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# Sensor Data Stream Processing in Health Monitoring

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**Abstract:** Health monitoring and e-Inclusion significantly increase the quality of healthcare since they allow patients to live at home while nevertheless receiving treatment and care immediately, when needed. However, health monitoring and e-Inclusion also impose several challenges to the underlying information infrastructure. These challenges are stemming from data streams that are generated by smart sensors attached to the patients and to their augmented environment. Essentially, these streams need to be processed with near real-time constraints. In addition, also the mobility of users and patients has severe consequences on the information infrastructure. Disconnections and reconnections have to be handled transparently to the user/patient and data stream processing has to be dynamically adapted to the actual processing resources.

## Health Monitoring

Health monitoring aims at dynamically gathering, managing, processing, and storing physiological data usually provided by smart sensors. Most importantly, it allows to monitor the health status of patients in an online fashion. By dynamically processing sensor data, physicians and care personnel are able to immediately react to critical, pathological changes or even to anticipate such changes. Therefore, health monitoring is considered to significantly enhance the quality of patients' lives and to increase overall quality of care, even in out-of-hospital conditions. The latter is particularly important since chronic ailments such as cardiovascular diseases, hypertension, and diabetes affect a significant number of the western population (a survey of the American Heart Association states that cardiovascular diseases are the leading cause of death in many western countries [AHA01]). According to a recent prognosis for healthcare in the year 2013, the use of direct permanent monitoring of patients' vital signs, as well as the direct synchronous transfer of this sensory data will significantly increase [HAHK02].

From a technical point of view, health monitoring is a rather novel domain that brings together experts from various fields such as computer engineering, networking, data and information management, and from (biomedical) signal processing. In terms of computer and sensor engineering, health monitoring greatly benefits from recent trends in smart sensors and ubiquitous and wearable computing (e.g., smart shirts [GTW03], ring sensors [ASR$^+$03], or smart bandages [NA00]). As a result, a new generation of sensor systems currently emerges that make unobtrusive, non-invasive monitoring applicable to an increasing number of patients and diseases. In terms of networking, wireless network connections with both minimal power consumption and transmission power are needed in order to increase the lifetime of sensors and to avoid unnecessary perturbation and side-effects. Experts from biomedical signal processing are providing efficient and effective algorithms for the (pre-) filtering of sensor signals and the processing of these signals that allows to identify critical and/or pathological behavior. From an information systems point of view, an infrastructure is needed that supports continuous querys and continuous processing of data streams.

## e-Inclusion

In our aging society, monitoring is not only required for patients suffering from chronic diseases, but also for elderly and disabled people living in their home environment while nevertheless having the guarantee to receive immediate treatment and care if needed. Elderly people, for instance, may suffer from one or more chronic diseases, therefore requiring a health monitoring infrastructure at home. But in addition, the activity of these people as well as their context have to be monitored. From the perspective of sensor technology, this does not only require wearable sensors but also sensors that are integrated into the home environment (e.g., "intelligent carpets" measuring the position of a person and also their activity, i.e., whether a person is active –moving– or whether he/she has fallen down). These people have to be electronically included (e-Inclusion) in the society by making adequate use of information technology when needed.

In this kid of monitoring applications, it is therefore necessary to consider the context of a person. A person without current activity may be fine at night when being located in the bedroom, but when the person does not show any activity at daytime when being located in the floor, an emergency situation is very likely. Consider furthermore people suffering from special age-related impairments and mental diseases like Alzheimer. In this case, even more emphasis has to be put on monitoring the activity of the person together within the current context. A warning has to be generated, for instance, when the person tries to leave the apartment without having switched off the oven. By all these extensions, the number of sensors, data sources, etc., and therefore also the number of data streams that have to be processed will be significantly increased compared to the monitoring of a single disease. This, of course, has severe consequences on the underlying information infrastructure.

## Infrastructure for Health Monitoring and e-Inclusion

Applications for data stream processing are not monolithic but are made out of basic building blocks (e.g., programs for sensor data filtering or processing, noise reduction, access to medical databases or electronic patient records, etc.). Each of these building blocks provides certain services that can be invoked. Application development in this context therefore requires to seamlessly combine these building blocks into a coherent whole rather than developing programs from scratch. Workflows or processes are a means to combine existing services.

In terms of managing and storing data streams, the requirements imposed by health monitoring and e-Inclusion by far exceed the capabilities of existing database systems [GO03]. Similarly, conventional workflow and process support systems are tailored to execute processes at dedicated points in time. Data stream processing, however, require processes to run continuously, similar to continuous query processing. Incoming stream data serves as continuous input to these standing processes. Special requirements are also the storage of streams, or joins between streams in order to combine the data produced by different sensors, etc. The bottom line of these requirements is that existing process support infrastructures have to be extended in order to continuously execute processes and to support further crucial requirements.

Driven by the nature of the domain where health monitoring and e-Inclusion is applied to, a stringent requirement is that the underlying information infrastructure running processes and workflows implementing data stream processing is highly dependable since its correct functioning may be potentially life-saving. In here, dependability comes with several flavors. First, the information infrastructure has to be highly available in order to provide dedicated quality of service guarantees, for example in terms of the real-time aspects of the data streams being processed. Critical situations must be detected immediately and alarms have to be raised on the spot; no delay due to overload situations of the infrastructure can be tolerated. Second, the process-based applications have to be built in a way that correct failure handling is guaranteed (e.g., by following the model of transactonal processes [SABS02]). This also means that applications, since they are vital to their users, have to be verified whether they behave correctly, even in failure situations. Third, the infrastructure has to be very flexible. The disease pattern of patients varies over time and the system should allow to tailor processes to the current monitoring needs of an elderly person or a patient. This includes new types of sensors, new types of services, new types of processes, etc., that must be supported.

## Mobility in Health Monitoring and e-Inclusion

A crucial requirement on an infrastructure for data stream processing is to take into account that users and patients, especially when being monitored in an out-of-hospital environment, are usually mobile. Mobility of users and patients poses a set of challenges to the design and development of an information infrastructure for health monitoring. Users and patients do not necessarily have access to the systems environment installed at their home (base station, home network).

However, even when being disconnected, data streams produced by the (body) sensors have to be processed by some the mobile device (e.g., a PDA carried by the patient), thereby taking into account the limited CPU and storage resources of these devices. Given these limitations, data (pre-)processing and simple hazard detection have to be applied on these devices instead of full fledged medical, activity, and context monitoring. In addition, synchronization is required whenever a device is connected to the home network. After reconnection, data stream processing should be automatically and smoothly migrated to the fixed network environment, thereby making use of the increased processing power and better network connection.

## Hyperdatabases for Health Monitoring and e-Inclusion

A *hyperdatabase (HDB)* [SBG+00, SSSW02] is an infrastructure that supports the execution of processes on top of distributed components using existing services. The HDB provides transactional guarantees for processes, sophisticated routing strategies to dynamically choose among the available components, and allows to balance the overall load among them. Hence, the HDB provides database-like functionality, but not at the data level but at the level of access to services.

Meeting the challenging requirements imposed by health monitoring and e-Inclusion applications as well as by the mobility of users and/or patients requires to significantly extend hyperdatabase environments in several directions. Among others, the following problems have to be solved:

- support for continuously runnig processes: essentially, streaming processes have to be continuously fed with incoming sensor data. Moreover, the hyperdatabase infrastructure has to be designed in such a way that dedicated quality-of-service guarantees, especially in terms of response times, can be provided. An important requirement is also to provide an easy-to-use graphical interface that can be used by physicians and care personnel to design new or to revise existing patient- and/or disease-specific streaming processes.

- support for mobile users and devices: mobility is an inherent characteristic of the users in health monitoring and e-Inclusion applications. The actual monitoring has to be provided by the underlying infrastructure in a way that is transparent to the user. In particular, he/she does not have to take care on the connection state and on the way, streaming processes are being executed. Rather, the infrastructure has to dynamically migrate processing tasks between the home infrastructure and the mobile devices depending on the connection status.

- support for load balancing: in order to meet the real-time constraints, the system has to automatically and equally distribute the load between all services of the overall system. When, for instance, several components in the home network provide sensor data filtering algorithms, then different streams should be distributed appropriately among these services. Similarly, when bottlenecks are detected, the system should be able to dynamically install new instances of services that can then be used for load balancing purposes.

## Conclusion

The above mentioned extensions to hyperdatabase systems reflect current activities at UMIT. In a joint effort that includes participants from different fields such as information systems, information and software engineering, computer engineering, and biomedical signal processing, but also with external partners from the biosignal processing and telemedicine groups of the Austrian research center in Seibersdorf (ARCS), we are currently developing a comprehensive infrastructure to support health monitoring and e-Inclusion activities. The basis for the information infrastructure is the OSIRIS system (Open Service Infrastructure for Reliable and Integrated process Support) [WSN+03].

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