The Smart House for older persons and persons with physical disabilities: structure, technology arrangements, and perspectives

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Abstract:
Smart houses are considered a good alternative for the independent life of older persons and persons with disabilities. Numerous intelligent devices, embedded into the home environment, can provide the resident with both movement assistance and 24-hour health monitoring. Modern home-installed systems tend to be not only physically versatile in functionality but also emotionally human-friendly, i.e. they may be able to perform their functions without disturbing the user and without causing him/her any pain, inconvenience, or movement restriction, instead possibly providing him/her with comfort and pleasure. Through an extensive survey, this paper analyzes the building blocks of smart houses, with particular attention paid to the health monitoring subsystem as an important component, by addressing the basic requirements of various sensors implemented from both research and clinical perspectives. The paper will then discuss some important issues of the future development of an intelligent residential space with a human-friendly health monitoring functional system.

Index Terms—Smart house, intelligent house, wearable sensor, health monitoring

I. Introduction

Smart houses include devices that have automatic functions and systems that can be remotely controlled by the user. The primary objective of a smart house is to enhance comfort, energy saving, and security for the residents in the house.

The notion of a "smart home" was first introduced in the early 1980s when the "intelligent building" concept was also used [W1]. In the concept, the intelligent implementation of consumer electronic devices, electrical equipment, and security devices aiming for the automation of domestic tasks, easy communication, and human-friendly control as well as safety was proposed. In the earlier development, the idea was oriented to building a smart home environment for ordinary non-disabled persons with the simple purpose of enhancing home comfort [1]–[5]. Recently, the same technology has become a bright perspective for people with special needs.

Recent statistics show a trend of rapid growth in the number of persons with physical disabilities and aged people who need external help in their everyday movement tasks [6]. The problem of caring for older persons and persons with physical disabilities will become more serious in the near future when a significant part of the increasing global population is in the 65 or over age group, and the existing welfare model is not

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able to meet the increased needs. It is obvious that such a problem cannot be solved by increasing the number of care-givers. On the other hand, an optimistic view that the quality of life for the people mentioned above can be significantly improved by means of various modern technologies, in particular, through intelligent houses, is growing [7], [8]. As a manifestation of this outlook, a new term, “gerontechnology”, was introduced by Jan Graafmans to mean a composite of gerontology and technology [9]. Two approaches are outstanding for realizing intelligent houses for the people with physical limitations:

1. *Special architecture solutions* adapted to the needs of the people with movement and physical limitations. The solutions can vary from simple barrier-free access to special village organization.
2. *Particular technological innovations* that facilitate the user’s independent life. The smart house for physically impaired people integrates, for example, devices for movement assistance of the inhabitant and devices for continuously monitoring his/her health status.

Smart houses will have a strong positive emotional impact on persons with physical disabilities and older persons, improving their quality of life, giving them privacy, and making them feel that they live in an ordinary house, not in a hospital or in a special nursing home. The same notion will reduce to some extend the medical care costs per person.

Depending on the health and movement condition of the inhabitants, a proper architectural organization of the smart-homes can be chosen. Whereas *separate apartments* installed with intelligent assistive technology may satisfy the needs of motor impaired people without health problems, special *smart-home villages* will be better for the independent lives of aged people, where many separate living residences are integrated with a building for the health care staff, house cleaning and food preparation staff, guards, psychologists, etc.

The smart houses for people with special needs should be designed to fulfill various requirements, while their control algorithms should be based on a small number of commands relevant to the specifics of the user’s motions. The level of installed technology in the intelligent house for physically impaired people should vary from person to person depending on his or her physical abilities, life habits, and desired safety conditions. The machines in the home should be capable of responding to the user’s exact commands correctly and also to the user’s intentions with a high level of “fuzziness” as well, treating and executing them in a proper way. The development of smart houses has become possible because of the recent fast progress of various intelligent technologies such as fuzzy logic, artificial neural net, and evolutionary algorithms. Thus, the smart houses are sometimes termed “intelligent houses”.

According to diverse sources, we may confirm that the concept of “smart houses” for older persons and persons with physical disabilities has been considered important by many social and economic institutions in the advanced countries. In fact, numerous research and demonstration projects on smart houses have been completed already or are in the phase of development all over the world. Many of these projects are often funded by international R&D organizations and involve participants from different countries. Research activity is relatively higher in Japan, Europe, and the USA, where there is a strong growth (by far) of the aged population along with the availability of broad high technology achievements.

The objective of this paper is to provide a summary of the works related to the notion of the smart house for older persons and persons with physical disabilities, with emphasis on the health monitoring systems for long period health assessment. The subject matter lies in the interdisciplinary area of many different branches of science and technology, and its successful design can be possible only from the result of joint efforts of many specialists in different areas. The problems and needs of older persons and persons with physical disabilities vary from person to person to a considerable extent, which add many serious requirements. Our survey is mainly oriented toward reporting those solutions and ideas corresponding to this users' group. We find that the technologies and solutions for such smart houses should be *human friendly*, i.e. the smart houses should be designed according to the notion of human-centeredness and should possess a high level of intelligence in their control, actions, and interactions with the users, offering them a high level of comfort and functionality. It is not our intention to give any definitions or make detailed didactic descriptions of the existing organizations and designs of human-friendly smart houses but rather to present such ideas and tendencies that have been generated and developed recently. Thus, we have reviewed products, research projects, and conceptions proposed regarding the technical structure of smart houses and health monitoring systems, with a focus on technology innovations that have been taking place. This paper does not treat non-technical components of the smart-house design such as architecture, interior design, organization of medical care and care-giver servicing, cost, maintenance, etc. The work of the present paper is based on the analysis of many publications on the topic as well as an extensive search on the Internet.

This paper is organized as follows. First, the building blocks of the smart house and its structure are described. Here, we consider the building blocks that are needed for the independent life of people of different categories, such as persons with physical disabilities, older persons, and people with low vision. Comments are also made about the functions and design of building blocks in relation to the various groups of users, and about new tendencies and solutions in the design of corresponding systems. Then some examples of smart house projects are briefly described. Next, the paper reviews examples of advanced health monitoring devices. Our survey includes both commercially available products and research results. Some basic characteristics and tendencies of the reviewed projects are summarized in a table. Some comments are given about the parameters of the health monitoring systems and about a set of basic requirements to the sensors. Then a proposition of a futuristic human-friendly smart house with health monitoring capability is given, and some important issues are commented upon.

II. Structure of the Smart House

The concept of a smart house has often been applied for the people with special needs (PSN), and various different models of smart houses have been developed. Each of such models is designed to adapt to the user's specific needs and physical limitations. Smart houses differ from one another by the types and arrangements of the installed devices and can be classified into the following groups:

A. Smart house for people with movement disabilities [10]–[13];
B. Smart house for older persons [11]–[15];
C. Smart house for people with low vision [16], [W9];
D. Smart house for hearing impaired people;
E. Smart house for cognitively impaired people.

The primary focus in the design of a smart house for the people with movement disabilities is the installation of the devices for assistance in mobility and manipulation, while the smart houses for aged people take into consideration changes in some of the organic functions of older persons. Smart houses for people with low vision and hearing impairments are equipped with special interfaces for communication. In addition, those houses often implement the technology to support home navigation. Smart houses for cognitively impaired people are equipped with devices that provide support in structuring their daily activities in the house.

It is not easy, however, to make a clear distinction between the groups of people mentioned above. Often persons with physical disabilities, apart from their movement limitations, may also suffer from other limitations or diseases. Frequently, many elderly people may have some chronic health problems, low vision [W9], hearing problems, or dementia [17], [18]. Some disabled people in a stable health condition may need home-installed devices for physical exercises. Some smart houses may need intelligent appliances that facilitate the inhabitant’s ability to do some work-, learning- and leisure-activities. Smart houses for people with low vision should provide the users with proper instructions and an appropriate way of navigation in the home environment. These considerations may result in different components and home automation functions. Some people may need more than one kind of technology – for example, people with both movement and vision problems need technology for movement support as well as magnifiers and other vision interface.

Regarding their functions, the installed devices can be classified into the following five groups:

1. Devices for automation and control of the home environment;
2. Assistive devices;
3. Devices for health monitoring of important vital parameters;
4. Devices for information exchange;
5. Leisure devices.

Of course, not all of these categories mentioned above should be present in every kind of smart house. Selection varies from one category to another with different applications and needs. The proper choice of the devices should give the user an integrated feeling of confidence for mobility, manipulation, communication, and environment control.

One example of the organization of the home-installed equipment in a smart house for people with disabilities is illustrated in Fig. 1.

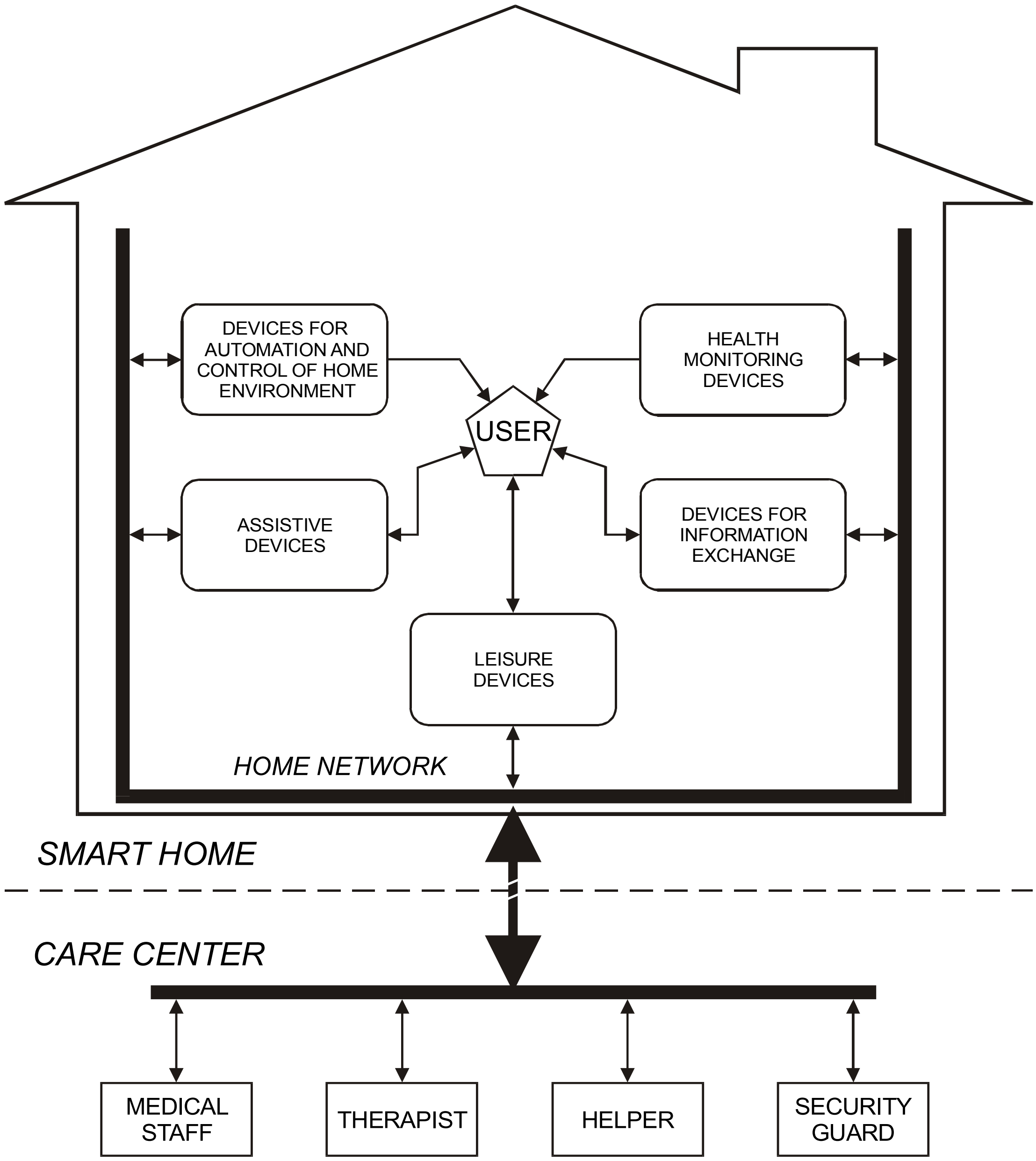


Fig. 1. Smart house for people with disabilities

Various home-installed devices in the smart house are connected in a common home network system. The home network is also linked with the care center via a data channel which transfers data about the health status of the inhabitant and home-installed devices. The same channel is used for audio and video conferencing and for remote control and adjustment of home-installed devices from the care center.

In Fig. 1, the intelligent home network is a part of the system for information exchange to provide data exchange between various devices in the smart house.

Various types of modules and subsystems of the smart house for people with disabilities are shown in Fig. 2, each of which will be briefly commented on in the next chapter.

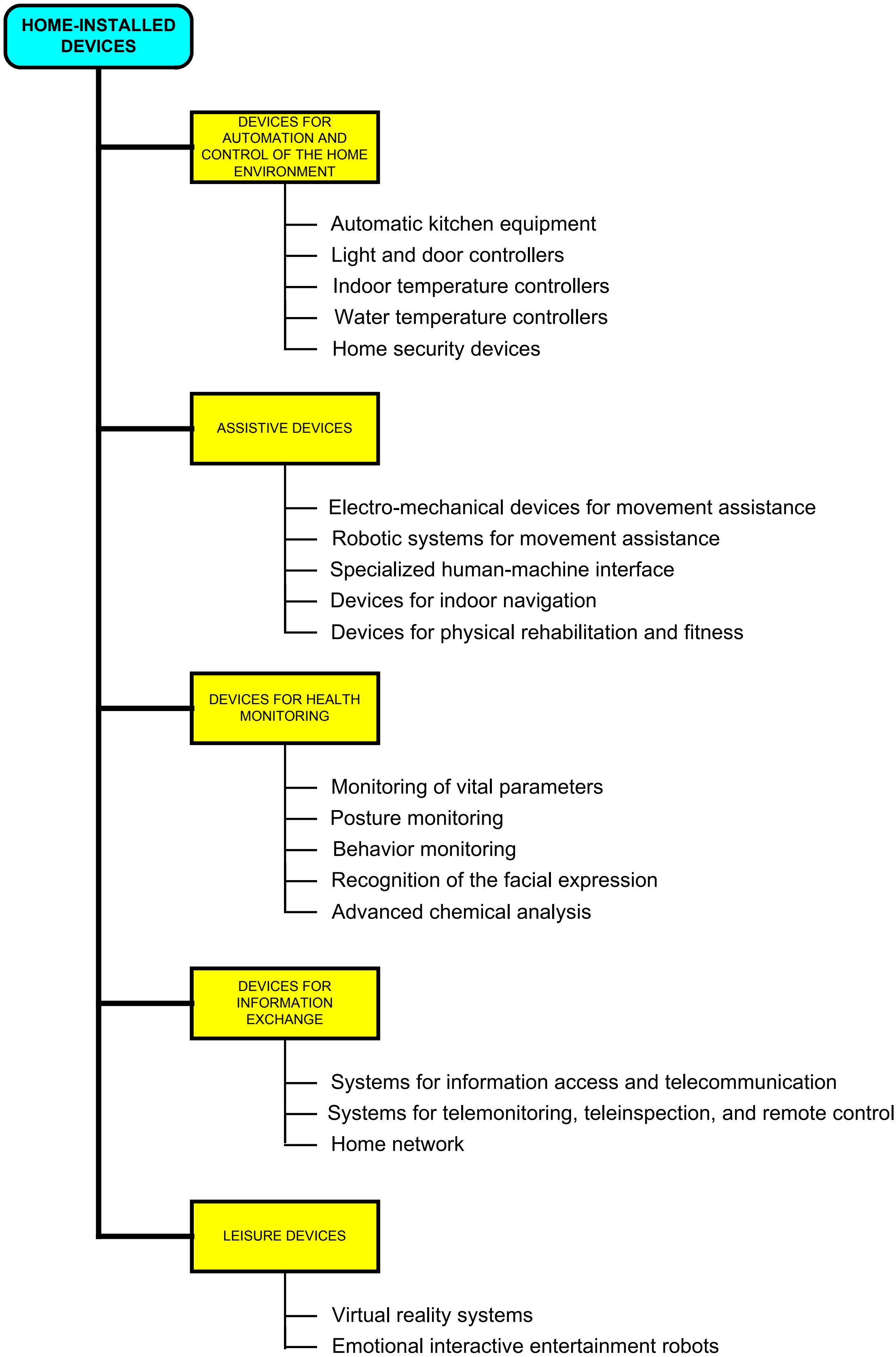


Fig. 2. A tree of home-installed devices

Home-installed devices are classified here into five groups: devices for automation and control of the home environment, assistive devices, health monitoring devices, systems for information exchange, and leisure devices.

It is noteworthy that any two different types of smart houses can include the same component of technological equipment, but in this case, the characteristics of the equipment should be relevant to the user's concrete needs. For example, the module "devices for physical rehabilitation and fitness" is present as a component in smart houses for non-disabled users as well as a component in those for people with disabilities, but the environment of the non-disabled users may contain fitness devices only, while the smart house for users with disabilities contains mostly devices for physical rehabilitation. Another example is the fact that both the group of non-disabled users and the group of low vision people may need human friendly interfaces for the control of home appliances. Although the ordinary interface is interactive, the interface for low-vision people, in particular, may well contain devices for navigation through voice-synthesized messages. In applications for people with a high degree of disabilities, the number of installed devices (and the price of the smart house accordingly) would increase.

Table 1 summarizes the typical relationship between the types of smart houses and the devices installed in them.

TABLE 1
THE TYPES OF SMART HOUSES AND THE DEVICES THAT MAY BE INSTALLED IN EACH OF THEM

Installed devices		Type of smart house					
Category	Type of installed device	Non-disabled users	Disabled users	Aged people	Low vision people	Hearing impaired people	Cognitively impaired people
Devices for automation and control of home	Automatic kitchen equipment	*	*	*	*	*	*
	Light and door controllers	*	*	*	*	*	*
	Indoor temperature controllers	*	*	*	*	*	*
	Water temperature controllers	*	*	*	*	*	*
	Home security devices	*	*	*	*	*	*
Assistive devices	Electro-mechanical devices for movement assistance		*	*			
	Robotic systems for movement assistance		*	*			
	Specialized human-machine interface		*	*	*	*	
	Devices for indoor navigation			*	*		*
	Devices for physical rehabilitation and fitness	*	*	*	*	*	*
Health monitoring devices	Devices for pulse rate monitoring			*			
	Blood pressure monitoring			*			
	Body temperature monitoring			*			
	Posture monitoring			*			
Systems for information exchange	Systems for information access and telecommunication	*	*	*	*	*	*
	Systems for telemonitoring, teleinspection, and remote control		*	*	*		
	Home network	*	*	*	*	*	*
Leisure devices	Virtual reality systems	*	*	*	*	*	*
	Emotional interactive entertainment robots		*	*			

An asterisk (*) in a cell indicates devices that are strongly related to the concrete type of smart house.

III. Components of the Smart House

Home-installed technology performs movement independence of the user, health monitoring, entertainment, security, and physical rehabilitation. The present chapter will consider the separate components and will comment upon some research outcomes.

III.1. Devices for automation and control of the home environment

One can find that there are various kinds of devices for automation and control of the home environment, such as:

1. Automatic kitchen equipment;
2. Light and door controllers;
3. Indoor temperature controllers;
4. Water temperature controllers;
5. Home security devices.

Note that the automatic kitchen equipment includes washing machines, programmable electric ovens, dishwashers, etc. [19]. In cases where these devices are handled by persons with physical disabilities and/or older persons, a suitable interface should be provided, for example, in the form of a large size display, simple command setting, suitable hand gripping devices, and switches. In some projects on rehabilitation robotics [20], [21], the control panels of kitchen-installed devices are modified for easy operation by the mobile robot. Technically-advanced structures of the home environment often integrate subsystems for temperature and humidity control, or subsystems for automatic windows opening/closure, remote control of entrance doors, kitchen appliances, and lights, as well as subsystems for the measurement of the concentration of gas, carbon dioxide, chemicals, etc.

The arrangement of devices for home automation and their control by the user become a central topic in many projects, such as the AID (Assisted Interactive Dwelling) Project [22], Smart House Project (developed at Social Housing SPRU – University of Sussex, UK) [W1], HS-ADEPT [23], HERMES, Integer [W1], the Subproject Smart Home (developed at Brandenburg Technical University, Cottbus (Germany) [W2], and domotics for older persons [24], etc.

III.2. Assistive devices

Assistive devices can be categorized as follows:

1. Electro-mechanical devices for movement assistance;
2. Robotic systems for movement assistance;
3. Specialized human-machine interface;
4. Devices for indoor navigation;
5. Devices for physical rehabilitation.

III.2.1. Electro-mechanical devices for movement assistance[4]

Typical electro-mechanical devices for movement assistance include powered wheelchairs, specialized lifting devices for transfer of the user between the bed and the wheelchair, specialized standing-up devices for powered wheelchairs, bath lifts, walking and lifting aids [25], etc. Historically, the rehabilitation technology was first developed to meet the needs of persons with physical disabilities, so most of the assistive products commercially available at present are still oriented toward these individuals. On the other hand, increasing concern for the aging society has resulted in the design of special movement-helping devices for older persons. Even though there exist some similarities between the devices for disabled people and those for older persons, we find they are different in some aspects. For example, the technology for older persons should consider some important specific needs due to age changes,

[4] Although the vehicles for outdoor personal transportation, such as terrain wheelchairs and scooters, are typical examples of electro-mechanical devices for movement assistance, we will not comment on them here because the present paper is primarily focused on home-installed technology.

such as decreased vision, speech and hearing disorders, tremors, etc. that set additional design requirements.

Some highly effective powered wheelchairs have been proposed, such as a self-balancing wheelchair named the INDEPENDENCE IBOT Mobility System and developed by Dean Kamen [26]−[28]. Gyroscopes and tilt sensors in the wheelchair monitor the user's center of gravity, while the transporter is capable of climbing stairs and navigating in the presence of sand, rocks, and curbs. Recently, the self-balancing idea has been further improved and applied to Dean Kamen's new invention named the Segway Human Transporter (a personal transport device that uses five gyroscopes and a built-in computer to remain upright) [29]. In addition, omni-directional powered wheelchairs with high maneuverability facilitate indoor mobility [30]−[35]. Because of their holonomic construction, such wheelchairs can change their movement direction instantly and can be easily positioned and oriented toward other household objects such as a table, bed, and walls, while requiring few commands to pass narrow doors. Such wheelchairs are capable of reducing the cognitive load of the user because maneuvering can be done by a small number of the operator's commands. Many omni-directional wheelchair constructions are based on synchronously driven wheels [36], [37], free rollers ("The Vuton1") [38], "The Vuton II" with Omni-Disc mechanism [39], balls [34], or Mechanum (Ilon) wheels [30]−[33].

It is noted that *mechanized furniture* can facilitate the user in sitting, standing, turning in the bed, etc. The user can adjust the bed or sofa configuration to change his/her position in the bed and to facilitate feeding, watching TV, book reading, etc. A sofa with a changeable seat and back are also used in some cases.

III.2.2. Robotic systems for movement assistance

Apart from the conventional devices for movement assistance, specialized robotic systems are considered in recent projects. Some examples include rehabilitation robots and self-navigated programmable wheelchairs (known also as "go-to-goal wheelchairs") [40] − [43]. Because of their automatic guidance in the home environment, these wheelchairs are often considered a special class of mobile rehabilitation robots for the transportation of a user.

Most of the rehabilitation robots are designed to assist disabled individuals in their everyday needs, such as eating, drinking, object replacement, etc. [44]. Some other rehabilitation robots perform assistance for the user in concrete vocational activities, such as office work [45], [46], programming (RAID and Epi-RAID) [47], work at chemical and biology laboratories (Walky) [48], visual inspection of hybrid integrated circuits (IRVIS) in a real manufacturing environment [49], [50], and the operation of a commercial lathe [51]. We find that three main types of robot schemes are in operation for robot-user interaction: *desktop-mounted robots*, *wheelchair-mounted robots,* and *mobile autonomous robots*. In some simple cases, the robot is fixed to a *desk* or to the floor. The operator is placed in a suitable position near the worktable and operates the robot that performs unaided pick-and-place ADL tasks [52]. *Wheelchair-mounted robots* [53], [54] can be used both for indoor and outdoor assistance for the user. The attachment of a robot to the wheelchair significantly increases the movement independence of the user because one can move freely to different home positions and can perform manipulative tasks in each position with the help of the rehabilitation robot. The drawbacks of such a solution are the inclination of the wheelchair due to the weight of the robot, enlargement of the wheelchair width (which is critical for narrow door passage), and changes of the dynamic characteristics of the wheelchair. The *mobile robots* are remotely controlled devices that navigate autonomously through the home environment and serve the user at a certain position for object replacement or for home inspection.

The cognitive load of a user can be reduced significantly if the robot automatically performs repetitive movements (in a pre-programmed mode of control). Programs can be successfully executed if the robot, the user, and the manipulated objects remain in the same initial position every time when the concrete task is performed. In the case of a wheelchair-mounted manipulator, the relative position of the user with respect to the manipulator remains the same, but the relative position between the manipulator and the objects may depend on the wheelchair position. In order to avoid this problem, a technique of vision-based automatic navigation of the gripper is adopted to handle the grasped object (KARES I, KARES II, TAURO, etc.) [55], [56], [57], or the user performs the end-point control in which the trajectory, orientation, and velocity of the gripper are directly adjusted (HOPE) [52].

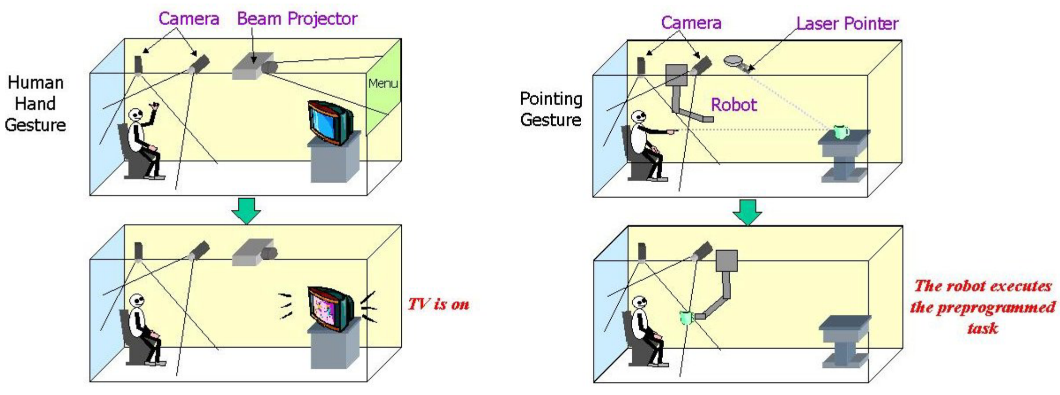
Commercialization of rehabilitation robots is often impeded by several factors, such as high cost, low efficiency, and existing welfare regulation. Despite these problems, there are some successful examples of commercially available rehabilitation robots, such as Manus (Netherlands) [58], [59], Raptor (USA) [60], and Handy1 (UK) [61], [62] which are everyday used by an increasing number of real end-users, offering them enhanced movement assistance and comfort in operation.

Automatically guided wheelchairs (AGW) facilitate individuals with severe dexterity limitations in their hands. After receiving the user's instruction about the destination point of the wheelchair, the navigation system first generates the travel routine and then independently steers the wheelchair to the desired destination. The automatic control of go-to-goal wheelchairs reduces the cognitive load of the user. In the wheelchair projects, wheelchair movement is often assumed to occur in a structured or semi-structured home environment. Localization of the current wheelchair position is based either on fixed-location beacons strategically placed at pre-defined locations within the operating home environment [40], [41] or on natural landmarks of the structured environment [43]. Beacon-based systems can be further grouped into systems that refer to active beacons (most often fixed active-beacon emitters installed on the walls) and systems that get navigational parameters from passive targets [40]. Usually, passive beacons are of low cost and can be easily attached to the walls, but the procedures of detecting such markers (typically CCD sensors) and extracting the coded information are rather complicated. The position location systems that are based on active-beacon emitters typically involve simple sensors for localization of the beacon positions and a simple information decoding procedure, but the beacon location cannot be easily changed because each sensor should be separately powered and controlled. The guidepath systems for wheelchair navigation can be considered a special class of beacon-based systems where the guide tracks are embedded in the floor. The magnetic-tape guidepath scheme [62] involves a strip of flexible magnetic material attached to the floor surface. The magnetic stripe follower is based on an array of fluxgate or Hall effect sensors, mounted on the board of the vehicle. Although the approach is widely used in many material-handling applications, its application for wheelchair guidance in the home environment is limited due to the complexity of the movement routines and the need for frequent reconfiguration of the path. An additional limitation comes from the requirement of embedment of the guidepath in the floor. The natural landmark navigation does not require installation of special beacons, and the algorithms allow faster adaptation of the wheelchair to the unknown home environment. The proposed navigation solutions vary from the detection of the location of ceiling mounted lamps [63] to the detection of doorframes and furniture edges [43], [64]. New travel routines can be easily added to the computer memory without assistance of a specialized staff. On the other hand, the solutions based on natural landmarks require complicated vision sensors, involve complex algorithms for analysis of the visual scene, entail detection of artifacts from ambient lights, and require fast (on-line) calculation of the current wheelchair location. In order to achieve successful wheelchair navigation in case of absence or malfunctioning of some beacons/landmarks, most of the control algorithms refer not only to the information from the beacon navigation system but also to the information on the angular position of both driving wheels (that allows simple calculation of the present wheelchair location by a dead-reckoning procedure). Apart from the automatic navigation to the goal, most of the automatically guided wheelchairs can perform obstacle avoidance maneuvers, referring to the information from range sensors (mostly sonar or optical retroreflective systems) that detect and localize unexpected obstacles in the path. In many wheelchair solutions, the same range sensors are used for running the wheelchair in a semi-autonomous mode in which the user's instructions can be modified in conjunction with the sensor information on nearly located objects. For semi-autonomous control, several schemes are proposed/tested, such as wall following, people following/avoidance, and narrow corridor passage [43].

III.2.3. Specialized human-machine interface

Human-**M**achine **I**nterface (HMI) refers to the operational subsystem to control a wheelchair, rehabilitation robots, and other home equipment such as lamps, TV sets, telephones, doors, home security systems, etc. If the user suffers from serious movement paralysis, he/she may be able to make only a few preliminary motions as the commands, and in this case, the HMI should be constructed to meet the needs and characteristics of the user. As an HMI, the head-tracking devices are widely used because of their ability to produce up to three independent proportional signals that correspond to the forward-backward head tilting, left-right head rotation, and lateral head tilting. The way of control is very natural for the user. Recently, some new head tracking techniques involving facial detection [65] and optoelectronic detection of light-reflective head-attached markers (Tracker2000, Head Mouse) have been proposed [66], [67]. Some new technologies such as eye-movement control, brain control [68], as well as gesture recognition [69] and facial expression recognition give new opportunities for natural human – friendly interaction/interface between the user and the home-installed devices and offer new perspectives for efficient solutions in the near future. Voice control is also considered as a natural and easy way of operation of home-installed devices, but its application is still limited because of the high dependence on the specific operator's voice and the ambient noise level. Recently, some new voice recognition algorithms based on neural networks have provided optimism that those drawbacks can be overcome soon, and the voice control could be applied in a noisy environment [70]. The soft computing technique[5] offers new perspectives on the application of the EMG signals in the control of the home environment, allowing effective extraction of informative signal features in case of high interference between useful EMG signals and strong noise signals [71].

A recent trend in the interface design hints at an increasing use of multimodal interface. Good examples can be found in the project MUSIIC (developed at the University of Delaware) and in the project at the University of Cambridge [69], [72]–[74], where the approach offers ease in the control for people with limited movement abilities. In addition, the integrated intelligent multimodal user interface developed under the HOME-AOM project in France [75] is based on the simultaneous use of three modalities: touch, hand gestures, and voice. Feedback is provided in text, graphics, sound, and speech. The project implements various techniques, such as a touch panel (touch sensitive control and graphics display), isolated-word recognition, sound, and speech synthesis. The project considers two types of gesture-recognition systems: a one-camera system working in the 2D plane and a three-camera system for the 3D space. The one-camera system recognizes only semantic gestures, while the three-camera system recognizes deictic gestures to give the user the possibility to select a device for control. In the "Intelligent Sweet Home" project at KAIST [76], gestures are adopted for the control of home-installed devices. The interface, called "soft remocon", consists of three ceiling-mounted video cameras that detect the orientation of the user's hand. The user controls the TV, VCR, and curtains by pointing at them. Special light signals confirm the user's selection. After choosing the desired device, the user makes a desired action by pre-defined hand gestures. A voice-generated message confirms the recognized gesture command before its execution. Fig. 3 shows the main idea of the "soft remocon" that is a component of the intelligent residential space developed at KAIST.



(a) (b)

Fig. 3. Gesture-based human-machine interface

(a) Soft remocon – The user's hand gesture is automatically recognized by the TV-based image recognition system and the desired action ("Turn the TV on!") is executed.

(b) Pointing recognition system – By pointing to the concrete object, the user specified the object that should be replaced, and the robot performs the preliminary defined task.

[5] Soft computing differs from conventional (hard) computing in that it is tolerant of imprecision, uncertainty, and partial truth. It includes neural networks, fuzzy logic, evolutionary computation, rough set theory, probabilistic reasoning, and expert systems.

The people with low vision may get help by means of some special type of HMI. For example, the specialized zooming devices (both optical and optoelectronic) allow them to control the home environment as well as book reading. Zooming devices often consist of a TV camera and a TV monitor that reproduce the printed material on a screen at a larger size [77]. Reading machines are mainly based on optical character recognition (OCR) systems. The printed material is scanned first and then the image is OCR-processed and converted into suitable output, such as a Braille display or synthesized voice. The Optacon II, co-developed by Telesensory Inc. and Cannon [W3], is an example. That portable device converts printed material into tactile images. The user moves a small hand-held scanner across a line of print with one hand and places a finger of the other hand in a slot to feel the vibration patterns of a miniature array of small vibrating pins. Another product of the same company, the Aladdin Ambassador and the Ambassador Pro, convert text from books, magazines, and other printed materials to high-quality speech using a scanner. Recently, Telesensory Inc. has announced their plan to develop a new HMI based on the retinal scanning display (RSD) technology [78]. The RSD is a small, head-worn device. A beam of light, which corresponds to rows of image pixels, is scanned directly onto the retina, creating a high resolution, full-motion picture. Synthesized speech output from the TV control unit, confirming the action of each button, can be applied to some specific needs of the people with low vision and older persons.

III.2.4. Devices for indoor navigation

Devices for indoor navigation are often based on home-installed remote sensors that detect the current location of the user, give him/her voice-synthesized instructions on how to navigate, and warn him/her about potential obstacles in the intended route. We can also count on some wearable, hand-held, or cane-located personal sensor-based navigation devices for obstacle detection. Constructions of such devices vary from ultrasonic sensors mounted on the spectacles frame [79] or on a special belt [80]−[83] to special navigation canes and motorized guidance devices (such as an "artificial guide dog for blind people"). Examples include the Travel Aiding Robotic Mate (TARM) developed at KAIST, Korea [84], the NavCane project [85] and the HITOMI project – Japan [86], and the PAM-AID project [87], [88], [89], [90], [W4]. The PAM-AID system and HITOMI provide the user with both navigational and physical support. The system WHERE (Walking and moving HElper Robot system) developed at KAIST [91], [92] aims to assist the user in walking and gait rehabilitation and provides body weight support to the user. The system automatically detects the user intention regarding walking speed and movement direction. A picture of the WHERE system is shown in Fig. 4.

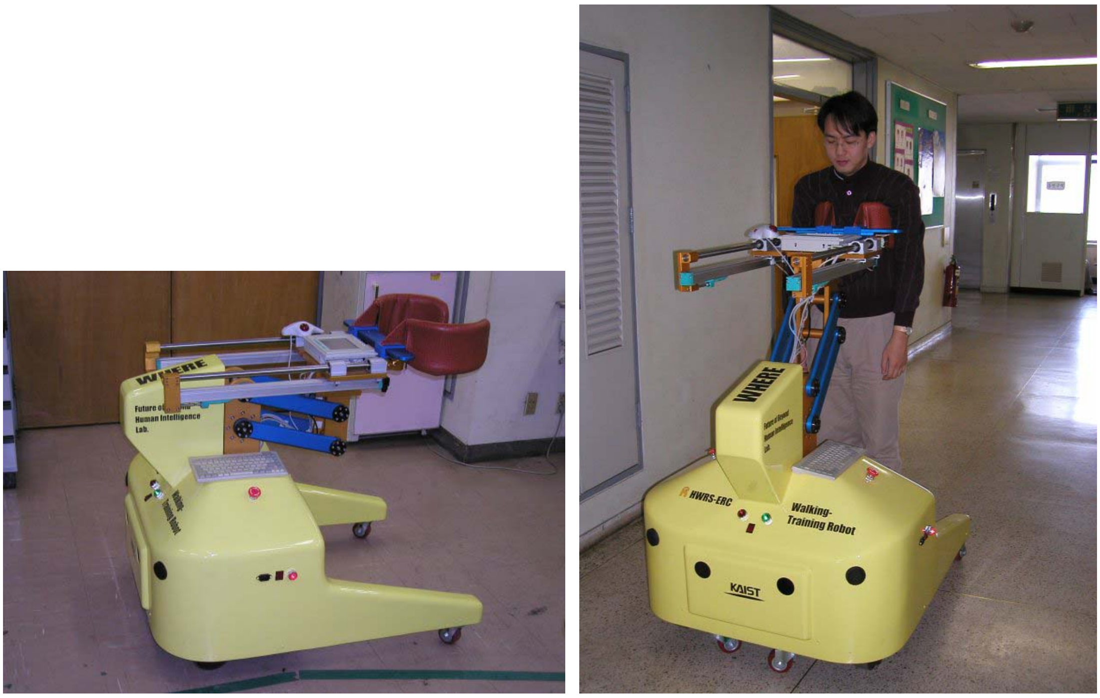


Fig. 4. Walking and moving helper robot system (WHERE) developed at KAIST (Courtesy of Ju-Jang Lee)

The system is used for gait rehabilitation and assists users in walking by providing body weight support. The system automatically detects user intention regarding walking speed and movement direction.

III.2.5. Devices for physical rehabilitation

Devices for physical rehabilitation are used both by persons with physical disabilities and by older persons. Different from the electromechanical devices for passive motion rehabilitation (such as the Artromot system of the ORTHOMED Medizintechnik Ltd) [W5], a recent trend is to develop robotic-based systems for movement rehabilitation. The related systems are the robotic device for stroke rehabilitation in the GENTLE/S Project [93], the robotic therapy system, called Stanford Driver's SEAT [94], the MIME project [95] of the VA Palo Alto Rehabilitation R&D Center, the robotic system for neuro-rehabilitation of the Newman Laboratory at MIT [96], and the system of the University of California, Irvine [97]. These robotic systems can be programmed to implement different rehabilitation exercises that fit the concrete needs of the users in which various parameters (such as range of flexion and extension, pause between the sequential motions, force, speed, etc.) can be easily adjusted. A picture of the MIME system for robotic therapy is shown in Fig. 5.

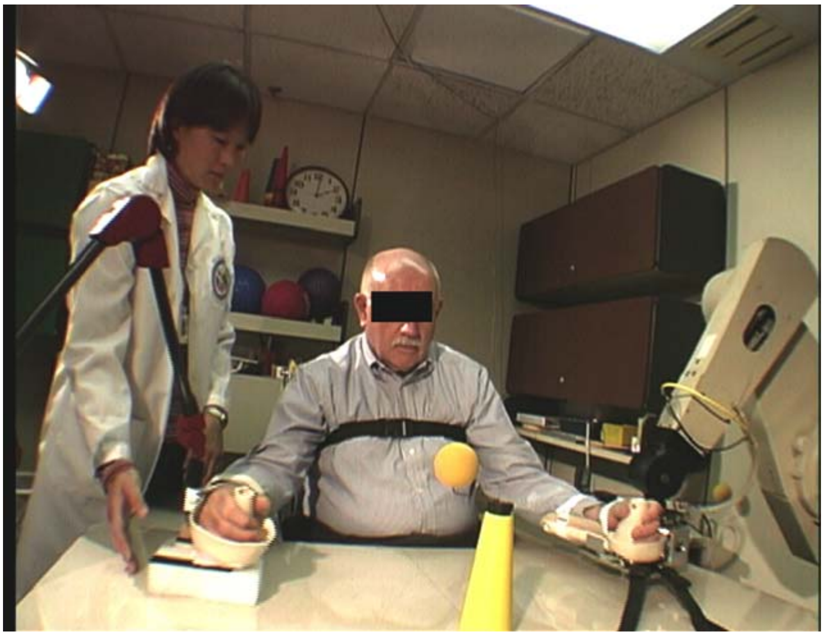


Fig. 5. The MIME system of the VA Palo Alto Rehabilitation R&D Center (Courtesy of H.F. Machiel Van der Loos)

The robotic system for upper limb therapy assists or resists elbow and shoulder movements in three-dimensional space and enables hemiparetic subjects to practice mirror-image upper limb exercises.

III.3. Devices for health monitoring of important vital parameters

Health monitoring devices are of great importance for the design of smart houses for older persons. Continuous monitoring of the health condition of the user may contribute to the extension of life expectancy and to a better quality of life. The system for continuous monitoring aims to observe if the body functions are maintained at a sufficiently normal level. Complications can be avoided by early detection of clinical disorders. People who suffer from chronic health problems and whose health status may quickly change as a result of heart diseases, diseases of the nervous system, etc., need continuous 24-hour monitoring of their health condition. On the other hand, it would not be a good idea to suggest some people, like older persons, to live in hospitals in order to monitor them. The modern concept advocates home-organized continuous health monitoring by noninvasive methods and by the technology that often does not require any attachments of wires and sensors to the user. The idea of design and construction of such devices is quite different from the devices in the emergency rooms at the hospitals. Apart from hospital-based devices that perform precise measurement of the absolute values of health parameters, the monitoring devices for home monitoring should not restrict the movement freedom of the user. In many cases, such devices estimate the current health status of the user through monitoring of the general trend of the monitored parameters. Whereas the devices for hospital health monitoring have a long history, the devices for individual health monitoring are relatively new but are becoming the items for active development. Recently, some increasingly sophisticated devices have become available as a result of significant progress in the computer technologies, solid-state micro sensors, the Internet, MEMS, and cellular telecommunication. Analysis of many recent projects shows that the intelligent health monitoring is a hot subject of active study with good theoretical, technical, and commercial potential. In the following section(s), we shall further comment on the recent design of human-friendly health monitoring systems.

Fig. 6 shows the basic block diagram of a typical health-monitoring system used in most of the smart-house projects.

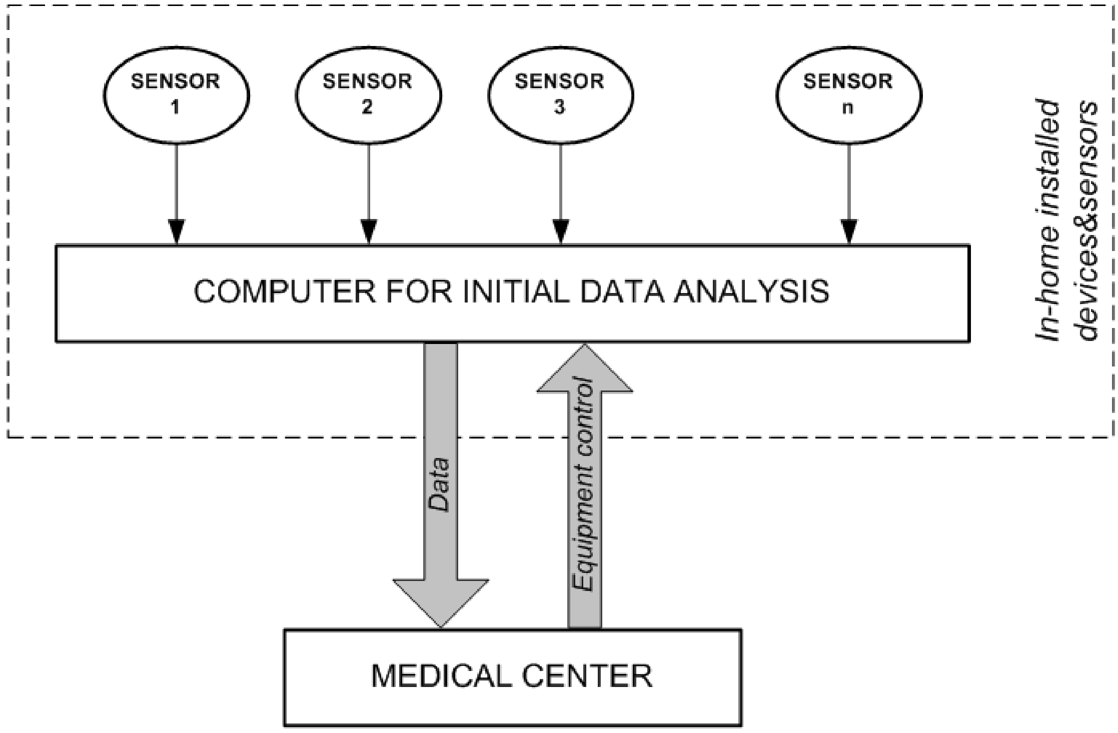


Fig. 6. Structure of the system for individual health monitoring

Initially processed at the user's home, the data regarding the health-monitored parameters are transferred to the medical center. The same data channel is used for remote control of the in-home sensor devices and communication to the inhabitant.

The smart house can be constructed in such a way that a group of devices will constantly deliver information about the health status of the inhabitants. All sensor devices are connected to a special home network under which each device interacts with others in a plug-and-play manner [7]. A home-installed computer performs routine data processing, and some relevant information can be transferred to a medical center when some current health parameters exceed their normal limits. In-home devices and sensors can be remotely controlled from the medical center. The same data channel is used for communication with the inhabitant. In some applications, the computer is designed as a miniaturized wearable computer that synchronizes the work of all sensors and communicates with the home-installed LAN through a wireless connection. The information from the health monitoring sensors can be used not only for estimation of the current user's health status but also for operation of other smart devices located in the same home. For example, decisions about the salt quantity in the meal and the choice of diet can be based on the current health parameters; the home temperature and the right dose of medication can be set by referring to them, too. The set of the measured parameters (and the set of the installed health monitoring sensors, respectively) will depend on the user's health specifics.

Health monitoring sensors should be human-friendly enough to be welcomed by the user with minimum rejection and should allow 24-hour inhabitant monitoring. Frequently-mentioned requirements of the sensors are listed below:

- Noninvasive and wearable;
- Convenient to install, to wear, and to use;
- Minimal restriction on the normal user movements;
- No vibrations, no noise, or no light signaling during measurement;
- Minimal high-frequency and light-energy emission to the user;
- Insensitive to motion artifacts and electromagnetic interferences caused by other sensors or home appliances;
- High reliability and long life;
- Wireless signal transmission;
- Automatic measurement;
- Waterproof and easy for sterilization;
- Low-power consumption in the case of an autonomous energy source.

Detailed classification of sensor requirements is presented in [7].

The health status is represented by numerous parameters that are derived from the physical and emotional conditions of the individual. Simultaneous observation of internal and external signs can significantly contribute to the precise detection and prediction of abnormality of the health state. In case of continuous health monitoring, the assessment of the current status should be based on parameters that can be easily monitored and contain enough information. Monitoring of the user's health can manifest: (1) the physical status by analyzing biosignals, (2) the behavioral status by examination of gait patterns, body posture, and gestures, and (3) the emotional status by observing facial expressions, gestures, and voice.

Biomedical signals contain signs of the chemical state and neurophysiologic state of the body system and can be captured by probes on the body surface. In consideration of the technical involvement and cost, the number of monitored biosignals is limited to a small number of very informative physical signals that express the homeostatic and defense mechanisms of the human's organism. These parameters are noted as "vital signs". Developed health monitoring systems refer to vital parameters that allow noninvasive observation. Usually they include sensors for measurement of body temperature, pulse rate, blood pressure, blood oxygenation level, ECG, and some breathing parameters.

The ring sensor [98] was developed at the d'Arbeloff Laboratory of MIT for Information Systems and Technology. The ring sensor is a compact wearable device in a ring configuration designed for noninvasive and continuous long-term monitoring of a person's arterial blood volume waveforms and blood oxygen saturation. Signals from the sensor are transmitted to a home computer through a digital wireless communication link for diagnosis of the inhabitant's cardiovascular condition. Operation of the ring sensor is based on the method of pulse oximetry [99], [100]. The ring sensor contains two LEDs with different wavelengths (red and near infrared) that illuminate one side of the finger. A photodiode, installed on the same ring, detects the light that has traversed the intervening vascular tissues. Digital signals are transmitted in an RF wave through the standard RS-232 protocol. The whole process is scheduled and controlled by a single microprocessor in the ring. To overcome the sensitivity to artifacts that result from hand motions and ambient light, a new modernized ring sensor has been recently announced [101], whose construction consists of two rings (an inner ring and an outer ring) which are mechanically independent of each other [102]. The sensor is powered by a small-sized battery.

The ECG provides important information on the current health status, as manifested in many recent projects. The project of Waseda University [103], [104] reports a wireless ECG monitoring device that contains a low-consumption detection part located on the user's chest and a relay transmitter (or micro data recorder) located on the user's wrist. The signals of the detection part are transmitted to the relay transmitter as an AC micro current flows through the tissue of the body. The detection part is designed as a separate wireless module attached to the user's chest. It contains four electrodes and a processing part. Three of these electrodes are used for detection of the ECG signals. After amplification and modulation, signals are applied between the fourth electrode and one of the sensing electrodes. The AC micro current flow is sensed from the relay transmitter. A system based on ECG monitoring during bathing was developed at the Tokyo Medical and Dental University [15]. The system includes 3 silver/silver chloride electrodes attached to the bath. The same system considers the monitoring of the ECG of older persons during sleep. The ECG was obtained by placing the conductive textile electrodes on the pillow and on the lower part of the bed sheet where the feet are positioned. An entirely conductive textile sheet, placed in the mat, was used for shielding against power line interference. In another project of the Tokyo Medical and Dental University, an automated health monitoring system which conducts temperature measurements in bed, ECG monitoring during bathing, and measuring of weight on the toilet [14], [15], [105]–[108] was described.

Noninvasive acoustic monitoring of heart and breath parameters, snoring, wheezing, etc. is reported in [109]. The sensor consists of a liquid-contained rubber bladder and a hydrophone that measures pressure changes. The sensor pad is in contact with the user's neck. The data possess a high signal-to-noise ratio, and the sensor can be used for assessment and detection of cardiac, respiratory, and sleep disorders.

A new technology for sensing internal organs' motion from outside of the body was announced by Lawrence Livermore National Laboratory (LLNL) [110], [W6]. It is based on a micropower impulse radar (MIR) invented and developed at the same laboratory. The device can be configured to detect the heart rate and pulmonary activity. It also perceives arterial wall motion, respiration, and vocal cord activity. A heart-monitoring sensor has extremely low power consumption. Its size is expected to be about 1 square inch in area. The reported RF emission level from the MIR is about 1 microwatt, which is about 1000 times lower than the safe dose for continuous human exposure that is recommended by most international safety standards.

A telecare system for cystic fibrosis monitoring was designed at the University of New South Wales, Australia [111]. Another project of the same research team deals with web-based longitudinal ECG monitoring [112].

Often one device consists of several sensors that are used for simultaneously monitoring *two or more* health parameters. The complex automated system can monitor daily activity, physiological parameters, life habits, and environmental parameters. Continuous health monitoring of complex parameters will allow for the detection of changes in health status, the identification of early signs of illness, and the use of the data to make suggestions for maintaining and improving health. This approach leads to easy and precise assessment of the current health condition. Some examples of such complex systems will be briefly commented on below.

VivoMetrix Inc. announced the LifeShirt System [113], [W7]. Six sensors, built into a special elastic vest, continually monitor the health of its wearer, measuring 40 bodily functions including blood pressure, heart rate, and breathing patterns. The vest can be worn under a shirt. The information from the sensors is recorded into a computerized data recorder worn on the subject's belt. The recorder is downloaded every 24 hours. Data from sensors can be sent via the Internet and be analyzed by medical specialists. Four inductive plethysmographic sensors assess various blood and respiratory flows at the neck, ribcage, stomach, and chest. Two carbon electrodes provide a single lead for the heart rate and rhythm determinations. A two-axis accelerometer monitors the posture of the inhabitant.

The SmartShirt [114] is a wearable health monitoring system of Sensatex. Inc., USA. The device monitors the heart rate, respiration rate, ECG, temperature, motion, position, barrier penetration, etc. The monitoring system is designed as an undershirt with various sensors embedded in it. A pager-sized device attached to the waist portion of the shirt transmits the data to a data server where the actual monitoring occurs. The SmartShirt implements the patented technology named Wearable Motherboard. The solution incorporates optical fibers, data bus, microphone, sensors, and a multifunction processor, all embedded into the basic textile grid.

The TERVA Project [115] was initiated at VTT, Finland, and aims at personal health monitoring of aged people. The system includes a blood pressure monitor, body temperature thermometer, and monitors the beat-to-beat interval of the heart (RR-interval of the ECG signal). A static charge sensitive bed (Biomatt system of Biorec Inc.) is applied to monitoring of the heart rate, balistocardiography, respiratory rate, and the amplitude of movements when the subject is in the bed.

The SleepSmart Project [116] (a collaborative project between the Rehabilitation R&D Center, Palo Alto VA Health Care System and Hosei University, Japan) studies unobtrusive vital signs by monitoring from the multisensory bed sheet where force-sensitive resistors (FSR) and resistive temperature devices (RTDs) are embedded. The frequency-based software algorithms extract information about the heart rate, breathing rate, body position, body motion, and surface temperature.

It is noted that the results reported in the reviewed projects show that most of the systems are only prototypes and experimental houses, tested mostly with non-disabled people (often students who work at the lab).

Recently, the health and emotional conditions of a user are derived from his or her posture. Whereas the monitoring of the vital parameters is often based on numerous sensors attached to the user, some recent methods for posture monitoring are free from any sensor attachments to the user's body and derive the posture information from force or capacitive sensors embedded in the floor and furniture, or by applying camera vision methods for recognition of the user posture.

Posture monitoring during lying or sitting was developed at the Intelligent Cooperative Systems Laboratory at the Mechano-Informatics Department of the School of Engineering, the University of Tokyo (Prof. Tomomasa Sato's lab) [117]. The methodology is based on pressure sensor arrays mounted on the bed or chair that deliver information about the body weight allocation. The user's posture recognition is based on the analysis of the pressure distribution image. The same approach was extended to developments of the intelligent bed for aged persons, intelligent bed for infants, intelligent chair, and pillow sensor system. The force sensitive bed is a part of an intelligent room for the elderly. An infant behavior recognition system has been developed at the same lab [118]. Another project of the same lab is concerned with an intelligent chair, where the posture of the user's body is determined by the information from sensors arrays mounted on the seat and the back of chair.

A team from the Tokyo Medical and Dental University developed a monitoring system in which the temperature distribution in the bed was used for identification of the body movement during sleep for older persons in the home [119]−[121].

Estimation of the body posture through the R-wave duration in the ECG was proposed at Tel Aviv University. The ECG signals are used both for estimation of the heart parameters and for posture monitoring during sleep [122].

Important information about the health condition and living patterns of the resident can be obtained by monitoring his/her behavior. The approach involves remote sensors whose measurement process does not disturb the user's living activity. Various approaches are used for estimation of the user's behavior.

In a project developed in Japan [123], various sensors are used to obtain information on the user's motion in the apartment and on furniture usage. The experimental system utilizes pyroelectric infrared positioning sensors, door-installed sensors, and magnetic sensors attached to the furniture. A monitoring system for measurement of the indoor mobility of older persons has been developed at Toulouse, France [124]. The project has handled the measurement of the functional parameters in older persons. A set of networked sensors monitors the user's movement including displacement, movement-to-bed, getting up, etc. Sensing is performed by passive infrared (IR) sensors and by pressure sensors located in the bed. The project on outdoor behavior monitoring developed at Ritsumeikan University of Japan [125] is about monitoring of the user's location and his or her gait patterns. Two piezo-resistive type accelerometers measure the posture of the subject. A differential GPS receiver provides precise information about the current location of the user. The sensor data are processed from a special portable digital device.

Monitoring the health conditions of older persons may count on devices that assess the user's behavior through observing the user's gestures and gait. Ordinarily, a non-impaired person is involved in active and frequent movement in the house. The gait pattern and posture of older persons under a progressive cerebral hemorrhage may change rapidly from a normal state to an abnormal state. Since early recognition of the health status prevents complications, and the person does not usually recognize the risk state by himself, recognition of the abnormal state of the gait and the posture is important and can be realized by a vision system in an integrated home health care system.

The assessment of the health status through continuous remote monitoring of the interaction of the inhabitant with his or her environment was reported from the Centre of Health Informatics at the University of New South Wales, Australia [126]−[127]. The project was aimed at monitoring the functional health status of older persons at home. The system includes 18 sensors and monitors changes of mobility, sleep patterns, utilization of cooking, washing, etc.

Recent progress of micro-electromechanical systems (MEMS) allowed integration of both complicated electromechanical sensors and on-site signal processing and offers a new design approach for fabrication of miniature health monitoring systems. Some examples of such systems are listed below.

Some advanced technologies, recently developed and applied in NASA's space programs, seem to be easily transferred to the design of home-installed health monitoring systems. Here we may mention the wearable sensor patches for monitoring of temperature, heart rate, blood pressure, and other physiological parameters [W8], as well as the sensor pills for physiological monitoring of the gastrointestinal tract [W9]. The small patches can be worn on the skin and contain miniature noninvasive microelectromechanical sensors and electronic circuitry for radio telemetry. The radio transceiver located nearby performs not only an information exchange but also radio-frequency excitation to energize the patch circuits. The sensor pills contain miniature sensors, electronic circuits for radio telemetry, and devices for local delivery of drugs. After swallowing, the sensor pill passes through the gastrointestinal tract in about 24 hours, measuring during that period the inner temperature and sensing for the presence of blood, bacteria, and chemicals.

In a project on health monitoring at Waseda University, a microcapsule has been developed, which can sense the pressure, pH, and temperature from the digestive tract [103], [104].

Not all of the projects listed above are oriented especially to individual health monitoring of people with disabilities, but all examples demonstrate non-contact monitoring of important parameters, and perhaps some ideas can be adapted easily to the user with specific needs.

III.4. Devices for information exchange

The following systems and devices can be counted as items in this group for information exchange:

1. System for information access and telecommunication;
2. System for telemonitoring, teleinspection, and remote control;
3. Home network.

The system for information access and telecommunication transmits audio and video broadcasting to the user's home, plays audio and video data, and connects the inhabitant to the medical staff, service personnel, or other individuals. Besides the widely used audio and video techniques and telephone connection, the Internet and Intranet are gaining popularity for such applications. Computers can be used by the PSN for work, educational, and entertainment activities. In case of body movement paralysis of a person, the computer cursor can be controlled for alternative and augmentative interfacing by devices such as a head-mouse [67], eye-mouse [128], and brain control equipment [129]–[131]. Wireless connections additionally facilitate the users with motor impairments by giving them easy communication access from any location.

A variety of special devices have been designed to facilitate verbal communication between non-disabled people and those with speech and hearing disorders. The converters can be divided into two types: devices that convert normal speech to alphabetic symbols or sign language and devices that convert sign language gestures into voice-synthesis speech, computer text, or electronic signals. These devices are important building blocks of the telephones for hearing and speech-impaired people and make possible the telephone communication between them. Speech-to-text software has been developed for many years, but the results are not yet satisfactory for successful communication with deaf people who cannot read. An inherent problem is the diversity of a sign language. The translation system SYUWAN [132] translates Japanese into Japanese Sign Language (JSL) and outputs video images and computer graphics that correspond to the JSL. The machine applies various techniques to find a suitable gesture that matches an input word. The Spelling Hand, developed under the project RALPH (**R**obotic **Alph**abet) [133], is a mechatronic device that converts text into sign language. Finger positions of the designed spelling hand correspond to the American One-Hand Manual Alphabet. The device offers deaf-blind individuals with improved access to computers and can be used as a communication tool for person-to-person conversation. The lip-reading project DIST (University of Genoa, Italy) [134] was developed as a multimedia telephone for hard-of-hearing persons. Normal speech is converted into a lip-movement image (presented on the computer screen) which allows phone communication between people without speech disorders and people with hearing impairments. Devices for recognition of the sign language solve the opposite problem, i.e. they translate the sign language gestures into normal text, so as to make the communication possible between non-impaired people who do not know the sign language and hearing and speech impaired people. Recent progress of the intelligent technique enables real time sign language recognition to be realistic. The wearable recognition system of the Media Laboratory at MIT [135] consists of a cap-mounted color camera that tracks the wearer's hand and a wearable computer that performs real time recognition and interpretation. The system can recognize sentence level American Sign Language. Current accuracy exceeds 97% per word in a 40-word lexicon. The eventual goal is to realize a system that can translate the wearer's sign language into spoken English. In the project, two methods of hand tracking were tried: the first, using colored gloves, and the second, tracking the hands directly without aid of gloves or marking. The recognition system of KAIST, Korea, translates from the Korean Sign Language [136]. In its first version, the hand posture was detected by sensing gloves (initially DataGlove and later CyberGlove), and the hand motions and orientation were sensed by the Polhemus System. The system with a fuzzy min-max neural network-based recognition algorithm can recognize more than 500 Korean sign words, and its recognition accuracy exceeds 92%. In its second variant, the KAIST system uses the color CCD camera for tracking the hand posture and orientation. The user is required to wear white gloves and a black cloth in front of a blue background, which simplifies the recognition procedure. The Hidden Markov Model is applied to recognize the image sequences. To date, the second variant of the system can recognize 20 Korean sign words with a 94% success rate.

Systems for telemonitoring, teleinspection, and remote control provide the service of communication between the care giving staff and user's home. These systems presume availability of (1) a data transfer system from the health monitoring devices to the medical center, (2) an image transfer system from home-installed video and security sensors to the security center, and (3) a remote control system. Such a home-installed remote control system may include door/window locks in case of emergency, a user's home monitoring/inspection robot, and some assistive and health supporting devices (such as automatic oxygen masks, etc.) which should be immediately activated when an emergency situation is detected in order to support the inhabitant's life until the medical staff arrives at the user's home. Data encryption should be compulsory for any transmission of identified personal data, including physiological records. A detailed study on web-based acquisition and the storage and retrieval of biomedical signals may be found in [137].

The *home network* keeps installed smart appliances all connected and realizes the information exchange among them. The specialized home LAN can be organized as a wired and/or wireless network. The wireless communication can be realized by infrared or radio links [13] among the various devices. Some wireless protocols developed recently offer convenient connection of indoor devices. Bluetooth is a low cost protocol that provides short-range radio links between mobile PCs, mobile phones, and other portable devices. The protocol uses 2.4 GHz ranges and allows 10Mbps of data transfer speed with an optimum operating range of 10 meters. The IEEE 802.11.b standard specifies a wireless LAN (WLAN) medium access and physical layer protocols. Currently, IEEE 802.11b dominates wireless home networking. It also uses 2.4 GHz ranges and has 11 Mbps data of bandwidth with an optimum operating range of about 50 meters. Since IEEE 802.11b and Bluetooth have the same frequency range, the protocols do not abide with each other well simultaneously. However, a solution is being sought. A range of new and much faster wireless devices based on the IEEE 802.11a protocol are already available on the market. The 802.11a protocol uses the 5 GHz frequency range and has 54 Mbps data of bandwidth with an optimum operating range of 50 meters. Another widely used technology for data exchange among home-installed devices is the transmission through the power line. Examples include X-10, Echelon LonWorks PLT-10 [138], etc. These protocols can be used to transmit the measured data of different home-installed sensors and devices to the home computer.

Integrated assistive devices need to be controlled in a coordinated manner. M3S (Multiple Master Multiple Slave) is a communication strategy especially designed for functional integration of home-installed rehabilitation devices. The M3S specification started as a TIDE Project [139], [140], and later it was developed as an open standard (available for free). M3S allows users to assemble a specific complete modular system and to extend or modify the system later in a plug-and-play manner. The whole M3S system can be turned on (or off) by a key switch operated by the user. In case of emergency, the system can be halted by a Dead Man Switch. The power of such an integrated system has been shown in several user evaluations in various countries around Europe.

The ICAN Project (**I**ntegrated Control for **A**ll **N**eeds) has further developed the idea of functional integration of the home-installed devices [141], [W10]. The results of the project will give the user an optimal control over all home-installed devices by a single device, such as a joystick or switch input. A portable device, named function carrier, will distribute the commands of a single interface device to various output devices. For example, depending on the setting of the functional carrier, the user will be able to control the wheelchair, the computer mouse, or the rehabilitation robot using one joystick. The function carrier itself will be based upon a portable computer, like a handheld or palmtop PC, that will communicate with the interface modules of the separate rehabilitation devices. The overall integration method will be based upon the M3S architecture and communication protocols. ICAN is a collaborative project supported by the Telematics Applications Programme of the European Commission [142].

III.5. Leisure devices

The leisure devices include:

1.Virtual reality systems;
2. Emotional interactive entertainment robots.

Virtual reality systems can entertain the inhabitant by such options as communication with virtual subjects or game play. Contact with a virtual interlocutor may increase the emotional comfort of older people who live alone and give them some emotional relief. Such computer programs can generate a screen image of a virtual interlocutor whose face, behavior, and voice are similar to those whom the user likes, and thus, a natural dialog with the user can be simulated. In some examples, the behavior of the virtual interlocutor is expressed based on the current emotional status of the user, resolved by image analysis of the user's face. The concept of interaction with a virtual creature was recently developed. The virtual creature "RITY", developed at KAIST, Korea [143], demonstrates a novel architecture and interactive learning method for an artificial creature implemented in the 3D virtual world. The artificial creature can decide its behavior by itself based on its own motivation, homeostasis, emotion, and external sensor information. A behavior is selected by both probabilistic method and deterministic method. The probabilistic method uses mathematically-modeled internal states and external sensor information, and the deterministic method, which imitates the animal's instinct, uses only external sensor information. Both methods are complementary to each other. A user can teach the creature to do a desired behavior by an interactive training method. Behavior learning is carried out with a reward and a penalty signal. The learning algorithm includes the emotional parameter by which the training efficiency is affected. The data architecture is separated into two parts (algorithm part and data part) that allow the user to modify the creature's personality easily without correcting the main algorithm part. An example scene of RITY and his virtual world are shown in Fig. 7.

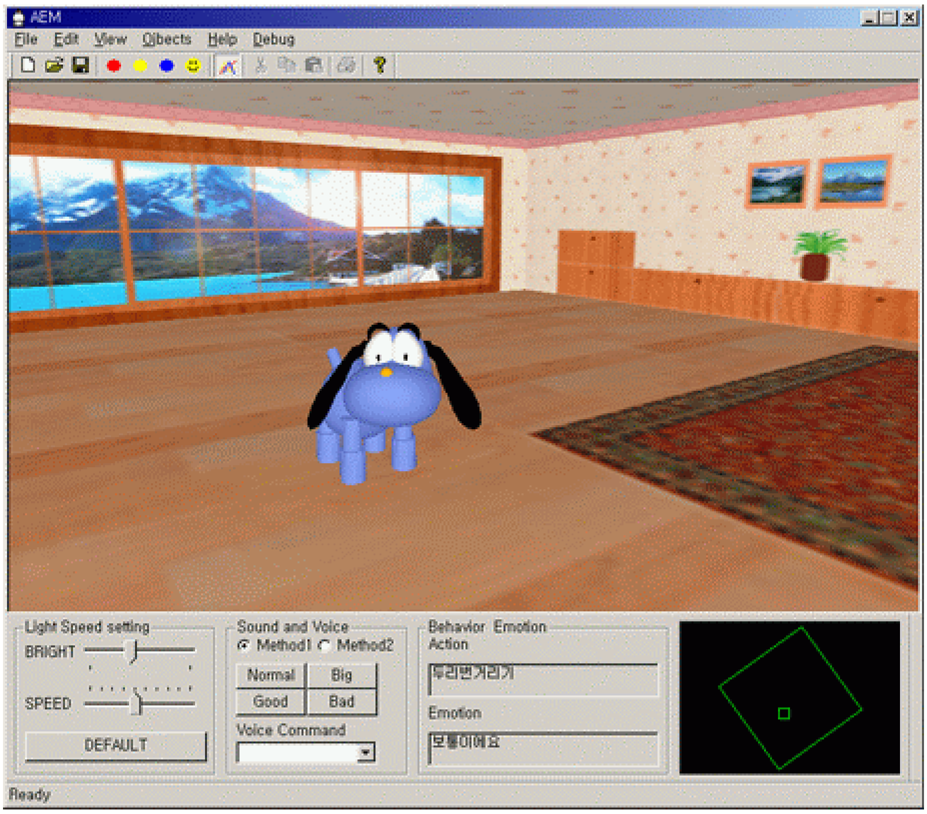


Fig. 7. The virtual creature "RITY" and his virtual world (Courtesy of Jong-Hwan Kim)

The artificial creature can decide its behavior by itself based on its own motivation, homeostasis, emotion, and external sensor information. A user can teach the creature to do a desired behavior by an interactive training method.

Similar to the virtual creatures, the *emotional interactive* entertainment robots (EIAR) [144] are intended to increase the emotional comfort of people who live alone in their smart houses. Although the virtual creatures appear only as images on the computer screen, the entertainment robots are mechatronics devices that express animal-like behavior. Pet robots are one of the latest tendencies in the development of entertainment home robots. Within the project HII House (Home Information Infrastructure House), National Panasonic has demonstrated a conceptual idea for the user-friendly interface for older people in their homes [W1]. Panasonic has developed an electronic home interface and memory jogger designed as cuddly toys – Tama the robocat and Kuma the robot bear. A speech synthesis device can reproduce a number of phrases as a voice response to particular user voice-activated inputs. The device can also be programmed to remind the user to take his/her medication at a particular time. Failure to respond to the device can activate a direct-dial call to the care-giving staff that can then check whether or not the user's condition is normal.

The interactive robot BECKY [145], developed at KAIST, Korea, demonstrates different behavior in accordance with the status of the user's emotions. BECKY recognizes the current emotion of the user by observing the user's response to its actions and considering the environmental information that can affect the user's emotional status. BECKY can adapt to the user's preferences by a learning mechanism based on neural networks. In addition, BECKY can play some music in accordance with the human emotion.

The seal robot and the cat robot, developed in Japan [146], [147], are recent results of the research study on the physical interaction between the human and pet robots. The robots were tested for aged people in the hospital in Japan.

IV. Recent Projects and Some Future Issues of Smart Houses

IV.1. Recent notable projects of smart houses

Intelligent houses for persons with physical disabilities and for older persons should provide their residents with better environmental conditions for independent indoor life. Numerous smart devices and systems, installed in the house, should be capable of being linked with each other, to process information from the inhabitant or from his/her environment, and to make independent decisions and actions for the survival of the resident in cases of emergency. An intelligent house should be part of a complex architecture solution that is barrier-free and facilitates association of the individual and the medical staff for the fast response in case of emergency.

There are various projects in which different concepts of a smart house have been developed and tested. These projects are aimed at different groups of PSN, different architecture, and social infrastructure. Some recently developed projects will be commented on below.

In several European countries, a number of demonstration projects with hundreds of smart houses were developed [148], [W2]. Some of these houses were designed for testing different strategies of older persons and persons with physical disabilities. The model house in Eindhoven was built by the Eindhoven University of Technology [149]. The house was equipped with intelligent systems technology and assistive technology. The model houses, located at five major cities around the Netherlands, and the technology in these smart houses have been evaluated by elderly people. In 1995, the Flemish government (Belgium) started a programme Zwijndrecht. Older persons have been involved in defining the specifications of the smart home systems. In Tönsberg, Norway, eight care flats have been designed to support the home lives of persons with dementia. The focus has been on choosing reliable technology that has a preventive effect upon accidents. SmartBo [150] is a two-room ground-floor apartment in a five-story building situated in a Stockholm suburb. This house together with seven others was built in co-operation with a housing association for senior citizens.

The Gloucester Smart House in the UK [151] is aimed at defining the specific needs of people with dementia. Some specific devices were developed under the project: the bath monitor controls the water level in the bath and the water temperature, while a special locator helps the inhabitant with dementia in finding the location of items that might be misplaced, such as keys, walking stick, glasses case, pension book, purse, etc. If an item is lost, the user simply presses the appropriate button. Then a sound is emitted from the lost object. The same house contains a monitor of an oven in the kitchen, picture phone with photographs of people on the front, and automatic control of the bedroom and toilet lights. The ENABLE Project [152] aims at the evaluation of technology that is oriented to the people with dementia.

Fifteen demonstration and research houses, known as Welfare Techno Houses, have been built across Japan. These innovative demonstration projects aim to identify and promote the idea of independence for older people and people with disabilities by creating accessible environments and maximizing the use of assistive technologies. The houses are used for tests and to exhibit new products and design concepts. Older and disabled people are able to stay in the houses for several days to try out the facilities; manufacturers are able to test their equipment. The concept was launched in 1995. Projects involve the Japanese Agency of Industrial Science and Technology, the Ministry of International Trade and Industry (MITI), the New Energy and Technology Development Organization (NEDO), and a number of private companies.

The "Robotic Room" is a project developed at the Sato Laboratory of the Research Center for Advanced Science and Technology in the University of Tokyo [153], [154]. The Robotic Room can be considered as a step ahead toward the realization of intelligent houses for persons with physical disabilities and the further development of the idea of Techno Houses. The environment of the Robotic Room consists of a ceiling-mounted robot arm (called the "long reach manipulator") and an intelligent bed with pressure sensors for monitoring of the inhabitant's posture. Modules are network-connected, and the room can monitor the sick person's respiration or rolling-over without attaching to anything. The robot arm can bring objects to the user. The developed life-support infrastructure is to comply with the needs of the rapidly aging society.

Although many projects are based on the assumption that the automatic controller should be tuned first, the main idea of the ACHE Project (an acronym for **A**daptive **C**ontrol of **H**ome **E**nvironments), developed at the University of Colorado, is that the home controller can be automatically adjusted by observing the lifestyle and desires of the inhabitants [155]−[157]. The user operates the home appliances as one would do in an ordinary home. At the same time, the sensors mounted to various home devices collect information about the preferred operational data on each environmental state. The learning algorithm is neural network based. A prototype system in an actual residence has been developed and tested. The project was originally intended to resolve the needs of non-disabled users, but the same idea can be applied to adaptive smart homes for older persons and persons with physical disabilities.

IV.2. Important issues for futuristic intelligent robotic house model

Earlier, we have discussed research results on smart houses in which older persons and persons with physical disabilities can have independent livelihoods by extending functionalities of and adding conveniences to conventional houses. Many people predict that one of the biggest reforms to occur in the residential space is to adopt various service robots to help the inhabitants in many ways. Such an intelligent residential space, in general, will also be equipped with advanced monitoring systems that observe not only the physical status of the inhabitants but also their behavior and emotional status with human friendly human-machine interface. All subsystems in the residential space should be capable of solving any local problems by themselves, and at the same time, all of them are connected to a central control unit to be supervised under a unified control policy. This structure resembles the control system of a human being in which, based on information from sensory organs, the human brain decides all the actions of the organs of locomotion, though each organ can play its own role using the autonomous nervous system and reflex movement. In this sense, this kind of structure of a residential space can be considered as a big robotic system, and thus a new concept, called "*Intelligent Robotic House* (*IRH*)," is proposed as a futuristic residential space. One example is shown in Fig. 8.

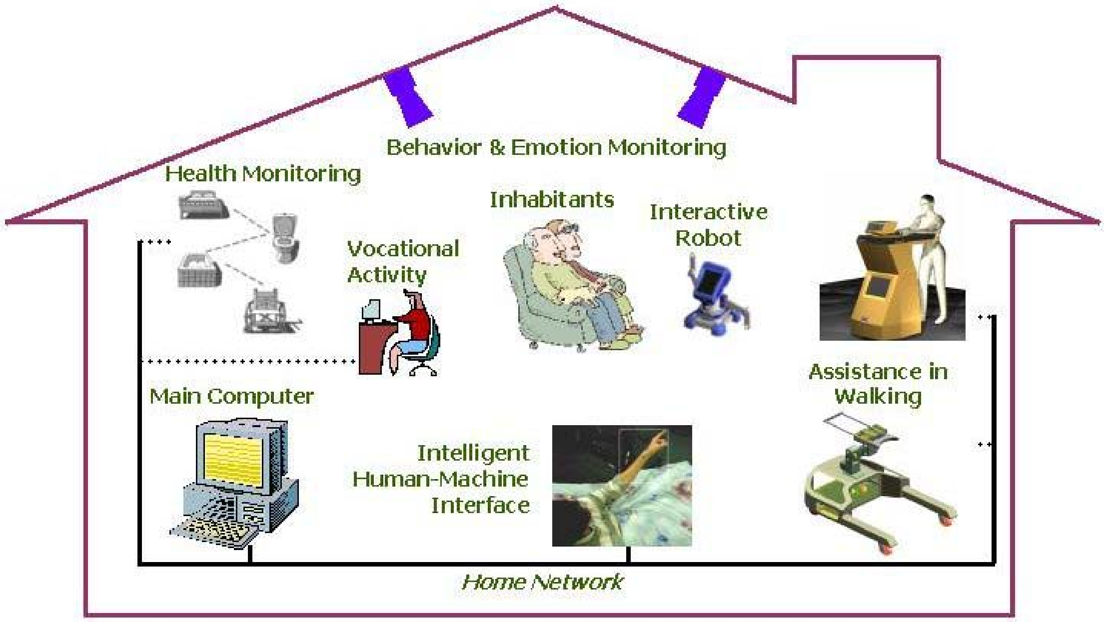


Fig. 8. A Futuristic Intelligent Robotic House Model
The intelligent robotic house integrates advanced technology for non-invasive health monitoring, movement assistance, and leisure activities, and offers easy human-machine interaction.

The intelligent robotic house is a residential space in which intelligent human-machine interaction takes place by means of an embedded computational mechanism of the robotic systems which observe the users and participate in everyday events. A block diagram to show the functional architecture of the example Intelligent Robotic Home is given in Fig. 9. Here, some information is used for many different subsystems. For example, the information on the user's temperature and heart rate is shared with the health monitoring system, the system for emotional status recognition, and the home environment controller; while the visual information of the home-installed TV cameras is used for gesture recognition, face expression recognition, walk pattern recognition, posture recognition, and for home security. The same visual information is used for monitoring the health and emotional status of the user, as well as for multimodal control of home-installed devices. In the above example, three service robots are included: kitchen service robot, robot for movement assistance, and entertainment robot. The control of these robots is based not only on their local vision sensors but also on the visual information from home-installed vision sensors. Audio and video programs in the intelligent home are selected and played automatically. Depending on the current emotional status of the user, music is turned on or off. The choice of the played music is done based upon the information on the current emotional status of the inhabitant. By observing the user's behavior during listening to the music or watching the video program, it is possible for the system to learn to recognize favorite audio and video programs and to include them automatically in the future play list.

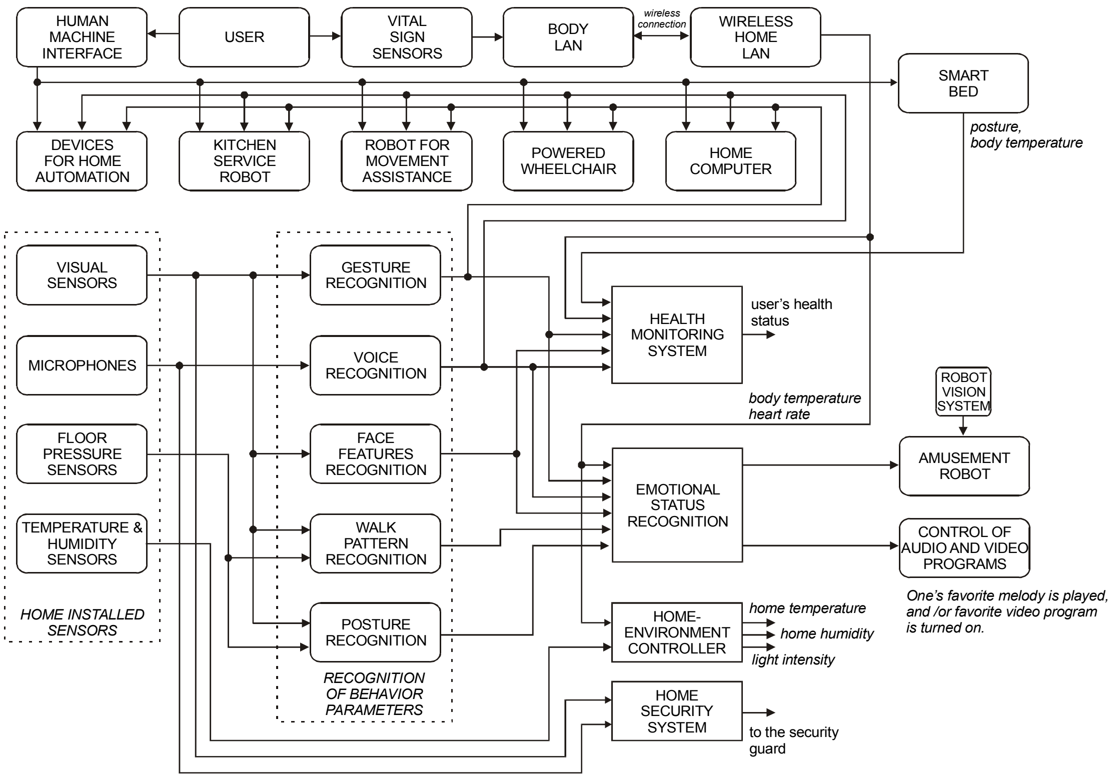


Fig. 9. Functional Architecture of a model Intelligent Robotic House

All home-installed devices and robotic systems are controlled by a common control system. The user can use different modalities in order to communicate with his/her house. Some information is used for many different subsystems.

In the following section, we discuss in some detail key issues in the construction of an intelligent robotic house model as a futuristic residential space for older persons and persons with physical disabilities.

A. Intelligent Sensing and Monitoring

Facial expressions and gestures are indicative of human intention and emotion. According to some statistics [158], 93 % of messages in the face-to-face communication situation are transmitted via facial expression, gestures, and voice tone, while only 7 % are via linguistic language. This shows that it is very important to use devices and systems for extracting information from nonverbal language. In a hospital, the nurse observes not only the patient's biosignals but also the patient's appearance, including facial color, facial expression, voice, and even smell. In the same vein, some recent vision-based health monitoring systems refer to recognition of the facial expression and the facial color (paleness) as an indication of the current health status of the patient. Engineering implementation of the nonverbal communication system is in its initial state. Emotion monitoring is another challenging subject for providing information on the human emotional state. While most existing systems are usually passive in acquiring emotional information, we expect that future systems can give emotion-invoking actions to observe the user's behavior and estimate his/her emotional state in a more effective manner. An initial result exploring this idea can be found in [159].

It is also noted that the smell of the inhabitant gives information on excretion and chemical changes in his/her body, while we can know the person's nutrition intake by the smell of the living room.

B. Intelligent Human Machine Interface

It is interesting to note that human affinity for convenient and comfortable interaction with home appliances has changed continuously. If those interfaces represented by manual operation are called the 1st generation interface, we may say that the interface by a remote controller is a second-generation device. The third generation interface is expected to be more convenient, human-friendly, natural, and autonomous, or simply, "intelligent." The typical problems of existing human-machine interface include difficulties in recognizing human intention, learning how to operate those complex appliances, and providing an individual-dependent operation mode. Those problems may be resolved by soft-computing technique-based autonomous operation along with recognition of human intention and learning capability.

C. Interactive Service Robots

We foresee that a major reform of the future residential space will take place by the advent of the use of various service robots. At present, one may find there are various service robots to help older persons or persons with physical disabilities for their independent daily lives. Typical examples include an interactive robot, nursing robot, walking-assistive robot, and entertainment robot. The interactive use of service robots will be more popular in building smart houses in the future. The robots should be designed to have an individual-dependent operation mode, so that older persons, persons with physical disabilities, or non-disabled people are distinguished properly by the robots.

D. Wireless Data Exchange

In many projects with wearable health monitoring systems, data exchange between different sensors is provided by wireless communication. At present, the wearable sensors can communicate with the home-installed network only. It is probable in the near future that the data transfer of health-monitored parameters to the health monitored center will take place via wireless local networks from any place at home, on the street, or in public buildings. For example, the Body LAN would be able to interact with the home-installed LAN, and the same information will be transmitted in the restaurant via a local network. The same Body LAN has extended functions. For example, it can not only collect sensor data and pass them on for further analysis, but the same information can be considered in the control of the home environment. For example, the room temperature can refer to the current health status of the user. The same wireless LAN can provide some specific information for the user when he or she visits public buildings or navigates in a wheelchair. The wearable devices can output information similar to the information of credit cards that will allow ease in shopping and usage of public transportation. Some of the functions of the PDAs, such as electronic address and phone books, can be performed by the same wearable health monitoring system, too.

V. Concluding Remarks

The idea of a smart house is not new; it has been around in the technical community for a long time. In fact, the smart home concept is not a science fiction but an important goal of development with strong social and economic motivations. Its realization will render a powerful solution for many existing problems in the society with increasing numbers of aged/physically weak and disabled people and will make human life more pleasant and easier.

In this paper, we have tried to classify those reported smart houses according to their design and the home-installed technologies in them. We have specified and commented on some important components of the smart houses, their characteristics and requirements, and some developments in the projects of various research laboratories and companies. We have tried to formulate and classify some recent tendencies of the research in the area so as to obtain our vision about the future tendencies in the development of the technology and its organization.

In our review, we have tried to show that the development strategy of the intelligent home-installed technology has changed from the design of separate devices (at the beginning) to a form of integrated system arrangement where many home-installed devices communicate with each other and synchronously serve/monitor different parameters of the house. Because the problem for the aging society becomes quite common for many countries, the research problems on the smart-home technology have already become an important subject of international research. Diverse forms of international cooperation, such as international conferences, international joint projects for development, and result evaluation, are in progress.

From the design point of view, we observe that the development strategy is also experiencing a rapid evolution. Although the first designs of home-installed devices were hardware-oriented, recent strategies are mainly oriented toward intelligent algorithms, where the software solution takes the main part of the whole design. As an example, we may mention the idea of “soft remocon”, i.e. remote control of home-installed-devices by means of gesture.

In addition, we have stressed the fact that the future smart home will include human-centered technologies where important technological components should provide human-friendly interaction with the user. The home-installed technology will further be oriented toward custom-tailored design where the modular-type components of the smart house will meet the individual user’s needs, emotional characteristics, and preferences.

Thanks to the advent of new technologies such as nano-technology, we are certain that miniaturization of the devices will make the appearance of the intelligent house for people with special needs quite similar to the appearance of an ordinary house without special modifications. The miniature health-monitoring devices will make the monitoring process smart, and such devices will not disturb a user while remaining "invisible" for the others visitors.

The modular design strategy will contribute to the customization of the smart houses. Such technology will be adapted to a concrete user in a cost-effective way. In such a sense, the *smart houses* with installed assistive and health-monitoring devices will not only be an alternative for the independent life of people with special needs but also become a popular *home* for some ordinary inhabitants. Although the present objective is focused on the development of "survival functions", the next step will aim at the entertainment aspect of the smart-house model.

The idea of smart houses started from the needs of the non-disabled people, and later it has moved to the needs of the people with disabilities. We believe that in the future some innovations in the smart houses for people with disabilities (such as advanced health monitoring systems) may be transferred to the non-disabled people, helping them with early diagnosis of some diseases and health disorders. In addition, wearable monitoring systems will become an important instrument for prolongation of the life expectancy in the near future.

Acknowledgement

This research has been supported by HWRS-ERC (sponsored by KOSEF), KAIST, Korea. In addition, the authors wish to thank the anonymous reviewers for their useful suggestions aimed at improving the quality of the paper.

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Appendix

Several web pages referred in the paper from the Internet are listed here as an additional information.

[W1] http://www.rethinkinghousebuilding.org/ – The Housing Innovation Site
[W2] http://www.smart-homes.nl/engels/smarthome.html – Smart Homes
[W3] http://www.telesensory.com/ – Telesensory: Products for People with Low Vision
[W4] http://www.cs.tcd.ie/PAMAID/ − PAM-AID Project
[W5] http://www.ormed.at/pages/produkte/medizin/medizin.html – ORTHOMED Medizintechnik Ltd., Artromot systems
[W6] http://lasers.llnl.gov/idp/mir/mir.html – Micropower Impulse Radar
[W7] http://www.lifeshirt.com/ – VivoMetrics: Continuous Ambulatory Monitoring
[W8] http://www.nasatech.com/Briefs/Feb00/NPO20651.html − Wearable Sensor Patches for Physiological Monitoring
[W9] http://www.nasatech.com/Briefs/Feb00/NPO20652.html – Improved Sensor Pills for Physiological Monitoring
[W10] http://www.tiresias.org/reports/subject.htm − Information Resource for People Working in the Field of Visual Disabilities
[W11] http://www.bath.ac.uk/Centres/BIME/projects/smart/smart.htm − The Gloucester Smart House for People with Dementia
[W12] http://www.crc.ie/ican/ − ICAN Project
[W13] http://www.phys.uts.edu.au/research/ht-mind-switch.html – The Mind Switch

[W14] http://augustachronicle.com/stories/010198/fea_brain.shtml − Mind Control Tool Operating System
[W15] http://www.ics.t.u-tokyo.ac.jp/researches/researches.html − Robotic Rooms
[W16] http://darbelofflab.mit.edu/HAHC/vision.htm − Home Automation and Healthcare Consortium
[W17] http://robotics.eecs.berkeley.edu/~pister/SmartDust/ − SMART DUST
[W18] http://www.lifeshirt.com/ − LifeShirts
[W19] http://www.sensatex.com/ − SmartShirt
[W20] http://www.gtwm.gatech.edu/ − Georgia Tech Wearable Motherboard
[W21] http://www.fitsense.com/ −FitSense
[W22] http://s2k.arc.nasa.gov/frameset.html – Sensors 2000
[W23] http://www.minimitter.com/vitalsen.htm − VitalSense: Physiological Telemetry System
[W24] http://www.stakes.fi/tidecong/ − TIDE: Technology for Inclusive Design and Equality