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Managing Chronic Conditions Using Wireless Sensor Networks

Raluca MARIN-PERIANU[a], Juan JIMENEZ GARCIA[a], Stephan BOSCH[a], Mihai MARIN-PERIANU[b] and Paul HAVINGA[a,*]
[a] *University of Twente, The Netherlands*
[b] *Inertia Technology B.V., The Netherlands*

Abstract. Physical activity, therapy and exercising are essential for the management of many chronic conditions. This is why human motion tracking for healthcare applications has received significant attention recently. In this chapter we describe the architecture in which we provide a person-centric healthcare solution for patients with chronic conditions based on the recent advances in wireless inertial sensing systems. We emphasize the role of the home as care environment, by providing real-time support to patients in order to monitor, self-manage and improve their physical condition according to their specific situation.

1. Introduction

In recent years, monitoring the level of daily human activity has gained interest for various medical and wellbeing applications. It has been shown that health condition and quality of life are directly influenced by the amount and intensity of daily physical activity [35]. This is particularly relevant to persons with chronic conditions, such as Chronic Obstructive Pulmonary Disease (COPD), asthma and diabetes [16]. The reason is that persons suffering from chronic conditions enter a vicious circle, in which being active causes discomfort, making them progressively more sedentary, and deteriorating their health. Monitoring the daily activity can stimulate people to perform exercises and to be more active in general by providing feedback and assistance to better manage the physical condition. Apart from medical applications, daily activity monitoring can also be useful for healthy users that want to assess and improve their overall fitness level. Activity monitoring systems can remind, stimulate and motivate people to be more active, especially when used within groups with a competitive nature.

Within the Ambient Assisted Living (AAL) Joint Programme, the IS-ACTIVE project [11] develops a person-centric healthcare solution for persons with chronic conditions – especially elderly people – based on the latest advances in the field of Wireless Sensor Networks (WSNs). WSNs provide distributed sensing and intelligent recognition of activities and situations, as well as simple and ubiquitous feedback modalities, thus taking complex computer interaction out of the loop and breaking the digital divide [17,18]. The home becomes the main care environment, where the users can continuously monitor, self-manage and improve their physical condition according to their specific situation. The IS-ACTIVE consortium designs, builds and tests systems that can be bought and used by the individuals, instead of being the property of health-

[*] Corresponding Author: Paul Havinga. E-mail: paul@havinga.org.

care institutions. IS-ACTIVE allows the shift of medical device technology into the mainstream consumer electronics market. This implies that there is a strong focus towards ease of use, integration and pricing.

The IS-ACTIVE system has two key drivers:

- *Paradigm shift in healthcare*. Population of Europe is ageing. The older the population, the higher is the frequency of chronic diseases. This poses an increasing burden on healthcare and social service systems and affects the quality of life by inducing both physical disabilities with frequent hospitalizations and social impairment. There is a need for a paradigm shift from the specialized care centers to the home as self-care environment. Persons with chronic conditions need to be continuously supported in their physical therapy, as the level of physical activity influences directly their status and progress.
- *Technology advances in wireless inertial sensing*. In recent years, miniaturized inertial sensors have become an increasingly popular solution for ambulatory human movement analysis [17]. Furthermore, recent advances in wireless communication and low-power chip design stimulated the development of pervasive technologies, such as wireless sensor and body area networks, foreseen to have a high impact in the wellness and healthcare domains.

Therefore, IS-ACTIVE has a combined solution: intelligent miniaturized inertial sensing systems with wireless communication capabilities. Such systems not only capture the motion parameters of the users, but also self-organize into an ad-hoc, dynamic wireless network, process data locally to extract relevant features, apply distributed inference to assess the physical activity and condition of the users, and eventually provide real-time feedback. The later aspect is of particular importance, as it can increase both the level of awareness and the motivation of following the physical therapy, thus contributing to a better education and self-management of chronic conditions.

IS-ACTIVE results are validated through field trials involving patients suffering from chronic obstructive pulmonary disease (COPD). COPD became the fourth cause of death worldwide due to an increase in smoking rates and demographic changes in many countries. Patients need to manage their chronic condition through extensive physical therapy. However, the physical therapy needs to be adapted to the situation of the patient and according to his/her progress. The field trials that will be carried out at three locations (in Norway, the Netherlands and Romania) will assess the added value of the IS-ACTIVE miniaturized wireless sensing system and reflect back how these objectives are met.

In this chapter we describe the objectives and the associated challenges, the specific innovations beyond state-of-the-art, the general architecture of the system including the various interaction modalities, the current project status and business opportunities.

2. State of the Art – COPD Treatment and Human Motion Tracking

Chronic diseases are the major cause of death and disability worldwide, accounting for 59% of the annual deaths and 46% of the global burden of disease [16,31]. In USA, 45% of the population suffers from at least one chronic condition and 26% from two or more chronic conditions. In 2007, USA spent \$1.7 trillion (75% of the total healthcare costs) on chronic conditions. Similar figures hold in Europe, for example in Denmark an estimated 70–80% of healthcare expenses are allocated to chronic conditions. In UK, 8 of the top 11 causes of hospital admissions are chronic conditions. In the central and eastern countries of the European Region, people die from chronic diseases at dramatically younger ages than in western Europe. Due to the overall trend of population ageing, the situation is to become only worse, with the number of co-morbidities increasing progressively with age and achieving higher levels among women.

One of the main factors accounting for almost 60% of the disease burden in Europe is physical inactivity. Our approach is to stimulate patients with chronic conditions to have more and better suited physical activities, through the use of simple to use, yet reliable and entertaining technology. For field trials, the target user group is represented by persons suffering from chronic obstructive pulmonary disease (COPD). COPD became the fourth cause of death worldwide due to an increase in smoking rates and demographic changes in many countries, and is estimated to become the third cause of death in 2020. COPD patients need to manage their chronic condition through extensive physical therapy. However, the physical therapy needs to be adapted to the situation of the patient and according to his/her progress.

Physical activity, therapy and exercising are essential for the management of many chronic conditions. In particular for COPD, a recent study that included approximately 2400 patients showed that regular physical activity reduces hospital admission and mortality [8]. The recommendation that COPD patients should be encouraged to maintain or increase their levels of regular physical activity should be considered in future COPD guidelines, since it is likely to result in a relevant public health benefit.

Therefore, human motion tracking for healthcare applications has received significant attention recently. The most important approaches can be summarized as follows:

- Non-visual tracking
  - Inertial and magnetic sensor based systems, such as MTx [34], G-Link [20], MotionStar [1], Liberty [22].
  - Ultrasonic systems, such as IS-600 Motion Tracker [10].
  - Electromyogram (EMG), such as Biofeedback [19].
  - Glove-based systems, such as CyberGlove [5], PowerGlove [23].
- Visual tracking
  - Marker-based tracking
    - Passive marker-based systems, such as Qualisys [25], VICON [30].
    - Active marker-based systems, such as CODA [4], Polaris [21].
  - Marker-free tracking
    - 2-D systems, such as [3,33].
    - 3-D systems, such as [12,28].
- Robot-aided tracking, such as MIT-MANUS [13], MIME [15], ARM Guide [26], HelpMate [7], Rutgers Ankle [2].

A number of clear limitations and drawbacks of these systems have been recognized in the related literature [35]:

- *High cost and complexity*. Current systems are specialized, utilize expensive, dedicated components and sensors, and require professionals for calibration and often even for operation.

- *Feedback in real-time is missing*, as data is usually processed offline on high-end platforms.
- *Current systems do not provide patient-oriented therapy* and hence cannot yet be directly used in home-based environments.
- *Size and usability*. Current systems are not compact and easy to apply/handle. This aspect is particularly important because patients are expected to have reduced movement abilities.
- *Poor performance in human-computer interface design*. From the practical point of view, an attractive interface will encourage users to carry out the physical therapy.

Starting from these points, we present the following innovations beyond state of the art:

- The ability of capturing motion parameters from a wireless network of relatively cheap and simple sensors.
- The feedback in real-time, by exploiting the distributed processing power available on sensor nodes and the wireless connections that can be established ad-hoc among sensors and the feedback devices.
- The possibility of assisting the patients continuously, in their own environment, instead of periodically, in specialized laboratories.
- The simplification in terms of usability due to the motion-based interfacing, especially with respect to elderly users (low affinity with technology, bad vision, etc.).
- The small scale factor, low-power and low-cost of this distributed solution compared to high-end systems, such as camera-based tracking systems.
- The link to daily objects, which can also be instrumented with wireless sensors, thus providing additional information on the patient condition, as well as leading to more natural or simpler interactions of disabled people with their environment.
- The ability of seamlessly integrating other physiological sensors to the same wireless sensor network system.

3. Architecture

Figure 1 presents the top-level view on the main architectural components taken into account.

We distinguish the following important building blocks:

- *Wireless sensors networks (WSNs)* – the core technology creating a pervasive environment around the user:
    - On-body sensors, such as inertial sensors (used for the analysis of user motions, activity monitoring and exercise coaching) and physiological sensors (used for checking safety limits of user's current condition). The on-body sensors form the Body Sensor Network (BSN).
    - Infrastructure sensors, such as environmental sensors (used for signaling possible adverse environmental conditions with respect to the user specific condition).

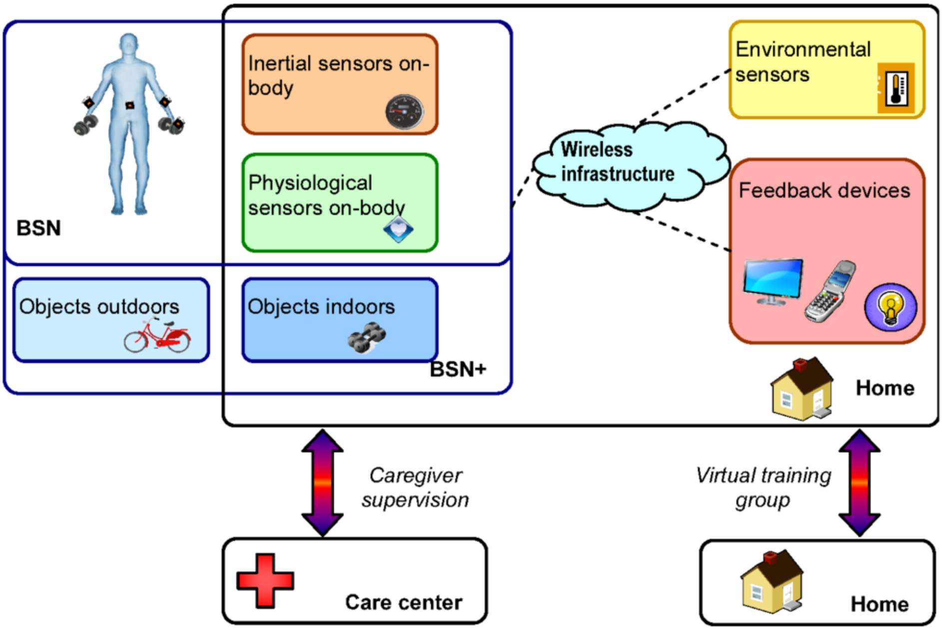

Figure 1. Block diagram of the IS-ACTIVE system architecture.

- *Technology-aided objects (TAOs)* – technology-enhanced daily objects (for indoor or outdoor usage) that contribute to monitoring and assessing the physical training performance of patients. They are mainly graspable objects with which the users carry out training task at home and outdoors. Together, the on-body sensors and TAOs form the Extended Body Sensor Network (BSN+).
- *Feedback devices* – covering all user interaction aspects, providing the information sensed and processed by the WSN in a simple and appealing way to the user. The main objective here is to enhance the user motivation for physical activity.

4. Wireless Sensors Networks (WSNs)

The objective of this section is to describe the hardware and software building blocks of sensor nodes used in the development of the wireless sensor network. Besides, this section includes information about the relevant networking protocols and also considers some of the critical networking issues.

4.1. Sensor Node

A sensor node is the main component of a wireless sensor network and it is capable of performing processing, storage and communication with other nodes in the network [6]. A sensor node has limited hardware resources, including the available power (usually a battery), therefore energy efficiency is an essential requirement for applications running on sensor nodes [9].

Figure 2. ProMove wireless inertial sensor node [24].

Since one of the main purposes of the system is motion sensing, the wireless sensor node developed in the project is a miniaturized platform – ProMove – that captures and wirelessly communicates full 3-D motion and orientation information and derived motion features through integrated accelerometer, gyroscope and compass sensors (see Fig. 2).

The access to the microcontroller, wireless transceivers and sensors is facilitated by a specific operating system, which is the interface responsible for coordination of activities and management of shared hardware and software resources.

4.2. Sensors Networking

A Wireless Sensor Network (WSN) is composed of sensor nodes that sense several environmental phenomena and form an ad-hoc network for the purpose of collaboratively processing and transmitting the data to the interested parties. A WSN is a self-organizing network that does not need user intervention for configuration or setting up routing paths. Therefore, WSNs can be used in virtually any environment, even in inhospitable terrain or where the physical placement is difficult [27].

Since WSNs differ largely from wireless networks, they require energy-preserving protocols and a suitable model to fit their dynamic topology [29]. Therefore, WSNs do not fully adhere to the ISO-OSI reference model [36].

Sensor nodes are the main building blocks of WSN applications and are mainly battery powered. Changing or recharging batteries at relatively short intervals is impractical and reduces the usability and reliability of these systems. Although the wireless communication standard IEEE 802.15.4 is a popular choice for WSNs due to its low power consumption, the constrained bandwidth utilization is an important problem for the performance of WSNs. Some applications, such as body sensor networks, require synchronized data sampling and communication at high data rates. Taking into account these considerations, the inertial sensor node features:

- Low-power, low-data rate IEEE 802.15.4 compatible wireless communication, for long term sensing and monitoring, e.g. for activity level monitoring applications.
- High-data rate, real-time motion capture networking protocol, for short term, detailed sensor data acquisition, e.g. for algorithm design and evaluation.
- Bluetooth interface for connectivity with off-the-shelf physiological sensors (e.g. heart rate and oxygen saturation) and feedback devices (e.g. smart phone).

Therefore, the ProMove sensor node represents a versatile hardware platform that can be used in all the development phases of the project: algorithm design, algorithm implementation and testing, integration with other sensors and feedback devices and experiments with end-users.

5. Interactive Devices

Interactive devices create a seamless relationship between the end-user's daily life and the sensor-based infrastructure. The latter comprises an invisible technology infrastructure for the patient. In order to incorporate this technology in the user daily life, interactive devices are required to bridge the functionalities of the system with the patient's routines and physical treatment. Interactive devices refer to all those devices with which the end-users interact in different ways to receive suitable and tailored feedback about their physical state and training progress. These devices monitor and evaluate patient's physical state in an unobtrusive way and provide feedback for physical training. They stimulate and encourage physical activity for COPD patients to explore self-monitoring of their physical condition, while improving social and emotional communication with other COPD patients, separated friends and caregivers. Special attention should be taken regarding the people's relationship to new technology and their technology literacy. For instance, it is commonly known that many elderly people are not familiar with technology, demanding a design of simple interfaces with emotional valuable interactions.

A general description about how the user interacts with these devices and what kind of feedback he/she would send and receive from them is depicted in. We categorize the interactive devices in the following way (see also Fig. 3):

- Technology Aided Objects (guidance and training coaching).
- On-Body Sensor devices (monitoring user's vital signs).
- Feedback Devices (communication with caregivers and final feedback).

In the following, we describe the characteristics of these devices and the different nature of the interaction with the user.

5.1. Technology Aided Objects (TAOs)

These objects comprise technology enhancements to monitor and assess the physical training performance of COPD patients. They are mainly graspable objects to coach and guide the patients with their training program (stretching, strengthening muscles, and breathing) at home and outdoors [18], encouraging physical activity and self-monitoring along with virtual training groups. They are meant to persuade COPD patients to follow daily routines and guide them to perform the suggested physical exercises in a correct way. Therefore, these devices provide low-level feedback in the form of immediate and short information while carrying out a physical exercise. It is important to create emotional attachments (trust and value) with playful and pleasurable interactions in order to guarantee daily and long usage. Examples of these devices include: daily objects, fitness equipment or outdoor devices (e.g. bicycle, walking stick) equipped with sensors.

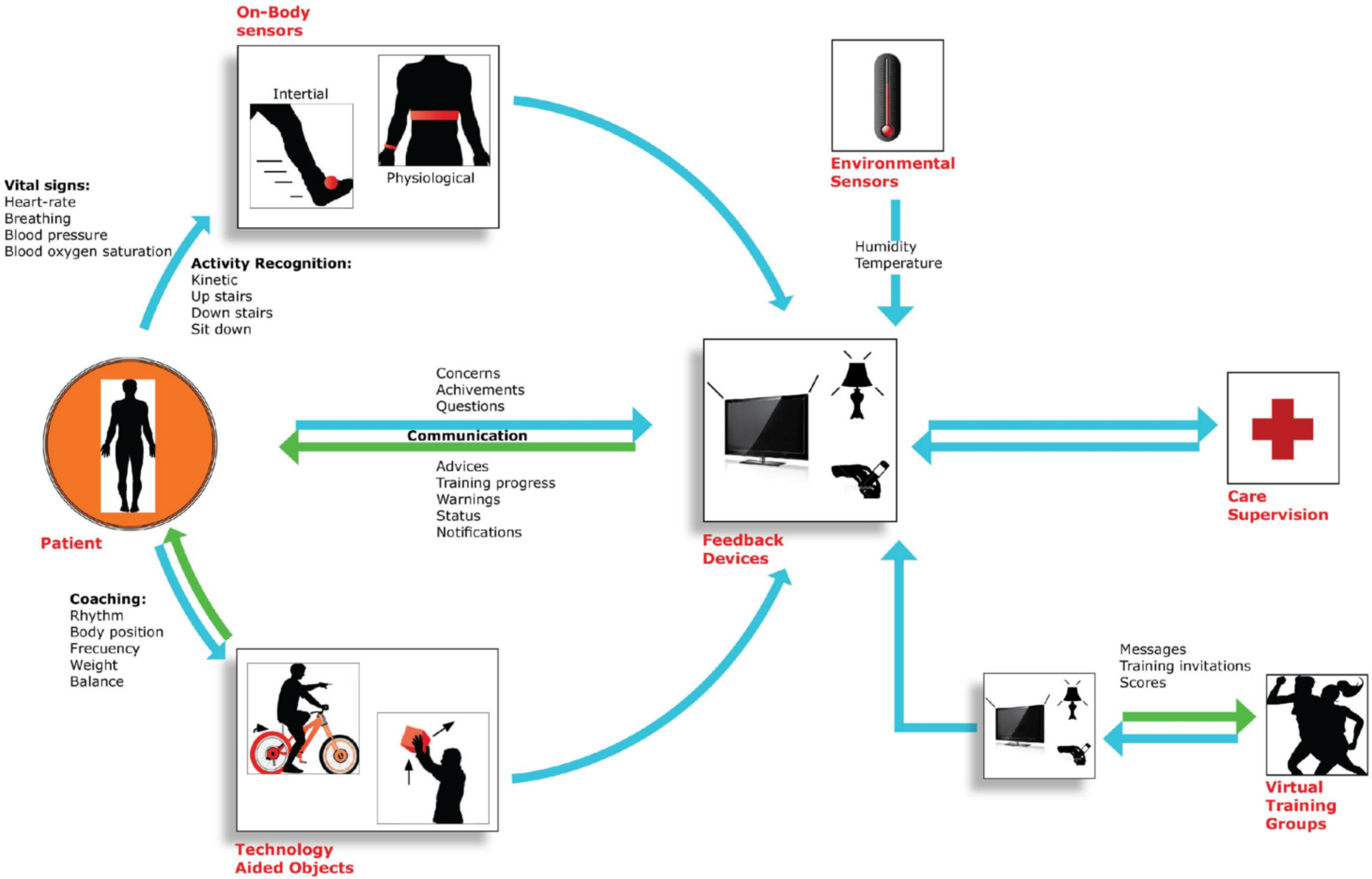

Figure 3. Overview of interactive devices.

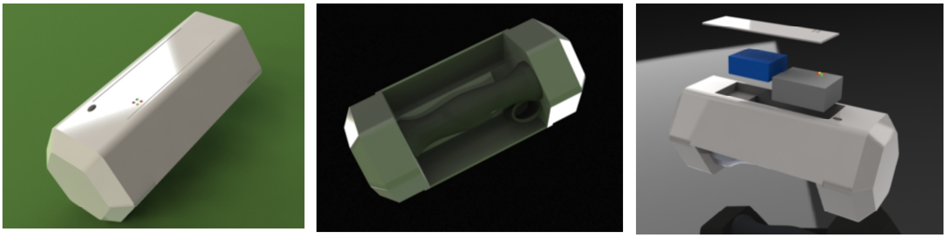

Figure 4. Dumbbell design for COPD patients.

We have designed a dumbbell to be used by COPD patients during their fitness exercises. This TAO incorporates a ProMove node and an oxygen saturation sensor for risk prevention (see Fig. 4).

5.2. On-Body Sensors

These devices are meant to monitor motion and vital signs of people (e.g. heartbeat, breathing, blood oxygen saturation). They are attached to the patient's body in an unobtrusive and comfortable way to wear for long periods. Although they do not have a special shape to interact with the user, and they aim to be invisible for the user and they should encourage patients to use the sensor daily. Therefore, the design should consider a non-invasive measurement of vital signs, simple structure and small size.

We have integrated off-the-shelf heart rate and oxygen sensors with the ProMove sensor node, in order to monitor the patient's status during exercising and thus prevent the risk of exacerbation.

5.3. Feedback Devices

These devices are targeted to manage a high-level feedback for the user in three different ways. Firstly, they are meant to communicate the information sent by the networked system to the user in a form of assessed information about the physical status or training program history. Secondly, they are intended to serve as a communication bridge between caregivers and the patient. Finally, they should enhance motivation for physical activity. In order to translate this feedback to the user, a multi-modal sensory interaction should be applied for these devices by displaying, receiving, accessing and sending information either with visual, auditory or tangible interfaces. For instance, there is a general idea that communicating feedback on already daily-life objects would enable intuitive and natural interactions, increasing the user-acceptance and truthfulness. These objects comprise those already embedded in user's home and life, such as TV, lamps, mobile and computer. It is also important to consider that these devices are meant to serve mainly elderly people, so that simplicity is required to accomplish the interaction with ease.

Feedback can be given when the patient is either inside or outside its home. This poses a question whether the feedback should be integrated into house appliances or it should be a portable device. For the initial experiments, we have chosen two such devices that together meet the requirements for both cases:

1. *Mobile phone.* Mobile phones can be used to access and facilitate the communication between patients, caregivers and friends remotely (outdoors and indoors), while providing feedback about physical status. A mobile phone can

be carried around by the patient and it is thus suitable for giving feedback on activities while the patient is on the move. A disadvantage is that the small screen and touch-based interface might not be suitable to COPD patients as they are unfamiliar with the technology. Elderly patients would find this particularly frustrating due to complex interfaces and usage difficulties, decreasing self-motivation making harder the acceptance of a new device. However, some target users seem to be familiar with integrated technologies (mobile and touch-based interfaces) into their daily life.

2. *Photo frame.* This is an integrated central device into people's daily life and patients are likely to be familiar with it. The photo frame offers an intuitive interface, making it a good opportunity to provide suitable feedback for in-home usage.

We are designing a friendly user interfaces for both mobile phones and photo frames that will be tested for usability and acceptance by COPD patients during the initial experiments. These experiments are expected give insight and motivation about the right feedback devices to be used with the targeted patients group.

6. Functional Overview

In accordance to the requirements analysis, the system architecture supports two main lines of functionality:

- Long-term, *daily physical activity monitoring and stimulation* using wireless sensor networks and intuitive, light-based feedback devices. The system monitors the amount of activity, type of activity, distribution of activity (daily activity pattern), activity intensity and certain types of activities like walking. Patients receive feedback about their activity in order to improve physical condition and quality of life.
- *Physical exercises – training and coaching* – specifically designed for COPD patients, using collaborative intelligence of wireless sensors and a stimulating gaming interface. Interaction and entertaining feedback are essential aspects for convincing patients to perform physical exercises that can be perceived as extremely tiring and tedious in their condition. Patients receive feedback about the right execution of the exercise and safety.

In the following we present the functional architectural overview, with respect to the two lines of functionality mentioned above. The reader is also referred for reference to the top-level architectural view from Fig. 1.

6.1. Activity Monitoring

The main characteristics of this function are the following:

- The primary technical concern is to ensure an optimal trade-off among performance (accuracy of activity monitoring), energy efficiency (for long-term operation of the system) and usability (simple to use, wear etc.).

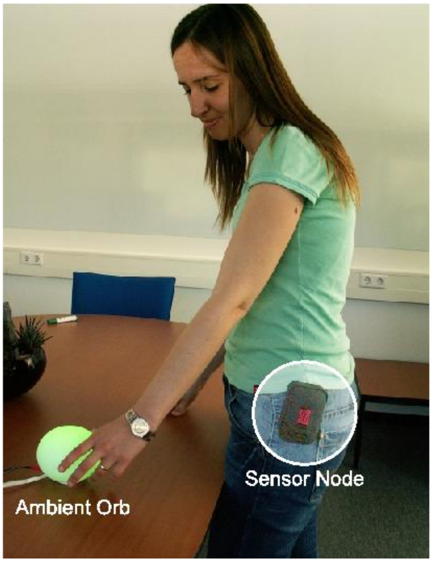

Figure 5. Initial prototype activity monitoring system.

- Because of energy efficiency and usability aspects, only a small subset of sensors from the BSN should be used. For simple activity monitoring, to assess the amount of activity for example, only one sensor node equipped with an accelerometer might be sufficient.
- Feedback should be provided in the form of summaries of long-term assessment of the user activity, but also on a daily basis.
- Summaries of the activity results are primarily targeted for the patient himself, but could be presented to caregivers as well.

Figure 5 shows the prototype activity monitoring system developed in IS-ACTIVE. The subject is wearing a ProMove node at the waist that estimates the energy expenditure by measuring the amount of motion a person performs during daily life. The ProMove node connects wirelessly to a LED-based lamp housed in a diffuse glass orb. The orb glows towards the activity level represented as a color between red and green, where red signifies that the subject was not sufficiently active, while green indicates that the subject has performed enough physical activity during the present day.

6.2. Exercise Coaching

The main characteristics of this function are the following:

- The primary technical concern is to provide accurate interpretation of the user's motions, along with motivating coaching during exercising. Energy efficiency is not a major concern due to the relatively short duration of the exercises.
- The BSN plus TAOs are involved to create a sensor-enhanced exercising experience to the user. Multi-source, multi-type sensor information is needed for accurate tracking of user motion. Additionally, physiological sensors should be in the loop, in order to ensure the safety limits of user's capabilities.

Figure 6. Gaming as exercise coaching.

- Feedback should be provided in a way that stimulates the correct and complete execution of the training exercises.
- The connection with the care center is less relevant. Possibly overall metrics characterizing the performance during training could be reported to the care giver for post-analysis.

Figure 6 shows a prototype game developed. This game is meant to stimulate patients to do exercises with a dumbbell. The up-down movement is detected by the ProMove sensor node attached to a regular dumbbell or embedded in the customized dumbbell presented in Section 5.1. The submarine goes up and down following the movement of the patient's arm and scores points by going through a sinusoidal arrangement of air bubbles. Oxygen saturation readings help prevent the risk of exacerbation: when the oxygen level reaches a certain threshold, the game stops and advises the user to take a break.

7. The Business Perspective

The project consortium aims to valorize the knowledge achieved and the technology developed concerning telemonitoring and coaching of COPD patients and to translate this knowledge into use in daily practice. Pilot programs will be first set up in the three countries involved (The Netherlands, Norway and Romania) to address the adoption of the technology into the COPD treatment program, the impact on the healthcare processes and health status of the patients. Health outcome will be assessed and changes in the health care process compared to the traditional treatment. In addition, privacy [14], patient satisfaction and compliance will be taken into account. If successful, parties with a proven track record in telemedicine service development and COPD care could realize the deployment.

Figure 7 shows the business chain that we foresee for the commercialization of the IS-ACTIVE system. The project partners generate the know-how, technology and validation means. The end users are not only the COPD patients, but they are also represented by family, insurance companies or housing companies. A third-party service provider is necessary for the installation, helpdesk and alarming towards the care center and family.

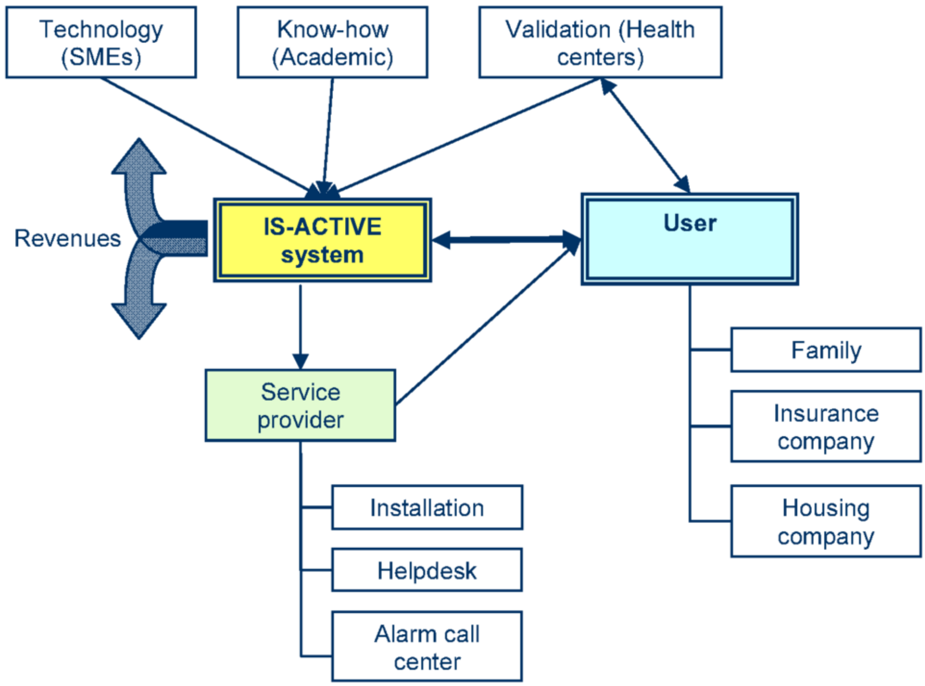

Figure 7. The business chain.

8. Conclusions

This chapter presented an architecture for monitoring, coaching, and stimulating patients with chronicle deceases. We emphasize the role of the home as care environment, by providing real-time support to patients in order to monitor, self-manage and improve their physical condition according to their specific situation.

The use of wireless sensor networking system provide distributed sensing and intelligent recognition of activities and situations, as well as simple and ubiquitous feedback modalities, thus taking complex computer interaction out of the loop and breaking the digital divide. The home becomes the main care environment, where the users can continuously monitor, self-manage and improve their physical condition according to their specific situation.

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