surgery, or for chronic conditions, in many cases, patients will soon be monitored at home, free to go about their normal activities, while a wireless device will transmit data to health-care providers, who will be alerted if vital signs vary from normal ranges [2]. Wireless medical applications include chronic disease management, post-surgical recovery, vital sign monitoring, proactive monitoring, eldercare,

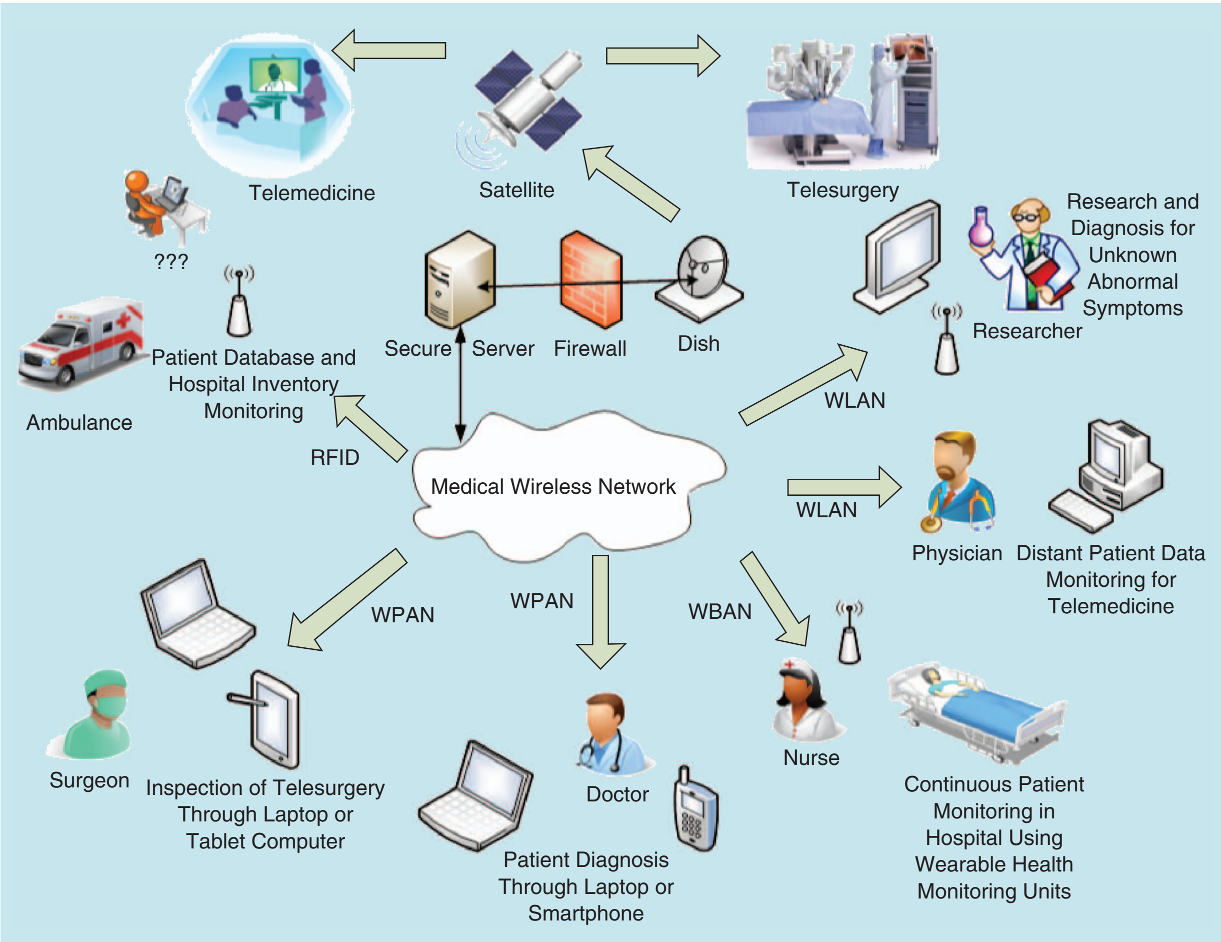

Figure 1. *A conceptual schematic of BioWireleSS network.*

remote diagnosis, emergency communications, wellness and fitness, telemedicine, facilities monitoring, asset and staff locating, positioning, asset management, tracking pharmaceuticals, imaging, and video. Wireless technologies for biomedical sensing systems potentially include wireless personal area network (WPAN)/WBAN/medical body area network (MBAN), wireless local area network (WLAN), Wi-Fi, WiMAX, ZigBee, Bluetooth, ANT, ultrawideband (UWB), E-textiles, radar, Web conferencing, capsule endoscopy, implantable and ingestible sensors, and epidermal electronics, smart bandages, smartphone apps, radio-frequency identification (RFID), real-time location system (RTLS), indoor positioning system (IPS), etc.

In recent years, a number of different types of wireless networks have been investigated and employed in health-care applications.

Wireless Body Area Network

WBAN integrates low-power sensor platforms incorporating micro- and nanosensors and complementary metal-oxide-semiconductor (CMOS) integrated circuits with body area network (BAN). Due to the inherent low-power requirement, these networks are best suited for integration into wearable health monitoring units (WHMUs) [3], which are usually incorporated with various types of implantable or transdermal sensors to measure various physiological parameters such as such as electrocardiogram (ECG), blood pressure, glucose, lactate, oxygen, pH, etc. [4]. WBANs are also employed in a hospital environment for monitoring of critical-care patients as well as in smart home care for real-time data acquisition and transmission over the secure internet to health-care providers.

Radio-Frequency Identification

RFID technology has become a very popular technology choice for a number of commercial, residential, and industrial as well as health-care applications. RFID tags are used in hospitals for inventory monitoring to provide a real-time status report to the staffs and the suppliers as well as for easy tracking of the positions of the patients and doctors within the hospital premises.

Wireless Personal Area Network

WPANs [5]–[7] using IEEE 802.15.4, which is the basis for ZigBee, ISA100.11a, WirelessHART [8], and MiWi [9] specifications, have potential uses in health care. These short-distance communication networks can be deployed inside a hospital room so that caregivers can monitor a patient remotely in real time from a nearby work station. WPAN can also be used for interfacing multiple smart medical devices within the hospital premises and the data transfer between the devices can be accomplished with minimum time overhead.

Zigbee technology can also be combined with WBANs to constitute smaller networks for real-time monitoring of the physiological activities of the patients. WLAN for untethered access to the Internet is provided by most health-care facilities in the United States. The WLAN channels are also utilized to transfer patient data around the hospital and to provide communication between various smart medical devices. Other wireless sensor networks such as general packet radio service (GPRS) and Universal Mobile Telecommunications System (UMTS) are also been used in health-care applications for monitoring the physiological activities of the patients.

Paradigm Shift from Clinic-Centric to Patient-Centric Health Care

The emergences of BioWireleSS technologies have enabled a distinct shift of the traditional clinic-centric health care to a patient-care centric health-care paradigm as illustrated in Figure 2. There are multiple levels of care for older adults in the United States. The most frequent levels seen are independent living (IL), assisted living (AL), and long-term care (LTC) facilities. Any of these may include adding unpaid family members or privately paid aides to provide further support in the living situation of the patients. The philosophy of IL is to provide a state-of-the-art health-care monitoring system for the patient while allowing a great degree of autonomy, peer support, and control by deinstitutionalizing the traditional older adult care services provided in LTC facilities. IL participants enjoy a much higher degree of freedom in deciding their daily activities compared to traditional AL. Ambient AL (AAL) is defined as "intelligent systems of assistance for a better, healthier and safer life in the preferred living environment and covers concepts, products and services that interlink and improve new technologies and the social environment, with a focus on older people" [10]. AAL and IL are largely synonymous—both focusing on using state-of-the-art technologies, the social environment, and preferred living environments to provide more autonomy and better quality of life for older adults, to enhance the quality of life for older adults by utilizing unobtrusive, enabling technologies that are seamlessly integrated into the living environment, to monitor vital signs and behavioral patterns, to provide instant feedback to the patient and enable patient-centered care, to detect accidents, and to understand and adapt with patient behavior for optimized IL/AAL. These technologies can extensively prolong the IL/AAL phase before progressing to AL and LTC facilities.

State of the Art in Ambient Assisted-Living Systems

Research and development of AAL systems has greatly increased in the last decade with many tools, sensors, systems, and integrated platforms being developed as a large percentage of the worldwide population begins to advance into their retirement years [11]. The sensors, tools, and infrastructure in AAL systems

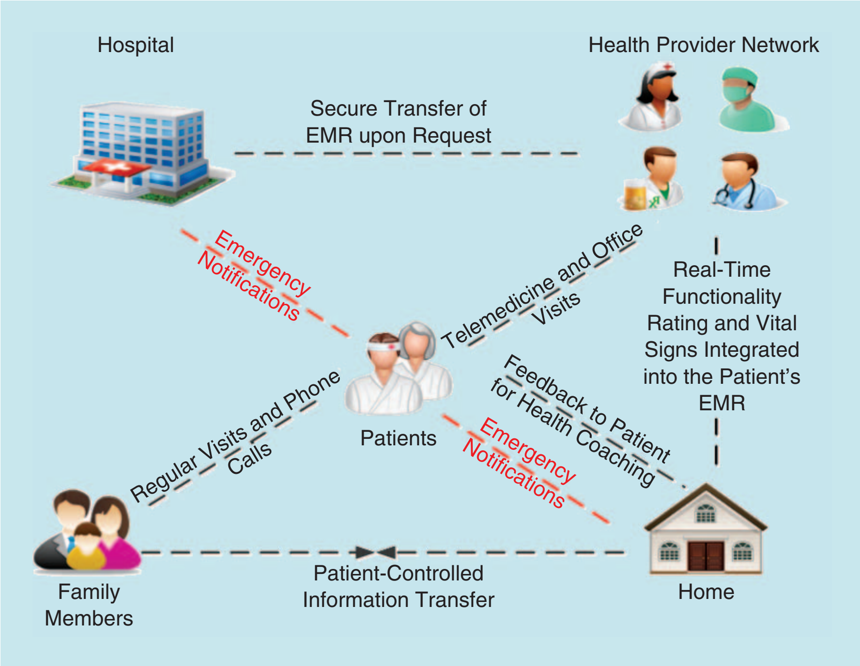

Figure 2. *An illustration of a patient-centric health-care paradigm.*

require sophisticated pattern recognition algorithms to decipher human activity and provide a higher level understanding of the living activities of a person. Ambient activity recognition (AAR) combines data from the multitude of sensors within the smart living environment and recognizes patterns of activities and sequences of sensor events to detect and track human activities. The growing cost of health care combined with a larger older adult population and a corresponding increase in the amount of needed health care and assistance in living is driving the need for more intelligent and autonomous AAL systems. These systems aim to offload the rapidly increasing cost and caregiver labor required to care for older adults in AL and LTC facilities. Sensing technologies that have been examined for AAL systems include passive infrared, active infrared, passive RFID, active RFID, pressure sensors, magnetic switches, ultrasound motion sensors, visible light cameras, and microphones.

Enabling Technologies for Patient-Centric Health Care

The core philosophy of the patient-centric health-care platform involves combining state-of-the-art engineering components with the best clinical practices to develop a technologically advanced nonintrusive living environment optimized for IL/AAL. Many of the basic engineering components needed to create a robust IL/AAL environment already exist within current state-of-the-art systems being developed within the research community and the commercial sector. The limited vision of the scientific and health-care industries has thwarted the development of a complete IL/AAL platform.

In terms of sensors and devices, the central difficulty in achieving success with the patient-centric health-care platform is developing and integrating nonintrusive technologies to monitor the vital signs and threats against the patient. The most direct system for monitoring the patient is through video monitoring, where surveillance cameras are placed inside the living area, and image processing and tracking algorithms are used to monitor patient activities and behavior. Although these systems could function autonomously, patients may feel an invasion of privacy by the activity-monitoring cameras. Some of the most promising alternative technologies that can also monitor patient activity and behavior are UWB localization and UWB see-through-wall radar systems. Integrating inertial sensing for fall detection and wearable wristband-based biosensors for vital sign monitoring will further strengthen the sensing capability of the patient-centric care platform and provide significant redundancy within the system.

Development of sensor platforms geared toward monitoring vital signs and activity levels are essential to AL and smart homes due to the increase in the aging population. It is believed that noncontact sensing technologies have the potential to revolutionize home health-care delivery. The developed platform can be utilized in hospitals, homes, office space, and AL facilities. These deployed systems can utilize various methodologies and technologies for fast gait analysis and vital sign detection and methods to track activity levels. For example, numerous laboratory-based studies have been reported on the use of accelerometers for gait and activity analysis particularly of elderly subjects. A drawback of such studies is the use of custom hardware platforms worn by subjects. Hynes et al. [12] introduced a system utilizing accelerometers embedded in off-the-shelf cellular handsets that allow medical professionals and caregivers to remotely monitor the activity characteristics of elderly patients in the home or in the community. Similarly, Reyes et al. [13] used a VitalTrack system based on a motion sensing radar capable of a person's activity level. An activity-level monitoring platform has been developed using a noncontact Doppler radar sensor. Reyes et al. [13] developed the noncontact radar to emit continuous-wave (CW) 5.8-GHz radar wave that is phase-modulated by the chest wall movement. The range of the radar sensor is on the order of 1.8–2 m. The same group developed computer vision algorithms that are used to detect and track a person as their movements are captured.

AL can include high-resolution imaging, which can be used indoors. Table 1 presents the state of the art of human imaging. The radars utilize various types of techniques such as UWB in the frequency domain or in the time domain using impulse techniques. Some of the radars are based on frequency-modulated CW (FMCW) as indicated in the Table 1 [14]. Meanwhile, for motion detection, most of the researchers and groups concentrate on using CW radar for Doppler detections due to its simpler system design and implementation, and lower development cost. For example, CW microwave Doppler radar operating at 2.4 GHz was developed for sensing a multimover in [25]. CW microwave Doppler radar was also widely used for vital sign detection and life detection [26]–[29]. In [30], CW Doppler radar was extended to extracting the Doppler signatures for biometric characterization. Signal processing and Doppler extraction method for CW Doppler radar were also discussed in [31]–[37]. Although it is simpler and cheaper to design and implement CW Doppler radar, CW radar does not give any range information or cannot track the location of the target at all. Those have significantly limited the utilization of CW radar in many applications, including monitoring the activities of elderly people at home, where both location and Doppler signatures of the radar targets are needed.

In order to achieve both Doppler detection and imaging features in one radar platform, a wideband FMCW Doppler radar was developed to operate at 500 MHz to 2 GHz for through wall imaging and motion detection [38]. In addition, UWB pulse compression radar can be used for detecting breathing information [39], [40], and an impulse radio UWB radar system has been introduced for vital signs monitoring [41]. Table 2 introduces the state of the art of the microwave Doppler radar systems.

Small displacement detection technology having resolution in the order of millimeters at microwave band is expected to be incorporated into a number of applications. CW radar system and UWB pulse radar system have been used for measuring the small displacement. CW radar has the advantages of low power consumption and simple radio architecture. Moreover, CW radar can also cancel out clutter noise by proper adjustment of the radio front-end architecture. The main advantages of the FMCW radar are simple solid-state transmitters, resistance to interception, and good range resolution. The FMCW method performs the velocity and range measurement, and it is considered a good solution for noncontact vital signs detection.

Ultrawideband Technology

UWB is a wireless technology that utilizes short wireless pulses (< 1 ns) for localization, radar, human gait analysis, and wireless communication. This innovative technology has been utilized in low-probability detection radar and communications systems for decades since its inception from time domain electromagnetics in the 1960s [42]. Interest in UWB for unique indoor communications and positioning applications has skyrocketed since the The U.S. Federal Communications Commission opened up the 3.1–10.6 and 22–29-GHz frequency bands for UWB use in 2002 [43]. Consequently, there has been extensive research and development of UWB localization systems for a number of different applications including indoor short range, outdoor urban environments, biomedical-related tracking and navigation, hospital tracking of personnel and assets, low power, and integration with UWB digital communications systems [44]–[47]. A UWB localization system has been developed at the University of Tennessee and is unique in achieving

TABLE 1. State of the art of human imaging radar.

Group/Company	Operation Frequency	Range	Display Mode	Resolution	Radar Technique
Dehmollaian et al. [15]	1–3 GHz	Not available	2-D	Not available	Frequency domain, UWB
Panzner et al. [16]	5 k–20 GHz	Not available	2-D	1–2 cm	Frequency domain, UWB
Klemm et al. [17]	3–10 GHz	Not available	3-D	4–6 mm	Frequency domain, UWB
U.S. Army Research Lab [18]	300 M–3 GHz	25 m	2-D	Not available	UWB pulse
AKELA Inc. [19]	500 M–2 GHz	40 m	2-D	10 cm	UWB FMCW
Yang [20], [21]	8–10 GHz	15 m	2-D	10 cm	UWB pulse
Time Domain [22]	3.1–6.3 GHz	20 m	2-D	Not available	UWB pulse
Cambridge Consultants [23]	1.7–2.2 GHz	20 m	2-D/3-D	30 cm	Not available
Camero-Tech Ltd. [24]	3–10 GHz	20 m	2-D/3-D	20 cm	Not available

TABLE 2. State of the art of Doppler detection radar.

Research Group	Technology	Operation Frequency	Range	Application
Lin et al. [25]	CW	2.4 GHz	10 m	Moving target sensing
Li et al. [26]	CW	5.8 GHz	Noncontact	Vital sign detection
Zhou et al. [27]	CW	2.4 GHz	Noncontact	Heartbeat monitoring
Chen et al. [28], [29]	CW	10 GHz	30 m	Life detection
Silvious et al. [30]	CW	400 MHz/17 GHz	Not available	Biometric characterization
Hunt [38]	FMCW	500 M–2 GHz	40 m	Motion detection
Zaikov et al. [39] and Sachs et al. [40]	Pulse compression	1 M–4.5 GHz	Not available	Trapped people detection
Lazaro et al. [41]	UWB pulse	3.1–10.6 GHz	Not available	Vital sign monitoring

three-dimensional (3-D) real-time tracking accuracy of 3–8 mm compared to 10–20 cm of 3-D tracking accuracy for commercial UWB systems [48], [49]. Millimeter accuracy opens up new applications for wireless tracking including surgical navigation and human gait analysis.

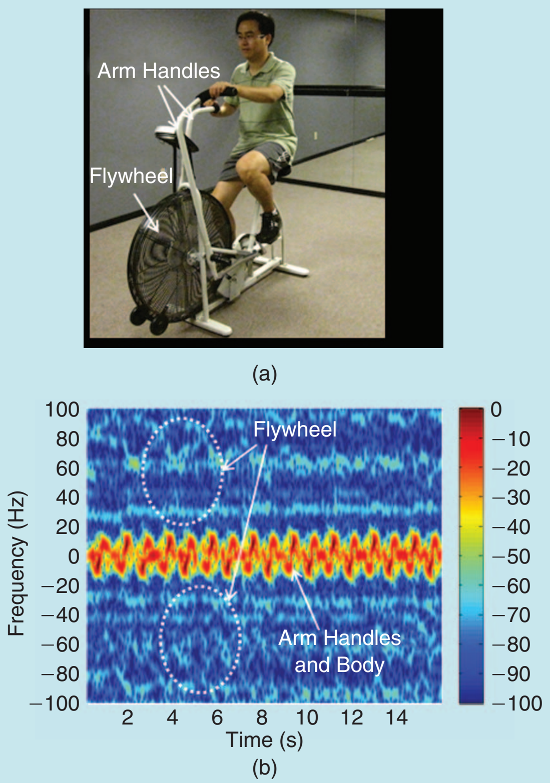

Figure 3. *(a) A patient on an exercise bike and (b) the spectrogram of the patient on an exercise bike where arm and body motion can be seen along with higher frequency motion caused by spinning of the flywheel [14].*

Ultrawideband See-Through-Wall Radar Monitoring System

The UWB see-through-wall radar-monitoring system developed at the University of Tennessee is in its second generation and has been used for human sensing applications including human gait analysis, vital sign monitoring, and human activity analysis [50], [51]. The system can simultaneously monitor multiple persons and combines UWB pulsed-based imaging with CW Doppler imaging for a complete time and frequency characterization best visualized as a spectrogram. Figure 3 shows a spectrogram for a person riding an exercise bike where torso and arm motion can be seen as well as high-frequency motion caused by the spinning flywheel on the exercise bike spinning.

Ultrawideband Indoor Localization System

The principal advantage of indoor UWB positioning systems is robustness to multipath interference compared to competing wireless technologies due to the large bandwidths of the transmitted signals allowing for highly accurate time gating of multipath signals in the time domain. UWB localization systems operate on the same principle as the global positioning system. The patients are only required to carry a small mobile tag that can be tracked within the wireless range of the base stations. An example of a typical indoor positioning system is shown in Figure 3. The base stations are connected to a master processing unit, and a reference tag is needed to calibrate out clock jitter and drift at the base stations. Time-difference-of-arrival is used for 3-D triangulation. Figure 3 also compares leading-edge detection at the UWB receiver to peak detection algorithms. In multipath conditions, significant pulse distortion occurs in the received signal, causing large errors in the accuracy of peak detection algorithms for one-dimensional ranging. Conversely, leading-edge detection shows robust performance even when the received pulse is greatly distorted. Typical 3-D dynamic accuracy of the system is 6–8 mm with four base stations and 3–5 mm with five base stations [48], [49], [52], [53]. Nonline-of-sight (NLOS) scenarios can also exist where the line-of-sight (LOS) path between the tag and base station is partially blocked. NLOS detection and mitigation is built into the system to increase system robustness in dynamic and harsh environments where LOS occlusion and scattering may occur.

Wireless Wristband Sensor with Inertial Tracking System and Biosensors

The patient-centric health-care AAL platform can utilize wireless technologies both from research activities at the University of Tennessee and those available commercially. According to IMS Research, over 50 million wireless health monitoring devices will be deployed globally from 2012 to 2026 [54]. There are many examples of commercial wireless biosensor systems currently available [55], [56] including a wireless blood pressure monitoring system [57], a wireless oximeter [58], and many others [59]–[62]. The inertial tracking unit (IMU) system designed at the University of Tennessee and the estimation algorithms were developed based on the theory of hyperdimensional statistics to measure orientation changes with high accuracy [63]–[65]. The system is also designed to be modular so that it can be tailored to a different application by simply switching out the appropriate sensing components. The current configuration has a root mean squared error of less than a degree in free hand motion experiments (Figure 4). This technology will be adapted for use in an IL environment.

The sensing components from the inertial tracking system can be used to measure sudden impact or rapid changes of angular momentum, which is ideal for fall detection. The wireless inertial tracking system can potentially be integrated into the patient-centric health-care platform as a wearable wristband and integrated with commercial biosensors and a UWB indoor location tag.

Software Architecture and Data Fusion

The success of patient-centric health care relies heavily on proper interpretation, storage, and dissemination of the large data sets generated by the implantable and wearable devices within the wireless network and the available computational solution for large-scale data management and analysis. The sensors, tools, and infrastructure in health-care systems require sophisticated pattern recognition algorithms to decipher human activity and provide a higher level understanding of the living condition of an individual within the system. A number of integrated platforms for monitoring health data from wearable sensors have been reported [66]–[69]. Data fusion is optimized using machine-to-machine (M2M) technology [70]. AAR combines data from the multitude of sensors within the smart living space and recognizes patterns of activity and sequences of sensor events to detect and track human activities. Given the unique signatures associated with human activities and the unique deployment of sensors within a given AAL system, it is not surprising that most AAR learning engines currently being developed are supervised and rely on training data [71], [72]. Many learning algorithms have been applied to AAR including decision trees [73], neural networks [74], mixture models [75], and Markov chains [76]. A conceptual framework of a virtual reality therapy to assist individuals, especially lung cancer patients or those with breathing disorders, to regulate their breath has been reported by Abushakara et al. [77]. A Web-based graphical workflow planning system that exploits the multiscale and modular nature of cancer and allows building complex cancer models by intuitively linking and interchanging highly-specialized models has been reported [78].

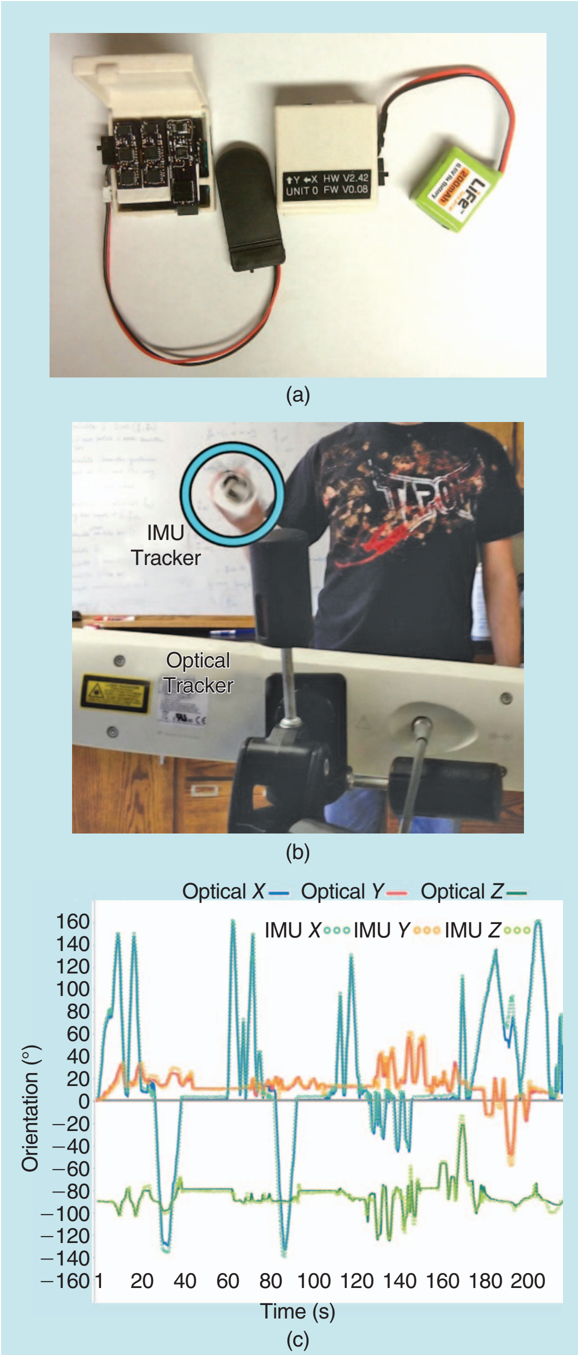

Figure 4. *(a) The current design of the wireless modular IMU tracking system; (b) free hand tracking with the IMU and optical systems, and (c) a comparison of data for both systems.*

Conclusions

A biowireless network represents an integrated platform combining novel wireless technologies and biosensors within an optimized living area to develop and evaluate a robust, intelligent AAL platform. The patient-centric health-care platform will be ready for real-world deployment in the near future. The sensor-enhanced environment encompasses a wide spectrum of smart technologies that includes robust wireless monitoring and tracking systems, inertial tracking systems, biosensors, data fusion software algorithms, and medical-grade software. This intelligent platform provides the opportunity for research and development as well as commercial realization of new sensors and devices, utilizing data to ultimately make intelligent decisions regarding the patient and using a simulation framework to understand and predict the effects of study participants and various diseases on the system.

References

[1] M. R. Haider, "System-on-package low-power telemetry and signal conditioning unit for biomedical applications," Ph.D. dissertation, Dept. Elect. Eng., Univ. Tennessee, Knoxville, TN, Dec. 2008.

[2] BiowireleSS: Market Opportunities in Wireless Healthcare. (2014). A new market study covering opportunities emerging in the use of wireless technologies in healthcare delivery. [Online]. Available: http://www.researchandmarkets.com/research/tkwlp8/biowireless

[3] D. Malan, T. Fulford-Jones, M. Welsh, and S. Moulton, "Codeblue: An ad hoc sensor network infrastructure for emergency medical care," in *Proc. Int. Workshop Wearable Implantable Body Sensor Networks*, 2004.

[4] E. Jovanov, A. Milenkovic, C. Otto, P. de Groen, B. Johnson, S. Warren, and G. Taibi, "A WBAN system for ambulatory monitoring of physical activity and health status: Applications and challenges," in *Proc. 27th Annu. Int. Conf. IEEE Engineering Medicine Biology Society*, Shanghai, China, Sept. 2005, pp. 3810–3813.

[5] N. Chevrollier and N. Golmie, "On the use of wireless network technologies in healthcare environments," in *Proc. Appl. Services Wireless Networks*, Paris, France, June 2005.

[6] N. Golmie, D. Cypher, and O. Rebala, "Performance analysis of low rate wireless technologies for medical applications," *Comput. Commun.*, vol. 28, no. 10, pp. 1255–1275, 2005.

[7] N. Golmie, D. Cypher, and O. Rebala, "Performance evaluation of low rate WPANs for sensors and medical applications," *Comput. Commun.*, vol. 28, no. 10, pp. 1266–1275, 2005.

[8] D. Chen, M. Nixon, and A. Mok, *WirelessHART: Real-Time Mesh Network for Industrial Automation*. New York: Springer-Verlag, 2010.

[9] K. S. Low, G. X. Lee, T. Taher, "A wearable wireless sensor network for human limbs monitoring," in *Proc. 2009 Int. Instrumentation and Measurement Technology Conf.,* Singapore, 5–7 May 2009.

[10] ERCIM, "Ambient assisted living and ambient intelligence: Improving the quality of life for European citizens," *ERCIM NEWS (Special Theme: Ambient Assisted Living)*, no. 87, p. 2, 2011.

[11] P. Rashidi, "A survey on ambient-assisted living tools for older adults," *IEEE J. Biomed. Health Inform.*, vol. 17, no. 3, pp. 579–590, 2013.

[12] M. Hynes, H. Wang, E. McCarrick, and L. Kilmartin, "Accurate monitoring of human physical activity levels for medical diagnosis and monitoring using off-the-shelf cellular handsets," *Pers. Ubiquitous Comput.*, vol. 15, no. 7, pp. 667–678, 2011.

[13] G. Reyes, D. Wang, R. Nair, C. Li, X. Li, and J. Lin, "VitalTrack: A Doppler radar sensor platform for monitoring activity levels," in *Proc. IEEE Radio Wireless Week*, Santa Clara, CA, Jan. 15–18, 2012, pp. 29–32.

[14] Y. Wang. (2012). UWB pulse radar for human imaging and doppler detection applications. Ph.D. dissertation, Univ. Tennessee, Knoxville, TN. [Online]. Available: http://trace.tennessee.edu/utk_graddiss/1370

[15] M. Dehmollaian and K. Sarabandi, "Refocusing through building walls using synthetic aperture radar," *IEEE Trans. Geosci. Remote Sensing*, vol. 46, no. 6, pp. 1589–1599, 2008.

[16] B. Panzner, A. Jostingmeier, and A. Omar, "Radar signatures of complex buried objects in ground penetrating radar," in *Proc. 11th Int. Radar Symp.*, Vilnius, Lithuania, June 2010, pp. 1–4.

[17] M. Klemm, J. A. Leendertz, D. Gibbins, I. J. Craddock, A. Preece, and R. Benjamin, "Microwave radar-based breast cancer detection: Imaging in inhomogeneous breast phantoms," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 1349–1352, Nov. 2009.

[18] C. Le, T. Dogaru, L. Nguyen, and M. A. Ressler, "Ultra wideband radar imaging of building interior: Measurements and predictions," *IEEE Trans. Geosci. Remote Sensing*, vol. 47, no. 5, pp. 1409–1420, 2009.

[19] A. R. Hunt, "A wideband imaging radar for through-the-wall surveillance," in *Proc. SPIE*, vol. 5403, pp. 590–596, 2004.

[20] Y. Yang and A. E. Fathy, "Development and implementation of a real-time see-through wall radar system based on FPGA," *IEEE Trans. Geosci. Remote Sensing*, vol. 47, no. 5, pp. 1270–1280, 2009.

[21] Y. Yang, "Development of a real-time ultra-wideband see-through wall imaging radar system," Ph.D. dissertation, Univ. Tennessee, Knoxville, TN, 2008.

[22] Time Domain Corp. PulsON 400 Radar Sensor Datasheet. [Online]. Available: http://www.timedomain.com/p400.php

[23] Cambridge Consultants Inc., Cambridge, MA. [Online]. Prism 200. Available: http://www.cambridgeconsultants.com/prism_200.html

[24] Camero USA Corp., Vienna, VA. XaverTM 800 Vision System. [Online]. Available: http://www.camero-tech.com/xaver800.shtml

[25] A. Lin and H. Ling, "Doppler and direction-of-arrival radar for multiple-mover sensing," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 43, no. 4, pp. 1496–1509, 2007.

[26] C. Li, J. Ling, J. Li, and J. Lin, "Accurate Doppler radar noncontact vital sign detection using the RELAX algorithm," *IEEE Trans. Instrum. Meas.*, vol. 59, no. 3, pp. 687–695, 2010.

[27] Q. Zhou, A. Host-Madsen, O. Boric-Lubecke, and V. Lubecke, "Detection of multiple heartbeats using Doppler radar," in *Proc. IEEE Int. Conf. Acoustics, Speech Signal Processing*, Toulouse, France, May 2006.

[28] K. Chen, D. Misra, H. Wang, H. Chuang, and E. Postow, "An X-band microwave life detection system," *IEEE Trans. Biomed. Eng.*, vol. 33, no. 7, pp. 697–701, 1986.

[29] K. Chen, Y. Huang, J. Zhang, and A. Norman, "Microwave life-detection system for searching human subjects under earthquake rubble or behind barrier," *IEEE Trans. Biomed. Eng.*, vol. 27, no. 1, pp. 105–114, 2000.

[30] J. Silvious, J. Clark, T. Pizzillo, and D. Tahmoush, "Micro-Doppler phenomenology of humans at UHF and Ku-band for biometric characterization," in *Proc. SPIE*, 2009, vol. 7308.

[31] V. C. Chen, "Detection and analysis of human motion by radar," in *Proc. IEEE Radar Conf.*, May 2008, pp. 1–4.

[32] J. Li, X. Zhu, P. Stoica, and M. Rangaswamy, "High resolution angle-Doppler imaging for MTI radar," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 46, no. 3, pp. 1544–1556, 2010.

[33] B. Armstrong and B. S. Holeman, "Target tracking with a network of Doppler radars," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 34, no. 1, pp. 33–48, 1998.

[34] T. Thayaparan, L. Stankovic, and I. Djurovic, "Micro-Doppler-based target detection and feature extraction in indoor and outdoor environments," *J. Franklin Inst.*, vol. 345, no. 6, pp. 700–722, 2008.

[35] J. L. Geisheimer, W. S. Marshall, and E. Greneker, "A continuous-wave radar for gait analysis," in *Proc. 35th Asilomar Conf. Signals, Systems Computers*, Nov. 2011, pp. 834–838.

[36] M. Otero, "Application of a continuous wave radar for human gait recognition," in *Proc. SPIE*, 2005, vol. 5809.

[37] B. G. Mobasseri and M. G. Amin, "A time-frequency classifier for human gait recognition," in *Proc. SPIE*, 2009, vol. 7306.

[38] A. R. Hunt, "Use of a frequency-hopping radar for imaging and motion detection through walls," *IEEE Trans. Geosci. Remote Sensing*, vol. 47, no. 5, pp. 1402–1408, May 2009.

[39] B. Lembrikov, *Ultra Wideband*. Sciyo, 2010, pp. 323–346.

[40] J. Sachs, M. Aftanas, S. Crabbe, M. Drutarovsky, R. Klukas, D. Kocur, T. Nguyen, P. Peyerl, J. Rovnakova, and E. Zaikov, "Detection and tracking of moving or trapped people hidden by obstacles

using ultra-wideband pseudo-noise radar," in *Proc. European Radar Conf.*, Oct. 2008, pp. 408–411.

[41] A. Lazaro, D. Girbau, and R. Villarino, "Analysis of vital signs monitoring using an IRUWB radar," *Progr. Electromagn. Res.*, vol. 100, pp. 265–284, 2010.

[42] R. J. Fontana, "Recent system applications of short-pulse ultra-wideband technology," *IEEE Trans. Microwave Theory Tech.*, vol. 52, no. 9, pp. 2087–2104, 2004.

[43] Federal Communications Commission, "The first report and order regarding ultra-wideband transmission systems," FCC 02-48, ET Docket No. 98-153, 2002.

[44] Venture Development Corp. RFID Business Planning Service 2005-2006. RTLS and wireless technologies. [Online]. Available: http://www.pencomputing.com/news/news_rtls.html

[45] IDTechEx. (2009). RFID Forecasts, Players and Opportunities 2009-2019. [Online]. Available: http://www.idtechex.com/research/reports/rfid_forecasts_players_and_opportunities_2009_2019_000226.asp

[46] Y. Zheng, M. A. Arasu, K. Wong, Y. J. The, A. P. H. Suan, D. D. Tran, W. G. Yeoh, and D. Kwong, "A 0.18μm CMOS 802.15.4a UWB transceiver for communication and localization," in *Proc. IEEE Int. Solid-State Circuits Conf.*, San Francisco, CA, 2008, pp. 118–119.

[47] C. Meier, A. Terzis, and S. Lindenmeier, "A robust 3D high precision radio location system," in *Proc. IEEE Int. Microwave Symp.*, Honolulu, HI, 2007, pp. 397–400.

[48] M. Kuhn, M. Mahfouz, N. Rowe, E. Elkhouly, J. Turnmire, and A. Fathy, "Ultra wideband 3-D tracking of multiple tags for indoor positioning in medical applications requiring millimeter accuracy," in *Proc. IEEE Topical Conf. Biomedical Radio Wireless Technologies, Networks, Sensing Systems*, 2012, pp. 57–60.

[49] M. Kuhn, M. Mahfouz, C. Zhang, B. Merkl, and A. Fathy, "A system level simulation framework for UWB localization," *IEEE Trans. Microwave Theory Tech.*, vol. 58, no. 12, pt. 1, pp. 3527–3537, 2010.

[50] Y. Wang, Q. Liu, and A. Fathy, "CW and pulse–Doppler radar processing based on FPGA for human sensing applications," *IEEE Trans. Geosci. Remote Sensing*, vol. 51, no. 5, pp. 3097–3107, 2013.

[51] Y. Wang and A. E. Fathy, "Advanced system level simulation platform for three-dimensional UWB through-wall imaging SAR using time-domain approach," *IEEE Trans. Geosci. Remote Sensing*, vol. 50, no. 5, pp. 1986–2000, 2012.

[52] C. Zhang, M. Kuhn, B. Merkl, A. Fathy, and M. Mahfouz, "Real-time noncoherent UWB positioning radar with millimeter range accuracy in a 3-D indoor environment: Theory and experiment," *IEEE Trans. Microwave Theory Tech.*, vol. 58, no. 1, pp. 9–20, 2010.

[53] M. Mahfouz and A. Fathy, "Achieving sub-mm accuracy with a novel indoor UWB positioning system in dense multipath environments for medical applications," Tech. Rep. NSF Grant ECCS-1002318, Aug. 2010–Sept. 2013.

[54] IMS Research. (2012, Mar. 30). Wireless opportunities in health and wellness monitoring—World—2012. [Online]. Available: www.imsresearch.com

[55] M. Mahfouz, G. To, and M. Kuhn, "Smart instruments: Wireless technology invades the operating room," in *Proc. IEEE Topical Conf. Biomedical Radio Wireless Technologies, Networks, Sensing Systems*, 2012, pp. 33–36.

[56] M. Mahfouz, G. To, and M. Kuhn, "No strings attached," *IEEE Microwave Mag.*, vol. 12, no. 7, pp. S34–S48, 2011.

[57] Panasonic Inc. (2013, May 8). Upper arm blood pressure cuff EW3106W. [Online]. Available: http://www.us.panasonic.com/

[58] Nonin Medical, Inc. (2013, May 8). Avant® 4000 Wireless Tabletop Pulse Oximeter. [Online]. Available: http://www.nonin.com/

[59] LifeSync Corp. (2013, May 8). LifeSync Wireless ECG System. [Online]. Available: http://www.lifesynccorp.com/products/wireless-system.html

[60] Neoprobe. (2013, May 8). 1100/1101 wireless probes. [Online]. Available: http://www.neoprobe.com/Bluetooth-Wireless-Probe.html

[61] (2013, May 8). Body Media FIT on-body monitoring system. Body Media Inc., Pittsburgh, PA. [Online]. Available: http://www.bodymedia.com

[62] Basis Science Inc. (2013, May 8). Basis Band. [Online]. Available: http://en.mybasis.com/

[63] G. To and M. Mahfouz, "Design of wireless inertial trackers for human joint motion analysis," in *Proc. IEEE Topical Conf. Biomedical Radio Wireless Technologies, Networks, Sensing Systems*, 2012, pp. 49–52.

[64] G. To and M. Mahfouz, "Modular wireless inertial trackers for biomedical applications," in *Proc. IEEE Topical Conf. Biomedical Radio Wireless Technologies, Networks, Sensing Systems*, 2013, pp. 172–174.

[65] G. To and M. Mahfouz, "Quaternionic attitude estimation for robotic and human motion tracking using sequential Monte Carlo methods with von Mises-Fisher and non-uniform densities simulations," *IEEE Trans. Biomed. Eng.*, vol. 60, no. 11, pp. 3046–3059, 2013.

[66] C.C. Bellos, A. Papadopoulos, R. Rosso, and D.I. Fotiadis, "Identitification of COPD patients' health status using an intelligent system in the CHRONIOUS wearable platform," *IEEE J. Biomed. Health Inform.*, vol. 18, pp. 731–738, 2014.

[67] L. Clifton, D. A. Clifton, M. A. F. Pimentel, P. J. Watkinson, and L. Tarassenko, "Predictive monitoring of mobile patients by combining clinical observations with data from wearable sensors," *IEEE J. Biomed. Health Inform.*, vol. 18, no. 3, pp. 722–730, 2014.

[68] X. Wang, Q. Gui, B. Liu, Z. Jin, and Y. Chen, "Enabling smart personalized healthcare: A hybrid mobile-cloud approach for ECG telemonitoring," *IEEE J. Biomed. Health Inform.*, vol. 18, no. 3, pp. 739–745, 2014.

[69] K. Cuppens, P. Karsmakers, A. van de Vel, B. Bonroy, M. Milosevic, S. Luca, T. Croonenborghs, B. Ceulemans, L. Lagae, S. van Huffel, and B. Vanrumste, "Accelerometry-based home monitoring for detection of nocturnal hypermotor seizures based on novelty detection," *IEEE J. Biomed. Health Inform.*, vol. 18, no. 3, pp. 1026–1030, 2014.

[70] (2013, June 2). Machine-to-machine communication. [Online]. Available: http://m2m.sprint.com/m2m-solutions/healthcare

[71] U. Maurer, A. Smailagic, D. Siewiorek, and M. Deisher, "Activity recognition and monitoring using multiple sensors on different body positions," in *Proc. Int. Workshop Wearable Implantable Body Sensor Network*, 2006, pp. 113–116.

[72] T. Barger, D. Brown, and M. Alwan, "Health-status monitoring through analysis of behavioral patterns," *IEEE Trans. Syst. Man, Cybern. A, Syst. Humans*, vol. 35, no. 1, pp. 22–27, 2005.

[73] U. Maurer, A. Smailagic, D. Siewiorek, and M. Deisher, "Activity recognition and monitoring using multiple sensors on different body positions," in *Proc. Int. Workshop Wearable Implantable Body Sensor Network*, 2006, pp. 113–116.

[74] M. Mozer, R. Dodier, M. Anderson, L. Vidmar, R. Iii, and D. Miller, "The neural network house: An overview," in *Proc. AAAI Spring Symp. Intelligent Environments*, 1998, pp. 110–114.

[75] T. Barger, D. Brown, and M. Alwan, "Health-status monitoring through analysis of behavioral patterns," *IEEE Trans. Syst. Man, Cybern. A, Syst. Humans*, vol. 35, no. 1, pp. 22–27, 2005.

[76] A. Mihailidis, J. Boger, M. Canido, and J. Hoey, "The use of an intelligent prompting system for people with dementia," in *Proc.ACM Int.*, 2007, vol. 14, pp. 34–37.

[77] V. Sakkalis, S. Sfakianakis, E. Tzamali, K. Marias, G. Stamatakos, F. Misichroni, E. Ouzounoglou, E. Kolokotroni, D. Dionysiou, D. Johnson, S. McKeever, and N. Graf, "Web-based workflow planning platform supporting the design and execution of complex multiscale cancer models," *IEEE J. Biomed. Health Inform.*, vol. 18, no. 3, pp. 824–831, 2014.

[78] N. Lasierra, A. Alesanco, and J. García, "Designing an architecture for monitoring patients at home: Ontologies and web services for clinical and technical management integration," *IEEE J. Biomed. Health Inform.*, vol. 18, no. 3, pp. 824–831, 2014.