Multi-agent Solution for Adaptive Data Analysis in Sensor Networks at the Intelligent Hospital Ward

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Abstract. This paper introduces a multi-agent solution for remote monitoring based on wireless network of sensors that are used to collect and process medical data describing the current patient state. A multi-agent architecture is provided for a sensor network of medical devices, which is able to adaptively react to various events in real time. To implement this solution it is proposed to partially process the data by autonomous medical devices without transmitting it to the server and adapt the sampling intervals on the basis of the non-equidistant time series analysis. The solution is illustrated by simulation results and clinical deployment.

Keywords: Multi-agent technology, intelligent devices, sensor networks, real time sensor processing, smart hospital, telemedicine, computer-aided diagnosis, software architecture.

1 Introduction

One of the essential challenges in computer-aided medical diagnosis is concerned with the implementation of software solutions and architectures capable to process large quantities of data in real time. Widespread medical equipment in hospital wards (e.g. medical monitors) is capable of solving this problem by capturing a number of parameters describing the current status of the patient, but it is quite expensive and requires fixed installation at the medical bed.

Modern mobile devices for diagnostics (like Holter monitors) have their own niche in medicine; some of them are comparatively cheap and portable, which makes them useful for every day patient status monitoring. Still, there are no solutions on the market based on the utilization of these devices for complex monitoring and diagnosis in real time. The reason for this is high complexity of centralized data capturing and analysis.

To cover this gap we propose a multi-agent architecture of a sensor network of medical devices. This network is able to adaptively react to various events in real time. The main difference from the existing approaches is that the process of data flow analysis provided by the proposed solution is distributed between the nodes of intelligent network, formed by multiple mobile devices with autonomous behavior.

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This makes it open for possible extension and integration with heterogeneous software and in demand for practical use at a number of hospitals.

2 Motivation

The request for the proposed solution was formed in the process of delivering a number of projects carried out by Magenta Technology [1]. During the last three years we have got extensive experience both in implementing multi-agent technologies for transportation logistics [2] and developing solutions for medical applications [3], which led us to the following conclusions.

Medical applications usually impose high requirements to hardware and software solutions being developed for practical use. This is the reason of their comparatively high costs and difficulty to enter the market. In addition, most providers of medical applications encourage to use separate products of the same brand name that solve different tasks. This helps integrating the pieces of software and hardware and provides high reliability of the whole solution.

From the pragmatic point of view providing the opportunity to integrate heterogeneous devices and associate the software from different providers, which seems to be common for most medical institutions, looks like a reasonable and attractive step. To achieve the desired aim, the IT infrastructure should be developed as an open system using unified protocols for data exchange and providing interoperability for the integrated devices.

It should be mentioned that the data flow in such a web of medical devices will have certain features. First of all it will be multi-directional, which means that each device at a certain node should provide an ability not only to accept and generate certain data, but transmit it as well, supporting the data exchange between other nodes. Next, the process of data exchange will be asynchronous. Time intervals between the messages will vary in time, so the process of data exchange could be described by non-equidistant time series [4]. Finally, the process of data exchange should be highly influenced by the current situation: the density of data exchange will be higher in case of emergency situations, inducing higher traffic in the system.

The combination of these features explains the necessity of some special approach to develop an architecture and technology for data exchange in the open network of medical devices. This process cannot be managed centrally as the time wasted on sending the description about the current situation to the center, analyzing it and providing the solution brings to nothing all the efforts to coordinate it in real time. To overcome this problem the devices themselves should be active and form a complex network of continuously running and co-evolving agents. Such architecture will be close to peer-to-peer (P2P) network [5] that is frequently used to describe and simulate the interaction processes of autonomous agents.

In this case the whole solution can be based on holons paradigm [6] and bio-inspired approach [7]. This paradigm and approach offer a way of designing adaptive systems with decentralization over distributed and autonomous entities organized in hierarchical structures formed by intermediate stable forms. Its implementation in practice requires the development of new methods and tools for supporting fundamental mechanisms of self-organization and evolution, similar to living organisms (colonies of ants, swarms of bees, etc) [8]. The opportunities provided by multi-agent technology in medicine are fully described in [9].

So we came to a challenge to develop a multi-agent solution for the coordination of a network of medical sensors which provides functioning in real time, paying maximum attention to adapting the frequency of data exchange to the rhythm of real processes.

3 State-of-the-Art

Intensive care medicine [10] is a branch of medicine concerned with the diagnosis and management of life threatening conditions, requiring sophisticated organ support and invasive monitoring. One of the most commonly used types of equipment in this area is a fairly wide range of bedside monitors for computer-aided diagnosis. These monitors capture data from a number of sensors, save it and send it to a centralized data storage, and determine emergency situations with visual and audio alarm notification. Bedside monitors can be a part of a distributed system of support for clinical decision-making[11], that has been coined as an active knowledge base, which uses patient data to generate case-specific advice to assist health professionals.

The system architecture for such a solution is illustrated by Fig 1. The algorithms of data analysis and decision-making support, provided by bedside monitors, are usually based on fixed rate sampling that allows consistent analysis of the dynamics of the indicated values, collected by several sensors during a certain period of time.

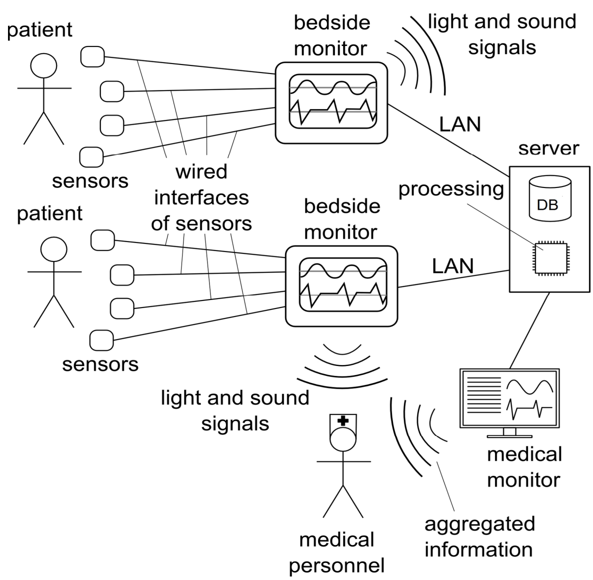

Fig. 1. Architecture of a fixed installation diagnosis system

In order to improve the quality of medical care and personalize it, there is a better solution for remote patient monitoring [12, 13] at general hospital wards. In this solution the vital signs are transmitted via wireless network technologies that provide flexibility and mobility for the patients. This solution is demonstrated in Fig. 2.:

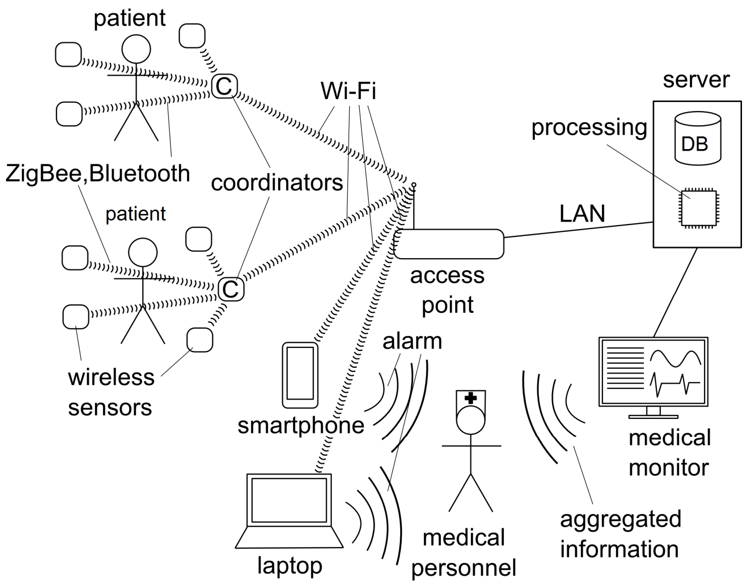

Fig. 2. Remote patient monitoring solution

Here, the sensors and the coordinator interact via ZigBee or Bluetooth protocols. The coordinator collects the data from the sensors and transmits it to the local computer network using Wi-Fi. Besides, the computer network contains the devices of data analysis and visualization in real time, alarm devices and a dedicated server for a specialized knowledge base. So the monitoring process remains centralized: the vital signs are gathered from the patients and sent for processing to a single control unit.

The most considerable benefit of such an approach is its flexibility: each diagnosis sensor is not bound to a particular patient care system, which allows combining a random set of devices to an arbitrary scanning system. The limitations of this approach include the unlicensed radio-frequency range of data transmitting between the sensors and the coordinators at 2.4 GHz, high density of sensors and the limitation of the number of channels supported by Bluetooth and ZigBee. This can cause negative stability of wireless communication. In addition, the data flows of diagnosis information that are translated to local network need to be processed in real time, which gives rise to a new set of requirements to this solution.

Technical capabilities of a medical systems based on sensor networks are also provided by the combined hardware and software platform for medical sensor networks, called CodeBlue [14]. This paper [15] describes a hospital healthcare monitoring system that uses wireless sensor networks: still, its sensors cannot transmit the messages between each other, they support only fixed-rate sampling and cannot be increased in number.

We propose to extend the existing approaches based on wireless technologies by introducing the active behavior of sensors that can be implemented by software agents and interact in P2P mode. Such basic features of P2P models [16, 17] like decentralization, sharing of resources and services, and autonomy make them applicable for a distributed computer-aided diagnosis system for personal medical care.

4 Problem Statement

Let us consider a generalized model where sensors (or devices) $s_j,\ j=1..N_s$ are combined into a P2P wireless network to collect the diagnosis data from patients $u_i,\ i=1..N_u$. Each measuring operation can be introduced as a Boolean variable: $e_{i,j,k}=e(u_i,s_j,v_{i,j,k},t_{i,j,k})\in\{0,1\}$, where $v_{i,j,k}$ is the value of the parameter of u_i collected by s_j at the time of $t_{i,j,k}$.

Let us select and denote an event that has the best description of the patient's state – enough to make a diagnosis and indicate it as a pattern:

$$\Theta_{i,n}=\{\varepsilon_{i,j,k}=1, k\in\Omega_{i,n}\} \tag{1}$$

where $\varepsilon_{i,j,k}=\varepsilon(u_i,s_j,v'_{i,j,k},t'_{i,j,k})\in\{0,1\}$ represents the real event of parameter value change in reality (external to our system).

Ideally the adaptive network of devices should perform as follows:

$$\sum_{i=1}^{N_u}\sum_{j=1}^{N_s}\sum_{k=1}^{N_\varepsilon}\varepsilon(u_i,s_j,v'_{i,j,k},t'_{i,j,k})\cdot\min_l\left(e(u_i,s_j,v_{i,j,l},t_{i,j,l})\cdot t_{i,j,l}-t'_{i,j,k}\right)\to\min \tag{2}$$

This can be calculated as the following:

$$\sum_{i=1}^{N_u}\sum_{j=1}^{N_s}\sum_{k=1}^{N_\varepsilon}\sum_{l=1}^{N_e}\varepsilon_{i,j,k}\cdot e_{i,j,l}\cdot\theta(t_{i,j,l}-t'_{i,j,k})\cdot\theta(t'_{i,j,k}-t_{i,j,l-1})\cdot(t_{i,j,l}-t'_{i,j,k})\to\min \tag{3}$$

where $\theta(x)$ – Heaviside step function [18]: $\theta(x)=\begin{cases}0, x<0\\1, x\ge 0\end{cases}$,

$\forall\varepsilon_{i,j,k},\exists e_{i,j,l}: t_{i,j,l}>t'_{i,j,k}$, $\forall e_{i,j,l}, l>1: t_{i,j,l}>t_{i,j,l-1}$ (the events are prioritized in the order of occurrence).

Statements (2) and (3) define the requirement for the time frames of measurement. The events of data collection should occur just after something happened with the patient. Conversely, in case nothing happens the sensors should not be triggered frequently.

This is a kind of a scheduling problem: the system should construct a plan of $e_{i,j,k}$ and adaptively correct it when needed. So, time is considered to be a continuous parameter, which is sampled in a process of measurements. The measurement plan should adaptively react to the changing situation and be able to collect the amount of data which constitutes a bare minimum to make a decision.

Still, there is another KPI left for consideration – the total number of measurements should be minimized:

$$\sum_{i=1}^{N_u}\sum_{j=1}^{N_s}\sum_{l=1}^{N_e} e\left(u_i, s_j, v_{i,j,l}, t_{i,j,l}\right) \rightarrow \min \tag{4}$$

It can be noticed that statements (1) and (3) are in contradiction with each other. This contradiction should be supported by a distributed software solution that will be able to provide the minimum of data broadcast in the network of autonomous devices (which will result in lower network load) and at the same time guarantee adaptive reaction in time.

5 Solution Architecture

To solve this problem there should be proposed an algorithm that will control sampling time interval at some reasonable value and increase it in case of a risk of emergency. To identify such a risk there can be used a simple heuristic like:

a) $v_{i,j,k}$ is outside the time interval $\left(v_{i,j}^{\min}, v_{i,j}^{\max}\right)$,

b) the increment $\frac{v_{i,j,k} - v_{i,j,l}}{t_{i,j,k} - t_{i,j,l}} > \Delta v_{i,j}$, $t_{i,j,k} < t_{i,j,l}$.

Otherwise, sampling time interval should adapt to a possible Pattern of the Emergent State (PES) – a hypotheses pattern describing a real situation $\Theta_{i,n}$, which is specific for each patient:

$$\Theta''_{i,n} = \left\{\varepsilon''_{i,j,k''} = 1, k'' \in \Omega''_{i,n}\right\}, \tag{5}$$

where $\varepsilon''_{i,j,k''} = \varepsilon''\left(u_i, s_j, v''_{i,j,k}, t''_{i,j,k}\right) \in \{0, 1\}$.

After identifying the risk, the set of devices responsible for the patient u_i should adapt the sampling intervals of their m\\\\\easurement to better react to the current situation.

Considering the jitter of real events in a pattern, the time series describing the current patient state should be treated as non-equidistant time series. So the function used for the identification should look like:

$$\rho''\left(u_i, e_{i,j,l_0}, \Theta''_{i,n}, \Delta\tau, \Delta v\right) = \sum_{j=1}^{N_s} \sum_{l=l_0}^{l_0+N''_{i,n}-1} \sum_{k=1}^{N_{\varepsilon''}} e_{i,j,l} \cdot \varepsilon''_{i,j,k} \cdot \theta\left(t_{i,j,l} - t''_{i,j,k}\right) \cdot$$
$$\cdot \theta\left(t''_{i,j,k} - t_{i,j,l-1}\right) \cdot \theta\left(t''_{i,j,k} + \Delta\tau - t_{i,j,l}\right) \cdot \theta\left(v''_{i,j,k} + \Delta v - v_{i,j,l}\right) \tag{6}$$
$$\cdot \theta\left(v_{i,j,l} + \Delta v - v''_{i,j,k}\right) = N''_{i,n}.$$

This solution was implemented by the intelligent software platform with distributed architecture (see Fig. 3, 4). The data gathered from sensors in real time is partially processed on their side and sent to the server for centralized processing only in case of risk identification. To provide complex analysis, the devices can interact and cooperate by exchanging the messages using ZigBee protocol and coordinating the sampling and accuracy of the measurements.

PES $\Theta''_{i,n}$ patterns (see Fig. 4) are created and stored on a dedicated server and are distributed to the diagnosis devices. According to the current situation each autonomous device determines the risk of emergency using the identification function (6). In case of emergency detected, they initiate data exchange for a deep analysis or an alarm notification sent to the handheld devices of medical personnel.

The benefits of such a solution include flexibility, adaptability to any external events, ability to function in real time and provide diagnosis decision-making support, and capability to process big data. Besides, it allows introducing individual configuration of diagnosis devices (sensors) for each patient without limiting the mobility of the patient.

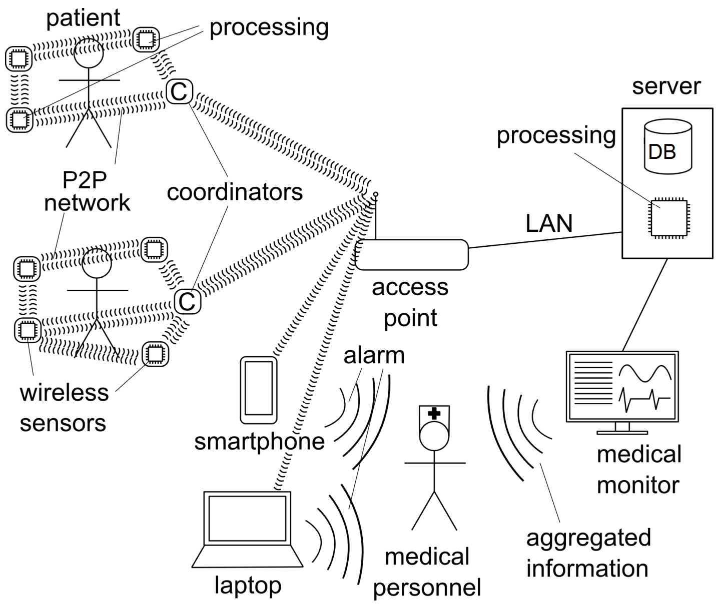

Fig. 3. Solution physical architecture

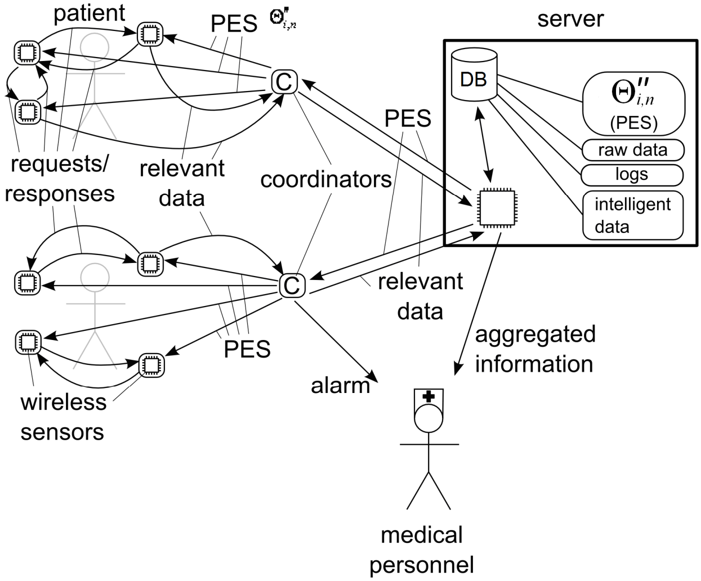

Fig. 4. Logical architecture of the proposed solution

6 Human Aspects of Distributed Medical Monitoring

New performance capabilities of remote medical patients monitoring via sensor networks provide an opportunity to increase the level of medical service and support people in medical, psychological and social aspects of their daily lives. Developments in this area should be first of all oriented on the actual requirements of end users; otherwise even using the most up-to-date technologies will not help getting closer to the expected benefits. The proposed approach for adaptive data analysis addresses this aspect. By reducing the size of the sensors and other medical devices and making them transportable, the users expect to get more comfort with the same reliability. This requirement set a problem of looking for new technologies of data processing, and the proposed approach can give a solution.

Another aspect of human-centric review of the problem of effective medical monitoring is the necessity to function in real time. No technical system can immediately react to the incoming unpredicted events, especially in distributed multi-agent technical environment. At the same time, continuous and permanent monitoring of the patient's medical condition, which can be provided by the sensor networks, allows the diagnostic software to detect changes at early stages.

In this regard, the logic of data collection and analysis should consider the time factor. For a certain period there can be enough time for analysis and decision making, but any moment there can emerge a sudden event that will require immediate reaction. The medical monitoring system should consider this factor and be able to function in adaptive mode in real time. In our opinion, the above-stated approach brings the solution closer.

7 Simulation Results and Implementation

The proposed approach for distributed real time sensor processing in sensor networks was tested and probated by cardio simulation: the results are illustrated in Fig. 5 – 7. A sample electrocardiogram tracking was generated by the simulating engine. In case of low sampling the measured signal can considerably differ from the original one.

Fig. 6 illustrates two possible cases, randomly generated by the simulating engine: the one with the emergency and the one with the normal P-wave. Generating the moments of measurement according to the proposed algorithm, the diagnosis device (see Fig. 7) can adapt its behavior to the real situation and reliably identify all the emergency P-waves. This proves the possibility to partially delegate the functionality of data analysis to the intelligent devices and thus reduce the traffic in P2P network.

The processes of interaction on the basis of the proposed architecture were tested for a couple of devices: a medical monitor and an autonomous infusion drop counter, which was developed in cooperation with the Samara State Medical University, Russia (see Fig. 8). The results of implementation proved the relevance of the proposed approach.

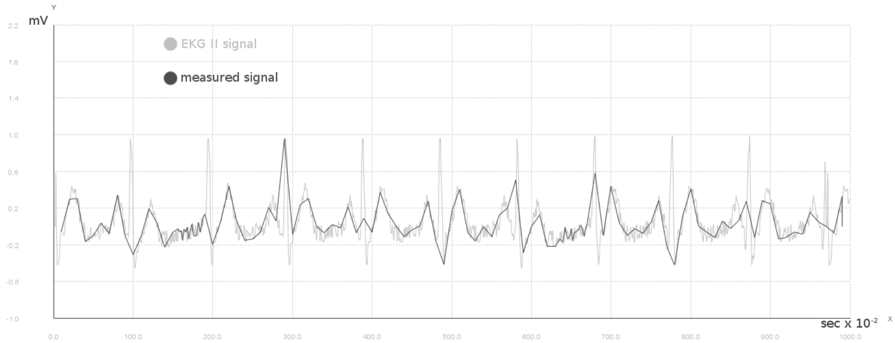

Fig. 5. Electrocardiogram simulation

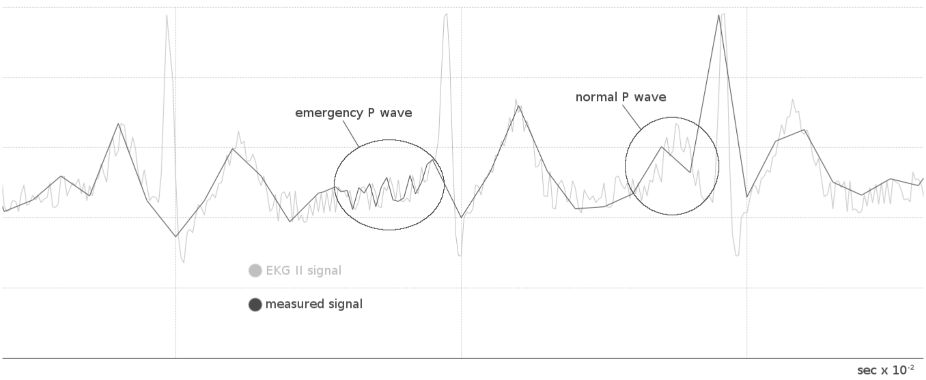

Fig. 6. Fragments of emergency and normal P-waves

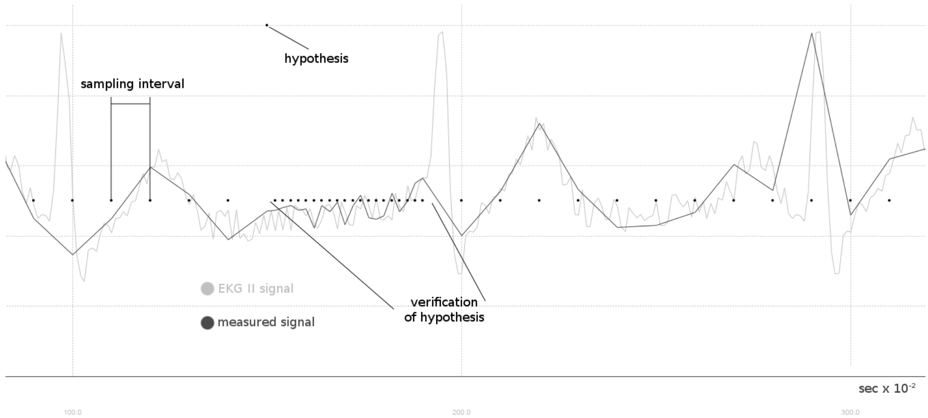

Fig. 7. Sampling times for adaptive analysis

Fig. 8. Intelligent drop counter being deployed in clinic

8 Conclusion

In this paper we have introduced a multi-agent solution for the remote monitoring of medical patients, based on the wireless network of sensors. The process of data flow analysis is distributed between the nodes of intelligent network, formed by multiple mobile devices with autonomous behavior. The benefits of such a solution include flexibility and possibility to function in real time.

One of the first devices developed using to the proposed approach was the autonomous infusion drop counter integrated with a cardio monitor, both able to adapt the sampling intervals and minimize power consumption and network load with no loss of data. First results of its practical use have proven the selected approach, so we plan to extend the number of the supported types of sensors as a further development.

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