A Taxonomy of Pervasive Healthcare Systems

Joanna Alicja Muras and Vinny Cahill
Distributed Systems Group
Department of Computer Science
Trinity College Dublin
Dublin 2, Ireland
{osinskaj, vinny.cahill}@cs.tcd.ie

Emma Katherine Stokes
Department of Physiotherapy
School of Medicine
Trinity College Dublin
Trinity Centre for Health Sciences
James's Street
Dublin 8, Ireland
estokes@tcd.ie

***Abstract*— Pervasive computing is a developing area. Due to significant technological developments, assistive devices that were impossible to make or that were not even considered for manufacture are now available. The creation of novel smart environments, context-aware assistive devices, and activity monitoring systems have the capacity to provide people with great opportunities to improve their quality of life and increase independence in daily living. These advances in information and communications technology run in parallel to developments in medicine, physiotherapy and psychology. To enable the design of increasingly advanced user-centred systems, dialogue between computer scientists and healthcare professionals is mandatory. In order to create a framework for dialogue, this paper presents a novel taxonomy of pervasive healthcare systems. The taxonomy extends the International Classification of Functioning, Disability and Health, which provides standard language and a framework for the description of health and health-related domains. The taxonomy is structured as a hierarchy of the properties of pervasive healthcare systems and can be used as a framework for system classification. It identifies a set of fundamental properties that enable a system to be described according to its user's characteristics, its purpose and environment of use, as well as the technologies employed.**

I. Introduction

Pervasive computing aims to provide people with a more natural way to interact with information and services by embedding computation into the environment as unobtrusively as possible [1]. The range of use of pervasive computing is very large. Emerging pervasive computing technologies are applicable in many areas of life such as healthcare, sport and education. They can be found in domestic appliances, cars, tools and even clothes. Smart homes [2], [3] equipped with sensors and reasoning algorithms, that can support their occupants' daily activities are currently being developed. Devices such as automatic lighting control, tap and cooker monitors [2] that are able switch devices off in case of emergency, as well as ambient displays and speakers to inform occupants about scheduled appointments or tasks [4] are all not available. Such smart homes are designed to make life easier and safer. This can be accomplished by systems that are able to detect falls or deviations from usual behaviour in addition to enabling communication with appropriate authorities in case of emergency [5]. This is an important issue when people with disabilities are considered. Thanks to emerging technologies people with limitations now have the opportunity to stay in their homes longer and manage everyday tasks without significant burden for their caregivers. Moreover, smart homes are not the only examples of using intelligent devices to improve the quality of life. Guides showing the shortest route from one place to another [6] or helping with a task by giving step-by-step instructions [6], devices monitoring time and amount of medication taken [7] and robotic interfaces combined with virtual-reality environments for rehabilitation [8] are other examples of emerging pervasive computing technologies.

Pervasive computing research covers a wide range of areas. It involves distributed and mobile computing, sensor networks, human-computer interaction, and artificial intelligence. Knowledge of all of these disciplines is essential to the creation of systems that are truly accessible to users. Researchers need to combine knowledge from medicine, physiotherapy, psychology, and information and communications technology (ICT) to create more user-centred systems. When the design of a pervasive healthcare system is considered understanding of its intended users is essential. An appropriate user description leads to a better understanding of the user's needs and a better design of the pervasive healthcare system. For that reason, dialogue in a common language between computer scientists and healthcare professionals has to be established.

To provide a common language for computer scientists and healthcare professionals our taxonomy of pervasive healthcare systems extends the International Classification of Functioning, Disability and Health (ICF) (WHO, 2001) [9]. The ICF is a multi-purpose framework for the classification of health and disability. It aids the description of changes in body functions and structures, what people can do in a standard environment as well as what they can do when using assistive devices or other people's help in their usual environment.

The ICF contains a list of body functions and structures, domains of participation as well as environmental factors that interact with all of these components. The term functioning refers to all body functions, activities and participation, while disability in contrast refers to impairments, activity limitations and participation restrictions.

The ICF can be used for many purposes at the individual, institutional and societal level. It can aid in assessment, treatment, evaluation, resource planning and education.In the context of defining a taxonomy of pervasive healthcare systems, use of the ICF allows us to define user limitations and impairments very accurately over a large spectrum of different aspects of individual experience. The ICF provides a common language for disability description and is known and applied all over the world. These features make it suitable as a basis for our taxonomy, which is intended to provide a common language for the description of pervasive healthcare systems [9].

The remainder of this paper is organised as follows. The next part of this section outlines the contribution of the taxonomy and overviews related work. Section II describes the structure of the ICF, its components and the relationships between them. Section III defines the structure of the taxonomy and describes the properties used for pervasive healthcare systems classification. Section IV presents a classification of existing pervasive healthcare systems, showing how they fit into the taxonomy described in this paper. Finally, section V presents a summary and some concluding remarks.

A. Contribution of the taxonomy

The taxonomy is intended to provide common language for computer scientists and healthcare professionals for describing pervasive healthcare systems. It is undeniable that this will lead to a better understanding of the connection between user needs and system features. In addition to providing a basis for describing and classifying pervasive healthcare systems, our taxonomy may be useful in specifying strategic research directions. For example, the taxonomy is expected to expose novel combinations of system properties resulting in the identification of research issues to be addressed in the future.

B. Related work

Our taxonomy identifies a large variety of properties of pervasive healthcare systems including their intended users' impairments and limitations, the environment and purpose of use of the systems as well as their inputs and outputs. In contrast, most existing work on classification of pervasive systems has focused on describing their properties only in terms of sensors, network structures and protocols.

In [10] the authors presented a taxonomy of wireless micro-sensor network models that aids the definition of network architectures according to communication functions, data delivery models, and network dynamics. The taxonomy of wireless devices in [11] provides a classification according to five categories - communication, sensing, power, memory, and other features. This classification enables the definition of the structure, communication and components of a pervasive network very precisely. However, when we consider pervasive systems, in the context of assistive technology, defining their network architecture is not enough to describe and classify them. A higher-level approach was presented by Estrin et al. [1] who defined three dimensions: scale, variability and autonomy in both time and space. Their properties are oriented toward describing systems according to their perception of environment. While such approaches can be useful for the description and classification of pervasive systems, they do not address enough properties to classify pervasive systems according to user conditions and needs.

A classification of technical aids for persons with disabilities can be found in ISO standard 9999:2002 [12]. This one-dimensional classification consists of three hierarchical levels. Each class, subclass or division consists of a code that allows the definition of a unique coding system for every family of device. The ISO standard also provides descriptions of the categories at each level. According to [13] the ISO norm will be connected with the ICF. A new version of ISO 9999 will be called 'Assistive products for persons with disability' and is expected to be extended with new product categories and match all described products with ICF domains.

II. International Classification of Functioning, Disability and Health

The ICF is based on the biopsychosocial model. The biopsychosocial model synthesises the medical model that views disability as a feature of the person and the social model that views disability as a socially-created problem. This approach enables all aspects of disability, which is always an interaction between features of the person and features of the overall context in which the person lives [9], to be described.

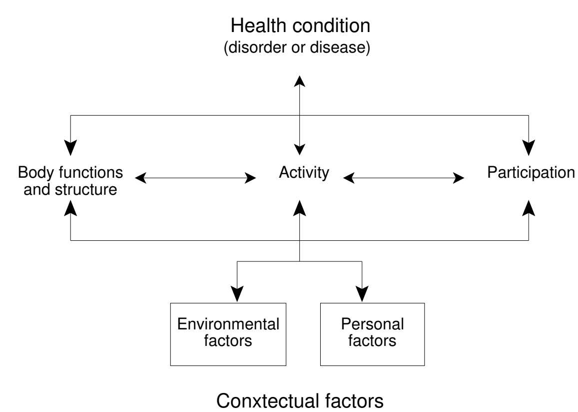

Fig. 1. The model of disability that is the basis for ICF [9].

Fig. 1 presents the model of disability that is the basis for the ICF. It considers disability and functioning as a result of interactions between health conditions (diseases, disorders and injuries) and contextual factors. The contextual factors are composed of external and internal factors. The external factors are called environmental factors and they represent the

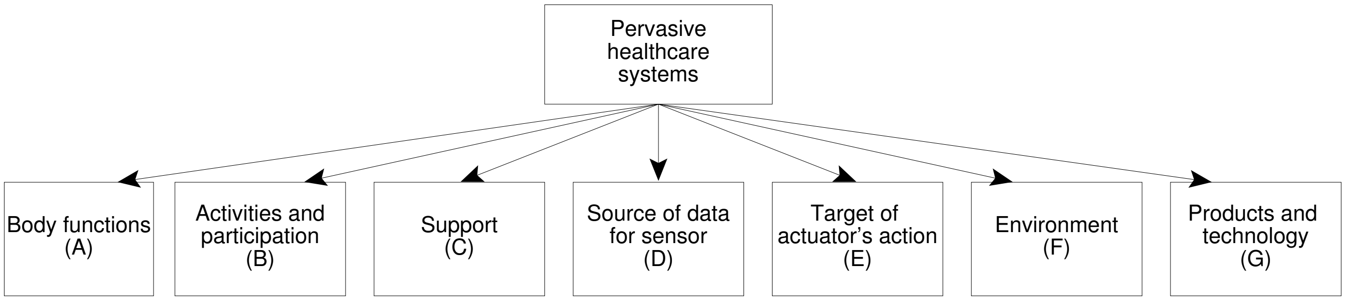

Fig. 2. The root of the taxonomy.

physical, social and attitudinal environment in which people live and conduct their lives. The internal factors are called personal factors and define the individual, their background, experience, overall behaviour pattern, character and other factors that influence how disability is experienced by the person. Fig. 1 identifies the three levels of human functioning classified by the ICF: functioning at the level of body or body part, the whole person, and the whole person in a social context. Disability therefore involves dysfunctioning at one or more of these same levels: impairments, activity limitations and participation restrictions [9].

The ICF offers a flexible framework for classification and description of human functioning and disability, for that reason, it was used as a basis for our taxonomy. Its hierarchical structure allows the choice of a suitable level of detail for describing a person and identifying impairments, activity limitations and participation restrictions.

III. Taxonomy

The root of our taxonomy, which is depicted in Fig. 2 defines seven main feature categories, that allow us to describe a system according to its different properties. Categories A, B, and part of G were taken directly from the ICF and not designed by us.

Two categories of the taxonomy provide the description of pervasive system properties according to potential user impairments, activity limitations and participation restrictions. Category A describes user impairments according to the physiological functions of body systems while category B allows the description of an assistive device according to the difficulties that a user may have in executing activities and involvement in life situations [9].

An important issue is defining who will be supported by the system. Classification according to feature C can distinguish systems designated for persons with disability, people living in the same house and, where appropriate, caregivers. This property influences the method used by the system to provide feedback. Some systems may support more than one class of person and the feedback provided can be different.

The next two categories (D and E) provide the description of the pervasive system according to its interaction with the user and the environment. Defined properties refer to the source of sensor readings and the outcome of system actions. The type of measurements taken by the system influences the manner in which the readings are processed and how the system's action is determined and triggered. When systems for people with disabilities are considered, the manner of user feedback is a crucial attribute according to which they can be classified.

The next category (F) describes the environment, in which the system can be used. This property is important, since it implies the architecture of the pervasive network, types of network devices and communication protocols used.

The last category (G) of our taxonomy is the most complex one. It enables us to describe the system properties according to the manner in which the system assists the user and what areas of the user's life it supports. Six categories of system assistance have been identified, which are locator, guide, reminder, communicator, monitor and assistant. These categories describe the type of assistance desirable during activities of daily living, and each address different user needs. As identified in the ICF, the areas in which this assistance might be used are daily living, indoor and outdoor mobility and transportation, communication, protection and health. This category there allows systems to be classified according to their precisely specified purpose.

In the next part of the article, the terms 'user' and 'participant' will be used interchangeable for the description of a person with a disability that uses a context-aware assistive devices. The term 'caregiver' and 'carer' will be used for the person who provides assistance to the user.

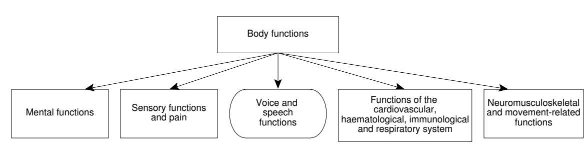

Fig. 3. Body function categories [9].

A. *Body functions*

The body function categories define user impairments according to physiological functions of body systems. This allows the categorisation of systems with respect to potential users' conditions. The type of user impairment implies the manner of feedback to the user. If a person has problems with hearing, the system should not use voice or sound to interact with this person. In contrast if a system is classified as an aid for a blind people it should not use any visual feedback to its user [14]. This category allows also to divide systems according to the manner in which their interface acts. The design of aids for persons with cognitive problems has to consider their characteristics and build interfaces that would be efficient for them [6]. As shown in Fig. 3, five distinct categories of body functions were directly taken from the ICF.

*1) **Mental functions**:* Mental functions allow us to describe functions of the brain. They are divided into two categories, which are global mental functions and specific mental functions, illustrated in Fig. 4. Each category allow us to describe a user's mental impairments in more detail. **Global mental functions** define general functions of the brain and include function of consciousness, orientation, intellect, personality, energy and drive and sleep. **Specific mental functions** include attention, memory, experience of self and time, and psychomotor, emotional, perceptual, though higher-level cognitive, calculation, sequencing complex movements functions as well as mental functions of language.

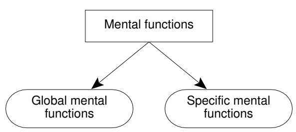

Fig. 4. Mental function categories [9].

*2) **Sensory functions and pain**:* Sensory functions and pain allow us to describe a system according to impairments in the users' senses. As illustrated in Fig. 5, three categories were defined, which are seeing and related functions, hearing and vestibular functions, and additional sensory functions. **Seeing and related functions** include quality of vision, functions of sensing light and colour and visual acuity of distant and near vision as well as all impairments connected with vision.

To keep consistency with the ICF, our taxonomy defines a category for **hearing and vestibular functions** which consists of two categories as follow hearing functions and vestibular functions. **Hearing functions** include sound detection and discrimination, localisation of sound source and speech discrimination. **Vestibular functions** include sensory functions of the inner ear related to position, balance and determination of movement.

The last category **additional sensory functions** include the senses of taste, smell and touch as well as functions related to temperature and stimuli.

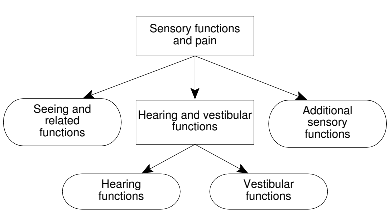

Fig. 5. Sensory function categories [9].

*3) **Voice and speech functions**:* Voice and speech functions include production, quality and range of voice as well as the manner of speech such as fluency, rhythm or speed. Systems supporting these user impairments, if they interact with the user based on its speech, tend to use advanced algorithms for voice recognition.

*4) **Functions of the cardiovascular, haematological, immunological and respiratory systems**:* This category allows us to describe functions of the heart and blood vessels, blood production and immunity, and functions of respiration and exercise tolerance. As depicted in Fig. 6, we have defined four different categories. Each of them allows us to describe a system user in more detail and classify the system more precisely. **Functions of the cardiovascular system** include functions of the heart, blood vessels, and blood pressure. All cardiac problems are covered by this category. **Functions of the haematological and immunological systems** include blood production, oxygen and metabolite carriage, and clotting functions as well as function of the body related to protection against foreign substances, including infections. **Respiration functions** cover inhaling and exhaling air into the lungs, the exchange of gases between air and blood and muscles involved in breathing. **Additional functions and sensations of the cardiovascular and respiratory systems** include functions such as coughing, sneezing and yawning, exercise tolerance and various sensations connected with heart and breath.

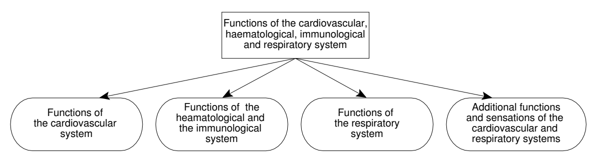

Fig. 6. Functions of the cardiovascular, haematological, immunological and respiratory system categories [9].

*5) **Neuromusculoskeletal and movement-related functions**:* This category allows the description of potential user movement and mobility, including functions of the joints, bones, reflexes and muscles. As illustrated in Fig. 7, three categories were defined, to better describe system properties. **Functions of the joints and bones** allow us to describe the pervasive system according to its potential user's mobility and stability of joints and bones. They include functions describing the range and ease of movement, and maintenance of structural integrity of a joint as well as the range and ease of movement of the scapula, pelvis, carpal and tarsal bones. **Muscle functions** allow us to describe an individual's muscle power as well as muscle tension and ability to sustain its contraction. The last category **movement functions** includes properties for identification of reflex, voluntary and involuntary movement control as well as related sensations and gait pattern.

B. Activities and participation

The activities and participation category provides the description of activity limitations and participation restrictions of potential system users. This category enables us to describe pervasive systems according to its user's restraints.

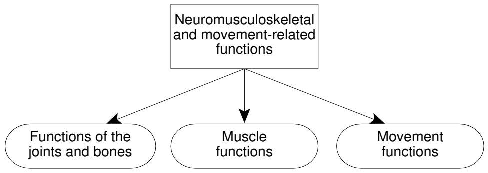

Fig. 7. Neuromusculoskeletal and movement-related function categories [9].

It provides properties to define types of tasks that the user cannot manage. The type of user limitation and restriction puts various requirements on systems created for the same purpose like i.e. assistance with exercise. If we consider systems for rehabilitation they can support improvement of different user capabilities. One can aim to improve user's ability to change body position, whereas another can intend to improve carrying out daily routine by providing appropriate exercises [8]. As illustrated in Fig. 8, five distinct categories of body functions were taken directly from the ICF.

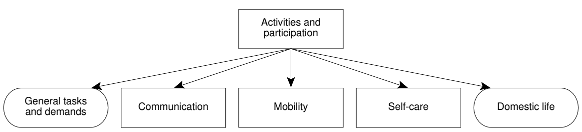

Fig. 8. Activities and participation categories [9].

*1) **General tasks and demands**:* General tasks and demands allow us to describe the potential user of the system according to the manner in which it copes with single or multiple tasks, organising routines and handling stress. This category includes activities like managing and completing the requirements of day-to-day procedures or duties, such as budgeting time and making plans for activities throughout the day or preparing, initiating and arranging time and space, as well as carrying out coordinated actions in order to complete the requirements of day-to-day procedures or duties. In addition, this category also covers carrying out tasks demanding significant responsibilities and involving stress, distraction, or crises, such as exams or driving a car in heavy traffic.

*2) **Communication**:* This category enables us to identify system's properties in relation to its user's communication disabilities. They include receiving and producing messages, carrying on conversations, using communication devices, and use of spoken language, signs, and symbols. As illustrated in Fig. 9, three distinct categories to better describe the system properties were taken from the ICF. **Communicating - receiving** covers comprehending the literal and implied meanings of symbols and drawings, messages in spoken and written language and ones conveyed by gestures. **Communicating - producing** includes producing the literal and implied meanings of messages that are conveyed through spoken and written language as well as gestures, symbols and drawings.

The last category **conversation and use of communication devices and techniques** was divided, as pictured in Fig. 9 into two more accurate categories. **Conversation and discussion** include starting, sustaining and ending an interchange of thoughts and ideas, carried out by means of spoken, written, sign or other forms of language, with one or more people. **Using communication devices and techniques** allows us to describe the capacity to use telecommunication devices like phones and faxes, writing machines such as typewriters, and communication techniques like lips reading.

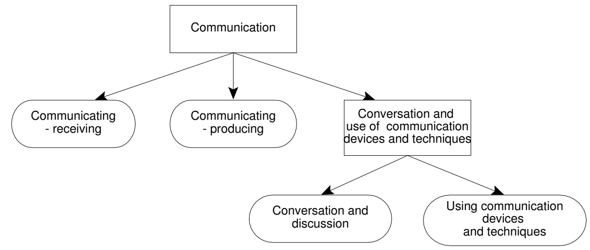

Fig. 9. Communication categories [9].

*3) **Mobility**:* Mobility refers to every kind of intended movement of the human body. This category describes the change of body position or location by walking, running or climbing, and by using various forms of transportation. It also covers carrying, moving or manipulating objects. As shown in Fig. 10, four categories are used. **Changing basic body position** includes performing and sustaining body position in such activities as lying down, squatting, kneeling, sitting, standing and bending as well as adjusting or moving the weight of the body or transferring oneself from one position to another. **Carrying, moving and handling objects** covers activities such as lifting and carrying objects with the hands, arms or on the shoulders, head, hip and back as well as pushing them with the legs or kicking. This category also describes properties of hand movements like picking up, grasping, manipulating or releasing, and arm use like pulling, pushing, reaching, turning or twisting, throwing and catching. The next category allows the description of all aspects of **walking and moving**. It defines user limitations in distance and surface of walking, types of movement like crawling, climbing, running, jumping and swimming, moving in different locations within or outside the home and building, as well as using specific equipment like skis or wheelchairs. The last category **moving around using transportation** contains the use of all means of transport, such as bus, boat, train or car including animals and animal-powered vehicles as a driver as well as a passenger.

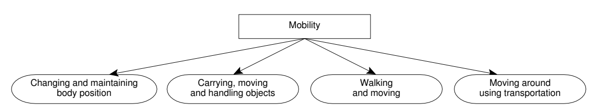

Fig. 10. Mobility categories [9].

*4) **Self-care**:* This category includes aspects of the user's ability to manage self-care activities. As illustrated in Fig. 11, seven categories were specified. **Washing oneself** includes washing and drying one's whole body, or body parts like washing the hands, feet, face or hair, using methods, such as bathing, showering, and drying with a towel. **Caring for body**

parts refers to looking after the skin, teeth, hair, fingernails and toenails. **Toileting** focuses on coordinating and managing the elimination of human waste (menstruation, urination and defecation), and cleaning oneself afterwards. **Dressing** covers all the activities involved in putting on and taking off clothes or shoes as well as their appropriate choice. **Eating** and **drinking** allows us to describe potential user ability to coordinate all the tasks and actions needed to consume served food or drink. The last category **looking after one's health** includes ensuring one's physical comfort, managing diet and fitness, and maintaining one's health by avoiding health risks, and following medical and other health advice.

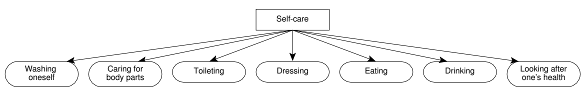

Fig. 11. Self-care categories [9].

*5) **Domestic life**:* This category enables the identification of the system properties according to its user ability to carry out domestic and everyday actions and tasks. It includes acquiring a place to live, food, clothing and other necessities also storing them, preparing meals, household cleaning and repairing, caring for personal and other household objects, using household appliances and assisting others.

C. Support

The support category in reference to pervasive healthcare systems allows the identification of who may benefit form the system. It does not have to be necessarily the person who is the direct target of the device's action. One device can support more than one person and not necessarily all of them have to be target of its feedback. If we consider a device that informs a caregiver in case of emergency, it also helps its user to stay safe and well even if that person is not direct target of device's feedback [5]. As illustrated in Fig. 12, we have defined three different targets for support, which are the participant, caregiver and vicinity.

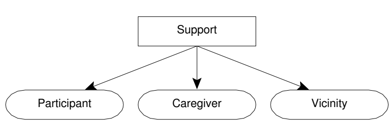

Fig. 12. Support categories.

*1) **Participant**:* The participant can be described as a person with disabilities who is a user of the system. They can receive support from the pervasive assistive device in several manners. That can be adjusting appliances to user's preferences, warning about potential danger [3], reminding about some events or fixed appointments [4], [15], help with exercises [8], guidance step-by-step through some task [6] or route [6] or contacting a caregiver in case of emergency [16].

*2) **Caregiver**:* The caregiver can be described as a person who supports the user, but not necessarily lives with them. For a caregiver the most important issue is the user's safety, so the advantage from using an assistive device could be informing them about emergency situations and the progress of daily routines or deviations from them [16], [17]. The caregiver can also be a healthcare professional (HCP), who is in charge of the user's health. He can for example be supported by obtaining vital sign measurements for analysis [5].

*3) **Vicinity**:* The vicinity can be described as people living with the user in the same flat, house or building, but are not responsible for taking care of them. They can be supported by pervasive systems that would manage domestic appliances and prevent them from causing damage like fire [2], [3].

D. Source of data for sensor

This category allows the description of system properties related to the source of its sensors' readings and enables the classification of the systems according to the kind of data that triggers its action. Depending on the purpose of the assistive device and its level of development various triggers can be used. If we consider a system that monitors vital signs its general purpose is to collect data from the user, however its action can be triggered by different factors. One of them could be time. In predefined periods of time outcome measurements could be sent to a storage server [5]. In this case, gathered data could be later used for analysis of the patient's health. In a second case, the system action could be triggered when collected readings indicate, that there is danger to the user's health. In this case information about risk could be sent to the appropriate authority [16]. Pervasive systems can use many sources as their input. Usually the more advanced the system is, the more information from different sources it uses. This category enables us to classify the pervasive healthcare system according to its sensor readings. As illustrated in Fig. 13, we have defined four distinct categories to describe the source of sensor readings, which are participant/individual, object, environment, and time.

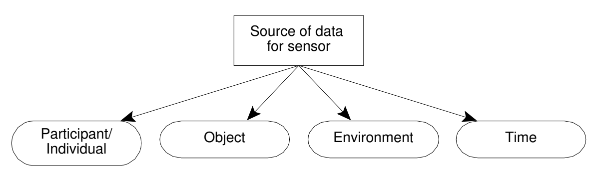

Fig. 13. Source of data for sensor categories.

*1) **Participant/Individual**:* This category describes systems that use the person as the source of their sensor readings. They can collect typed messages, information about the person's location [18], body movements [8], and voice recordings as well as readings such as vital signs like blood pressure. In addition, to what ever system action is triggered by the outcome of processing the data described above, the user can also activate device action by pressing the button [16]. The source of collected measurements influences the type of sensors used. Depending on the system's purpose wearable or stationary sensors can be used for measurement collection.

*2) **Object**:* This category allows us to identify systems that use some objects as the source of their sensor readings. Examples of objects that could be used as the source of measurements are domestic appliances like ovens, beds, chairs, light switches, taps, or doors. The system's sensor can be embedded in the objects listed above or focused on them like cameras and they can collect data about the object's location, temperature, movement and state (for example if a window is opened or an oven is on) [3].

*3) **Environment**:* This category describes systems that use sensor readings from a wider area using special data processing algorithms to receive useful informations. As a result of this approach, a lot of different information can be obtained. Collected data can be used to recognise people, objects or activities [14], [18] and obtain required information about them cameras and microphones are often used. These type of devices allow the data acquisition from a wide area. Systems classified in this category due to processing of gathered data are more likely to require higher processing power.

*4) **Time**:* The systems having this property, can use time readings in two ways. Information about the time can be used for saving other sensor readings with a time stamp that can be useful for later data processing and obtaining an outcome that is situated in space-time [18]. Collected data can be used to infer the probability of events or user activities that depend on day time or to place detected events in sequential order. A use of information about time can also be utilised to trigger reminders about some scheduled tasks.

*E. **Target of actuator's action***

This category describes properties of a system's action. It enables us to define, on what identity or object a device's outcome is executed. Pervasive systems can be used for gathering data for future analysis by a HCP, informing individuals about some events or fixed appointments or controlling some other device [3]. Depending on purpose of the system, the target of system feedback can vary. The aim of this category is to describe final target of the system's action. As illustrated in Fig. 14, we have defined four distinct categories to describe the final recipient of device's action, which are participant, caregiver, object, and data storage. If we consider reminding the participant about taking medicines, the ubiquitous assistive device can use text message, sound or blinking lights for this purpose [14], [16]. All of the systems, regardless of the method of communication they use, whose purpose is informing the participant, are covered by category participant. This category enables the division of systems according to their actuator's characteristics.

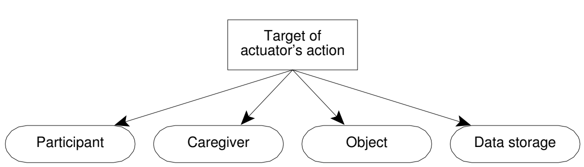

Fig. 14. Target of actuator's action categories.

*1) **Participant**:* This category describes systems in which the user is the recipient of the final action. This user can be instructed or reminded about some event, informed about some fact, e.g., that front door is open, or in case of using a computer can see the system's action on the screen [19]. Assistive devices can also provide assistance with participant's activities. They can help with, e.g., walking, or medication delivery [7].

*2) **Caregiver**:* This category defines the caregiver as the final recipient of a system's action. The main aim of assistive devices, when we consider the caregiver as the target of their action, is informing them in case of danger and about daily routine or some particular event like the participant leaving the house. The caregiver can obtain this information by phone, text message or email. As well as receiving emergency messages he can also obtain periodic reports with vital sign measurements such as blood pressure or heart and respiration rate.

*3) **Object**:* As objects we include all domestic appliances, devices and equipment. This category allows the description of all systems whose action is executed on an object. That could be automatic change of water temperature from the tap, light control or turning off the oven when it is no longer used [2]. The action may be triggered depending on environmental conditions and specific user presences or actions.

*4) **Data storage**:* Data storage can be used for medical purposes as well as for saving the outcomes of monitoring either a room [18] or a person [5]. This category enable us to describe systems that do not have a direct impact on their surrounding. Examples of such informations could be checking if a participant took medicine or who entered some room in the last three hours.

*F. **Environment***

This category defines where the pervasive system is used. This category provides the classification of systems according to the network architecture used, types of network devices and the manner in which they communicate. As illustrated in Fig. 15 we identified two main categories, which are indoors and outdoors. This determines the range of system deployment. Environment characteristics also influence the accuracy of measurements that have to be taken to accomplish the objectives of the system.

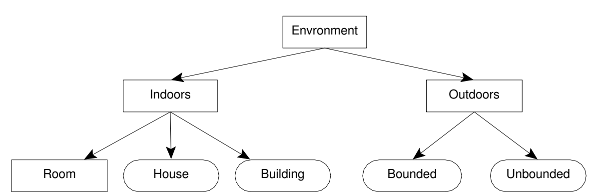

Fig. 15. Environment categories.

*1) **Indoors**:* The characteristics of indoor environment allows the use of wireless communication technologies as well as cable connections. As illustrated in Fig. 15, it distinguishes between room, house and building. These categories were defined to separate systems depending on their range of deployment and the manner in which they interact with their users. Technology utilised in a **house** aims to interact with its residents, so it is more likely that it is able to be customised to particular user. In contrast systems used in **buildings** are designated to support many unknown users. In this case, they are supposed to be more flexible and universal.

When we consider systems used in one particular room, they usually do not have as developed a structure and number of devices as ones placed all over a house or building. As illustrated in Fig. 16, **room** can be better described using five more detailed categories, which are kitchen, bathroom, living room, bedroom and other. All of these places put different requirements on a system which is placed in them and include different types of appliances. The most important issue for the systems placed in **bedrooms** is their users' privacy. Pervasive systems that are used in the **bathroom** must be unobtrusive to respect user's privacy, additionally they should be very reliable and react quickly, since this environment is potentially dangerous. The systems placed in **kitchen** should also be very reliable, due to the presence of appliances that are more likely to cause harm. They tend to use advanced processing algorithms and efficient user feedback, due to the relatively complex type of tasks supported. Context-aware assistive devices placed in **living rooms** are more likely to customise to user preferences quickly and accurately. The **other** category refers to systems, which are not placed in any of previously described rooms.

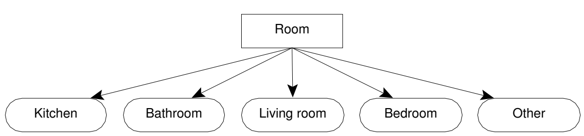

Fig. 16. Room categories.

*2) **Outdoors**:* This category allows us to describe properties of systems, that are used outside houses or buildings. In contrast to the systems working indoors, assistive devices used here will use technologies that require communication over a large area. Because the area of the system deployment is bigger than a house or building and a very high level of accuracy of sensor's readings is not available in these kinds of systems mostly GPS technologies will be used. The pervasive systems that are applicable outdoors mostly use wireless sensors, due to user convenience and environment characteristics [20].

As depicted in Fig. 15, we have defined two categories, which are bounded and unbounded. The term **bounded** refers to an area that is restricted in some dimensions. That can be a garden outside a house, a car park or a football pitch. Technologies used to cover this space use sensors that are fixed to some static objects, for example, cameras. The term **unbounded**, in contrast, refers to the world at large. That puts demand on use of wireless and mobile technologies.

*G. **Products and technology***

This category provides a description of pervasive healthcare systems according to two distinct aspects, which are the type of assistance provided and area of use. If we consider systems that guide users, information about the type of guidance is essential. If the device gives user directions about a route [6] it has different requirements to the device that gives step-by-step instructions to complete some activity [6]. Some devices can have more than one function and can be used in more than one area. Smart homes [2], [3] equipped with many context-aware devices can support user's memory with reminders and monitor its occupant well-being.

1) Areas of use: To give a comprehensive view of device use, areas in which it can be used should be defined. The taxonomy specifies five areas of use, as illustrated in Fig. 17. They cover these life areas, in which people with neurodegenerative diseases need assistance. Depending on area, devices with different characteristics may be found.

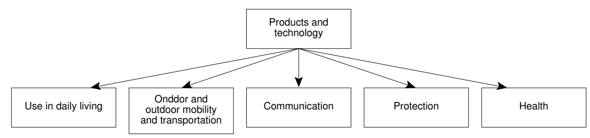

Fig. 17. Products and technology categories [9].

- **Use in daily living**: It includes all the devices that can be used to help in activities of everyday living like cooking, washing, following a schedule, or controlling appliances.
- **Indoor and outdoor mobility and transportation**: This area contains all the devices that assist the user in changing the body position or its location. They can support physical impairments such as problems with walking as well as cognitive ones like finding the right the way home.
- **Communication**: This includes all the devices that help to communicate with another person or device like systems that provide simplified languages based on pictures or specialised computer interfaces.
- **Protection**: This area includes devices that prevent harm to the user and keep him as safe as possible. This can be monitoring systems informing caregivers in case of any danger, appliance managers switching them off when needed or reminder about taking medication.
- **Health**: This area contains devices that support well-being or recovery. These can be devices for rehabilitation or vital signs monitoring.

2) Types of assistance: This category enables us to describe the pervasive healthcare systems according to their purpose of use. The pervasive assistive devices are designed to support various user's needs. That could be reminding about some fixtures, locating missing objects or assistance with some tasks. We have defined six categories to describe distinct functions of the systems.

- **Locator**: The function of these devices is localisation of objects or people. The systems can help the participant to find necessary items or inform caregivers about a participant location.
- **Guide**: These systems aim to give the user assistance needed to finish some task. They can support performing

TABLE I

RELATIONSHIP BETWEEN AREAS OF USE AND TYPES OF ASSISTANCE

Areas of use / Types of assistance	Locator	Guide	Reminder	Communicator	Monitor	Assistant
Use in daily living	•	•	•			•
Indoor and outdoor mobility and transportation		•				•
Communication				•		•
Protection	•		•	•	•	•
Health			•		•	•

activities by giving step-by-step prompts or following the appropriate route by giving the right direction.

- **Reminder**: The assistance provided by these systems is reminding a user about scheduled events, actions or activities. Depending on user characteristics the type of device feedback can be different. That can be, e.g., text message or sound alarm.
- **Communicator**: The purpose of these systems is to provide communication between the system user and third parties. That can be contacting appropriate authorities in case of emergency or providing suitable language to enable mutual understanding of participants of conversation.
- **Monitor**: The function of these devices is surveillance of people or places. In case of people, things like vital signs, performed activities or mobile status can be monitored. In case of places, rooms or houses can be monitored and desired information like room occupancy can be received by data analysis.
- **Assistant**: The purpose of these devices is to aid their user in some particular activity. To this category belong haptic devices supporting the computer use without hand tremor or devices that help with walking.

3) Relationship between areas of use and types of assistance: To provide more specific system descriptions, we have combined types of assistance with areas of system use. This approach enabled us to create a relationship matrix, illustrated in Tab. I. If relation between some areas of use and types of assistance exists it is marked with '•'. As pictured, not every function of assistance can be applied to all the areas, therefore the matrix defines possible connections. This assignment was based on a review of the literature and existing devices, however it is possible to add more assignments in case of such a need.

IV. CLASSIFICATION OF PERVASIVE HEALTHCARE SYSTEMS

In order to evaluate our taxonomy, several examples of applying the taxonomy to existing pervasive systems are illustrated in Tab. II. The summarised systems were chosen to cover various properties like system purpose, user characteristics and technology used.

'The Activity Compass' [6] is hand-held device whose purpose is to show the direction to a specified location. It can be used outdoors (GPS is used for the determination of user location) to pinpoint for example, home, or indoors (infrared ID tags are used) to locate, e.g., a bathroom. It can be useful for people with Alzheimer's disease (wandering) or other users with orientation problems. 'The OrientingTool' [15] is also a hand-held device designed to provide reminders for people with cognitive decline. 'The Tremor Control System' [19] was created to help people with hands tremor to use computer pointing devices by applying appropriate values to parameters like speed, gain, band and backlash. 'The In-home elder healthcare system' [14] that monitors patients' medication in take provides information about the amount of medication taken by the user and enables reminders if the user is in its vicinity and the time is appropriate. The last summarised pervasive system, 'The Millennium Home' [3] is the most complex one. Its purpose is to assist users in daily activities like controlling house appliances or adjusting them to the environmental state as well as monitoring its user and the house where it is deployed providing appropriate alarms in case of emergency.

V. CONCLUSION

This paper presented a novel taxonomy of pervasive healthcare systems. The taxonomy identifies a set of fundamental properties that enable a system to be described according to user characteristics, its purpose and environment of use, as well as the technologies used. These properties are arranged in a hierarchical manner starting from the root of the taxonomy, which defines the relationships between all seven main feature categories. In addition, our taxonomy is based on the ICF, which provides standard language and a framework for the description of health and disability.

Our taxonomy is unique in considering the attributes of the users in a number of different ways. Existing work focuses on providing a framework designed either for the description of technologies used or user conditions. The set of properties covered by our taxonomy, that describe systems according to their environment and purpose of use as well as the technology applied and their potential users, provides a better framework for identification of system dimensions in more detail. As a result, it can be used for classification of pervasive healthcare systems, in which understanding characteristics of their potential user is essential.

Pervasive healthcare systems are emerging technology and are evolving in parallel to developments in the ICT, medicine, physiotherapy and psychology. The next generation of systems may support novel features, benefiting from technology advancement, to better address user needs. As a result of its hierarchical structure, the taxonomy is flexible and provides easy adjustment to description of new system properties. New categories and properties can be easily added depending on

TABLE II

CLASSIFICATION OF PERVASIVE HEALTHCARE SYSTEMS

	Activity Compass	**OrientingTool**	**Tremor Control System**	**In-home elder healthcare system**	**Millennium Home**
Body functions	Global mental functions	Specific mental functions	Movement functions	Specific mental functions	Mental functions
Activities and participation	Walking and moving	General tasks and demands	Using communication devices and techniques	Looking after one's health	Changing and maintaining body position, Looking after one's health, Domestic Life
Support	Participant	Participant	Participant	Participant, Caregiver	Participant, Caregiver, Vicinity
Source of data for sensor	Participant	Participant, Time	Participant	Participant, Object, Time	Participant, Object, Environment, Time
Target of actuator's action	Participant	Participant	Participant	Participant, Data storage	Participant, Caregiver, Object, Data storage
Environment	Unbounded (PDA)	Unbounded, House, Building (PDA)	Room (computer)	Room (portable pad)	House
Products and technology	Indoor and outdoor mobility and transportation - Guide	Use in daily living - Reminder	Communication - Assistant	Protection - Reminder Protection - Monitor	Use in daily living - Assistant, Protection - Monitor

system characteristics. For that reason, our taxonomy may be extended for novel system properties without reorganisation of its existing structure.

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REFERENCES

[1] D. C. Deborah Estrin, K. Pister, and G. Sukhatme, "Connecting the physical world with pervasive networks," *Pervasive Computing, IEEE*, vol. 1, no. 1, pp. 59–69, 2002.

[2] (2004) The Aware Home. Georgia Institute of Technology. [Online]. Available: http://www.awarehome.gatech.edu/

[3] M. Perry, A. Dowdall, L. Lines, and K. Hone, "Multimodal and ubiquitous computing systems: Supporting independent-living older users," *IEEE Trans. Inform. Technol. Biomed.*, vol. 8, no. 3, pp. 258–270, Sept. 2004.

[4] M. E. Pollack, L. Brown, D. Colbry, C. E. McCarthy, C. Orosz, B. Peintner, S. Ramakrishnan, and I. Tsamardinos, "Autominder: An intelligent cognitive orthotic system for people with memory impairment," *Robotics and Autonomous Systems*, vol. 44, no. 3-4, pp. 273–282, 2003.

[5] F. Axisa, P. M. Schmitt, C. Gehin, G. Delhomme, E. McAdams, and A. Dittmar, "Flexible technologies and smart clothing for citizen medicine, home healthcare, and disease prevention," *IEEE Trans. Inform. Technol. Biomed.*, vol. 9, no. 3, pp. 325–336, Sept. 2005.

[6] H. Kautz, L. Arnstein, G. Borriello, O. Etzioni, and D. Fox, "An overview of the assisted cognition project," in *AAAI'02: Proceedings of workshop on Automation as Caregiver: The Role of Intelligent Technology in Elder Care*, July 2002.

[7] R. Jafari, F. Dabiri, P. Brisk, and M. Sarrafzadeh, "Adaptive and fault tolerant medical vest for life-critical medical monitoring," in *SAC '05: Proceedings of the 2005 ACM symposium on Applied computing*. ACM Press, Mar. 2005, pp. 272–279.

[8] M. K. Holden, "Virtual environments for motor rehabilitation: Review," *Cyberpsychology & behavior*, vol. 8, no. 3, pp. 187–211, 2005.

[9] *International Classification of Functioning, Disability and Health: ICF*. Geneva: WHO, 2001.

[10] S. Tilak, N. B. Abu-Ghazaleh, and W. Heinzelman, "A taxonomy of wireless micro-sensor network models," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 6, no. 2, pp. 28–36, 2002.

[11] S. Cheekiralla and D. Engels, "A functional taxonomy of wireless sensor network devices," in *Second IEEE/CreateNet Workshop on Broadband Advanced Sensor Networks (BaseNetS 2005)*, The University of Nottingham, Oct. 2005.

[12] *Technical aids for persons with disabilities: Classification and terminology*, ISO Std. ISO/FDIS 9999, 2002.

[13] WHO Family of International Classifications (ICF), "Newsletter," 2004. [Online]. Available: http://www.rivm.nl/who-fic/newsletter/newsletter2004-1.pdf

[14] L. Ho, M. Moh, Z. Walker, T. Hamada, and C.-F. Su, "A prototype on RFID and sensor networks for elder healthcare: Progress report," in *E-WIND '05: Proceeding of the 2005 ACM SIGCOMM workshop on Experimental approaches to wireless network design and analysis*. ACM Press, Aug. 2005, pp. 70–75.

[15] M. Wu, R. Baecker, and B. Richards, "Participatory design of an orientation aid for amnesics," in *CHI '05: Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM Press, Apr. 2005, pp. 511–520.

[16] K. Z. Haigh and L. M. Kiff, "The independent lifestyle assistant (I.L.S.A.): AI lessons learned," in *IAAI'04: Proceedings of Innovative Applications of Artificial Intelligence Conference*. American Association for Artificial Intelligence, July 2004, pp. 852–857.

[17] S. Consolvo, P. Roessler, and B. E. Shelton, "The CareNet display: Lessons learned from an in home evaluation of an ambient display," in *Lecture Notes in Computer Science - UbiComp 2004: Proceedings*

of 6th International Conference on Ubiquitous Computing, vol. 3205. Springer Berlin/Heidelberg, Sept. 2004, pp. 1–17.

[18] G. C. de Silva, B. Oh, T. Yamasaki, and K. Aizawa, “Experience retrieval in a ubiquitous home,” in *CARPE ’05: Proceedings of the 2nd ACM workshop on Continuous archival and retrieval of personal experiences*. ACM Press, 2005, pp. 35–44.

[19] P. Feys, A. Romberg, J. Ruutiainen, A. Davies-Smith, R. Jones, C. A. Avizzano, M. Bergamasco, and P. Ketelaer, “Assistive technology to improve PC interaction for people with intention tremor,” *Journal of Rehabilitation Research and Development*, vol. 38, no. 2, p. 235243, 2001.

[20] J. Loh, T. Schietecat, T. F. Kwok, L. Lindeboom, and P. Joore, “Technology applied to address difficulties of alzheimer patients and their partners,” in *Proceedings of the conference on Dutch directions in HCI*. ACM Press, June 2004.