A Review of Smart Homes—Past, Present, and Future

Muhammad Raisul Alam, *Student Member, IEEE*, Mamun Bin Ibne Reaz, *Member, IEEE*, and Mohd Alauddin Mohd Ali, *Member, IEEE*

***Abstract*—A smart home is an application of ubiquitous computing in which the home environment is monitored by ambient intelligence to provide context-aware services and facilitate remote home control. This paper presents an overview of previous smart home research as well as the associated technologies. A brief discussion on the building blocks of smart homes and their interrelationships is presented. It describes collective information about sensors, multimedia devices, communication protocols, and systems, which are widely used in smart home implementation. Special algorithms from different fields and their significance are explained according to their scope of use in smart homes. This paper also presents a concrete guideline for future researchers to follow in developing a practical and sustainable smart home.**

***Index Terms*—Healthcare, home automation, pervasive computing, smart homes, telemedicine, ubiquitous computing.**

I. Introduction

SMART homes constitute a branch of ubiquitous computing that involves incorporating smartness into dwellings for comfort, healthcare, safety, security, and energy conservation. Remote monitoring systems are common components of smart homes, which use telecommunication and web technologies to provide remote home control and support patients remotely from specialized assistance centers.

Smart homes offer a better quality of life by introducing automated appliance control and assistive services. They optimize user comfort by using context awareness and predefined constraints based on the conditions of the home environment. A user can control home appliances and devices remotely, which enables him or her to execute tasks before arriving home. Ambient intelligence systems, which monitor smart homes, sometimes optimize the household's electricity usage. Smart homes enhance traditional security and safety mechanisms by using intelligent monitoring and access control.

By 2050, approximately 20% of the world's population will be at least 60 years old [1]. This age group will face problems with living independently and is more likely to suffer from long-term chronic diseases. According to the World Health Organization, 650 million people live with disabilities around the world [2]. The most common causes of disability include chronic diseases such as diabetes, cardiovascular diseases, and cancer, and injuries due to road traffic accidents, conflicts, falls, landmines, mental impairments, birth defects, malnutrition, and HIV/AIDS and other communicable diseases. It is not possible or logical to support all of these patients in medical centers or nursing homes for an uncertain period of time. The solution is to accommodate healthcare services and assistive technologies in patients' home environment.

The most recent survey on smart homes was written by Chan *et al.* and describes a general overview of smart home research [3]. It also includes a discussion on wearable and implantable devices and assistive robots. The project reviews are arranged according to country and continent, i.e., the U.S., Asia, Europe, and Australia; this organization is not efficient for the readers who are interested in smart home architecture.

Location awareness is an important prerequisite to create an intelligent environment in smart homes. Hightower and Borriello summarized the location detection techniques and discussed several taxonomies of the location detection system [4]. This survey categorized the properties of location detection systems according to physical position, symbolic location, and absolute and relative measurements. Issues related to accuracy, precision, measurement scale, and cost were also evaluated to compare different location systems. Manley *et al.* categorized location detection systems based on the mobility of objects and tagging capability [5]. However, their work is more related to object tracking than tracking people.

Robles and Kim discussed context-aware tools for smart home implementation [6]. This review presents a brief overview of rule-based smart home architecture, aware community systems, networked robots, and context-aware gateways. A comparison between various smart home protocols, e.g., X10, Zigbee, and WiFi, is also provided. However, the review does not discuss the algorithms that are the key components of context awareness.

Pishva and Takeda presented a taxonomy of security threats in smart homes [7], [8]. They discussed different types of attacks and prevention methodologies. A summarized threat-likelihood level is presented, which categorized attack possibility according to appliance type and attack category.

This paper is a survey on smart home projects, which are arranged according to their intended services. It also discusses the significance and limitations of smart home components and the procedures that are followed to overcome their drawbacks. It explains the current trends of smart home research and future challenges that must be overcome to design a feasible smart home.

II. Smart Home Definition

A smart home is an application of ubiquitous or pervasive computing or environment. Several synonyms are used for smart

Manuscript received April 28, 2011; revised August 1, 2011 and November 27, 2011; accepted February 3, 2012. Date of publication April 3, 2012; date of current version December 17, 2012. This paper was recommended by Associate Editor R. Alhajj.

M. R. Alam was with the Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia. He is now with the Department of Systems and Computer Engineering, Carleton University, Ottawa, ON K1S 5B6, Canada (e-mail: mraisul@gmail.com).

M. B. I. Reaz and M. A. M. Ali are with the Department of Electrical, Electronic and Systems Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia (e-mail: mamun.reaz@gmail.com; mama@vlsi.eng.ukm.my).

Digital Object Identifier 10.1109/TSMCC.2012.2189204

home, e.g., smart house, home automation, domotique, intelligent home, adaptive home, and aware house.

An early definition of smart homes was provided by Lutolf [9]. According to Lutolf, "the smart home concept is the integration of different services within a home by using a common communication system. It assures an economic, secure, and comfortable operation of the home and includes a high degree of intelligent functionality and flexibility." The definition is influenced by home automation terminology and does not mention anything about home intelligence.

Berlo *et al*. implicitly include home intelligence as an automatic control and define a smart home as "a home or working environment, which includes the technology to allow the devices and systems to be controlled automatically, may be termed a smart home" [10].

According to Winkler, a "smart home" is a home that is able to proactively change its environment to provide services that promote an independent lifestyle for elderly users [11]. Winkler limits smart home users to the elderly.

Briere and Hurley define a smart home as a harmonious home, a conglomeration of devices and capabilities based on home networking [12]. However, this definition is too generic to express the smart home concept.

An elaborated definition of a smart home was published by Intertek in 2003, which was involved with the Department of Trade and Industry smart home project in the UK [13]. According to Intertek, a smart home is a dwelling incorporating a communications network that connects key electrical appliances and services and allows them to be remotely controlled, monitored, or accessed. A home needs three things to make it smart:

1) internal network—wire, cable, wireless;
2) intelligent control—gateway to manage the featured systems;
3) home automation—products within the home and links to services and systems outside the home.

Intertek omits home intelligence and places more emphasis on remote access.

A recent definition by Satpathy provides a more appropriate concept of smart homes. According to Satpathy, "a home which is smart enough to assist the inhabitants to live independently and comfortably with the help of technology is termed as smart home. In a smart home, all the mechanical and digital devices are interconnected to form a network, which can communicate with each other and with the user to create an interactive space" [14]. The author does not include remote access in the definition.

Considering the current trends in smart home research, we can define the smart home as an application of ubiquitous computing that is able to provide user context-aware automated or assistive services in the form of ambient intelligence, remote home control, or home automation.

III. Review of the Projects

Smart home projects have been conducted over the last several decades; they convey different ideas, functions, and utilities. Smart homes are extending into different branches of specialization focusing on the interests of researchers and user requirements and expectations. This section presents a study of smart home projects according to research objectives and desired services. Smart homes provide comfort, healthcare, and security services to their inhabitants. Comfort and healthcare services can be provided locally as well as remotely. Security measures not only provide authentication services to the user but also restrict unauthorized access to the household devices. Fig. 1 presents the categorization of smart home projects according to the intended services.

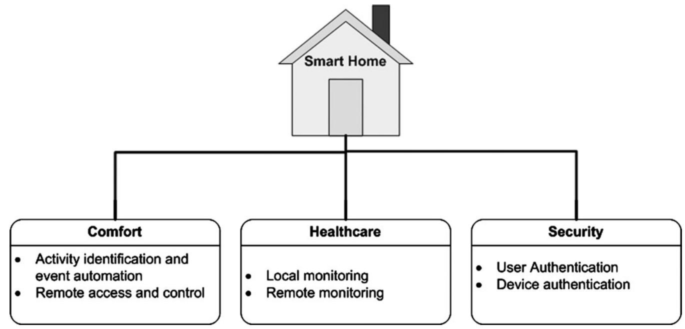


Fig. 1. Categorization of smart home projects according to the intended services.

A. Comfort

One of the main objectives of smart home research is to ease daily life by increasing user comfort. This is achieved in two ways. One is related human activity identification and event automation in local environments. The other is remote home management from distant locations. The following smart home projects aim to automate home appliances using knowledge of human activity and behavior. These assistive services sometimes optimize energy usage because the house is intelligent enough to reduce energy use by controlling unattended home appliances.

1) Activity Identification and Event Automation: Context awareness is an important prerequisite to employ intelligence in smart homes. A context-aware smart home can distinguish location, identity, activity, and time. The projects discussed in this category can learn user behavior, track user location, identify the user, and automate tasks to optimize comfort in the local environment.

The managing an adaptive versatile home (MavHome) project at the University of Texas, Arlington, was first introduced by Das *et al.* [15]. MavHome uses a combination of multidisciplinary technologies: artificial intelligence, multimedia technology, mobile computing, and robotics. Its architecture is divided into four abstract layers: physical, communication, information, and decision. The X10 protocol is used to control and monitor more than 60 X10 devices plugged into the home electric wiring system [16]. An active LeZi (ALZ) algorithm is implemented, which makes a decision tree based on a finite-order Markov model. ALZ predicts the future actions, calculating the probability of all previous actions by applying prediction by partial matching method [17]. Although MavHome utilizes AI algorithms to make accurate predictions and decisions, it can only predict the behavior of a single inhabitant [18].

A snow-flake data model was designed by Zhang *et al.* to represent residents' activity in smart homes [19]. They used a homeML (an XML-based schema to represent the information of smart homes) structure to store sensory information. A novel prediction algorithm is proposed to classify the activities of daily life (ADL) from the observed episodes and time information. The learning output is a joint probability distribution. The distribution can also be measured by the distance to the true underlying probability distribution using the Euclidean metric. Smaller distance implies a better learned model when compared with the true situation. The algorithm is based on a probabilistic distribution and is able to predict the ADL of more than one inhabitant. The system cannot correct itself in cases of false classification and can identify only one task.

The adaptive control of home environment (ACHE) system was developed by Mozer in the U.S. ACHE monitors the device usage pattern of residents, utilizing different types of sensors, and builds the adaptive inferential engine of a neural network to control temperature, heating, and lighting. ACHE can control three main components of a house while maximizing user comfort and conserving energy [20]. ACHE is one of the earliest smart home projects. However, its capabilities are limited to light, temperature, and heat control.

The Rehabilitation Engineering Research Center on Technology for Successful Aging at the University of Florida introduced the "House of Matilda" [21]. The home is inhabited by a dummy called Matilda. This research utilizes ultrasound technology for location detection. The location tracking system consists of four pilots at each corner of the home and a beacon attached to Matilda. Its coverage area is not more than 6 m. After two years, they designed the second generation of this home named "GatorTech" [22]. GatorTech is actually the integration of smart devices with sensors and actuators to optimize comfort and safety. Smart appliances, such as smart mailboxes, driving simulators, ultrasonic location tracking, smart front doors, smart mirrors, smart bathrooms, smart blinds, smart displays, smart floors, and smartwaves, were developed to make a pervasive space. The researchers proposed a middleware architecture that contains separate physical, sensor-platform, service, knowledge, context-management, and application layers. The physical layer accommodates home appliances, devices, and sensors. The sensor-platform layer creates an abstraction between physical-layer devices and other layers so that a programmer does not need to know the low-level configurations of the devices. The service layer registers the sensor platforms based on an OSGi framework and leases desired services, which may include voice recognition, text-to-speech conversion, scheduling, and media-streaming services. The knowledge layer maintains the ontology between services, devices, and appliances. The context-management layer defines the context of service activation and prevents the smart home from becoming unstable. The application layer enables the user to define contexts and control services. Next-generation devices in the smart home provide an assistive environment. Indeed, GatorTech is a good example for future smart home researchers.

At the University of Tokyo, Noguchi *et al.* designed an intelligent room to support the daily life of an inhabitant. The system has three main components: data acquisition, data processing, and integration of processed data. It learns the current state of an environment from the sensors attached to beds, floors, tables, and switches. A summarization algorithm is used to track any change in the system. The algorithm segments the collected sensory data at points where the sensor output changes drastically (i.e., switch sensors are changed or pressure data appear suddenly). The segments are labeled as "room states." The algorithm joins the state of each segment to quantize the collected data and ties up the changed situation [23]. The proposed summarization algorithm can detect user activities, which has been tested for a single room. No autonomous service has been implemented utilizing this algorithm.

The PRIMA research group of the LIG laboratory at the INRIA Grenoble research center in France has defined a model for contextual learning in smart homes. The authors developed a 3-D smart environment consisting of cameras, a microphone array, and headset microphones for situation modeling. It relies on 3-D video tracking and role detection regarding the activities of the inhabitant. Roles are learned using support vector machines (SVMs). It can also learn the speed of the inhabitant and distance from the interacting object. The proposed system can identify situations such as introduction, presentation, aperitif, game, and siesta. Its identification error rate is 82% [24].

The EasyLiving project of Microsoft implements an intelligent environment to track multiple residents using a distributed image-processing system. It can identify residents through an active badge system. Measurements are applied to define geometric relationships between people, devices, places, and things [25], [26]. The project is focused in different directions, such as distributed computing (middleware development) and geometric world modeling, to create a true dynamic smart environment. Its significance lies in its ability to track multiple users. The system works efficiently in a single room and can track up to three residents simultaneously.

Yamazaki has constructed a "Ubiquitous Home," a real-life test bed for context-aware services. The system supports the creation of new home services by connecting devices, sensors, and appliances across a home network. Active and passive radio frequency identification (RFID) receivers located above the ceiling and at the entrance of the door are used to detect and recognize inhabitants. Pressure sensors are employed to track user movements and furniture locations. The home is equipped with plasma panels, liquid crystal displays, and microphone to facilitate user interaction. A network robot is employed to perform certain home services. The authors concluded that the goal of smart home research is not to design an automated home but to develop an environment using interface technologies between humans and the system [27]. Although the researchers installed enough sensors and interfacing devices, the system is only practical for a few task automations such as TV program selection, cooking recipe display, and services used to search for forgotten property.

Swaminathan *et al.* proposed an object-recognition system using visual image localization and registration. Appliances are first registered in the image-processing system by a direct feature-matching approach. An improved version of this method features a k-means algorithm and a geometric relationship. The desired object is selected using an environmental map according to the voice command of the user [28]. An existing speech-based smart home system called INSPIRE [29] was developed at Deutsche Telekom Labs in Berlin is used to verify the methods. It is actually a home automation project utilizing a speech-recognition system to process user commands. Commands are given to the objects, which are already registered in the system.

The controlling system and status retaining system (CSnSRS) was proposed by Kumar and Qadeer to automate home appliances. The system features a computer as the controlling device and uses the X10 protocol to control home appliances. The researchers used a device called a “Safe Mode” panel to retain the status of home appliances in case of a power outage. A power-saving mode was also proposed to turn OFF the controlling device when the status of the appliances is not changing. The authors did not implement the CSnSRS [30].

A growing self-organizing map (GSOM) [31] uses a self-adaptive neural network (SANN) to detect and recognize residents' daily activities [32]. The GSOM is based on the basic principle of the Kohonen self-organizing map influenced by adaptive architecture. The learning process starts by generating an initial network composed of four neurons on a 2-D grid. The system has demonstrated the ability to detect 22 distinct activities of a resident when it was tested in a single-room apartment for approximately two weeks. Like other SANNs, it depends on several learning parameters to be determined in advance, such as an initial learning rate and the size of the initial neighborhood.

Shehata *et al.* designed a runtime policy interaction management module to implement user-defined policy in smart homes [33]. To distinguish the interaction patterns between smart home appliances, the authors used identifying requirements interactions using semi-formal methods (IRIS), which use graph- and table-based human interaction detection. To apply the policies, the authors proposed to extend the KNX protocols in S-mode as a part of the Engineering Tool Software suite. This research provides a solution for constraint management in smart homes. Another important contribution of the research is the application of the KNX protocol, which seems to be expandable based on user requirements. The proposed methodology is not suitable for real-time analysis because the IRIS method is only applicable to offline processing.

At National Taiwan University, Lu and Fu built a prototype of a smart home named “CoreLab.” The authors developed a location-aware activity recognition system for an attentive home. Instead of using simple sensors, CoreLab uses integrated components called ambient intelligence compliant objects (AICOs). There are different types of AICO that are used for different purposes, such as power usage, contact, pressure, location, and motion-detection AICOs. An enhanced version of the Naive Bayes classification method is used to detect the location-aware activities of inhabitants. The proposed system can classify ADL at high confidence levels. The authors developed an application called “Activity Map” to represent graphical contextual information regarding humans and their environment. This approach is only applicable to single-inhabitant tracking [34].

Ma *et al.* emphasized context awareness to provide automated services in smart homes. The authors used case-based reasoning (CBR) for the provision of more appropriate services. CBR depends on previous interactions and experiences to provide solutions to current problems. The system can adopt any manual adjustment by modifying case data [35]. It is in the initial state of the project that few scenarios such AC, TV, and lamp interactions are evaluated. In the future, the authors plan to add more contexts and enrich the features of case tables.

At the Industrial Technology Research Institute in Taiwan, Chen *et al*. developed a smart home that integrates different communication protocols into a home network. The authors initiated the smart appliance alliance net standard, which combines different communication protocols such as universal plug and play (UPnP), digital living network alliance (DLNA). The OSGi framework is used as middleware to integrate heterogeneous devices. The researchers also developed intelligent home appliances. These appliances use microcontrollers to receive commands and send their status to the system. They constructed a smart energy home laboratory to reduce energy wastage. This research is an excellent example of a smart home with distributed intelligence [36].

Rashidi and Cook developed CASAS at Washington State University. CASAS is an adaptive smart home that uses machine learning techniques to discover user behavior patterns and automatically mimic these patterns. The user can modify the automation policies, provide feedback on the proposed automation activities, and introduce new requests. CASAS can automatically identify changes in resident behavior. The frequent and periodic activity miner (FPAM) algorithm identifies frequent and periodic activity patterns after processing activity information. The patterns are modeled by a hierarchal activity model for a satisfactory automation policy utilizing temporal and structural regularities [37]. The authors are planning to add a voice recognition system, which is an efficient tool in creating a robust and interactive smart home. The CASAS project has benefited from the aid of researchers who previously worked on the MavHome [15] smart home.

2) Remote Access and Control: These projects enable the user to remotely access, monitor, and control their home environment. The internet is the most common and widely used technology that provides bidirectional communication between the home and the user. Sometimes, telecommunication infrastructure is used for this purpose. The following projects enable users to control and monitor home appliances from remote locations by direct interaction. In these cases, the home does not possess intelligence; it only creates a platform for remote access and control.

Perumal *et al.* from the Institute of Advanced Technology, University Putra Malaysia, presented a design and implementation of simple object access protocol (SOAP)-based smart homes [38]. They designed a SOAP-based control module to allow for the interoperation of home appliances in smart homes. Fifteen web-based feedback control channels were designed within a residential management system. If the server goes down, the system can also be controlled remotely via an SMS module. It offers a complete, bidirectional real-time smart home control, and monitoring system. This system has been implemented using relay-based switches, which do not follow any standard communication protocols.

Wang *et al.* designed a smart home monitoring and controlling system. The system can be controlled from remote locations through an embedded controller. The authors have developed different GUIs for mobile devices and PCs. Each device has a unique address. A new command format to control the devices is introduced [39]. Although the existing protocols are adequate to be used in this scenario, the researcher proposed a new protocol with a new command format.

Yongping *et al.* developed an embedded web server to control equipments employing the Zigbee protocol. For this purpose, they used a S3C2410 microprocessor, which was programmed with Linux 2.6 kernel. To provide online access, a small web server (only 60 KB) named Boa was installed. The authors have designed an interface to communicate with the Zigbee module (MC13192). This is a remote home automation project. The system does not possess any type of intelligence [40].

Wu *et al.* proposed a service-oriented architecture of a smart home based on OSGi and a mobile agent [41]. The architecture is a peer-to-peer (P2P) model based on multiple OSGi platforms. The mobile agent specification markup language is used to interact with the mobile agent by web services. In each OSGi platform, a web service bundle is deployed, which allows for the publishing of intercompatible services. Instead of a server-centric model, the authors proposed a P2P model with multiple OSGi platforms, which shows better performance because of distributed resource utilization. The proposed architecture was implemented on Knopflerfish 1.3.4 [42], which is an open-source OSGi R3 application. The results show that it reduces task execution time because of parallel task processing and local services execution. The authors also presented a detailed architectural overview of the proposed smart home.

Nikolaidis *et al.* proposed a solution to combine CPE wide area network management protocol (CWMP) with UPnP following DSL forum standardization [43]. The authors discussed a method that sends UPnP information to a CWMP client. The CWMP client transfers this information to a UPnP control point. The UPnP control point undertakes the configuration and management of the UPnP network. This architecture presents a remote diagnostic solution to the service provider. Their future works include security and multiprovider access to the home network.

B. Healthcare

Smart homes provide healthcare facilities for patients, elderly people, and healthy people. Healthcare services can be implemented on-site as stand-alone solutions to generate health reports locally. Another effective way is to use remote healthcare service providers for emergency support. The projects in this category present effective ways to provide healthcare support in smart homes.

1) Local Monitoring: Smart homes provide patient-monitoring services in the home environment to identify health conditions, ensure assistive services, and generate local warnings or alarms if required. A home can produce long-term trends of user health, which can be analyzed by a medical office or by the user. The projects discussed here present the methodologies used to implement healthcare support in the home environment.

A health integrated smart home information system is an experimental platform for home-based monitoring [44]. IR sensors and contact switches are used to track inhabitant activities, and information is transmitted via a controller area network (CAN) to a local computer. The CAN also acquires physiological data, e.g., blood pressure, heart rate, weight, and SaO_2 information. The proposed methodology is based on a 24-h circadian cycle, which is subdivided hourly for activity monitoring. Statistical mean and deviation measurement methods are applied to this hourly information to alert in an abnormal situation. This research is limited to single-inhabitant monitoring. The presented results are based on a simulated design in LabVIEW (a tool from National Instruments). However, the hourly summarization method is not efficient with respect to the detection of long-term deviations such as weight changes or sleeping disorders.

Mihailidis *et al.* developed a computer vision system for pervasive healthcare. It consists of three agents: sensing, planning, and prompting. Physics- and statistics-based skin color segmenting methods are utilized for face and hand tracing [45]. It can detect user activities by extracting information from hand and face images. However, this simple hand- and face-tracing algorithm is not sufficient to create an effective smart home. The system should include body tracking and hand-gesture recognition, which were not considered by the designer.

Casattenta is an ambient intelligent system developed by Farella *et al.* in Italy. The authors used a wireless sensor network (WSN) to monitor elderly inhabitants for recognizing activity disorders such as falls, immobility, reaction incapacity, etc. The proposed system used wearable kits to gather information from the user. For this purpose, TinyOS-based motes were employed in a TmoteSky platform. The system can only identify motion-based changes. The acquisition of such physiological data as body temperature, heartbeat rate, and blood pressure has yet to be demonstrated [46].

The ENABLE project evaluates the impact of assistive technologies on patients suffering from mild or moderate dementia. The researchers installed two devices (cooker and night light) in the apartments of several patients in different locations to estimate the efficiency of the system [47]. The proposed project places a greater emphasis on psychological impact rather than on technical development. The researchers have found that a good relationship (consistent communication and presentation) between the caregivers, evaluators, and project staff is essential for long-term evaluation. The authors concluded that to evaluate the current technology, the researchers should have patience and a better understanding of people with dementia. The scope of this research was limited to only two household devices. To satisfy this type of patient, there should be more assistive services, which were not considered in this design.

Sensorized Environment for Life (SELF) is an intelligent environment that enables a person to maintain his or her health through "self-communication." SELF observes a person's behavior using distributed sensors invisibly embedded in the daily environment, extracts physiological parameters from them, analyzes the parameters, and accumulates the results. The accumulated results are used to report useful information to maintain the person's health. The researchers constructed a model room for SELF, which consists of a bed with pressure sensor array, a ceiling lighting dome with a microphone, and a washstand with a display [48]. SELF is a self-assessment system used to evaluate human health. The proposed system only considers the respiratory system and sleeping disorders, which are not sufficient to fully assess health conditions.

Arcelus *et al.* measured sit-to-stand (SiSt) duration to estimate the physical mobility of patients. To measure SiSt duration, the authors used pressure sensors placed underneath the bed and on the floor. The start time is determined by an algorithm based on the motion of the center of pressure (COP) on a mattress toward the front edge of the bed. The end time is estimated using a third-order transfer function by modeling the foot pressure on the floor. To determine the start or end time error, the authors reviewed video-recorded data. The system cannot determine other characteristics of SiSt transfer, such as the use of hands to assist in the transfer, a measure of the leaning of the forward trunk, the occurrence of unsuccessful transfers, and a measure of stability in the standing position [49].

At the Tampere University of Technology, Vainio *et al.* developed a proactive fuzzy home control system. An adaptive fuzzy logic algorithm is applied to evaluate the test on the obtained results. The goal of this research is to assist the elderly to live independently at home. The developed system can recognize routines and deviations from routines. It can provide residents' information to caregivers with respect to daily rhythm, sleeping disorders, and medicine taking [50]. It works sensibly for lighting control.

2) Remote Monitoring: Remote monitoring employs specialized healthcare service providers to deliver instant medical support in emergency situations. The house monitors the patient using physiological sensors and contacts the caregiver automatically if any vital sign is found. Normal sensors along with information processing systems are used to observe the elderly which generates an alarm in remote healthcare center in case of user inactivity. The following projects discussed smart homes that aim to provide remote patient-monitoring services. These projects require real-time human intervention from remote locations.

Barnes *et al.* evaluated the life-style monitoring data of elderly using the infrastructure of British Telecom and Anchor Trust in England. The system detects the inhabitant's movement using IR sensors and magnetic contacts at the entrance of the household doors. It uses a temperature sensor in the main living area to measure the current temperature. An alarm activation system is implemented, which detects abnormal behavior and communicates to a remote telecare control center, the clients, and their caregivers [51]. The researchers presented a low-cost solution to implementing a smart telecare system. It is limited to detecting abnormal sleeping duration, unexpected inactivity, uncomfortable home temperature, and fridge usage disorder. Moreover, it uses a special new telecom protocol called "No Ring Calling," which requires the service providers to modify the existing telecom protocols. A No Ring Calling is a phone call that occurs without ringing. It provides a lower-cost solution to collecting data from the client's home using existing telephone line. Its priority is less than that of a normal phone call so that any incoming or outgoing call can override it.

CarerNet is an architectural model of an integrated and intelligent telecare system proposed by Williams *et al*. Its core components are a sensor set, a sensor bus, an intelligent monitoring system, and a control unit. The authors use ECG, PPG, spirometer, temperature, galvanic skin response, colorimeter, and pulse measurement tools to collect physiological data. The communication network is an integration of HomeLAN and body area network, which is responsible for recording real-time data, event data, and command and control data. It has a distributed intelligent system in the form of smart sensors, smart therapy units, body hub, local intelligence unit, and client's healthcare record. The system provides an emergency alarm, health information, and ambulatory monitoring services [52]. CarerNet is an abstract model of the health-monitoring smart home and its interconnected components. No prototype of the model has been developed. Only a hypothetical case study of an individual who had undergone brain surgery after suffering from a subarachnoid is discussed.

Raad and Yang developed a cost-effective user-friendly telemedicine system to serve the elderly and disabled [53]. It consists of physiological sensors (pulse oximeter sensor and the blood pressure sensor) and general-purpose sensors (weight sensors, motion detectors, and light sensors). The physiological sensors are attached to a wheelchair, which can communicate to a database server through a personal digital assistant or laptop. The doctor can analyze the patient's health condition from the database remotely. Other sensors are used to track the location and detect the activities of the residents. It automatically contacts the doctor through SMS via a GSM modem if any abnormal vital sign is detected. It cannot detect health conditions by analyzing real-time data from physiological equipments. It still depends on human interaction for medical report analysis.

C. Security

Smart homes are vulnerable to security threats. Most security problems are related to weak user- and device-authentication schemes. Security attacks may be generated locally or remotely. The projects that deal with security issues in smart homes are discussed next. From this review, it is obvious that most security mechanisms are adopted from existing techniques of computer security.

Pishva and Takeda proposed a product-based security model for smart home appliances [7], [8]. The model suggested the involvement of a third-party network operator to implement security measures that are related to multivendor products. It uses a home gateway as the key component to impose security features. The main purpose of the gateway is to implement a user-authentication scheme. It can log user access and billing information based on authorized access control. It is equipped with a firewall and virus-protection software. Another important part of this paper is the presentation of a taxonomy of common security threads according to product functionality. The assumptions are actually based on previous experiences regarding computer network security such as user impersonation, device impersonation, service interruption, data alteration, worm/virus, phishing, data wiretapping, firmware alteration, and OS/software vulnerability. The authors categorized the common threats into several difficulty levels and proposed solutions to prevent these security problems. The authors assume that all the smart appliances function using internet technology. Therefore, the security threats and the model discussed here are only applicable in computer networks. The security issues related to other coexisting protocols, e.g., Zigbee, X10, KNX, etc., are not included.

Kalofonos *et al.* proposed a user-intuitive security framework for smart homes named IntuiSec [54]. The proposed scheme provides a level of abstraction to ease the system for nonexpert users. Its device authentication process uses public key cryptography, which takes place during the Easy Setup phase. IntuiSec maintains an ordered list of common secrets that are generated randomly by IntuiSec middleware. During the Easy Setup process, the entire list is transferred to the devices. This process enables the user to grant time-limited access permission to guest devices. This framework also proposed an application programming interface for the application developer to represent the device authentication status graphically. The developed prototype used Symbian mobile phones as mobile devices and Linux-based laptops as fixed and infrastructure devices. It assumes that home appliances are accessible in limited ranges via RFID, IR, etc., protocols. Therefore, it works only inside the home and is limited by protocol-specific boundaries.

Vaidya *et al.* proposed an authentication mechanism to secure remote access to a smart home network. The system uses an HMAC-based one time password, a hash chaining technique, and smart cards based on strong password approach. It consists of an integrated authentication server (IAS), which is located outside the home network, to provide authentication, authorization, and accounting services. At the initial registration phase, the user chooses an ID and password, which are used by the IAS server to generate a smart card. This smart card, along with the coded information, is used to implement secure access in smart homes. It requires higher computational overhead than that used in the previous schemes [55].

IV. Discussion

The design of a smart home depends on user requirements and user living styles. Generally, smart homes offer comfort, safety, security, remote control, and energy conservation.

Smart homes provide healthcare support to the elderly and disabled. These patients normally suffer from long-term diseases, which do not require critical medical support. It is not efficient to provide healthcare support to these patients in a traditional medical center for an uncertain period of time. Some elderly people are not alert and suffer memory problems, and many of them cannot even make their way to a hospital. They require safety, security, and immediate health support in case of emergency. Smart homes can support the disabled, e.g., patients with bone fractures, hearing problems, blindness, and mental disorders. These consumer groups require continuous monitoring in an intelligent environment. Smart homes transfer medical facilities to citizens' dwelling places.

Patients suffering from other diseases can benefit from using smart technologies. Biosignal monitoring equipment can be employed for smart healthcare support. The technology is more applicable to hospitals and nursing homes.

Smart homes can offer services to healthy inhabitants as well. They can monitor a resident's wellness and generate warnings if any abnormal vital sign is detected.

There are some ethical issues related to user privacy. Users' private lives should not be exposed to public. Although telehealthcare has improved the healthcare sector, it also creates problems regarding the ease of access to private information. Security problems can be eliminated using security mechanisms, e.g., data encryption, cryptography, which are currently being used in computer systems [55], [56].

Future homes should also be concerned about user satisfaction. The monitoring devices should be installed in such a way that the inhabitant can easily forget about their presences. More research is necessary regarding user life styles, satisfaction, requirements, and adaptation to smart systems.

Smart homes provide services and utilities to optimize user requirements. A network of home appliances creates real-time data connectivity by utilizing different media and protocols. Algorithms and data-processing methods add decision support facilities to introduce and expand services. The following sections discuss smart home components that are responsible for the functionality and efficiency of smart homes.

A. Devices and Equipment

Smart homes rely on data acquisition equipment and devices to assess the states of residents and their environments. These monitoring devices can be classified into three categories: sensors, physiological devices, and multimedia devices. Sensors are used to measure environmental parameters. Physiological devices monitor health conditions and vital signs. Multimedia devices capture audiovisual information and provide an interface between the system and the user. Table I describes the taxonomy of home and user monitoring equipment and devices.

A sensor network is responsible for environmental data acquisition in smart homes. The use of light and temperature sensors is very common because of their simplicity [20]–[22], [56]. Light sensors are normally used to measure the illumination intensity of a specific location. Pressure sensors are widely used to detect inhabitant location [9], [57]. Researchers also utilize RFID and passive infrared sensors for location identification [21], [22], [27], [58]–[60]. Power sensors are used to identify devices that are currently active [34]. Sensors utilize a very low data bandwidth for communication.

Smart homes use medical instruments to provide healthcare facilities. Equipment that measures blood pressure, body

TABLE I
CATEGORY AND PURPOSE OF SMART HOME MONITORING DEVICES

Category	Name	Purpose
Sensor	Light	Measure intensity of light
	PIR	Identify user location
	Temperature	Measure room temperature and body temperature
	Pressure	Identify inhabitant location
	Switch sensor	Door open or close status detection
	RFID	Object and people identification
	Ultrasonic	Location tracking
	Current	Measure current usage
	Power	Calculate power usage
	Water	Measure volume of water usage
Physiological device	ECG	Pulse rate and variability
	PPG	Pulse rate and blood velocity
	Spirometer	Respiration rate, peak flow, inhale /exhale ratio
	Galvanic skin response	Sweating.
	Colorimeter	Pallor, throat inflammation
	pulse oximeter	Measure oxygen saturation of blood
	Sphygmomanomet er	Blood-pressure measurement
	Weight	Measure patient weight
	Pulse meter	Monitor heart rate
Multimedia device	Camera	Monitoring and tracking
	Microphone	Voice command
	Speaker or headset	Announce alert and information
	Display (LCD, Plasma panel)	Show visual information

TABLE II
TAXONOMY OF COMMUNICATION PROTOCOLS ACCORDING TO MEDIUM

Media Type	Media	Name	Significance	Disadvantage
Wired	AC Power Line	X10	Lower cost, easy to install, bit rate 20bit/s	Prone to noise
		KNX (PL110)	Higher data rate compared to X10 (1200 bit/s)	Interference from AC signal
	Phone line	Traditional Telephone	Voice communicatio n	Human operator required
		DSL	Remote access via home gateway	Only works in IP network
	ISDN line	ISDN	Higher dedicated bandwidth	Expansive compared to other internet services
	Twisted Pair	Ethernet	Builds IP network, provides remote access	Applicable only for IP network
		KNX	For TP-1 bit rate 9600 bit/s, for fast Ethernet	Ethernet has not been implemented
Wireless	RF	Zigbee	Low-power wireless protocol	Tight power and bandwidth constraint
	ISM	Wi-Fi	High bandwidth	High power requirement
Hybrid	Ethernet, IR, RF	UPnP	Zeno configuration	Lack of default authentication

temperature, body weight, and heart rate is frequently utilized to monitor patients' health [44], [52], [61]. Sometimes, researchers use sophisticated medical equipments such as ECG, PPG, etc. [52], [61]. Biosignal data formats vary according to the type of devices used. A common data format was proposed by Yoo *et al.* based on MFER standards [62]. The equipment was chosen according to target patients and diseases.

Multimedia devices have been introduced to create an interactive and robust home environment [24], [27], [28], [56], [58]. Cameras and microphones are common data-acquisition tools. Plasma displays, headsets, and LCDs create a platform for information exchange. The technology enhances living environment.

Recently, motes have been used in smart homes [46], [57]. A mote is a wireless node used in a WSN. It provides an integrated, stand-alone, predefined functionality for the rapid development of a sensing network. Motes are expensive and limited to specific uses.

To enrich intelligent systems, smart homes must be provided with sufficient information from sensors, cameras, microphones, and other interfacing devices. Sensory information is prone to noise that misguides the information-processing system with wrong input signals. There should be additional methods to improve the accuracy of detection of sensor networks. Image-processing systems require extra hardware resources and relatively long times to detect and reorganize residents. A system becomes unstable if the home exceeds its inhabitant limit or the inhabitant changes his location frequently [25], [26]. Voice-recognition systems sometimes fail to detect commands and the repetition of the same speech makes the user frustrated. Multimedia data processing is still in its primitive stage. More research is required to obtain effective image-processing and voice-recognition systems for smart homes.

B. Communication Media and Protocols

Smart home equipment is connected through a communication network to share and exchange information. Protocols from other established technologies such as telecommunication and the internet have been adopted for greater functionality.

Table II presents the taxonomy of protocols used in smart homes. The protocols can be classified into three major categories based on media: wired, wireless, and hybrid. Wired media can be further classified into power line, phone line, ISDN line, and twisted pair. Wireless protocols use RF and ISM bands for communication. Hybrid protocols use both wired and wireless media.

X10 is a popular communication protocol used in smart homes [15], [20], [30]. It uses an electrical power line to transmit signals. Its data transmission rate is 20 bit/s and can address up to 256 home appliances. X10 uses preinstalled house wiring to transmit data, which is processed by X10 devices. It is very slow and limited to few command functionalities. Moreover, some noise-filtering device used in modern electrical equipment may filter X10 data as noise.

Zigbee [63] is another well-accepted protocol for wireless home networks [40]. Zigbee constructs a low-speed wireless ad hoc network of nodes. The CSMA/CA method of access control provides reliable data transfer through the wireless medium. The physical layer and media access control of Zigbee are specified in the IEEE 802.15.4 standard. Zigbee is a complex protocol with tight power and bandwidth constraints.

KNX is an open standard that has been developed by integrating Batibus, European Installation Bus (EIB), and European Home System (EHS) [64]. It supports different types of communication media such twisted pair, radio frequency, power line, and IP/Ethernet. The KNX Association is responsible for quality control and standardization. Moreover, KNX provides software tools to design, visualize, and troubleshoot home-automation systems. Many researchers are using KNX to implement smart home services [32]. KNX has an advantage over other protocols with respect to the number of supported media, software support tools, and adaptable configuration. In the real world, the only supported media is twisted pair with low voltage.

The internet is a cost-effective and readily available solution for remote communication. It provides data-access facilities for telehealthcare centers from distant locations [62]. Ethernet is also used to connect home-monitoring equipment [65]. It has a wide area of coverage over a low-cost public network and can provide high-data bandwidth for multimedia data transmission.

Residential gateway or home gateway devices have been introduced to provide remote access and control. Gateways function in IP or broadband networks. They provide seamless access to home devices. WiFi is mandatory for residential gateways. The home gateway initiative (HGI) [66] involves improving the interpretability of the gateways with connected home devices. HGI is working with the existing standard, e.g., UPnP [67], DLNA [68], and Broadband Forum (previously DSL Forum) [69], to provide specifications and standards for intercompatibility among various equipments.

Telecommunication facilities have recently been introduced for telehealthcare support. Researchers are using video conferencing over ISDN networks [61]. The traditional telephone line is used to communicate between the client and the caregivers [51], [52]. The SMS-based system is also an effective solution for information exchange [38].

OSGi [41], [70] is a popular middleware for integrating heterogeneous devices. OSGi creates a common platform on which to construct an interoperating environment enabling the communication between multivendor and multipurpose devices. It solves the incompatible service-oriented communication problem between heterogeneous devices by providing a rigid standard, which is a burning issue in creating a ubiquitous environment. UPnP [43], [67], which was promoted by Microsoft, is now a well-accepted and well-supported protocol for home networking. Other protocols such DLNA [68], HomePNA, G.hn, etc., are also popular for home appliance control [36].

Smart homes deploy protocols using different technologies. Thus, there are inconsistencies between the data formats generated by heath-monitoring equipment. For data storage and interoperability, a common data format must be developed.

TABLE III
ALGORITHMS AND METHODS USED IN SMART HOMES

Category	Algorithms and methods	Purposes
Artificial Neural Network	Artificial Neural Network	Prediction of the future states of home environment [20] Create and evaluate behavioral model [25-26] Detect and recognize activities of daily life [32]
Multiagent System	Distributed intelligent system	Health monitoring from remote location [52]
	Multiagent system	Simulation of agent interactions and task interactions [74], [75]
Statistical methods	Hidden Markov model	To create and evaluate behavioral model [25-26]
	Bayesian statistics	ADL recognition [34] To determine location of the inhabitants [45], [49] Location aware activity detection [34]
	Summarization algorithm	To track any changes in the system [23]
	Statistical predictive algorithm	To model circadian activity rhythms (CARs) [76] To predict activities of daily life(ADL)[19]
C4.5	C4.5	Build spatiotemporal context [71]
Data compression	Active LeZi	Next activity prediction [17]
CBR	CBR	Context awareness [35]
Fuzzy logic	Fuzzy logic	Recognize routines and also deviations from routines [50] Control lighting system [50]
SVM	SVM	Activity recognition [24]

The reliability of smart homes depends on the communication protocols, services, and systems used. The most significant problem is the compatibility between different protocols from different vendors. Most appliances support a specific protocol, which is a problem when using different vendor products without changing existing devices and protocols. The transition is costly and slows down smart home implementation.

C. Algorithms and Methods

The purpose of the algorithm is to provide intelligence to create an interactive home environment. Location-detection algorithms are derived to gather information about user location-based activities. Prediction, classification, and summarization algorithms have added functionalities of behavior tracking and activity recognition. Table III lists many currently used methods and algorithms.

Artificial neural networks (ANNs) can predict the future state of a home environment by detecting usage patterns of home appliances [20]. They can also be utilized to detect and recognize the ADL of the resident [32]. Human behavior modeling is another possible application of neural networks [25], [26]. ANNs require high processing power and huge storage space for data processing. Vast amounts of information should be used to train an ANN system, which requires a long time to obtain reasonable efficiency. Neural networks are still popular because they do not require any previous knowledge about the home environment or the residents, which is very effective in designing systems as complex as smart homes.

The C4.5 algorithm is used to build the spatiotemporal context of the home user [71]. C4.5 [72] is a popular machine learning algorithm that is used to classify data according to different data attributes to predict future behaviors. Smart home researchers have applied C4.5 to match the current behavior patterns of inhabitant to a class of previous patterns to recognize states of activity. A major disadvantage of C4.5 is that it requires long CPU times and additional memory for rule sets.

Bayesian filtering methods are used to determine the location of the inhabitants [60], [73]. These methods use the last-known position and last sensor state to improve the accuracy of location prediction. Dynamic Bayesian algorithms can identify ADL utilizing a hierarchical recognition scheme [58]. These methods are derived from statistical inference, which classifies gathered information and filters it according to some predefined rules. Bayesian methods only consider the immediately previous state to predict the future.

Fuzzy logic is efficient for home appliance control [50]. Instead of using only binary logic, fuzzy systems use multivalued logic for logical reasoning. It is popular for control systems but not for home intelligence.

Multiagent systems are effective when there are different types of agents used for different purposes, and the agents should cooperate with each other by sharing knowledge. Each agent is responsible for its own domain and information, which has a significant impact on total system performance. In smart homes, multiagent systems have been used to simulate agent interactions and task interactions [74], [75]. It is the best option in employing distributed intelligence. It increases processing overhead in cases of improper design and implementation.

Hidden Markov models (HMMs) can be applied to create and evaluate behavioral models [25], [26]. Markov models depend on several previous states for prediction. HMMs are used when some states of a Markov model are missing or hidden from the information system. An HMM must be optimized according to the number of states and accuracy.

Image-processing methods allow for human activity recognition. They segment the skin color of a digital image for face and hand tracing [45]. These methods seem to be the most likely to be adopted in future smart homes. However, their implementation is very complex and requires more research.

CBR and prediction algorithms make decisions based on previous states. Context awareness, a common feature of smart environments, can be achieved by CBR [35]. ALZ and other predictive algorithms also work with previous history to predict the ADL of the resident [17], [19]. Recent changes in user behavior take time to reflect back to the system. Statistical predictive algorithms are used to model circadian activity rhythms [78].

The FPAM algorithm was developed by CASAS at WSA to detect frequent and periodic activity patterns [37]. The user can set policies and provide feedback to customize the system. SVM can also be applied for activity recognition [24].

Algorithms are used to process information and provide services but are limited to specific functions. Total home automation with reasonable intelligence is still a dream. Although different methods are being used for location detection, next-event prediction, face and hand tracing, ADL recognition, and pattern classification, they fail to provide reliable task automation. Processing huge amounts of information generated from input devices requires advanced data-processing equipment. Using only AI algorithms will never make a system automated; systems must utilize interface technologies such interactive displays and voice-recognition systems to understand user requirements at any given moment [27].

Algorithms are the most challenging part of smart home research. There are not enough algorithms to track multiple inhabitants at the same time. Moreover, the accuracy of the algorithms is not sufficiently satisfactory to completely rely on them [17]. Instead of aiding people in household tasks, the algorithms implemented may irritate the user, thus alienating people from this technology. Although researchers are using various algorithms and methods for smart homes, smart homes are still partially dependent on human interaction for accurate decision making [27].

D. Services and Utilities

Smart home technology has achieved significant improvements in healthcare efforts, such as patient monitoring, telemedicine, and wellness monitoring. Healthy people should be concerned about their wellness and take precautions against illness. Self-monitoring systems graphically assess the wellness condition of the resident [77]. Smart homes track the user and generate an alarm if any abnormal vital sign is detected [44]. Respiratory and sleeping disorders can also be detected [48]. Smart homes can monitor physiological data and are able to recognize sleeping stages [65].

Smart homes are devoted to providing comfort and safety to the elderly [21]. Houses can recognize falls, immobility, and reaction incapacity [46]. Services are targeted to specific groups such as dementia patients [47]. A housing facility can control night lights and cooking facilities for this type of patient. A recent project has been devoted to measuring SiSt duration as a wellness parameter of patients suffering from bone fracture [49].

Telemedicine is an alternative way of ensuring patient healthcare. Patients' physiological information is monitored from remote health support centers [53], [61]. A house may be equipped with videoconferencing facilities to connect the client and service provider [60]. These homes can identify sleeping disorder, inactivity, abnormal temperature, and appliance usage disorder by the elderly and can automatically contact the caregiver [51].

Inhabitant activity classification, recognition, and modeling are important in implementing home intelligence. Smart homes can model circadian activity rhythms and spatiotemporal contexts. They can detect [23] and classify [34] ADL and mimic these patterns [37]. Researchers refine ADL to coarse and fine levels [58]. The system can recognize AC, TV, and lamp usage patterns [19], [35]. Recent projects have successfully identified up to 22 activity patterns, which represents a great improvement in this area [31], [32]. A project at MIT is devoted to the study of residents' psychological behavior [56].

One of the major objectives of smart homes is the optimization of user comfort by reducing interactions between the inhabitant and home devices. Smart homes can control basic environmental parameters such as light, temperature, and heating according to user choice and habits [12], [15], [35]. Researchers add extended facilities such as TV program selection, cooking recipe display, and forgotten property service to smart home systems [27]. Smart homes can rearrange the equipment according to the resident's preference [25], [26]. Recent smart homes can identify situations such as introduction, presentation, aperitif, game, siesta, etc., and can control the lighting and music according to these situations [59].

Home appliance monitoring and control from remote locations is a popular service that can easily be provided via smart homes [38]. Web-based solutions are readily available for this purpose [39], [40]. Mobile devices can also accommodate this service [39].

A web-based data repository service has been introduced for biological data logging [63]. Voice-operated systems are replacing traditional home automation systems [44]. Intelligent appliances are being used to afford greater functionality [36]. Energy conservation is also achievable through smart homes [36].

Most services are applicable only to single-resident smart homes. Sometimes, they are even limited to a single room. Some projects are devoted to location detection and do not implement any service [57], [59], [60], [73]. Several hypothetical smart home designs have been proposed, almost all of which will be equipped with healthcare services, but practically they are still a dream [52]. People are claiming that their project may accommodate many services, but in reality, such systems function in only a few situations [50].

Table IV presents a categorized summary of smart home services and utilities. Smart homes are now providing limited services, which can be extended to fulfill consumer satisfaction. Their widespread utilization cannot be achieved without adequate services and utilities. Additional research is required to make these services cost effective, efficient, and acceptable.

TABLE IV
SMART HOME UTILITIES AND SERVICES

Category	Services	Function
Comfort	To provide comfort	Lighting, temperature and heating control [20] Arrange home environment according to the resident's desire [25-26] Home appliance control [15] Identification of introduction, presentation, aperitif, game and siesta [24] TV program selection, cooking recipe display and forgotten property service [29]
Remote access	Remote access, monitoring and control	Appliance monitoring and control via mobile devices and computers from distance location [39] Appliance monitoring and control through web browser from remote location [40] Controlling and monitoring home appliance from remote location [38]
Home automation	Automate home appliances control	Voice-operated appliance control [28]. Intelligent appliance monitoring and control [36].
Repository	Data repository	Web based repository of bio-signal data [62].
Energy optimization	Energy conservation	Reducing energy wastage [36].
Healthcare	Wellness monitoring	Graphical representation of wellness [77] Respiratory and sleeping disorder assessment [48] Activity tracking and alarm generation [44] Sleeping stage recognition [65]
	Aging in place	Fall, immobility and reaction incapacity identification [46] To provide comfort and safety to the elderly [21] Lighting control [50]
	Telemedicine	Support elderly and disabled [53] Abnormal sleeping disorder, unexpected inactivity, uncomfortable home temperature, fridge usage disorder detection and contact to career [51] Health monitoring and support from remote location [61]
	Patient support	To measure sit-to-stand (SiSt) duration [49] Cooker and night light control for the patient suffering dementia [47]

V. FUTURE CHALLENGES

Future homes will be able to offer almost all required services, e.g., communication, medical, energy, utility, entertainment, and security. People spend a significant amount of time in their houses, which attracts potential investors to promote the integration of all possible services into traditional homes.

Current trends in smart home research imply that healthcare services will receive more emphasis in the future. One of the main objectives will be providing assistive services for the elderly and disabled. Remote patient monitoring will become more popular because providing healthcare services to certain groups of patients requires less manpower. Other services related to comfort and security will be improved gradually with the improvement of associated components.

Recently, a new research area regarding the intelligent control of electricity usage has emerged. This new branch of study is called smart grid research [78]. A smart grid is an intelligent electricity network that provides bidirectional communication between electricity suppliers and consumers. A supplier may implicitly control home appliances to ensure uninterrupted electricity supply. Smart meters are an integral part of a smart grid; they enable intelligent energy control. The integration of smart homes, smart grids, and smart meters will become essential part in providing for consumers.

Similar to the smart grid concept, there is the possibility of more new service networks emerging that will connect homes to share information. These networks will act as a platform for local authorities and utility providers to gain easy access to every home for service delivery and payment transactions. From the home owner's perspective, a networked home provides emergency telemedicine service, natural disaster assistance, time-sensitive information delivery from law enforcement department, and social support from local government.

Smart homes require an understanding of human behavior and effective algorithms to solve the uncertainty problem within a home. The previous discussion on smart home algorithms implies that although smart home research was initiated several decades ago, it still faces problems of immature home intelligence because of inadequate algorithms, improper activity recognition methods, and low rates of prediction accuracy. Providing distributed intelligence to all appliances may be an effective solution because it removes the burden of processing huge amounts of information from a central intelligent system. Each device will be responsible for its own domain and share only important information with the central intelligent system. The system will eventually transform into a multiagent system with distributed intelligence by integrating smart appliances.

According to our previous discussion, sensors are prone to environmental noise. A solution to this problem is using numerous types of input sensors or input devices to improve performance. There should be multiple sensors dedicated to gathering the same information, and the processing unit should cross check the sensory input for validation. In this case, any input signal can be revalidated with other types of input signals containing the same information. Multiple types of sensors for the same information solve inconsistency, improve accuracy, and reduce processing time. For example, we can identify multiple inhabitants using cameras, but their accuracy will improve if we attach RFID tags to the people. The more sensors we use, the more accuracy we will achieve. Multimodal user interfaces should be utilized to obtain positive and negative feedback from residents. A network of objects can also be achieved by attaching passive or active tags (e.g., RFID tags) to the objects, which are capable of exchanging information regarding the current status of the environment. Voice and image processing require further research for adaptation.

There are problems related to integrating heterogeneous devices, which can be solved by using middleware such as OSGi [41], [70]. A middleware creates a common platform to exchange information between multivendor, multipurpose devices. An object becomes discoverable using a plug-and-play feature and creates a network of objects, which is a key element of pervasive computing.

The protocols involved in smart home development have been adopted by industry and have significant importance according to consumer requirements. Because different protocols coexist in the market, problems may arise if a combination of different protocols needs to be installed. Future research should take into account these intercompatibility issues [79]. To overcome such situations, vendors and standardization bodies should work together and propose some guidelines for stakeholders. Hopefully, the standardization process has already been started. The developers of EIB, EHS, and Batibus standards jointly initiated the KNX standard, which has already been approved by European, Chinese, and U.S. standardization bodies. The HGI and Broadband forum signed an agreement for collaboration. In the near future, well-accepted and intercompatible home automation standards will dominate the industry.

There is also the issue that smart homes may violate user privacy. Because the flow of information is sometimes unprotected over the internet and telemedicine systems, there is a possibility of exposing user private information to others. To protect user privacy, concerned authorities in the U.S. have already prepared an e-Health Code of Ethics, which sets four guiding principles under eight main headings: candor, honesty, quality, informed consent, privacy, professionalism, responsible partnering, and accountability [80]. Other countries are also requiring the approval of an ethical committee and placing emphasis on obtaining the written and oral consent of the user [81].

To maintain confidentiality, the communication system should be secure and safe. A way to ensure secure communication systems is to use data encryption and cryptography methods, which are currently being used to impose security in computer systems [7], [8], [54], [55].

Smart homes constitute an interdisciplinary domain. The architecture of a smart home depends on other branches of engineering, e.g., sensor technology, communication, and information technology. Smart homes will benefit from the improvement and diffusion of these technologies.

Finally, the general public evaluates smart homes by their functionality and services. People are not particularly concerned about the associated design complexities, internal components, and architecture. Therefore, future smart homes should carefully consider the satisfaction of the user to accelerate rapid adoption.

VI. Conclusion

Smart homes represent a potential research area, and their significance is growing rapidly because of increasing industrial demand. This study presents a general overview of smart home projects that are arranged according to their intended services. It also discusses the significance and limitations of smart home building blocks. The taxonomy of devices, media, protocols, algorithms, methods, and services presents an informative comparison between the associated technologies.

This paper identifies several future directions of smart home research. The trends indicate the increasing popularity of using middleware to integrate heterogeneous devices. Because multivendor devices will coexist in future, the use of middleware is an efficient solution to create networks that will overcome the limitations of diverse device integration. It seems that home intelligence will be employed in a distributed manner. This distributed intelligence may be applied in the form of smart devices. The system will also use different user interfaces to acquire user feedback, most of which will be based on auditory, visual, and haptic perceptions. Recently, people have become concerned about information security, which can be easily solved by using concepts from computer security and cryptography.

The future healthcare service provider will consider the smart home an effective way of providing remote healthcare services, especially to the elderly and disabled who do not require intensive healthcare support. For the same reason, assistive healthcare services will draw more attention to prospective researchers. In the future, smart homes will be connected to various service providers to automate and optimize services. The smart grid is one of the most recent examples of service integration, which is intended to optimize electricity usage according to electricity consumption and production capacity. Smart homes will gain massive popularity in the future because current trends indicate that they are becoming the center of intelligent service consumption.

REFERENCES

[1] (2008, Dec. 1). [Online]. Available: http://www.un.org/News/Press/docs//2007/pop952.doc.htm 2012.

[2] (2009, Jun. 23).[Online]. Available: http://www.who.int/disabilities/en/

[3] M. Chan, D. Estève, C. Escriba, and E. Campo, "A review of smart homes-Present state and future challenges," *Comput. Methods Programs Biomed.*, vol. 91, pp. 55–81, Jul. 2008.

[4] J. Hightower and G. Borriello, "Location systems for ubiquitous computing," *Computer*, vol. 34, pp. 57–66, Aug. 2001.

[5] E. D. Manley, H. A. Nahas, and J. S. Deogun, "Localization and tracking in sensor systems," in *Proc. IEEE Int. Conf. Sensor Netw., Ubiquitous, Trustworthy Comput.*, 2006, pp. 237–242.

[6] R. J. Robles and T.-H. Kim, "Review: Context aware tools for smart home development," *Int. J. Smart Home*, vol. 4, pp. 1–12, Jan. 2010.

[7] D. Pishva and K. Takeda, "A product based security model for smart home appliances," in *Proc. 40th Annu. IEEE Int. Carnahan Conf. Security Technol.*, 2006, pp. 234–242.

[8] D. Pishva and K. Takeda, "Product based security model for smart home appliances," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 23, no. 10, pp. 32–41, Oct. 2008.

[9] R. Lutolf, "Smart Home concept and the integration of energy meters into a home based system," in *Proc. 7th Int. Conf. Metering Apparatus Tariffs Electr. Supply*, 1992, pp. 277–278.

[10] A. V. Berlo, A. Bob, E. Jan, F. Klaus, H. Maik, and W. Charles, *Design Guidelines on Smart Homes: A COST 219bis Guidebook*. Brussels, Belgium: Eur. Commission, 1999.

[11] B. Winkler, "An Implementation of an ultrasonic indoor tracking system supporting the OSGi architecture of the ICTA Lab," Master thesis, Univ. Florida, Gainesville, 2002.

[12] D. Briere and P. Hurley, *Smart Homes for Dummies*. New York: Wiley, 2003.

[13] (2008, Dec. 3). [Online]. Available: http://www.changeagentteam.org.uk/_library/docs/housing/smarthome.pdf

[14] L. Satpathy, " Smart housing: Technology to aid aging in place. New opportunities and challenges," M.S. thesis Mississippi State Univ., Starkville, 2006.

[15] S. K. Das, D. J. Cook, A. Battacharya, E. O. Heierman III, and T.-Y. Lin, "The role of prediction algorithms in the MavHome smart home architecture," *IEEE Wireless Commun.*, vol. 9, no. 6, pp. 77–84, Dec. 2002.

[16] G. M. Youngblood, L. B. Holder, and D. J. Cook, "Managing adaptive versatile environments," in *Proc. 3rd IEEE Int. Conf. Pervasive Comput. Commun.*, 2005, pp. 351–360.

[17] K. Gopalratnam and D. J. Cook, "Online sequential prediction via incremental parsing: The active LeZi algorithm," *IEEE Intell. Syst.*, vol. 22, no. 1, pp. 52–58, Jan./Feb. 2007.

[18] G. M. Youngblood and D. J. Cook, "Data mining for hierarchical model creation," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 37, no. 4, pp. 561–572, Jul. 2007.

[19] S. Zhang, S. McClean, B. Scotney, X. Hong, C. Nugent, and M. Mulvenna, "Decision support for alzheimer's patients in smart homes," in *Proc. 21st IEEE Int. Symp. Comput.-Based Med. Syst.*, 2008, pp. 236–241.

[20] M. C. Mozer, "The neural network house: an environment that's adapts to its inhabitants," in *Proc. AAAI Spring Symp. Intell. Environ.*, 1998, pp. 110–114.

[21] S. Helal, B. Winkler, C. Lee, Y. Kaddoura, L. Ran, C. Giraldo, S. Kuchibhotla, and W. Mann, "Enabling location-aware pervasive computing applications for the elderly," in *Proc. IEEE 1st Conf. Pervasive Comput. Commun.*, 2003, pp. 531–536.

[22] S. Helal, W. Mann, H. El-Zabadani, J. King, Y. Kaddoura, and E. Jansen, "The gator tech smart house: A programmable pervasive space," *Computer*, vol. 38, pp. 50–60, Mar. 2005.

[23] H. Noguchi, T. Mori, and T. Sato, "Construction of network system and the first step of summarization for human daily action in the sensing room," in *Proc. IEEE Workshop Knowledge Media Netw.*, 2002, pp. 17–22.

[24] O. Brdiczka, J. L. Crowley, and P. Reignier, "Learning situation models in a smart home," *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 39, no. 1, pp. 56–63, Feb. 2009.

[25] J. Krumm, S. Harris, B. Meyers, B. Brumitt, M. Hale, and S. Shafer, "Multi-camera multi-person tracking for EasyLiving," in *Proc. 3rd IEEE Int. Workshop Visual Surveillance*, 2000, pp. 3–10.

[26] B. Brumitt, B. Meyers, J. Krumm, A. Kern, and S. Shafer, "EasyLiving: technologies for intelligent environments," in *Proc. 2nd Int. Symp. Handheld Ubiquitous Comput.*, 2000, pp. 97–119.

[27] T. Yamazaki, "Beyond the smart home," in *Proc. Int. Conf. Hybrid Inf. Technol.*, 2006, pp. 350–355.

[28] R. Swaminathan, M. Nischt, and C. Kuhnel, "Localization based object recognition for smart home environments," in *Proc. IEEE Int. Conf. Multimedia Expo*, 2008, pp. 921–924.

[29] S. Moeller, J. Krebber, A. Raake, P. Smeele, M. Rajman, M. Melichar, V. Pallotta, G. Tsakou, B. Kladis, A. Vovos, A. Hoonhout, D. Schuchardt, N. Fakotakis, T. Ganchev, and I. Potamitis, "Inspire: Evaluation of a smart-homesystem for infotainment management and device control," in *Proc. Language Resources Eval.*, 2004, pp. 1603–1606.

[30] S. Kumar and M. A. Qadeer, "Universal digital device automation and control," in *Proc. 2nd IEEE Int. Conf. Comput. Sci. Inf. Technol.*, 2009, pp. 490–494.

[31] D. Alahakoon, S. K. Halgamuge, and B. Srinivasan, "Dynamic self-organizing maps with controlled growth for knowledge discovery," *IEEE Trans. Neural Netw.*, vol. 11, no. 3, pp. 601–614, May 2000.

[32] H. Zheng, H. Wang, and N. Black, "Human activity detection in smart home environment with self-adaptive neural networks," in *Proc. IEEE Int. Conf. Netw., Sensing Control*, 2008, pp. 1505–1510.

[33] M. Shehata, A. Eberlein, and A. O. Fapojuwo, "Managing policy interactions in KNX-based smart homes," in *Proc. 31st Annu. Int. Comput. Software Appl. Conf.*, 2007, pp. 367–378.

[34] C.-H. Lu and L.-C. Fu, "Robust location-aware activity recognition using wireless sensor network in an attentive home," *IEEE Trans. Autom. Sci. Eng.*, vol. 6, no. 4, pp. 598–609, Oct. 2009.

[35] T. Ma, Y. D. Kim, Q. Ma, M. Tang, and W. Zhou, "Context-aware implementation based on CBR for smart home," in *Proc. Int. Conf. Wireless Mobile Comput. Netw. Commun.*, 2005, vol. 4, pp. 112–115.

[36] C.-Y. Chen, Y.-P. Tsoul, S.-C. Liao, and C.-T. Lin, "Implementing the design of smart home and achieving energy conservation," in *Proc. 7th IEEE Int. Conf. Ind. Inf.*, 2009, pp. 273–276.

[37] P. Rashidi and D. J. Cook, "Keeping the intelligent environment resident in the loop," in *Proc. 4th Int. Conf. Intell. Environ.*, 2008, pp. 1–9.

[38] T. Perumal, A. R. Ramli, and C. Y. Leong, "Design and implementation of SOAP-based residential management for smart home systems," *IEEE Trans. Consum. Electron.*, vol. 54, no. 2, pp. 453–459, May 2008.

[39] Z. Wang, S. Wei, L. Shi, and Z. Liu, "The Analysis and Implementation of Smart Home Control System," in *Proc. Int. Conf. Inf. Manage. Eng.*, 2009, pp. 546–549.

[40] J. Yongping, F. Zehao, and X. Du, "Design and application of wireless sensor network web server based on S3C2410 and zigbee protocol," in *Proc. Int. Conf. Netw. Security, Wireless Commun. Trusted Comput.*, 2009, vol. 2, pp. 28–31.

[41] C. Wu, C. Liao, and L. Fu, "Service-oriented smart-home architecture based on OSGi and mobile-agent technology," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 37, no. 2, pp. 193–205, Mar. 2007.

[42] (2011, Apr. 25). [Online]. Available: http://www.knopflerfish.org/

[43] A. E Nikolaidis, S. Papastefanos, G. A. Doumenis, G. I. Stassinopoulos, and M. P. K. Drakos, "Local and remote management integration for flexible service provisioning to the home," *IEEE Commun. Mag.*, vol. 45, no. 10, pp. 130–138, Oct. 2007.

[44] G. Virone, N. Noury, and J. Demongeot, "A system for automatic measurement of circadian activity deviations in telemedicine," *IEEE Trans. Biomed. Eng.*, vol. 49, no. 1, pp. 1463–1469, Dec. 2002.

[45] A. Mihailidis, B. Carmichael, and J. Boger, "The use of computer vision in an intelligent environment to support aging-in-place, safety, and independence in the home," *IEEE Trans. Inform. Technol. Biomed.*, vol. 8, no. 3, pp. 238–247, Sep. 2004.

[46] E. Farella, M. Falavigna, and B. Ricco, "Aware and smart environments: The casattenta project," in *Proc. 3rd Int. Workshop Adv. Sens. Interfaces*, 2009, pp. 2–6.

[47] T. Adlam, R. Faulker, R. Orpwood, K. Jones, J. Macijauskiene, and A. Budraitiene, "The installation and support of internationally distributed equipment for people with dementia," *IEEE Trans. Inform. Technol. Biomed.*, vol. 8, no. 3, pp. 253–257, Sep. 2004.

[48] Y. Nishida, T. Hori, T. Suehiro, and S. Hirai, "Sensorized environment for self-communication based on observation of daily human behavior," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2000, pp. 1364–1372.

[49] A. Arcelus, C. L. Herry, R. A. Goubran, F. Knoefel, H. Sveistrup, and M. Bilodeau, "Determination of sit-to-stand transfer duration using bed

and floor pressure sequences," *IEEE Trans. Biomed. Eng.*, vol. 56, no. 10, pp. 2485–2492, Oct. 2009.

[50] A.-M. Vainio, M. Valtonen, and J. Vanhala, "Proactive fuzzy control and adaptation methods for smart homes," *IEEE Intell. Syst.*, vol. 23, no. 2, pp. 42–49, Mar./Apr. 2008.

[51] N. M. Barnes, N. H. Edwards, D. A. D. Rose, and P. Garner, "Lifestyle monitoring technology for supported independence," *Comput. Control Eng. J.*, vol. 9, pp. 169–174, Aug. 1998.

[52] G. Williams, K. Doughty, and D. A. Bradley, "A systems approach to achieving CarerNet—An integrated and intelligent telecare system," *IEEE Trans. Inform. Technol. Biomed*, vol. 2, no. 1, pp. 1–9, Mar.1998.

[53] M. W. Raad and L. T. Yang, "A ubiquitous smart home for elderly," in *Proc. 4th IET Int. Conf. Adv. Med., Signal Inf. Process.*, 2008, pp. 1–4.

[54] D. N. Kalofonos and S. Shakhshir, "IntuiSec: A framework for intuitive user interaction with security in smart spaces," in *Proc. 18th Annu. IEEE Int. Symp. Personal, Indoor Mobile Radio Commun.*, 2007, pp. 1–5.

[55] B. Vaidya, J. H. Park, S.-S. Yeo, and J. J. P. C. Rodrigues, "Robust one-time password authentication scheme using smart card for home network environment," *Comput. Commun.*, vol. 34, pp. 326–336, Mar. 2011.

[56] S. S. Intille, K. Larson, J. S. Beaudin, J. Nawyn, E. Munguia Tapia, and P. Kaushik, "A living laboratory for the design and evaluation of ubiquitous computing interfaces," in *Proc. Extended Abstracts Conf. Human Factors Comput. Syst.*, 2005, pp. 1941–1944.

[57] S. Hussain, S. Schaffner, and D. Moseychuck, "Applications of wireless sensor networks and RFID in a smart home environment," in *Proc. 7th Annu. Commun. Netw. Services Res. Conf.*, 2009, pp. 153–157.

[58] S. Park and H. Kautz, "Hierarchical recognition of activities of daily living using multi-scale, multi-perspective vision and RFID," in *Proc. IET 4th Int. Conf. Intell. Environ.*, 2008, pp. 1–4.

[59] K. N. Ha, K. C. Lee, and S. Lee, "Development of PIR sensor based indoor detection system for smart home," in *Proc. SICE-ICASE Int. Joint Conf.*, 2006, pp. 2162–2167.

[60] H. H. Kim, K. N. Ha, S. Lee, and K. C. Lee, "Resident location-recognition algorithm using a bayesian classifier in the PIR sensor-based indoor location-aware system," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 39, no. 2, pp. 240–245, Mar. 2009.

[61] S. Guillen, M. T. Arredondo, V. Traver, J. M. Garca, and C. Fernandez, "Multimedia telehomecare system using standard TV set," *IEEE Trans. Biomed. Eng.*, vol. 49, no. 12, pp. 1431–1437, Dec. 2002.

[62] S. Yoo, D. Rho, G. Cheon, and J. Choi, "A central repository for biosignal data," in *Proc. Int. Conf. Technol. Appl. Biomed.*, 2008, pp. 275–277.

[63] (2010, Feb. 21). [Online]. Available: http://www.zigbee.org

[64] (2010, Feb. 21). [Online]. Available:http://www.knx.org

[65] H. Andoh, K. Watanabe, T. Nakamura, and I. Takasu, "Network health monitoring system in the sleep," in *Proc. SICE Annu. Conf.*, 2004, vol. 2, pp. 1421–1424.

[66] (2010, Feb. 23). [Online]. Available: http://www.homegatewayinitiative.org

[67] (2010, Feb. 23). [Online]. Available: http://www.upnp.org

[68] (2010, Feb. 23). [Online]. Available: http://www.dlna.org

[69] (2010, Feb. 23). [Online]. Available: http://www.broadband-forum.org

[70] (2010, Feb. 23). [Online]. Available: http://www.osgi.org

[71] Y. Isoda, S. Kurakake, and H. Nakano, "Ubiquitous sensors based human behavior modeling and recognition using a spatio-temporal representation of user states," in *Proc. 18th Int. Conf. Adv. Inf. Netw. Appl.*, 2004, vol. 1, pp. 512–517.

[72] J. R. Quinlan, *C4.5: Programs for Machine Learning*. San Francisco, CA: Morgan Kaufmann, 1993.

[73] Y. Rahal, P. Mabilleau, and H. Pigot, "Bayesian filtering and anonymous sensors for localization in a smart home," in *Proc. 21st Int. Conf. Adv. Inform. Netw. Appl. Workshops*, 2007, vol. 2, pp. 793–797.

[74] V. Lesser, M. Atighetchi, B. Benyo, B. Horling, A. Raja, R. Vincent, T. Wagner, P. Xuan, and S. X. Q. Zhang, "The intelligent home testbed," in *Proc. Autonomy Control Software Workshop*, 1999, pp. 291–298.

[75] A. Assim, M. B. I. Reaz, M. I. Ibrahimy, A. F. Ismail, F. Choong, and F. Mohd-Yasin, "An AI based self-moderated smart-home," *Informacije MIDEM – J. Microelectron., Electron. Compon. Mater.*, vol. 36, pp. 91–94, Jun. 2006.

[76] G. Virone, M. Alwan, S. Dalal, S. W. Kell, B. Turner, J. A. Stankovic, and R. Felder, "Behavioural patterns of older adults in assisted living," *IEEE Trans. Inf. Technol. Biomed.*, vol. 12, no. 3, pp. 387–398, May 2008.

[77] I. Korhonen, R. Lappalainen, T. Tuomisto, T. Koobi, V. Pentikainen, M. Tuomisto, and V. Turjanmaa, "TERVA: wellness monitoring system," in *Proc. 20th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 1998, vol. 20, no. 4, pp. 1988–1991.

[78] M. Amin and B. F. Wollenberg, "Toward a smart grid: Power delivery for the 21st century," *IEEE Power Energy Mag.*, vol. 3, no. 5, pp. 34–41, Sep./Oct. 2005.

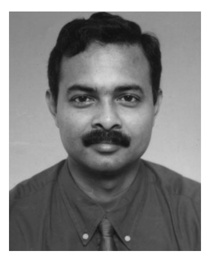
[79] K. Wacks, "The successes and failures of standardization in home systems," in *Proc. 2nd IEEE Conf. Standardization Innovation Inf. Technol.*, 2001, pp. 77–88.

[80] H. Rippen and A. Risk, "e-Health code of ethics," *J. Med. Internet. Res.*, vol. 2, no. 2, 2000.

[81] K. Matsuoka, "Aware home understanding life activities," in *Proc. Int. Conf. Smart Home Health Telemetric*, 2004, pp. 186–193.

Muhammad Raisul Alam (S'10) received the B.Sc. degree in computer science and engineering from Shahjalal University of Science and Technology, Sylhet, Bangladesh, in 2007, and the M.Sc. degree in microelectronics and nanoengineering from the Universiti Kebangsaan Malaysia, Bangi, Malaysia, in 2011. He is currently working toward the Ph.D. degree with the Department of Systems and Computer Engineering, Carleton University, Ottawa, ON, Canada.

He was involved in the area of smart homes for his Master's degree and currently working in the same area for his Ph.D. His research interests include smart home, smart grid, ubiquitous computing, radio frequency identification, intelligent systems, and artificial intelligence.



Mamun Bin Ibne Reaz (M'02) was born in Bangladesh, in December 1963. He received the B.Sc. and M.Sc. degrees in applied physics and electronics from the University of Rajshahi, Rajshahi, Bangladesh, in 1985 and 1986, respectively, and the D.Eng. degree from Ibaraki University, Hitachi, Japan, in 2007.

He is currently an Associate Professor with the Universiti Kebangsaan Malaysia, Bangi, Malaysia, where he is involved in teaching, research, and industrial consultation. He has been a Regular Associate of the Abdus Salam International Center for Theoretical Physics, Trieste, Italy, since 2008. He has vast research experiences in Norway, Ireland, and Malaysia. He has published extensively in the area of IC design and biomedical application IC. He is author and coauthor of more than 150 research articles in design automation and IC design for biomedical applications.

Mohd Alauddin Mohd Ali (M'94) received the B.Eng. (Electrical), B.Sc. (Mathematics), and M.Eng.Sc. (Electrical) degrees from the University of Tasmania, Hobart, Tas., Australia, in 1978, 1979, and 1984, respectively, and the Ph.D. degree from the University of Nottingham, Nottingham, U.K., in 1994.

He was involved in the area of microelectronics for his Master's degree and medical electronics for his PhD. He is currently a Professor with the Department of Electrical Electronic and Systems Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia (UKM), Bangi, Malaysia. He was also Head of the department and Deputy Dean of the faculty for the periods 1995–1997 and 1997–2002, respectively. He is currently the Director of the Institute of Space Science, UKM. His research interests include biomedical signal processing, instrumentation, integrated circuit design and testability, and ionospheric studies.