Centralized Healthcare Cyber-Physical System's Architecture Development

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***Abstract* - For many years medical specialists are trying to improve patient treatment methods to increase its speed as well as to minimize treatment process pain. Cyber-physical systems have a huge potential in healthcare for improving treatment quality and patients' assistance speed. Cyber-physical systems will help automatizing treatment process that can be realized by the continuous monitoring of each patient's health state, and if necessary, using multiple medical devices. That allows gathering information about patient's health and perform operations on patients, in order to reduce the progressions of a disease and improve patient's healing process. The aim of article is to research cyber-physical system abilities, CPS application in medicine, and develop centralized healthcare cyber-physical system architecture concept. Proposed concept will allow identifying causes of diseases, research new diseases, provide actual information about existing disease and treatment methods for clinics that are a part of centralized healthcare cyber-physical system, and, finally, automatize patients' health monitoring and remote treatment.**

***Keywords* - Healthcare cyber-physical system, embedded systems, sensor networks, healthcare CPS architecture, centralized healthcare system**

I. Introduction

Since the beginning of time world's best minds try to improve human life and make it easier, and nowadays, when people have a lot of technologies that help to automate most of the work. Year by year people work to develop new technologies that would change an approach of interaction with technologies. The evolution of modern technologies, such as cyber-physical systems, give an opportunity to use these technologies to interact with the physical world and automate physical processes in different fields, such as medicine, and introduce new level of interaction when systems interact with people, not only vice versa.

The main goal of the research is to develop cyber-physical system architecture and application strategies for the use in medical organizations and telemedicine.

Particular attention will be paid to such essential components as usage, architecture, sensitivity, data management, data security and information exchange.

Cyber-physical systems (CPS) are the future for an automated medicine that could guarantee high quality, speed and reliability services in real time, with an ability to save patient's life 24/7, with respect to patient's privacy.

II. CPS Overview

Cyber-physical systems are integrations of real physical processes and virtual computational processes. According to the Cyber-Physical Systems Week - CPS are complex engineering systems that rely on the integration of physical, computation, and communication processes [1]. Nowadays most of everyday used devices are cyber-physical systems.

Cyber-physical systems that interact with physical world will never be operating in controlled environment, must be ready for unexpected conditions and be adaptable to any system or subsystem failures [17]. Chapter contains introduction to cyber-physical systems, their history and overview of their main components and characteristics.

A. From Embedded Systems to Cyber-Physical Systems

The constant growing demand for different purpose information management systems leads to optimization of computing tools design techniques. Most of the current world's used information management systems are embedded systems and networks. They are closely related to the control or management objects.

Embedded systems by the area of use are separated into:

- Automatic control systems;
- Measuring systems and systems that read information from sensors;
- Real-time "question – answer" information systems;
- Digital data transmission systems;
- Complex real-time systems;
- Moving objects management systems;
- General purpose computer system subsystems;
- Multimedia systems.

The concept of embedded systems appeared in the early 50's and its development is still actively evolving. The evolution of embedded systems allowed them to become an essential part of the modern life and be spread all over the world. The integration and security level of embedded system increases, as well as the opportunity to combine them in controlled networks.

Downturn in embedded systems' elements prices, and increased connection with physical management objects led to appearance of cyber-physical systems.

Cyber-physical systems are specialized computing systems that make it possible for software application to interact with

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objects and events in physical world. In embedded systems the main focus is computing elements, but in cyber-physical systems - connection between calculation and physical elements. Cyber-physical systems are used in areas such as medicine, traffic management, industrial and process control, ecological monitoring, industrial robots, and protecting systems. For the wide use of cyber-physical systems in medical institutions it must be adaptive, scalable and cost-effective, providing safety, security and efficiency for all processes.

Wireless sensor networks can become an important part of cyber-physical systems, because of high sensitivity capability, which is one of the main driving factors of cyber-physical systems application distribution. The rapid development of WSN, medical sensors and cloud computing systems makes cyber-physical systems impressive candidates for use in inpatient and outpatient health care improvement [3]. Cloud computing maturity is a direct result of a few technologies such as distributed computing, internet technology, system management and hardware development [4].

B. M2M systems

According to researches [16], cyber-physical systems are the result of M2M (machine-to-machine) application and modernization. M2M refers to the communications between computers, smart sensors, embedded processors, and other devices minimizing human participation. M2M systems have many important characteristics for modern cyber-physical systems [19]:

- Multitude – system contains a lot of different devices that interact with each other that allows improving effectiveness and precision of services. However, it impacts on overall system load and can produce scalability problems.
- Invisibility – devices have to deliver their services without human control, that will reduce amount of errors during work. One of main advantages is that the invisibility allows delivering services without disturbing human.
- Criticality – system elements can be part of life-critical infrastructure, and interact with elements that can irretrievably influence human life, which means that system must have stringent requirements upon latency or reliability.

M2M systems are inseparable part of cyber-physical systems, where main components are electrical devices that communicate with each other.

C. Concept of Cyber-Physical Systems

Compared to embedded systems much more physical components are involved in CPS. In embedded systems the key focus is on the computing element, but in cyber-physical systems, it is on the link between computational and physical elements. Cyber-physical system elements exchange information with each other, which are controlled by computer based algorithms. For this reason, cyber-physical system is denoted by the symbol C3 (Computation, Communication and Control) (see Fig. 1). Link improvement between computational and physical elements, extends cyber-physical systems usage possibilities.

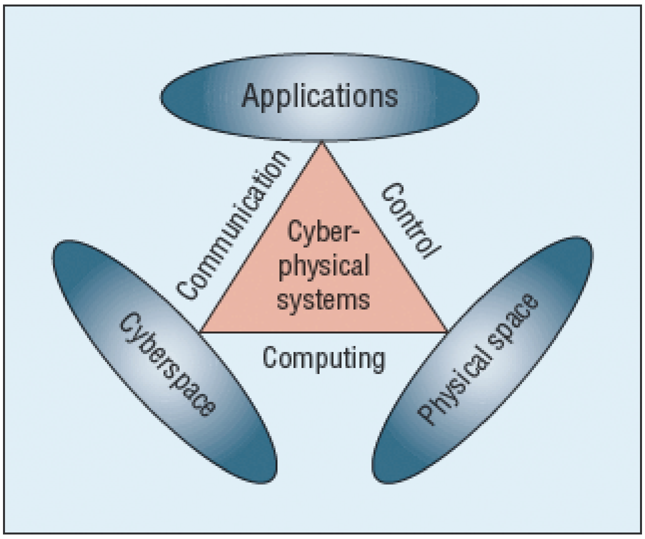

Fig. 1. Three main components of Cyber-physical system [15]

III. Cyber-Physical Systems Application In medicine

Cyber-physical systems are used in multiple areas such as traffic management and security, automotive engineering, industrial and process control, energy saving, ecological monitoring and management, industrial robots equipment, biological systems technology and so on. Comparing usage in these areas with usage in medicine, it is obvious that in medicine cyber-physical systems must be the most accurate, precise and with extremely minimal probability of error to occur. Systems that are designed to help people must not be able to harm their health. For this reason healthcare CPS must be human safe, secure and reliable.

A. Internet of Things and Industry 4.0

A network that consists of multiple electronic devices that communicate with each other is termed as Internet of Things. It connects not only household appliances such as refrigerators, thermostats, but also sophisticated production equipment [[4], [7], [8]]. For medical devices connected to the network for interrelated communication is used a new term – Internet of Medical Things, where all devices are connected to healthcare IT systems. Cyber-physical systems and Internet of Things appeared due to the fourth industrial revolution – Industry 4.0 that was designed to automate and improve information exchange between systems for the use in a manufacturing process, customer relationship management and supply chain management processes, combining it all into one system. Smart manufacturing lines communicate with each other in order to optimize the production process.

The comprehensive use of cyber-physical systems for the commerce, industry and public health, military and civilian purposes, makes the protection of these systems a matter of the national significance. That is why embedded systems security systems, mainly an anomaly detection system that enables a resist spoofing and a service failure type attacks, are currently actively being developed [9].

B. Healthcare Cyber-Physical Systems

Cyber-physical systems are widely used all over the world in the various industries including healthcare. Currently, only a small number of hospitals in the world perform remote operations with the help of a robotic hand and high-resolution cameras [10]. However, there is still a long way to a fully autonomous surgery when cyber-physical system itself, without human management, will be able to perform operations.

Human-in-the-Loop Cyber-Physical Systems can greatly improve lives of people with special needs. Human-in-the-Loop Cyber-Physical Systems formulate notions about the user's intentions based on his cognitive performance by data, received from the sensors attached to the patient's body or head, analysis. Embedded systems convert data from human body to robot control signals, which, due to robotic management mechanisms, allow users with prosthesis to interact with the surrounding natural environment. The example of Human-in-the-Loop CPS is robotic assistance systems and intelligent prosthesis [11].

Healthcare cyber-physical systems can be categorized by application (assisted, controlled), architecture (infrastructure, data requirement, composition system), sensing (sensor type, method, parameter), data management (data integration, data storage, data processing), computation (modelling, monitoring), communication (scheduling, protocol), security (privacy, encryption), control/actuation (decision-making, mechanism) [12].

There is an existing detailed taxonomy already that was developed specially for a healthcare CPS. Existing healthcare cyber-physical systems were mapped to this taxonomy and number of healthcare CPS groups (with several examples) were allocated: notable CPS applications (*Electronic Medical Records, Medical CPS and Big Data Platform, Smart Checklist*), daily living applications (*LiveNet, Fall-Detecting System, HipGuard*), medical status monitoring applications (*MobiHealth, CodeBlue, AlarmNet*), medication intake applications (*iCabiNET, iPackage*.).

Using this taxonomy and mapping, different cyber-physical systems can be categorized. In addition, it is quite convenient to use this taxonomy for formulation of the new cyber-physical system requirements.

IV. Development Process

Cyber-physical system development process can't be realized without the involvement of a different sector professionals, that can adjust system capabilities to the required level for the field of use. Knowledge of computers, software, networks, and physical processes, which will be integrated into the system, is required for a CPS development process [18].

Cyber-physical system, as well as any embedded system design process includes requirements management, project management, test and safety plan.

Real-time operating systems manage embedded systems according to regulations.

The development of cyber-physical systems, which closely interact with physical processes, requires technically sophisticated low-level design. CPS developers are forced to cope with break controllers, memory architecture, processes planning, assembler level programming, network interface design and installation of drivers. However, it would be better to focus on system functionality and behavior definition.

Cyber-physical system used in the healthcare must support wide range of information exchange standards that is used by the most of existing and medically useful devices that receives and, in advance, processes patient's health state information. To store information of patient's health state indicators, system must distinguish information source, and source trust level that can be evaluated by experts, that would allow system to measure data reliability and make decision about an information further usage. [18]

Cyber-physical system's design should be based on the common systems behavior modelling and hardware, software, network and physical processes single design[13].

A CPS design process is an iterative process, which consists of three phases: modelling, design and analysis (see. Fig. 2). In order to develop systems, which will be able to work in the real world, the real world analysis should be performed first, and physical processes identified as well, which will interact with cyber-physical system. Next step is to start development of an abstraction of the real world processes. A model design allows to overcome some of the fundamental problems in the cyber-physical system design, such as security, determinism and time.

Every system is designed to address a specific problem or complete a task. System requirements can be described in a simple language, in a formal way or with models. The formal description reduces the number of possible errors, but modelling serves to illustrate the system dynamics.

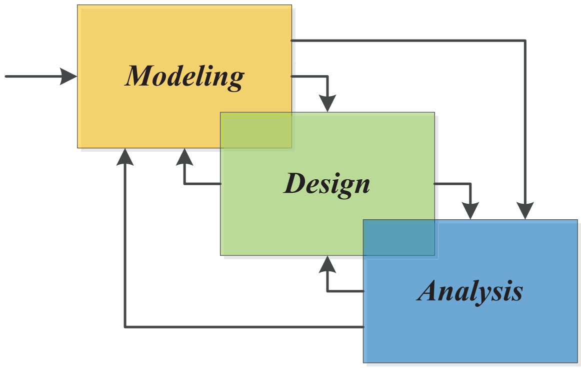

Fig. 2. Cyber-physical system design process

During the process of analysis, the extent to which the system has met the requirements specification can be determined. CPS are either commissioned or altered in accordance with the previous and the new requirements. New desires, needs and requirements for a cyber-physical system will also arise in a process of use.

A set of regulations and standards are applied to all medical systems which indicates that the system is electrically, physically, biologically and chemically safe for the end user. Cyber-physical system sensors generate the sensitive data that must be protected and shared only in a secure manner. Currently there are no standards and regulations, which relate directly to healthcare cyber-physical systems [[6], [12]]. However, it is worthwhile to be acquainted with medical equipment standards, regulations and clinical standards.

The regulations for a medical equipment are similar in several countries, but they are not identical. It means that the same medical device can be recognized as safe for use in medical institutions of the European Union countries, but not in the United States. The European Union is using CE marking to certify a product, that must correspond to EU regulations and standards in United States similar marking is U.S. FDA – United States Food and Drug Administration, that indicate the medical equipment compliance with the USA regulations and standards.

Countries, which have not developed or adopted any medical equipment regulations primarily, apply the WHO (World Health Organization) regulations.

While standards of healthcare cyber-physical systems are not yet developed, a number of industrial, communications (for example, Bluetooth - IEEE 802.15.1, Wi-Fi - IEEE 802.11), quality (ISO 9001, ISO 13845, ISO 14971), medical equipment (ISO/IEEE 11073, HL7 - Health Level 7, DICOM - Digital Imaging and Communications in Medicine) and clinical standards can be applied to them. [18]

ISO/IEEE 11073 is a standards set for personal healthcare devices. The general context of it is data communication and interface between the agent and the manager.

Health Level 7 is a group of standards for the exchange, integration, sharing, and retrieval of electronic health information. HL7 determines many adaptable standards, guidelines, and methodologies that enable communication of various computer systems in hospitals and different healthcare providers. [18]

Medical equipment standards have been drawn up to improve the quality and number of facilities, and equipment interoperability. It is worth to emphasize that in healthcare facilities only certified cyber-physical systems must be in use.

V. Architecture

The architecture of a centralized healthcare cyber-physical system must contain four main layers (see Fig. 3) – Physical layer, Communication layer, Intelligent Service layer and Data Analysis layer that have their specific roles and functionality. All devices, that are used in the system must be certified, according to standards and regulations of the country where medical facilities are located. If country does not support standards and regulations that are used in centralized healthcare CPS, then medical facilities of that country can't be a part of a considered system to avoid problems of inconsistency and keep system's effectiveness for each medical facility in system and patients in advance.

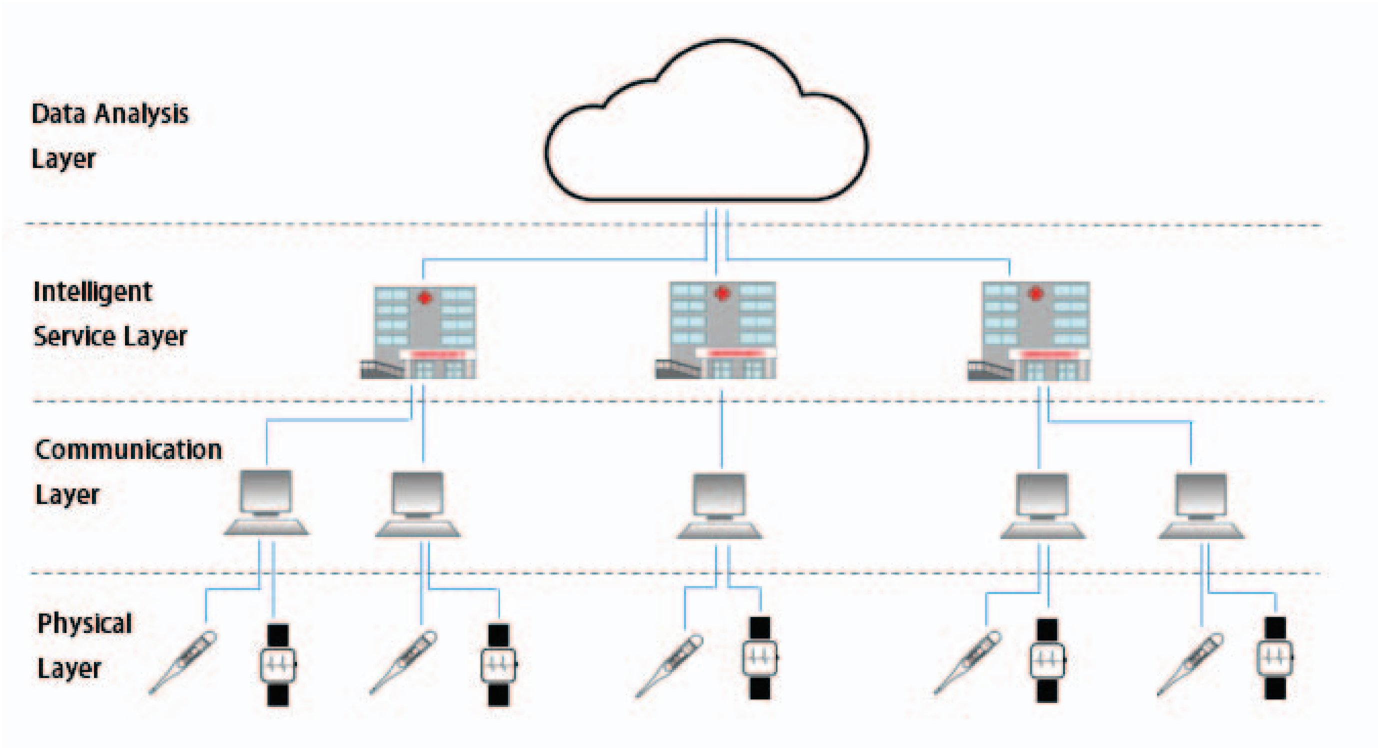

Fig. 3. Centralized Healthcare Cyber-Physical system architecture.

A. Physical Layer

Layer is designed for devices to interact with patients, receiving information about patient health devices send information to the communication layer if any of bound computers are available in range. The most important part of the physical layer is that all devices can receive command from the communication layer and interact with patient according to received instructions considering each other's interaction. All devices must be bound to a computer in a secure way before data interchange to eliminate possibility of data interchange with devices or computer that don't belong to the system.

B. Communication Layer

Collects information from physical layer and send it to Intelligent Service layer. Main role of Communication layer is to be a connecting link between these two layers and make decisions in situations when Intelligent Service Layer is unavailable.

C. Intelligent Service Layer

Manage received information about every single patient, including personal information, information about current health state, diseases history and health index tendencies. To get updated information about patient health it sends history data and new data to the data analysis layer to the receive processed information back, according to the received information the Intelligent Service Layer send commands (if necessary) to the Communication Layer. Communication Layer request necessary information from the Physical Layer or give commands to the devices to help patient.

D. Data Analysis Layer

Process all received information (excluding private information) from the Intelligent Service Layer, and send response back to the requester including information about possible diseases and solutions to prevent or treat diseases. The main role of the layer is to collect information from different clinics and use all received information for further data mining, analysis, discovering new diseases and treatments. Layer is designed for common use, for example, clinics in the EU that support cyber-physical systems can communicate with data analysis layer to get latest information about diseases and its treatments, or send data for processing.

VI. Conclusion

During the research cyber-physical system was reviewed, including evolution from embedded systems, that are the one of the important part of the modern cyber-physical systems. A CPS application in medicine was reviewed as well, that show current situation of the CPS evolution in healthcare field, according to the future prognoses and plans about next steps in healthcare CPS that can be made. Architecture of the centralized cyber-physical system was developed, that allow multiple medical facilities to be a part of one system and interchange information about diseases, treatment methods, and statistical data using data analysis layer.

Using proposed architecture concept, treatment automatization can be reached much faster, taking into account the fact that all medical facility experiences are collected in one place and are analyzed using expert methods, data mining, etc. A continuous monitoring of patients can be attained, using certified medical devices, that in secure manner can interchange data with upper layers and implement commands that can be received from patient's medical facility, using proposed system architecture.

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