Distributed Medical Diagnostics Based on Self-Mediator Sensor Networks

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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 it is proposed to partially process the data by autonomous medical devices without transmitting to server and adapt sampling intervals based on the analysis of non-equidistant time series. The solution is illustrated by simulation results and deployment at clinic.**

I. INTRODUCTION

Modern medical diagnostics requires software solutions and architectures capable to process large quantities of data in real time. Widespread medical equipment at hospital wards (e.g. medical monitors) is capable of solving this problem capturing a number of parameters describing the current status of the patient, but it is considerably expensive and requires being stationary installed 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 at the market based on the utilization of these devices for complex monitoring and diagnosis in real time due to 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, which 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. This makes it open for possible extension and integration with heterogeneous software and be in demand for practical use at a number of hospitals.

II. STATE OF THE ART

Intensive care medicine [1] 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 provide data capturing from a number of sensors, saving and sending it to a centralized data storage, and determination of accidental situations with visual and audio alerting notification. Bedside monitors can be a part of a distributed clinical decision support system [2] that has been coined as an active knowledge base, which uses patient data to generate case-specific advice to assist health professionals. 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 indicated values collected by several sensors during the certain period of time.

In order to improve the quality of medical care and personalize it there is proposed a solution for remote patient monitoring [3], [4] to be used at general hospital wards. In this solution the vital signs are transmitted using wireless network technologies that provide flexibility and mobility to patients. The process of interaction between the sensors and coordinator is implemented using ZigBee or Bluetooth protocols. Coordinator collects the data from 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 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 the 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 coordinators at 2,4 GHz, high density of sensors and limitation of the number of channels supported by Bluetooth and ZigBee. This can cause negative stability of wireless communication. In addition to this 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 medical systems based on sensor networks are also provided by the combined hardware and software platform for medical sensor networks, called CodeBlue [5]. There should be also mentioned the paper [6] that describes a hospital healthcare monitoring system using wireless sensor networks: still in this system sensors cannot transmit the messages between each other, support only fixed-rate sampling and cannot be increased in number.

These ideas are studied in technical level under the popular concept of the Internet of Things [7], [8] that is rapidly developing nowadays. Using several devices with different functionality as a cloud can improve the quality of diagnostics in real time. Modern protocols and architectures of wireless networks allow implementing a variety of topologies at technical level.

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 [9 – 11] like decentralization, sharing of resources and services, and autonomy make them applicable for a distributed computer-aided diagnosis system for personal medical care.

In this case the whole solution can be based on holons paradigm [12] and bio-inspired approach [13]. 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. It's implementation in practice requires 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). The opportunities provided by multi-agent technology in medicine are fully described in [14].

The devices themselves should be active and form a complex network of continuously running and co-evolving agents. The process of their interaction 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. Each event that occurs here can influence the whole network and needs a collaborative reaction from all dependable components. Due to such group behavior and to be able to function in real time this network of intelligent systems and their users should be considered as a complex system with evolvable dynamics and investigated from statistical point of view. Another one requirement for a decision making process based on the agents' negotiation is that the final decision can require a complicated and time consuming process of data exchange between the agents.

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

III. PROBLEM STATEMENT

Let us consider a generalized model where sensors s_j=1..N_s are combined into a wireless network capable to collect and analyze health care parameters $u_1 = 1..N_u$.

Each event that corresponds to a remarkable human state parameter change is represented by $e_{i,j,k} = (v_{i,j,k}, t_{i,j,k}, w_{i,j,k}), k = 1..N_k$, where $t_{i,j,k}$ – the moment of measurement time, $v_{i,j,k}$ – measured value, $w_{i,j,l}$ – quantitive characteristic of source energy at the moment of measurement, N_k – the number of measurements performed.

Real parameter value change is presented by the event $\varepsilon_{i,l} = (u_i, v'_{i,j,l}, t'_{i,j,l}), l = 1..N_l$, where $v'_{i,j,l}$ – parameter u_i value, determined at time $t'_{i,j,l}$, N_l – the number of events.

To identify the exact situation it is necessary to provide a required number of measurements that can be specified as a pattern. The pattern is presented as a number of intervals $p_{i,m,n} = (v^p_{i,m,n}, t^p_{i,m,n}, \Delta v^p_{i,m,n}, \Delta t^p_{i,m,n})$.

Each pattern can be represented as a set of $P_n = \{p_{i,m,n}\}, n = 1..N_p, m = 1..N(P_n)$, $m : i_1 \neq i_2 \rightarrow m_1 \neq m_2$.

Identification of the measurement correspondence to a specified pattern is:

$$g(\hat{v}, v^p_{i,m,n}) = \delta[\hat{v} \in (v^p_{i,m,n}, v^p_{i,m,n} + \Delta v^p_{i,m,n})] = \{0,1\} \tag{1}$$

where $\delta[x] = \begin{cases} 1, \text{if } x \cdots true \\ 0, elsewise \end{cases}$.

Measurement result identification in value and time is:

$$\begin{aligned} h(v', v^p_{i,m,n}, t_s, t', t^p_{i,m,n}) &= g(v', v^p_{i,m,n}) \cdot \\ \cdot\, \delta[(t' - t_s) &\in (t^p_{i,m,n}, t^p_{i,m,n} + \Delta t^p_{i,m,n})] = \{0,1\} \end{aligned} \tag{2}$$

In (1) and (2) t_s specifies the time of pattern identification, v' correspond to the value, and t' points on the time that corresponds to this parameter value.

The moment of time of the first possible pattern detection t_n^0 can be defined as:

$$\begin{aligned} t_n^0 = \sum_{l=1}^{N_l} \sum_{i=1}^{N_p} \Bigg(g\left(v'_{i,l}, v^p_{i,N(P_n),n}\right) \cdot t'_{i,l} \cdot \\ \cdot \left(\sum_{l_1=1}^{N_l} \sum_{i_1=1}^{N_p} \prod_{m_1=1}^{N(P_n)-1} h\left(v'_{i_1,l_1}, v^p_{i_1,m_1,n_1}, t^p_{i,1,n}, t'_{i_1,l_1}, t^p_{i_1,m_1,n_1}\right) \right) \Bigg) \end{aligned} \tag{3}$$

The time of the first positive pattern detection t_n^* can be defined as:

$$\begin{aligned} t_n^* = \sum_{k=1}^{N_k} \sum_{j=1}^{N_s} \sum_{i=1}^{N_u} \Bigg(g\left(v_{i,j,k}, v^p_{i,N(P_n),n}\right) \cdot t_{i,l} \cdot \\ \cdot \left(\sum_{k_1=1}^{N_u} \sum_{j_1=1}^{N_s} \sum_{i_1=1}^{N_u} \prod_{m_1=1}^{N(P_n)-1} h\left(v_{i_1,j_1,k_1}, v^p_{i_1,m_1,n_1}, t^p_{i,1,n}, t'_{i_1,j_1,k_1}, t^p_{i_1,m_1,n_1}\right) \right) \Bigg) \end{aligned} \tag{4}$$

Detection of the pattern during the process of measurement corresponds to its' resultative identification in the time series. The number of identifications is evaluated as:

$$I_p = \sum_{n=1}^{N_p}\sum_{k=1}^{N_k}\sum_{j=1}^{N_s}\sum_{i=1}^{N_u}\left(g\left(v_{i,j,k}, v^p_{i,N(P_n),n} \right) \cdot \right.$$
$$\left. \cdot \left(\sum_{k_1=1}^{N_u}\sum_{j_1=1}^{N_s}\sum_{i_1=1}^{N_u} \prod_{m_1=1}^{N(P_n)-1} h\left(v_{i_1,j_1,k_1}, v^p_{i_1,m_1,n_1}, t^p_{i,1,n}, t'_{i_1,j_1,k_1}, t^p_{i_1,m_1,n_1} \right) \right) \right) \tag{5}$$

Based on this model there was formulated a set or efficiency criteria that describe energetic efficiency, reliability and accuracy of distributed medical diagnostics.

Correctness of diagnostics can be represented as attitude of the detected number of patterns to the real number:

$$K_p = \frac{I_p}{N_p} \to 1 \tag{6}$$

Criterion of power consumption efficiency of the diagnostics system can be presented as the following:

$$K_Э = \sum_{i=1}^{N_u}\sum_{j=1}^{N_s}\sum_{k=2}^{N_k}\left(w_{i,j,k} - w_{i,j,k-1} \right) \to 0 \tag{7}$$

The fact that diagnostics is performed in time (productivity) can be presented as:

$$K_c = \sum_{n=1}^{N_p}\left(t^*_n - t^0_n \right) \to 0 \tag{8}$$

The statements (6 – 8) formulate the problem of medical data collection and processing in a distributed healthcare diagnostics system. The system requires multi-criteria optimization: it should provide minimum energy consuming with enough number of measurements for coordinated decision making to be done in time. Considering the random factor of events that need to be identified and processed the problem cannot be solved using the existing optimization techniques and requires intelligent decision making support.

To solve this problem using multi-agent technology it is proposed to increase the autonomy of every device involved in data collection and processing by implementing a specialized software capable to perform data pre-processing on the side of a device and introduce data interaction between the devices in the process of pattern identification. Leaf devices should perform the operations of measurement at a certain moments of time to better identify the corresponding situation.

So the statements (6 – 8) can be formulated and solved as a scheduling problem: there should be formed a sequence of measurement events $e_{i,j,k}$, which is actualized and updated according to measurement results in an adaptive manner.

Under this condition the devices used for data collection and processing as a part of a distributed medical diagnostics system should not only implement their directive functionality but also participate in the process of coordination of measurement and identification procedures in flexible and self-organized manner.

IV. SOLUTION ARCHITECTURE

To solve the stated problem we propose to implement one of the existing algorithms for data transmission in decentralized P2P networks. Utility-type sensors can interact via ZigBee or Bluetooth protocols. In complex environments there can be used an overlay network to simulate the sensor network and can be introduced special agents that will provide data exchange optimization.

The proposed solution is described by logical architecture given in Fig. 1.

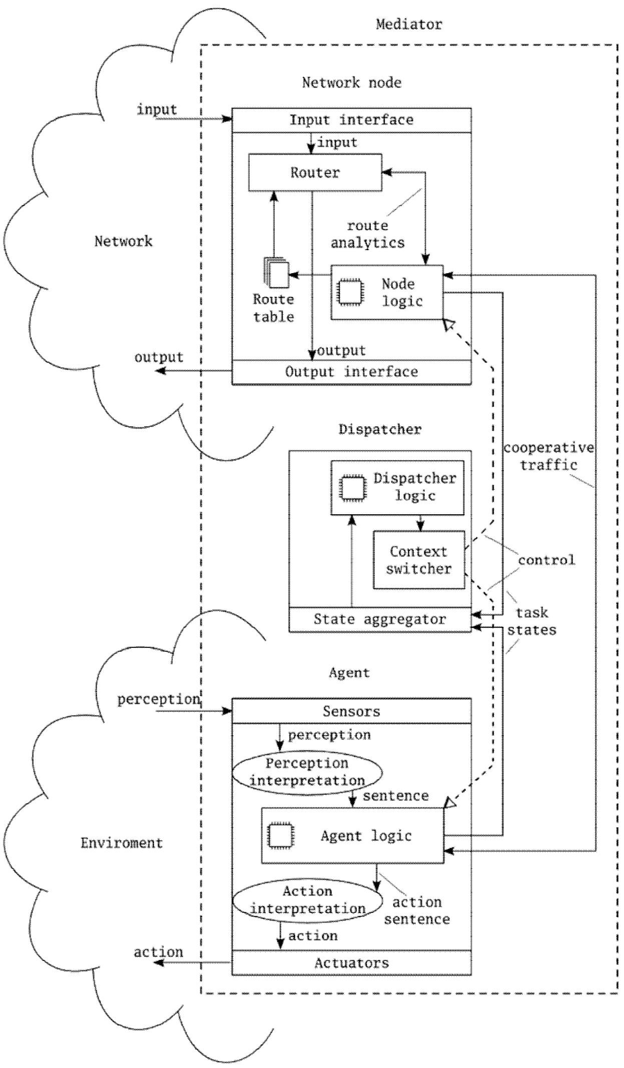

Fig. 1. Self-mediator software implementation

The following principles are implemented on the basis of multi-agent technology [15], [16]:

- P2P architecture that contains interlinked nodes (peers) combined into an interlinked network;
- Peers are autonomous devices with multi-agent software that supports a special protocol of interaction and provides data preprocessing and initial diagnosis;

- Each peer can act as a mediator helping others to transmit the data in network in addition to it's general role and objectives;
- Under the interaction protocol the messages between the agents are prioritized in the form of events' queues;
- Peers have an ability to analyze and balance their current loading by measurement tasks and data traffic;
- In case of early detection of an emergent state the sensor agent adapts its behavior terminating data transmitting tasks and reducing measurement sampling interval.

This solution can be implemented using either existing multi-agent platform or by developing a new system. There should be noted three challenges specific to the proposed solution:

- Agents should find the best route for data exchange in the process of self organization;
- Agents need to identify the best proportion of resource loading by data transmission and data collection.

Self-mediator software implementing the proposed architecture should provide mediating behavior of each agent in addition to its basic functionality. UML class diagrams for mediator internal architecture and specialized software pattern that can be used in implementing software are presented in Fig. 2 – 3. With this purpose the agent's internal architecture should include a virtual dispatcher that monitors the agent internal component's states. On the basis of current state analysis this dispatcher will make a decision on load balancing of agent resources between the tasks considering their priority.

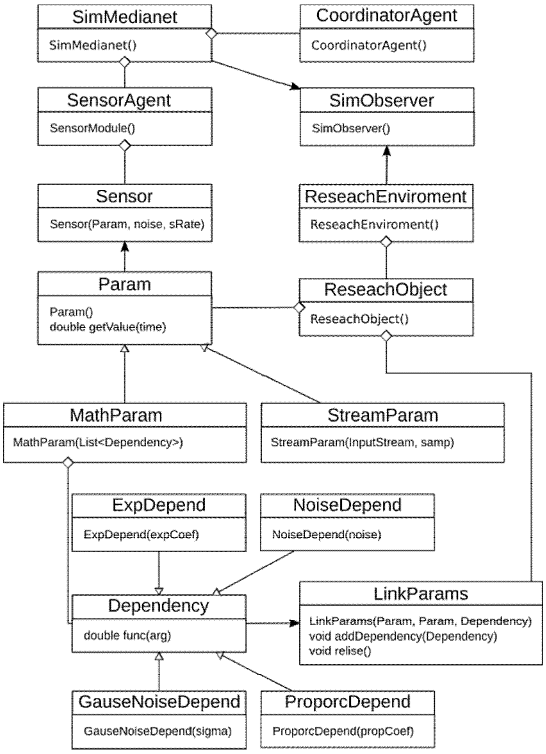

Fig. 2. Mediator internal architecture

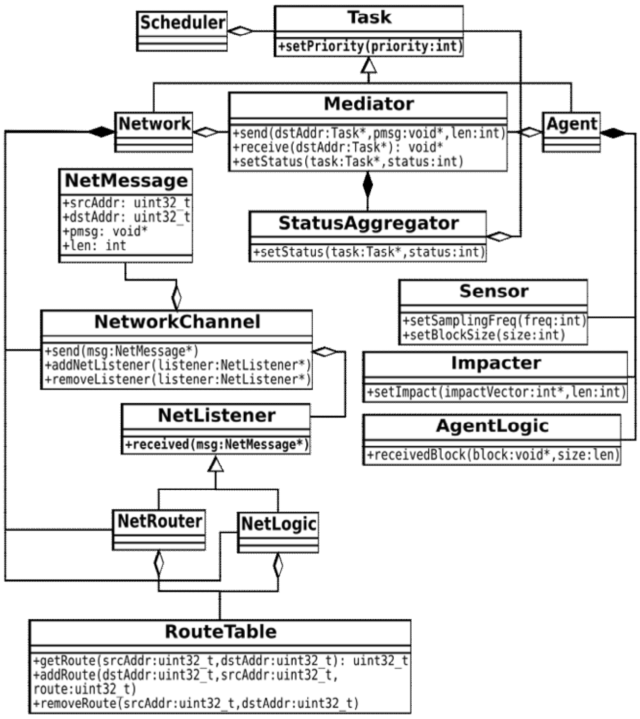

Fig. 3. Mediator-based pattern to be used for implementation

Considering the jitter of real events in a pattern, the time series describing the current object state should be treated as non-equidistant time series. So the data gathered from sensors in real time should be partially processed on their side and sent to the server for centralized processing only in case of risk identification. Risk identification can be implemented by an embedded service that calculates productivity, adequacy and power consumption. The sensor agent triggers this functionality on a regular basis and determines the possibility of load balancing. Taking into account the sensor type distinction and the method of data collecting and processing as well as the geometry of the target system the calculating algorithm can vary in logic and scale. To provide effective routing each agent gets its own local network vision that contains an overlay network describing the neighborhood.

In case the agents can be implemented under the multitasking operating system load balancing can be implemented by stream management. But autonomous agents introduced for a distributed sensor network cannot afford this capability being implemented on microcontrollers having no memory management units (MMU), which results in low calculation capacity. So the agent tasks together with load balancing functionality should be realized under the same activity execution context. The gaps of such a solution includes no possibility of context saving and recovery, which impairs balancing potentials and limits the portability.

Under the proposed solution there was utilized FreeRTOS real-time operating system for embedded devices that implements multiple threads under the global address space with predefined priorities. The operating system is open and allows introducing different multithreading models. Agent tasks' balancing is implemented by single interface.

Mediator, Task, Network and Agent describe the mediator pattern that is responsible of tasks distribution. Status Aggregator sets the priority considering the current task state. Scheduler is a part of FreeRTOS and switches the contexts of balancing tasks according to the predefined priority.

V. ANALYSIS AND TESTS

The results of experimental analysis of the proposed solution are presented in Fig 4 – 5. The simple configurations of diagnostics network that include 10 devices can give up to 14,9% productivity effect with satisfactory correctness (2,3% increase) and power consumption (0,2% decrease). The results for a more complicated test are presented in Fig 3 – 4.

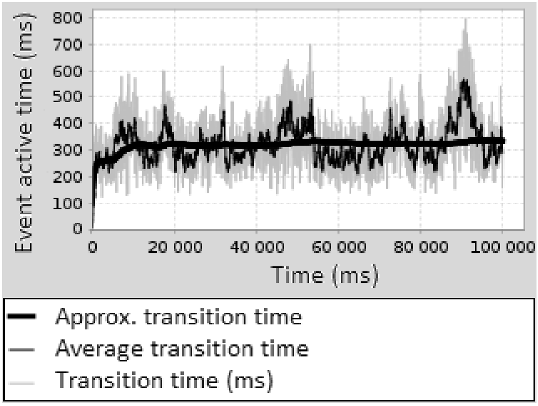

Fig. 4. Events' processing with no mediating

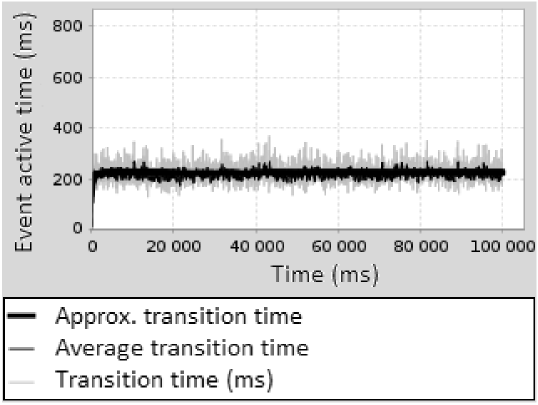

Fig. 5. Using the self-mediator network for measurement events' processing in real time

The described approach for self-mediator software was successfully utilized in practice to provide load balancing of diagnostics devices in a medical sensor network. Device logical scheme is presented in Fig. 6, and Fig. 7 – 8 illustrate one of such devices practical use at clinics: an autonomous infusion drop counter that detects the moment of medical procedure finalization and informs personnel by handheld devices.

The solution was successfully probated at clinic and proved the ability to function in real time with high reliability (up to 20 devices being simultaneously installed at one ward). The developed 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 devices.

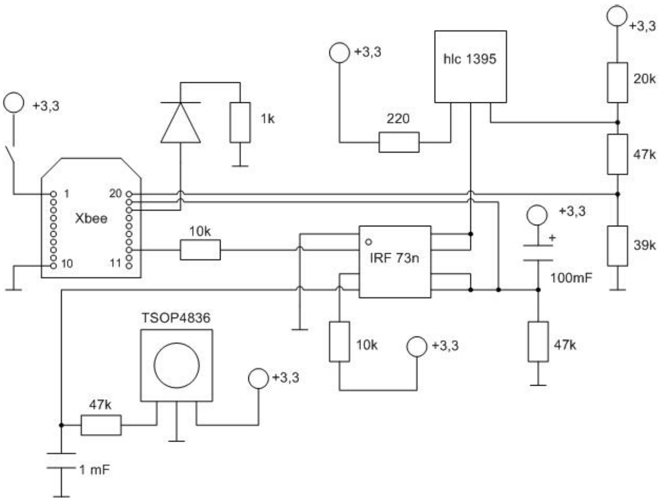

Fig. 6. Diagnostics device logical implementation

Fig. 7. Autonomous infusion drop counter based on self-mediator software

This makes it open for possible extension and integration with heterogeneous software and in demand for practical use at a number of hospitals. New performance capabilities of remote medical patients monitoring using sensor networks provide an opportunity to increase the level of medical service and support humans in their daily living in medical, psychological and social respects. Developments in this area should be first of all oriented to 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 sensors and other medical devices and making them transportable the users expect getting 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.

Fig. 8. Autonomous infusion drop counter deployed at clinics for probation

The proposed solution was also used in a Software Development Kit (SDK) to provide IT developers a platform to build new simulation technologies for medicine. The proposed approach allows the developers of new medical diagnostics solutions to better specify the requirements, concretize the scope, prepare effective tests and improve the efficiency of medical applications.

The proposed SDK architecture contains a number of components that can be used to implement a large variety of medical solutions. Mediator pattern can become a useful tool as a component of this SDK. SDK also contains some other software and hardware components to adjust the simulation scenarios, a universal module platform, and cloud services for technical support and professional communications. Therefore, these common modules should be separated and implemented with a high degree of universality of applications. As every up-to-date information system the diagnostics suites support distributed architecture with cloud services and local information environment build on top of data exchange system.

VI. CONCLUSION

In this paper we have introduced a self-mediator software solution based on multi-agent technology for sensor networks. 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.

The proposed solution has a high potential for practical use, which is proved by the results of its implementation in computer-aided medical diagnostics. One of the first devices developed according to the proposed approach was the autonomous infusion drop counter able to adapt sampling intervals and minimize power consumption and network load with no loss.

VII. ACKNOLEDGEMENT

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