Sensors for health-related parameters and data fusion approaches

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Abstract: Living a long lasting self-dependent and self-determined life is not a mere selfish aim, but becomes an economical need in our ageing societies. Knowledge about the current state of health and personal risks is necessary for informed and healthy decisions in every day life. Due to recent developments health enabling technologies are on the horizon allowing everyone to access one's own personal state of health along with associated risks and recommendations as well as reminders for behavioural changes. Increase of computational power along with the miniaturisation of electronic components and new developments in sensor technology allow for the ubiquitous deployment of sensors for health related parameters. Based on literature reviews and experiences from ongoing projects a categorization of sensors for health-related parameters is provided. Examples for the combination of sensors to monitor an individual state of health based on relevant diseases are presented. The problems arising with the expected amounts of data are discussed and data stream management systems are introduced as a possible way to address the problem. The growing field of sensor networks for health related parameters needs to address the problem of configurable and adaptable analysis of resulting data, preferable in a distributed fashion.

1 Introduction and motivation

The assessment of a detailed state of health or an individual's personal risk profile nowadays requires a trained physician. Based on her senses she constructs a mental image of her patient. To safeguard this image she augments her senses with biomedical technologies like lab-tests or ultrasound imaging providing further information. These technologies help to make the patient and his physical structure and physiological processes more transparent. Transparency can be reached on macroscopic, microscopic or molecular level. It can regard structure (anatomy), function (physiology) as well as biochemistry and terminology. Medical tests are performed to prove or invalidate hypotheses arising from the knowledge gained so far. Though there is information technology at hand to support this effort, an experienced and sometimes specialized physician is needed to interpret and combine the measured data to a virtual reproduction of the patient. Due to this limiting factor, the burden for the patient, and the costs of available systems only unavoidable measurements are performed. Therefore information about the health state of a patient consists of unconnected snapshots or short episodes in time.

A current trend in sensor technology is the construction of devices to be used by the patients. The term coined for it is *personal health* with its acronym (pHealth). Everyone will be able to monitor relevant health parameters, thus receiving data of one's individual state of health and valuable individualised information to improve health. In our ageing societies the increase of health-information combined with automated methods of data-fusion and interpretation might help to improve the quality of health care, while improving the cost-efficiency and decreasing the utilisation of personnel per person. Only this decrease in personnel needed to care for the aged will allow for adequate health care as the potential support ratio is decreasing [UN01]. The potential support ratio is the number of people aged 15–64 per one older person aged 65 or older.

Continuous monitoring is established only in few areas, but with high implications on the patient's well-being. The Holter monitor is an example for a sensor device used since the 1950s to gain a more precise image of a patient's cardiac problems by measuring the ECG over a prolonged period of time [HG49]. Data from a Holter monitor is usually stored in the device and interpreted later on by a trained physician. Many similar devices neither perform an on-line evaluation nor emit warnings or automated emergency calls. Most diabetics measure their blood glucose frequently to control and adjust their medication. These measurements and adaptations need to be performed by themselves. Thus they require compliant, reliable, and trained patients. Recent studies have proven the beneficial effect of continuous glucose measurements for long term outcome [LBS06].

Continuously monitoring patients' parameters could enhance the understanding of their state of health and even generate new knowledge of aetiology and development of diseases and their prognoses. Earlier recognition would improve the chances and sustain the range of usable methods to delay, stop or cure diseases. Many parameters and parameter patterns are known to reflect aspects of a person's state of health. Intensive care units (ICU) use some of these measures to closely monitor changes and analyse trends in serious cases. Advances in sensor and communication technology now allow shifting the focus of this sensor-based electronic state of health reproduction to a more ubiquitous scenario and to different aspects of health. This shift is reflected in the monitored measures as well, as patients are mobile and e. g. even the kind and intensity of this mobility can be an interesting indicator for their state of health.

2 Sensors for health related parameters

The ideal device for continuous monitoring would be a device that is installed once, measures and reports continuously, needs no maintenance, and does not constrain or affect its user in any way. No existing device fulfils all these requirements. Based on available technology every device is a compromise focusing on some aspects, leaving it to the user to cope with negative effects.

2.1 Categorization of sensors

Due to their properties different schemes are useful to classify sensors (see figure 1). First of all the measurement category divides sensors into different groups (e. g. biochemical, electrical, and mechanical properties). Another axis to differentiate sensors is the technical property of the measurement process determined by the information carrier (e. g. optical, mechanical or electrical).

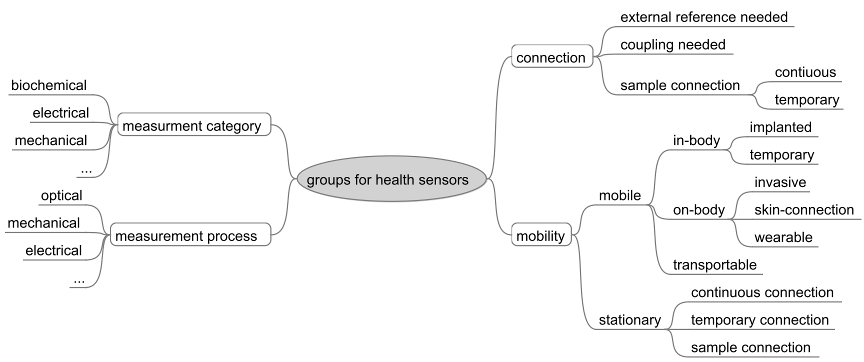

Figure 1: Mindmap illustrating the different axes useful for grouping of sensors

The way a sensor is connected to the patient leads to another useful grouping highly related to user acceptance. E. g. a patient can only be weighed in respect to an external reference system implying an external sensor, while measurements of biochemical parameters require (at least temporary) wet connections between the body compartments containing the measured substances and the measuring device (e. g. the extracellular compartment for continuous blood glucose measurement). Other measurement processes need a direct contact between sensor and skin. Some sensors can be carried around in pockets or clipped on belts e. g. accelerometers measuring body-movement or just counting steps.

The last dimension in this categorization is the mobility of the sensor. As stated some measurements are only feasible using a stationary device. A sensing device (e. g. cardioverter defibrillator) implanted into the body to observe parameters denotes the other extreme. In this setting the bio-compatibility becomes a major issue. Another way to temporary insert a device inside the body is e. g. having the patient swallowing a camera capsule. An inserted probe can connect a device worn by the patient to the observed compartment. Even less invasive are devices needing only skin contact or even allowing to be worn inside a pocket or on a belt. To monitor a parameter continuously and ubiquitously implanted, in-

rank	disease or injury	% of deaths
1	ischaemic heart disease	15.8
2	cerebrovascular disease	9.0
3	tracheal, bronchial and lung cancers	5.1
4	diabetes mellitus	4.8
5	chronic obstructive pulmonary disease (COPD)	4.1

Table 1: Rank prediction of causes for mortality in high-income countries for the year 2030 [ML06]

vasive or wearable devices are necessary. Sometimes mobile devices are not feasible and a stationary installation of the instrument is unavoidable.

Unmentioned is the connection of the whole sensor system to the outer world. A sensor can support different ways of reading its data. First of all a device can just show its measurements to the user, making him responsible for interpretation and storing. Many heart rate monitors for training purposes work that way. But even in this field approaches for storing and later retrieval and analyses of the measured data are commercially available. Most sophisticated is the on-line transmission of data to a information system for further storage, query, retrieval, analysis, display, and generation of warnings. Some commercially available sensor systems allow the access to their data, but only few conform to existing standards (like ISO 11073). At present most devices need cable connections to transfer the collected data as well as proprietary software to retrieve them. Open standards and wireless connections to transfer measurements continuously are hard to find.

2.2 Health related choice of sensors

Different people with their specific medical risks and state of health have different requirements for ubiquitous health monitoring, e. g. the blood glucose level in diabetics or the ECG for patients with arrhythmias. A patient-specific set of sensors to monitor the relevant parameters should be compiled to help each individual to handle their diseases more effectively.

Table 1 shows the expected rank of diseases according to their mortality [ML06]. This projection for the year 2030 provides a basis for a prognosis of which health enabling technologies are needed for effective prevention. Heart and respiratory diseases as well as diabetes mellitus will remain the main concern in the years to come. Therefore sensors to monitor or even help prevent these diseases should be the ones with most impact.

Thinking of heart disease some basic measures come to mind. First of all there are electrical parameters like heart rate and ECG or the thermodynamic measure blood pressure, but there are others as well. The heart sounds carry important information and are classically observed by physicians with a stethoscope, but there are technical solutions under development as well [Bru05]. Besides these there are bio-chemical parameters as well e. g. Troponin present after a heart attack or even markers predicting the individual risk for heart attacks [AAT07]. A parameter very easy to measure, but of great importance is body weight for patients with chronic cardiac insufficiency. Rapid increase in body weight is an alarm signal and can easily be observed by daily weighing.

These are measures classically associated with heart diseases. But if there is the possibility to monitor patients continuously for longer periods of time, new measures gain importance. One of the major risk factors for heart diseases and for diabetes is the amount of physical activity and exercises. Sport has many positive effects on the whole organism while a lack of activity is an established and agreed risk factor for many diseases. Capturing the amount of activity and giving positive feedback as well as reminders to the patient might improve the way diseases are prevented.

Simple measurement of the daily activity level is on the one hand important to assess the individual risk of a patient and can on the other hand provide control for a prescription of physical exercise in secondary or tertiary prevention. There is a lot of research in the field of recognition of daily activity and unobtrusive measurement of the activity level and even some commercially available instruments [DTK07].

3 Data fusion approaches

The chance to integrate sensors for health-related parameters in the everyday life of all patients at risk is not only a promising development for medicine, but provides new challenges for medical informatics.

There are new amounts of data, produced in a distributed fashion that have to be managed, aggregated and interpreted. Let us perform a rough calculation taking into account only a simple triaxial accelerometer often used to measure activity [DTK07]. The accelerometer provides three values for the linear acceleration on three orthogonal axes. These can be digitized with e. g. a precision of 12-bit each and a sampling rate of 100 Hz. Additionally timestamps with at least 24 bit are needed to identify each measurement in a day. To have a more standards based representation assign 32 bits for a second based unix-timestamp and 8 bits to identify a measurement within each second. Thereby we need 40 bits for the timestamp and a minimum of 48 bits for the accelerometric data, resulting in 88 bits or 11 bytes per measurement. A day consisting of 8 640 000 measurements therefore results in 90 MB of data. The bandwidth needed to transmit these data is 8 kbit/s. Of course there are ways to optimize the amount of data transferred, both with and without loss of information, but there are additional sensors providing further data and information on the health status of the person.

The challenge arising is to automatically combine and analyse the measured data with the aim of supplying the patient, his relatives and physicians with individual views on his or her state of health. Taking into account the demand to compose a individual set of sensors for at least each group of patients, the need to network different devices arises. Therefore systems able to combine the data streams from different sensor systems in a distributed while configurable manner are needed. Development of data stream management systems (DSMS) is an active field of research. These systems are often used to monitor traffic or weather sensor systems. The main difference between database management systems (DBMS) and DSMS is that the latter are designed to perform a long-running or continuous query on constantly changing input streams, while DBMS mainly perform changing queries on at largely stable datasets [BBD02, Gz03]. Typical representatives of DSMS are TelegraphCQ [Cha03], STREAM [ABW06], COUGAR [YG02], PIPES [KS04], and AURORA [ACC03]. With PIPESmed a prototype demonstrating the use in a sleep laboratory was presented [KSP06]. An interesting project is TinyDB [MFH05]. As part of the TinyOS operating system it is designed to process queries to the sensor network. Being research prototypes none of these systems fulfil all the features needed in distributed health sensor networks. To give an example the ability to perform historic queries is an often missed feature currently under investigation [CCD03, RSW07]. However, a lot of work has been done and provides a solid base for further developments.

4 Conclusions and further work

There are numerous parameters measurable providing additional data and hopefully information about a person's state of health. The presented classification helps to categorize different sensors and assess their usability. To perform continuous monitoring a sensing device needs to be unobtrusive. Unfortunately this objective is not easy to fulfil. Thus most of the current systems hinder the users in some way, are not designed for continuous monitoring, hard to operate or do not allow access to their data in an easy, standards based way. A lot of work remains to produce devices that are so easy to operate that the user forgets about them.

Individual people with dissimilar health problems need various sets of sensors as well as various ways to process and analyse the gathered data. With data stream management systems a promising approach mainly applied in non-medical domains has been presented and some typical systems introduced. Unfortunately these systems pursue different approaches and use different query languages. This lack of standardization makes decisions for the wrong system costly. While none of theses systems addresses all issues of the distributed data fusion and analysis problem, some implement interesting and essential features.

Though there are lots of sensors for health related parameters and body area networks have been under research for some while, there are still important issues to be addressed by future research. Especially the seamless integration of sensor networks into trans-institutional health information systems is a major task.

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