

HealthNet: A System for Mobile and Wearable Health Information Management

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ABSTRACT

Medical health care is undergoing a significant change of paradigm. Moving health care from health centers to home environments poses new challenges for acquisition, management and mobile exchange of information. The HealthNet project at RWTH Aachen University has developed a prototype which addresses these new challenges: a Body Sensor Network (BSN) collects information about the vital functions of a patient while she is in her home environment; the integration of smart textile sensors increases the acceptability of such technology; mobile communication and data management enables the exchange of health data between patients and doctors; data stream mining techniques tuned for mobile devices provide immediate feedback of the collected data to the user; and finally, advanced security and privacy features increase user acceptance and cope with legal requirements. This paper summarizes the challenges and achievements in the development of this prototype.

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Keywords

Health Information Management, Data Acquisition, Data Analysis, Body Sensor Network

1. INTRODUCTION

The demographic change with a growing population of elderly people and the associated increase of health care related expenses require new models for health care management. Moreover, there is a growing group of health-aware people that would like to take more personal responsibility for their own health, e.g., by monitoring their vital parameters during sport activities. New innovative technologies are necessary to fulfill these new requirements. Mobile and remote health monitoring has demonstrated positive influence on patients disease courses, especially for chronic diseases [20, 13], and promises high cost reductions [16]. While various systems have been proposed to measure the physiological state of mobile users, most of these systems are restricted to a certain set of sensors, or can monitor only a few vital parameters [6].

In this paper, we describe an extendable and flexible monitoring system for the case study of physiological state monitoring of runners. The system has been developed in the context of the HealthNet project [14]¹, which addresses interdisciplinary challenges such as sensor network design, manufacturing of smart textiles, information exchange, data mining, security and privacy, and mobile communication. The HealthNet project is part of the UMIC Research Cluster at RWTH Aachen University which focuses at Ultra high-speed Mobile Information and Communication systems supporting the demands of future mobile applications and systems. In the prototype developed by the HealthNet project team, the vital functions of athletes (or patients) are monitored by a BSN (e.g., ECG, skin humidity / temperature, activity) which are partly integrated into textiles. These sensors produce data streams that are integrated, consolidated, and aggregated in a device which acts as a peer in a network. Other trusted participants in the network are, for example, other runners or trainers who want to observe the performance of a runner. In a medical scenario, other peers in the network might be doctors or nursing staff who monitor the state of a patient while (s)he is at home. Furthermore, data can be stored in a server system for long-term monitoring and analysis. An intensive monitoring of vital parameters of patients is especially important after they have

¹<http://dbis.rwth-aachen.de/cms/projects/UMIC/healthnet>

been released from hospital. Changes in environment and medication often result in expensive re-hospitalizations of patients which could be avoided by more detailed observation of vital parameters [10]. Thus, both scenarios (sports and medicine) share a common basis; in addition, specific features like the identification of critical situations are relevant for both cases, although the definition of a critical situation is different. Nevertheless, the same techniques for data analysis can be applied. Furthermore, merging the acquired sensor data with additional information such as position, time, or weather conditions improves the expressiveness of pure health data and can lead to new insights.

Using a mobile communication infrastructure (e.g., UMTS, LTE, or Wi-Fi), mobile devices can communicate with each other such that peers can easily exchange health information. Especially, the mobility of patients is improved as detailed monitoring can now be performed at home: periodically or in the case of important events, the device sends the collected and pre-processed data to information systems maintaining patient health records (e.g., hospital information systems) which can be accessed by medical experts.

The main challenges in this project are

- the design and development of wireless medical sensors, which are able to monitor vital functions of a person,
- the integration of these sensors into textiles and development of electronic units as textiles (e.g., conductive paths) for unobtrusive and comfortable usage,
- the integration of the data collected by various sensors in one data stream, and
- the analysis, mining, and aggregation of the sensor data to detect emergency events, to reduce communication costs, and to predict near future.

We addressed these challenges in the HealthNet project and report in this paper our experiences in developing an integrated prototype. Section 2 first describes the requirements analysis which we have done with a group of athletes. An overview of the prototype system and its architecture is given in Section 3. The main components of the prototype are an intelligent T-Shirt with integrated conductive leads/electrodes (cf. Section 4) and a Body Sensor Network (IPANEMA, Integrated Posture and Activity NETWORK by Medit Aachen) which aggregates multiple data streams from a range of sensors (cf. Section 5). The data are transmitted wirelessly over a Bluetooth interface to a mobile device for visualization and a first lightweight analysis (cf. Section 6). A more detailed analysis of the data is done on a server which receives periodically or in case of peculiar events data from the mobile device. We also performed a case study in a running event of which we will briefly summarize the results in Section 8.

2. REQUIREMENTS AND USE CASES

For gathering of requirements, four active runners on semi-professional level were interviewed. All interviews were conducted by two interviewers with one interviewee. The interviews used a unique set of 14 questions regarding mobile health monitoring, and eight questions regarding a stationary counterpart. The questions especially targeted the usability of smart phones as supporting device in runs and

the information needs of the runners and the willingness to share information during training and competitions. All interviews took about one hour, and were recorded for post-interview analysis.

2.1 Participants

The interviewed runners are male, three between 20 and 25 years old, and one between 30 and 35 years old. All runners participate in competitions on national level. The disciplines range from 3000 meters steeplechase to marathon distance, and triathlon. All interviewed persons do intensive training between 5 and 15 sessions per week.

2.2 Information Requirements

2.2.1 Personal Information Sources

All interviewed persons consider their self-assessment as the most important source of information, which is even more reliable than any physiological measure. They stated to ignore measured high peaks of their pulse if feeling good, and also low measures if feeling bad. That means, that their subjective rating of their state is more important for them than an objective measurement. They treat many technologies as fun, which could be more interesting to increase motivation in mass sports.

2.2.2 Medical Information Sources

In addition to the self-assessment, all interviewed runners were interested in heart rate (they all measure it in training). The data could be used to trigger a notification if exceeding upper or falling below lower personal limits. Furthermore, the sportspersons consider breathing rate and oxygen absorption relevant to detect exhaustion in advance. Sweat analysis could lead to an estimation of water balance of the body, useful for reminding the runner to drink or to determine the amount of liquid to drink for convalescence after a training session. Determining the blood sugar level could signal a low sugar level or hunger knock². Last but not least, all interviewed runners had measured lactate in the past. It is probably the best indicator for the current personal fitness. Noticeably, none of the interviewed runners associated any value with blood pressure information, even if explicitly asked by the interviewers.

Most measurements listed above require settings incompatible with daily outside use. Some request tests in medical labs, some include in addition blood analysis (such as blood sugar level, lactate) which is not compatible with mobile use. All interviewed runners agreed that therefore it will be challenging or impossible to apply these measurements in their training sessions or competition.

2.2.3 Track, Time and other Information

Speed measurements have a strong influence on the running speed. All runners pointed out that speed measures from cars or bicycles are not usable because of the meaningless unit (mph, km/h) and low precision. They request measures of time needed for the last lap (on cycle tracks), the last 400 meters or the last 1000 meters (all preferable in a unit of minutes:seconds) to adjust their personal running speed accordingly.

²a completely run out of energy, also known as “bonk” or “hit the wall”

For uphill sections, the absolute distance and remaining distance of the uphill part are valuable for all interviewed runners. The gradient is less important because of the low absolute number.

Other information, like weather conditions, weather forecast or condition of the ground are important in preparation of training or competition; it is of no value while being on the move.

2.2.4 Personalization

All interviewed persons request methods for personalisation of the measurements and accompanied items, such as frequency, upper/lower border.

2.3 Mobile Monitoring

2.3.1 Use of Technology

All interviewed runners had applied technology for monitoring heart rate; all interviewed runners knew technology for gathering track data (i.e., GPS). None used other technology, like step counters or sensors in shoes. Only one person carries the mobile phone in training sessions, in a back pocket together with keys. They do their sports without listening to music.

All interviewed runners track heart rate in training, only two do the same in competitions. Two do not track the heart rate in competition mainly because of losing comfort, i.e., chest belt slipping out of place and making the runner feeling confined. The interviewed runners do not agree to carry any additional device. In competition, none of them would be willing to carry a mobile device.

2.3.2 Carrying a Mobile Device

Carrying a mobile device while doing sports is considered burdensome. There must be a reasonable benefit from doing so. It must not require any attention by the runner, it must not swing (e.g., on a neck strap), it must not disturb the rhythm of arms, legs or breathing (the latter nearly excludes speech interfaces). The device must be lightweight, small, waterproof and shock resistant. The touch-sensitive surface, if any, must come in a sweat resistant cover.

The shape and feeling of a watch was considered most appropriate, as applied in current monitoring systems for heart rate. It can be worn at one arm and operated with the hand of the other arm. If more functions are to be integrated, the only sensible way of carrying a larger mobile device seems to be a pocket at the arm. It supports a similar way to operate it using the hand of the arm not carrying the device.

2.3.3 Operating a Mobile Device

Operation of a 1-button-watch was considered sufficient; nevertheless the operation of buttons of a mobile device were considered to require too much attention and too fine granular movements for hand and finger. A mobile device at the arm can be similarly operated by touch on the display.

The interviewed persons see the problem with touching the display that it might get dirty and smeared by the runner's sweat, making checking current values from the display impossible. Because of disruption of rhythmic breathing, speech-based operation is only considered feasible for a few short commands.

2.4 Sharing of Information

2.4.1 Live-sharing

Live-sharing information with others is considered a minor issue by the interviewed runners. Together with personal trainers, post-processing (for long distance runs) and frequent analysis after smaller sessions (e.g., in interval training) was seen to be more important than live data transmission. One interviewee had the idea that the trainer might interrupt over-pacing of a runner in a hopeless intermediate state of a competition, especially if it is one in a row of competitions. All interviewed persons declined to lively share personal or medical information with other external persons like friends, training mates, online communities, or event organisers or competitors. It was only acceptable for notification in case of emergency.

To receive information from others, trainers and supporters call out time information and intermediate state of the competition to the runner on track. The interviewed runners think that receiving more information, e.g., about personal state of competitors, is rather distracting. One of the interviewed persons stated a value of knowing intermediate state of competition within the same age group, in particular if persons nearby are of the same or another group like the runner. Getting the positions of the team mates was considered not interesting, neither in training nor in competition.

As an open question, the interviewees brainstormed about other ideas for valuable live-sharing of information. As a result, it could be valuable for optimisation of the handover in relays, especially in long distance relays. It would be of value to the successor to know the personal health state of the predecessor in order to adjust warming and preparation phase. If the predecessor is in good shape, the estimated arrival time is earlier than if the person is in bad shape, influencing the point of time to start preparation.

2.4.2 Post-event sharing

After a training session or competition, the runners were open to share track and time data with team mates and online communities, which is already implemented by portals like <http://www.gpsies.com>.

2.5 Persistent Storage

Post-processing of the collected data is very important to all interviewed runners. They asked to file all information to a computer system for persistent storage. They all use a kind of training diary, two use already computer applications for this purpose.

2.5.1 Connecting with PC

The interviewed runners asked for easy connection with the PC, and easy to handle download.

2.5.2 Post-Processing

All interviewed runners do intensive performance analysis combining tracking data, time data, health information, and comments on personal feeling. If applicable they compare current data with past datasets for recurring events, competitions, tracks, or distances. The main goal of the analysis is identification of flaws in performance (absolute speed, endurance, power to go uphill) requesting updates of the training method and plan.

The triathlete analyses shifts in performance of the single disciplines, e.g., intensively training one discipline has contradictory influence on the performance in the other two.

One runner mentioned to use the post-processing also to estimate lifespan of used hardware, e.g., professional running shoes that loose suspension after 3000 km of use, demanding for replacement to prevent damage from tendons and ligaments.

2.6 Use Cases

Based on the requirements analysis, several use cases were identified which are described in this section. The use cases are grouped in four categories: Sensor management, mobile monitoring, sharing, and archiving.

2.6.1 *Managing Sensors*

The sensor managing use cases describe the setup, configuration and maintenance of the set of sensors delivering information to the system. The actor usually is the user. In addition, other persons or organizations might perform the use cases as well, e.g., an emergency doctor who adds a sensor after the user had an accident, or a physician who adjusts the upper border of a physiological parameter to raise notification earlier. The actor employs a plug-in / plug-off mechanism to add or remove sensors to the network; this should be as automatic as possible. The added sensors perform registration and de-registration at the controlling component of the sensor network. Configuration of the sensors should be also possible, so that user can adjust the properties of the sensor (e.g., sampling rate, sensor identifier, measure unit, data transmission rate) to his/her personal needs.

2.6.2 *Monitoring*

The monitoring use cases describe the use of a mobile system to monitor the health status. The user employs the system for observing specific parameters, being informed about the current status and alarming himself or another entity during a personal activity. The user can also turn off all monitoring and notification functions by muting the device.

2.6.3 *Sharing*

The group of sharing use cases describes the information exchange between all parts of the system with external entities (e.g., server or other users). It applies to sharing information while being mobile as well as sharing information from the other parts of the system like the archive. The group contains:

2.6.4 *Archiving*

The archiving use cases describe the use of and retrieval from a persistent storage. The user employs a stationary device (such as a laptop or desktop PC) to search for information of a specific type, date and time, activity, or value. The archiving use-cases are:

3. SYSTEM ARCHITECTURE

The HealthNet prototype is based on a BSN integrated into a textile platform (i.e., T-shirt) measuring the physiological state of a person. An overview of the system is illustrated in Fig. 1. A registry server manages the communication between different peers in the network. The sensor data is received by a smartphone via Bluetooth which sends the data to other peers in the network. Other peers in the network are an advanced data mining & analysis service or other trusted parties such as trainers and doctors.

In the current prototype, the BSN consists of an ECG sensor, a combined temperature/humidity sensor, two 3D acceleration sensors, and a master node. The master node collects the data from the individual sensors and sends it to the smartphone. Conductive yarn acts as electrodes as well as leads. The signals are received by the ECG sensor attached to the shirt. The sensor processes the ECG and infers the current heart rate from it.

On the smartphone, a mobile application integrates the health data with data measured by the phone, such as the current GPS position. The mobile application also visualizes, stores, and analyzes the data. If enabled by the user the integrated data is sent via UMTS or Wi-Fi (IEEE 802.11) to a registry server which distributes it to registered third parties, such as a trainer, a doctor, or a server analyzing the data. The architecture also allows sending feedback and results of the analysis of the data to the users smartphone.

4. TEXTILE PLATFORM

The state-of-the-art electrodes used for most medical applications are, for example, disposable electrodes glued onto the skin. These electrodes are coated with electrolyte-gel to improve the conductivity. The advantages of those electrodes are low contact impedance and a fixed position. However, they are not suitable for a continuous long-term measurement because the electrolyte-gel can dry and may also cause allergic reactions. Moreover, the wires between electrodes and the sensor exacerbate the handling for untrained users. To achieve the aim of a continuous and mobile monitoring system, another solution has to be found.

Textile electrodes could be a good alternative for the standard ones. They can be used for long-term measurements because they are not coated with electrolyte-gel. The yarn for the textile electrodes must possess high conductivity, good elastic behavior to assure a good skin conformance and it should be biocompatible due to the constant skin contact. Another advantage of textile electrodes is that these electrodes can be integrated into garments which lead to a very high mobility of the whole system and intuitive handling. Mobility can be further increased by using textile integrated conductive paths instead of cables. A reversible interface is necessary to remove the sensor node before washing. However, textile electrodes also have disadvantages: the contact impedance is higher and movement causes motion artifacts.

Suitable yarns matching all requirements mentioned above have been researched and tested. The best one was a silver-coated polyamide yarn. A circular foam padded textile electrode with a radius of 2.5 cm was used. In addition to the ECG electrodes, the same material was also used to manufacture the textile conductors (see Fig. 3). The textile conductors were applied to the outside of the T-shirt with metal push buttons to connect both electrodes and the sensor. Preliminary results with this T-Shirt show the suitability of textile electrodes for the application as ECG electrodes.

5. BODY SENSOR NETWORK

Body Sensor Networks (BSN) usually consist of a varying number and diverse types of sensors. They are wirelessly connected either to each other, called mesh network, or to a central master node, called star network. The acquired data is then transferred over wide area networks (WAN) to

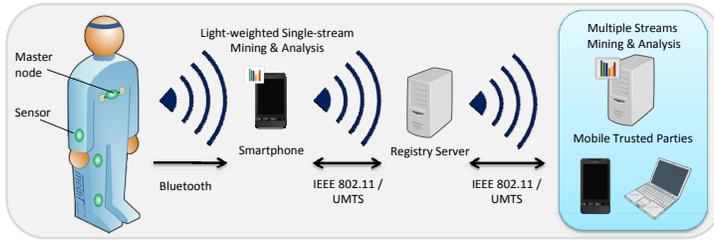


Figure 1: Overview of the system architecture

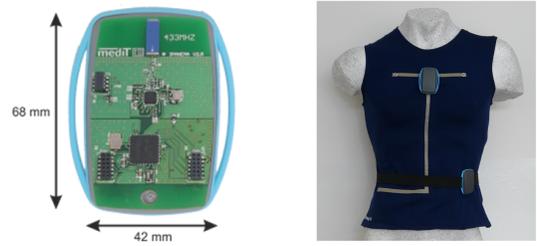


Figure 2: BSN node Figure 3: Sensor shirt

central data and health service providers for further processing. This section focuses on the challenges in developing the medical sensors, connecting them in a BSN, and processing the measured signals.

Bringing health status monitoring to personal health care environments presents a new set of challenges: devices have to be small, unobtrusive and easy to handle. Preferably, they need no or only minor interaction and are connected via wireless technology to the supervising medical professional or health care center.

The IPANEMA BSN is designed to be easily modified for different application scenarios, e.g., cardio-vascular monitoring or hydration status monitoring [11]. It is small (68 x 42 mm, see Fig. 2), light (30 g) and wireless enabled. A sensor node consists of a base board which includes a low power microprocessor (MCU, MSP430F1611, Texas Instruments), power management circuitry, and a low power radio transceiver (CC1101, Texas Instruments). Modularity is ensured by using a pair of connectors to attach different sensor extensions. Two connectors (Samtech Inc.) enable the use of digital (SPI, UART, I2C) sensors, five analog-to-digital converter inputs and three interrupt capable inputs. The MCU is running at 8 MHz with an additional precision 32.768 kHz crystal for the real time clock. It is powered by a lithium polymer battery which can be recharged over an on-board MicroUSB connector.

The sensors of the current prototype produce a raw data stream of about 14 kbit/s which is transmitted over a 433 MHz ISM band transceiver with a proprietary protocol.

The network is structured in a star topology. The leaves are formed by a flexible number of modules which can be equipped with different types of sensors. The sensor data is sent over-the-air to a central master module. The main tasks of the master node include network management, data transfer to a mobile device and creating time synchronization beacons for the sensor nodes.

6. MOBILE APPLICATION

The goal in the design of the architecture of the mobile application was to have a very flexible and extensible system. As explained before, the HealthNet project is not limited to a particular application domain, our solution should be applicable in a healthcare domain as well as in a sports domain. To allow easy customization and adaptation to new domains, we identified four main components for the mobile application on the smartphone (cf. Fig. 4).

The *HealthNet Controller* is the central unit for managing the set of active sensors, and notifying dependants if measures changed value or the composition of the network changed. The *Data Cache* stores recent sensor data in a

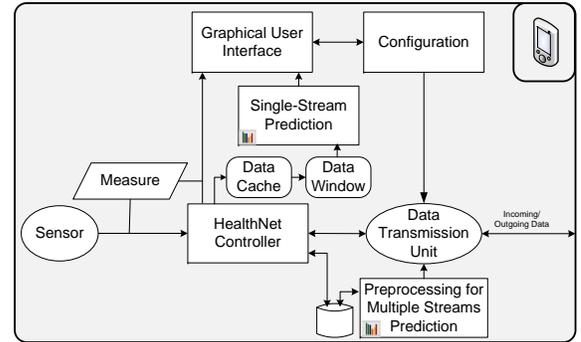


Figure 4: Architecture of the mobile application

Data Window such that a single-stream prediction over a short timeframe is possible. The windows are implemented as a circular data structure - if a window is full, the latest incoming data will flush the oldest data. Furthermore, the cache stores also all data (if desired by the user) such that the data can be uploaded to a server for detailed data mining and analysis later on.

The *Data Transmission Unit* (DTU) takes care of the information exchange among different stakeholders. Four methods of sending data to authorized entities have been implemented. Any external entity must prove eligibility to receive any data from the mobile application. The DTU supports three communication modes:

1. *Request-response*: an external entity requests information from the mobile application. The DTU retrieves the requested data from the cache and transmits the response. This is for example done when a trainer wants to see detailed data about a runner.
2. *Time-based submission*: A fixed interval after which a selected data set is sent, e.g., data is sent from the runner to a trainer only every 10 seconds to reduce required bandwidth and communication costs.
3. *Direct transmission*: The relevant data is transmitted directly to the receiver. This mode is used for audio feedback from a trainer to a runner.

Due to the modular design, peer mobile applications use roughly the same architecture, with the only difference that these applications receive data via the DTU and not from sensors.

On the user interface level, the data which is received from the sensors or other peers is managed according to the use cases as described in section 2.

6.1 Data Analysis

To get the maximum benefit of the HealthNet application the measured data has to be analyzed to detect critical situation or events, and to make a short term predictions. Data mining techniques in this context are restricted by two important constraints: (i) the data is a continuous stream and has to be analyzed in real-time; persistent storage and long time series of data are not available as in classical data mining tasks, (ii) the resources (CPU power, battery life, memory) of the mobile device are very limited.

To cope with the problem of limited resources, we developed: (i) an adaptive technique for anytime classification, which is capable of both, classifying under varying time and resource constraints, and incrementally learning from data streams to adapt to possible evolutions of the underlying data stream [15], (ii) and a novel in-network distributed sensor data clustering technique that efficiently aggregates similar sensor readings using coordinators [8].

Context prediction is an emerging topic in the field of data mining, e.g., predicting the location of mobile objects was a frequently tackled subtask of mobile context prediction in recent researches. For scenarios of managing health information of mobile persons, the prediction of the near future health status of persons is at least equally important to predicting their location. A first method for predicting the next health context of mobile persons equipped with body sensors and a mobile device has been developed and implemented [7]. The proposed PrefixSpan-based method searches for sequential patterns within multiple streaming inputs from the body sensors as well as other contextual streams that influence the health context.

Our main observation is: frequent sequential patterns appearing in rules containing multiple streams, are completely built using frequent patterns existing in each single stream. Thus, predicted values were directly presented to the user in the mobile application using a light-weighted resource-aware algorithm that was implemented locally on the user's mobile phone. More accurate predicted values were sent to the user from a multiple stream prediction algorithm which was implemented on a server using the preprocessed frequent patterns on each stream (cf. Fig. 4).

6.2 Security and Privacy

A rigorous evaluation of security and privacy risks was done, requirements were derived from it, and the implementation was developed accordingly [3]. The measured data is kept confidential at all times: during collection, in storage, and during transmission within and between all components of the system. To reduce the risk of data extortion from stolen devices, secure authentication methods are used both for wireless links as well as user interfaces on the devices themselves. Generally, data may only be read by persons authorized by the user. Finally, no more data than required for a given monitoring application shall be stored.

Confidentiality during data collection is achieved by using ZigBee AES-128 encryption between the sensor nodes and the master node, and Bluetooth encryption E0 is used between the master node and the smartphone. Confidentiality during data storage is achieved using AES-128 encryption on

the devices, so that no data can be recovered wrongfully by someone who has physical access to a device. During communication between trusted devices, we do not rely on the security mechanisms of the technologies used (e.g., UMTS, LTE, WLAN) because the data must not be revealed to the network operators, and wireless technologies such as UMTS, LTE, and WLAN typically only encrypt the air interface. Instead, all data transfers apply AES-128 encryption and message authentication codes on the application layer.

In wireless connections to trusted parties, all parties are identified using certificates with shared keys. The implementation of the encryption is transparent to the application as standard interfaces of the Android SDK are used to implement secure storage and communication. In addition, we found that the authentication and encryption mechanisms had no significant influence on battery life or performance of the handheld device.

7. RELATED WORK

The interest in mobile healthcare applications started with systems like [19, 12] supporting professionals (like physician, nurse, therapist, or midwives) to enter, receive and exchange information about their patients. Systems for professional users in hospitals like [2] considered specific design aspects to support local mobility in the hospital by interconnecting PDA, laptop and desktop computers. Examples of systems for non-professional users are the self-monitoring application for overweight people [22], alcohol consumption monitor [4], or dietary advisor [9]. The results of these studies point to a high degree of monitoring by those using a mobile monitoring device compared to other monitors. In difference to the aim of the HealthNet project, these systems are not equipped for continuously monitoring vital parameter in silent mode.

7.1 Textile Sensor Platforms

A reasonable idea to integrate real-time monitoring into daily life activities are the application of wearable or textile sensor platforms. This section therefore reviews the integration of sensors into garments, such as sport shirts or similar. In [5] two types of textile sensor platforms are distinguished: while *textile sensors* are realized by special yarns, *non-textile* or *textile-integrable* sensors are singular units which are applied to the garment, e.g., printed onto the textile. The advantage of textile sensors is that these can be produced in one manufacturing process [17]. A disadvantage is that current technologies for textile sensors have to be moistened to deliver acceptable results [5].

To integrate multiple vital parameters into one textile platform, several sensors are combined to form a sensor network. Often, a master component controls the network and centralizes data acquisition, short-term storage and transmission. These can be realized either wired or wireless.

7.2 Textile-based Monitoring Applications

The MyHeart-project³ led by Philips was dedicated to the prevention, diagnosis and therapy of cardiovascular diseases. The monitoring is based on sensors integrated into daily life textiles, such as undergarment. A sensor shirt has been

³<http://www.hitech-projects.com/euprojects/myheart/>

developed using conductive and piezoresistive yarn for monitoring of heart (ECG) and respiratory activity (impedance pneumography), core and skin temperature with non-textile sensors and an accelerometer [1]. The shirt has been used for monitoring during outdoor activities and at home. A proprietary user device or PDA is used for interaction [21].

The respiratory sensing technology was also used in the Wealthy project⁴ [18, 17]. For the data processing and transmission a relatively heavy and big Portable Patient Unit (250g) was connected with the sensors by wires. The data is transmitted from the PPU via GPRS to a central system analysing and visualizing the data.

A project that supports medical treatment and behaviour of elderly people suffering from cardio-vascular disease is described in [23]. The system comprises a front worn array of body sensors, a user interaction system for a PDA for displaying information and entering simple answers and a back-end system for professionals analysing data and providing feedback.

7.3 Products for Sports Monitoring

Commercial products are available on the market in particular to support ambitious sports(wo)men. The products do not aim on sophisticated measuring medical data. Usually, it is considered sufficient to provide heart rate and calories burned, and location and time related information. The often use wrist or chest bands.

A large set of wrist-mounted computers is available for example from Polar, ranging from low-end technology for beginners to high-end systems for professionals like the RS800⁵. They receive body signals from chest straps, display and store the information on the watch, and allow for downloading and post-processing with the personal computer. A similar system is the Garmin Forerunner⁶. It monitors time, distance, pace, heart rate and calories burned. As Garmin's unique selling proposition, it additionally tracks the position of the sportsperson by the use of a high-sensitive GPS receiver built into the wrist watch. The GPS antenna is partially integrated into the watchstrap. The heart rate is measured by the use of a chest strap. The system supports different profiles, e.g. for swimming, cycling, and running of triathlons.

A more sophisticated system is the adidas miCoach⁷. It is an integrated system to plan, work-out, and analyse personal training. As the main part of the system, it combines three components to support the work-out: an auditive display (miCoach Pacer) for heart rate measures, speed and distance which reacts to the speed; a bundle of a chest belt measuring heart rate and a wristwatch (miCoach Zone); an application running on the user's mobile phone for coaching (miCoach Mobile).

As a main advantage, the textile strap for monitoring the heart rate can be replaced by two different bra's (adidas supernova glide/sequence bra) or a shirt (adidas supernova cardio shirt). Nike+⁸ is a training system similar to miCoach developed by Nike and Apple. The main differences to miCoach is that Nike+ combines the features from Nike's

running shoes with an integrated step counter (with the drawback of getting depended on the Nike's brand), and that it uses the iPod instead of a mobile phone (with the same drawback of dependency).

8. CONCLUSIONS AND LESSONS LEARNED

We implemented an end-to-end prototype for a runner scenario (training and competition mode) with one or more runners and a trainer. Case studies with the implemented prototype have been conducted during the Lousberglauf 2011 & 2012 (a local running event in Aachen with about 2000 participants). A team of five runners has been equipped with the sensors and smartphones. In addition, a trainer monitored the performance of the runners using also a smartphone. Data communication and management did not cause any problems; the trainer could always see the position and vital parameters of the runners. Due to excessive motion artifacts during running, we used standard electrodes for the run. In the meanwhile, we did some additional measurements with a new version of the textile electrodes in a lab environment on a treadmill which gave better results. We also improved the algorithm for inferring the heart rate from the raw ECG data, such that it is less sensitive to movement artifacts. This improved the data quality in the second case study in 2012, but the data quality is still too low for deriving health-related advices.

We have shown in this project that health monitoring using mobile wearable sensor networks is feasible. Data management and analysis can be done in real-time although the data is coming at a high frequency. Security and privacy issues have been addressed by implementing suitable encryption and authentication mechanisms into the application. In another related project (Nanoelectronics for Mobile AAL-Systems⁹), a similar approach for data management has been developed in the context of Ambient Assisted Living (AAL). Some results (e.g., the architecture of the mobile application in Fig. 4) have been applied also in this project.

However, we have seen that with the current technology, problems like data management, analysis, security, and privacy can be solved as mobile devices are powerful enough in terms of CPU and communication bandwidth. The real challenges are at the two ends of the data processing flow: firstly, the sensor data must have *very high* quality to be useful in any kind of application (for sportspeople or patients), false alarms will be annoying, missed alarms might be fatal; secondly, the potential users have to be convinced about the usefulness of such technology. In our interviews, the sportspeople were sceptic about the benefit of such an application. The same applies also to elderly people who might be even more reluctant in wearing any device that monitors them.

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9. REFERENCES

- [1] O. Amft and J. Habetha. Smart medical textiles for monitoring patients with heart conditions. In *Smart*

⁹<http://www.mas-aal.eu/>

⁴<http://www.wealthy-ist.com>

⁵http://www.polar.fi/en/products/maximize_performance/running_multisport/RS800CX

⁶<http://www8.garmin.com/marathon/forerunner/>

⁷<http://www.micoach.samsungmobile.com/>

⁸<http://nikerunning.nike.com/>

- textiles for medicine and healthcare: Materials, systems and applications*. Woodhead Publishing Ltd., 2007.
- [2] J. Bardram, T. A. K. Kjær, and C. Nielsen. Supporting local mobility in healthcare by application roaming among heterogeneous devices. In L. Chittaro, editor, *Proc. ACM MobileHCI'03*, volume 2795 of *Lecture Notes in Computer Science*, pages 161–176. Springer, 2003.
 - [3] J. Barnickel, H. Karahan, and U. Meyer. Security and privacy for mobile electronic health monitoring and recording systems. In *IEEE International WoWMoM Workshop on Interdisciplinary Research on E-Health Services and Systems*, pages 1–6, 2010.
 - [4] R. L. Collins, T. B. Kashdan, and G. Gollnisch. The feasibility of using cellular phones to collect ecological momentary assessment data: Application to alcohol consumption. *Experimental and Clinical Psychopharmacology*, 11(1):73 – 78, 2003.
 - [5] A. Ehrmann, E. Flacke, A. Brücken, and A. Büsgen. Intelligent umgarnt. *Textile Sensorik. Physik in unserer Zeit*, 41(6):282–286, 2010.
 - [6] Y. Hao and R. Foster. Wireless body sensor networks for health-monitoring applications. *Physiological Measurement*, 29:R27, 2008.
 - [7] M. Hassani and T. Seidl. Towards a mobile health context prediction: Sequential pattern mining in multiple streams. In *Proc. Intl. Workshop on Managing Health Information in Mobile Applications (HIMoA)*, pages 55–57, 2011.
 - [8] M. Hassani and T. Seidl. Resource-aware distributed clustering of drifting sensor data streams. In *Proc. 4th Intl. Conf. on Networked Digital Technologies (NDT)*, 2012.
 - [9] S. Intille. Just-in-time technology to encourage incremental, dietary behavior change. In *Proc. AMIA '03*, page 874. Wiley, 2003.
 - [10] V. Jones, V. Gay, and P. Leijdekkers. Body sensor networks for mobile health monitoring: Experience in europe and australia. In *Proc. Intl. Conf. Digital Society (ICDS)*, pages 204 –209, 2010.
 - [11] S. Kim, L. Beckmann, M. Pistor, L. Cousin, M. Walter, and S. Leonhardt. A versatile body sensor network for health care applications. In *Proc. Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP)*, pages 175 –180, 2009.
 - [12] J. Kjeldskov and M. B. Skov. Supporting work activities in healthcare by mobile electronic patient records. In M. Masoodian, S. Jones, and B. Rogers, editors, *Computer Human Interaction*, volume 3101 of *Lecture Notes in Computer Science*, pages 191–200. Springer Berlin / Heidelberg, 2004.
 - [13] C. Klersy, A. D. Silvestri, G. Gabutti, F. Regoli, and A. Auricchio. A meta-analysis of remote monitoring of heart failure patients. *J. American College of Cardiology*, 54(18), 2009.
 - [14] P. Kranen, D. Kensche, S. Kim, N. Zimmermann, E. Müller, C. Quix, X. Li, T. Gries, T. Seidl, M. Jarke, and S. Leonhardt. Mobile mining and information management in healthnet scenarios. In *Proc. Conf. on Mobile Data Management (MDM)*, pages 215–216. IEEE, 2008.
 - [15] P. Kranen, E. Müller, I. Assent, R. Krieger, and T. Seidl. Incremental learning of medical data for multi-step patient health classification. In C. Plant and C. Bhm, editors, *Database Technology for Life Sciences and Medicine*, pages 321–344. World Scientific Publishing, 2010.
 - [16] R. Litan. Vital signs via broadband: Remote health monitoring transmits savings, enhances lives. Technical report, Better Health Care Together, 2008.
 - [17] M. Pacelli, G. Loriga, N. Taccini, and R. Paradiso. Sensing fabrics for monitoring physiological and biomechanical variables: E-textile solutions. In *Proc. of 3rd IEEE/EMBS Intl. Summer School on Medical Devices and Biosensors*, pages 1–4. IEEE, 2007.
 - [18] R. Paradiso and D. De Rossi. Advances in textile technologies for unobtrusive monitoring of vital parameters and movements. In *Proc. EMBC'06*, pages 392–395. IEEE, 2006.
 - [19] J. Pollard, S. Rohman, and M. Fry. A web-based mobile medical monitoring system. In *Proc. Intl. Workshop on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications*, pages 32 –35, 2001.
 - [20] J. Riley and M. Cowie. A clinical perspective on remote monitoring of chronic disease. *Eurohealth*, 5(1), 2009.
 - [21] R. Schmidt, J. Habetha, and M. Harris. Myheart - fighting cardio-vascular diseases by prevention and early diagnosis. In L. Azevedo and A. R. Londral, editors, *HEALTHINF (1)*, pages 296–300, 2008.
 - [22] C. C. Tsai, G. Lee, F. Raab, G. J. Norman, T. Sohn, W. G. Griswold, and K. Patrick. Usability and feasibility of PmEB: a mobile phone application for monitoring real time caloric balance. *Mob. Netw. Appl.*, 12:173–184, March 2007.
 - [23] E. Villalba, M. Arredondo, A. Moreno, D. Salvi, and S. Guillen. User interaction design and development of a heart failure management system based on wearable and information technologies. In *Proc. EMBC'06*, pages 400 –403, 2006.