Human-Centered Architecture of a Medical Cyber-Physical System

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Abstract. In this paper is presented a dedicated architectural design framework for Medical Cyber Physical Systems (MCPS). This framework is a dynamic event based sensing and monitoring system designed by integrating the full functionality of cyber physical system. The system adapts the concept of local and global awareness for intelligent decision making in physical and cyber world. Moreover, the new introduced concept of human-centered architecture allows improving the efficiency of the decisional process by fusion of data perceived by human senses and environment data measured by sensor networks.

Keywords: cyber-physical system, event driven system, human perception, human-centered architecture, decision making.

1 Introduction

In a previous work [1] an analysis of the current trends in the development and use of medical cyber-physical systems (MCPS) has underlined that medical device industry is undergoing a rapid transformation, embracing the potential of embedded software and network connectivity in a distinct class of distributed systems that simultaneously control multiple aspects of the patient's physiology using a combination of embedded software controlling the devices, networking capabilities, and complicated physical dynamics that patient bodies exhibit. The MCPS requires a large number of dispersed sensors to collect information and high-performance computing to control the physical unit to execute tasks. However, by placing MCPS in a network environment a lot of potential uncertainties in the decision-making process should be solved, while respecting the time limits imposed by this process. Therefore, it is necessary to predict the influence of the result of the decision within the time and the physical environment according to the uncertainty factors. MCPS must be able to combine the characteristics of information world and the physical world to build a stable coalition system, and predict the cyber physical system overhead and performance at the same time. In the decisional process, the person is the designed initiator, while the physical unit is an interactive bridge of the digital world and the real environment.

Accepting the decisive role of the person in decision-making, this paper aims to describe a human-centered CPS architecture. Such system needs to collect environmental information, personalized information and human behavior information, then transform the information into useful knowledge for understanding environmental and people. The architecture is a multilevel layered one and includes the concept of data aggregation, knowledge classification and enrichment based on events generated from the physical world.

2 Related work

Even if at about 8 years after US National Science Foundation (NSF) has identified (in 2006) cyber-physical systems (CPS) as a key area of research [2], the concept of CPS is not unified as a clear definition, one can consider for the distinct class of medical CPS the approach of Lee and Sokolsky [3] which believe that MCPS is a assembly which integrates computing medical devices, communications, and physical processes, embeds computer real-time monitors and controls the physical process is satisfactory. There are three common points of these theories: 1) interconnection by network between the computation system and the physical system; 2) monitoring capabilities; 3) real-time performance. What we intend to bring to your attention is the constantly increasing role of human factor in the decision to be taken as a result of the events that cause changes.

Event based approach for systems' control is becoming a hot topic in different domains. Makedon *et al* [4] presents an architectural framework to assist human's daily activities using identification mechanisms for events that influence the actuators and alter the human behavior in a closed loop process. The advantages of the framework are dynamic context awareness, adaptiveness, self-repairing and high confidence that couples computational power with physical testbed control. A similar idea can be found in [5], where the authors propose a human-interactive HILS (Hardware-In-the-Loop Simulation) framework developed to support CPS reliability and reusability in a fully distributed operating environment. Yuanyuan *et al* [6] suggest a dynamic hierarchical model for health monitoring system which adapts fusion of event driven context model. Don *et al* [7] propose an architectural design framework for remote health care monitoring system. This framework is a dynamic event based sensing and monitoring system designed by integrating the full functionality of cyber physical system. The system adapts the concept of local and global awareness for intelligent decision making in physical and cyber world.

Efficient communication is needed between physical world and the cyber world. Kyoung *et al* [8] present a novel information centric to support CPSs. The architecture is based on a cluster of real time embedded databases which communicate and control wireless sensors networks to extract important collective information. From the above surveyed research papers, the most important is model design frameworks. Such a framework having the potential to manage different events from different sources, aggregate those events and generate meaningful information augmented with those offered by the human perception system will be discussed in the next section.

3 Design principles of a human-centered CPS architecture

Medical cyber physical systems combine both physical and cyber world resources. Fig. 1 shows the proposed architecture.

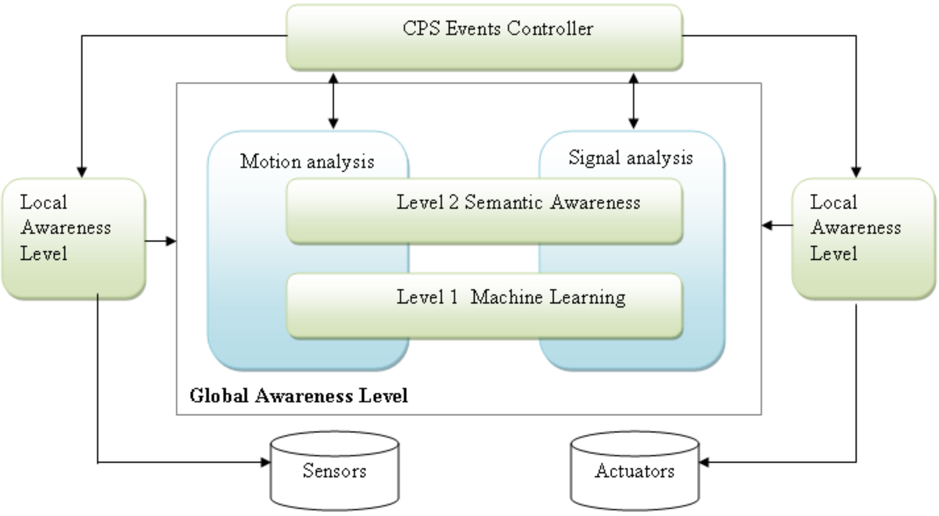

Fig.1. MCPS architecture

Two types of data analysis were considered in the design stage. The first one is the motion analysis which includes capturing the body motion of a patient for analyzing the patient behavior. The second one is signal analysis i.e., analysis of the data received from various sensors connected to the patient. This architecture is based on two levels of data processing. The lower (Level 1) is the machine learning which includes different algorithms for event identification. The upper (Level 2) is the semantic awareness level. At this level the system can generate the highest interpretation about the current situation semantically. The system is generic multi-layered architecture with the following components:

1) Sensors and Actuators: Sensors captures motions and signals that provides a communication interface between physical and cyber world. The signal sensor captures various body parameters such as ECG, blood pressure, temperatures etc.

These signal attributes can represent various body conditions of a patient. The motion sensors capture various body movements. With the help of actuators the systems are able to change the physical attributes such as triggering alarm, wheel chair movement etc.

2) Local and Global Awareness: Awareness is an understanding of the activity of others, which provides a context for your own activity. From the proposed system point of view, Global awareness is the ability to sense and retrieve meaningful information from the physical and cyber world as a single entity, whereas local awareness is the ability to sense the physical world as an individual entity.

3) Local Event Controller: An event can be defined as any occurrence in the physical world at a specific time and location, denoted by E. The type of event considered are the events generated from different biophysical and motion sensors. The local event controller process the events based on local event policies, and only those which are meaningful will be send to the cyber world for further analysis. Each event is characterized by set of features (the event header) $E=\{E_a, E_i, E_t, E_l\}$ where E_a is the event attribute, E_i is the event identification. E_t is the time at which the event is occurred and finally E_l is the location where the event happens. Event policies are set of policies based on the conditional operators *CO*, each of them having a fixed set of preferential choices by which the event can be further processed or discarded.

The triggered events from the physical world, with the help of communication channel will be received at the cyber space. The received events are then stacked as either motion analysis unit or signal analysis unit depending on the type of event received. The received signals are then processed by the CPS event processing controller. CPS event processing is an inner closed loop controller by which the received events are further processed. The preprocessed events accepted by the policy manager are forwarded to different levels for processing. In our system, we have proposed two levels which can process individually and take action based on the status notifier. Status notifier works as the same concept of lookup tables. It checks the events and provides meaningful information for selecting the levels inside the controller. Level 1 includes machine learning algorithms for predicting simple events. Level 2 will be considered if the system needs a global awareness of the event happening at the physical world. The corresponding actions are taken in each level in the cyber space and forwarded to the physical world for taking necessary actions in real time.

4 Human perception-based decisional process

In a MCPS, human always plays an important role, being in the same time the object of the system services and the decision maker. CPS is the communication bridge of the physical world and the digital world. People play a leading role in the physical world; therefore, the systems not only need to perceive the environment, but also perceive the people. With the aid of the human perception system one can help the system to act in the form the people perceive the world and thus approaching closer to the people's decision-making in order to enhance the intelligent effect of the decisional process.

The human perception system is usually divided into sensation and perception. The sensation is the reflection of individual properties that directly act on the individual sensory stimulation, including external and internal feeling. External feeling is caused by an external stimulus, reflecting the sense of the characteristics of external things, such as vision, hearing, smell, taste and feel of the skin. The receptors located on the body surface, as skin sensory receptors and taste receptors are known as contact receptors, while visual, auditory and olfactory receptors, which can detect external things at a distance, are known as long-distance receptors. Internal feelings, also known as the body's sleep, relative to reflect the feeling of the external environment such as vision, hearing, feeling reflects the internal state of the body and internal changes, including the use of feeling, sense of balance and visceral sensation.

The perception is the procedure that organizes individual sensory information into meaningful perception, object perception and social perception. The CPS system is more concerned about physical perception. Object perception is the perception of material things and external relations. Any matter or thing present spatial characteristics, time features and movement change. Therefore, the perception of the object includes space perception, time perception and motion perception. The spatial perception reflects the perception of the spatial characteristics of the object like shape, size, depth, orientation, etc. The time perception reflects continuity and sequence of the objective phenomenona. Motion perception reflects objects spatial displacement and speed.

All external stimulation perceived by humans must first be received, stored and analyzed by the human perception system, and then can have effect on people. Sensory reacts to appropriate stimulation and process the information, thus forming a meaningful sense of perception, then filter, according to the subjective demand, in order to select only useful information, while ignoring other insignificant things. At this point, we can consider that the human sensory system can complete the data collection in the physical layer of the CPS system, and the organization of the perception system knowledge base and of the CPS system knowledge base are very similar.

In is true that in early CPS system, people and physical units (sensors) perceived the environment, gathered information, analyzed the data collected, made decision, and finally complete the execution of tasks by sending control commands to the remote execution unit. However, with the advance of the intelligence in the CPS system, information analysis and decision-makers gradually shifted from people to computing unit. People only need to perceive the environment and make the demand, and then the computing unit and physical unit deal with all the subsequent work. In order to allow the computation unit to take decisions that meet people’s need, we need to understand and perceive the environment from people’s perspective.

Based on the CPS architecture of human perception, the computation unit is divided into three levels: the computation layer, network layer and physical layer (see fig. 2). The computation layer is the core of the CPS system, where data storage, decision-making and the formation of a knowledge base are. In other words, knowledgebase is the brain of CPS. The purpose of the knowledge base is to make the machine to understand better the data meaning, and its role is similar to the perception, ultimately in order to assist decision making. The formation of the knowledge base not only allows the data to fit into the system, but also improves the efficiency of decision-making. The network layer is a communication layer in the CPS system, primarily as a channel of communication exchanges, in which routing, data transmission, data forwarding etc. are completed. The physical layer is the interactive terminal between the CPS system and the physical world, where sensors are used to collect the data of the physical world, and actuators to change the physical world environment. Thus, at the same time of the perception of the physical world, CPS system also needs to perceive people by perceiving what people perceive.

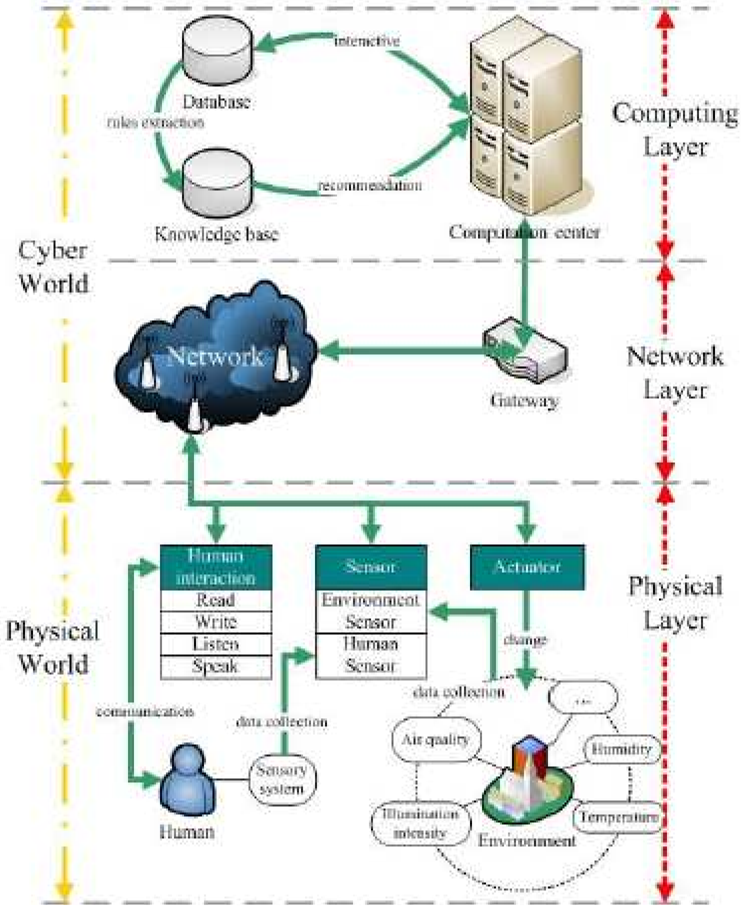

Fig.2. Human sensory architecture for MCPS

The physical layer of the CPS architecture based on the human perception includes interactive communication function. The communication interaction according to people's exchanges is divided into reading, listening, speaking, writing and observing; the traditional human-computer interaction command is initiated by the way of writing commands input through the keyboard and other external devices. The system then starts to execute commands after reading inputs. However, with speaking and listening added to this behavior, one can improve the performance of a more complex CPS, while simplifying the operation of human behavior, so that the human-computer interaction is more convenient. Observation is a deeper interaction; if the system can observe the behavior of the person and analyzes it to identify the human needs, it can play a very good supporting role on decisions classification and prediction. Moreover, by the system self-learning the system is able to improve the decisional process, mostly by observing the timely receipt of feedback after the task is completed. In general, interactive communication can lead on the one hand to the optimization of information processing, and on the other hand, can improve the convenience of the human-computer interaction, using a variety of means of communication that makes easier to convey the demands to the system, capable of making the formulation of a strategy closer to the people's need.

Unlike the traditional process control systems whose architecture basically centers on machines for the acquisition of environmental information and for the execution of tasks according to specific rules, the CPS architecture based on human perception will understand multi-faceted information by its own knowledge base on the environment status, and will apply dynamically adjustable rules for performing tasks. The CPS data may be divided into environmental, human, time, positional and historical information. The system unifies the existing rules to formulate the decision-making according to these five types of information. Time and location information is the key relationship between human and environment. Historical information is in order to find the context of data information and rules that can discover a way to deal with the similar issue. Therefore, it is the simplest step to enhance the function of efficiency. Data acquisition is basically completed by sensors, but in a human-centered CPS architecture, the information is separated in two categories: human data and environment data. There is an internal link between human and environment information which offers a certain significance that is the same under time and space and hence, make time and space information as a condition for the human and environment data fusion. After this information fusion, the system could make a reasonable decision by using the knowledge base, and then send the appropriate command to actuators. If the result is not ideal, one can return to the knowledge base, adjust the decisions and proceed to the new execution, until satisfied. To summarize, let mention the steps of the decision making process in a human-centered MCPS :

1. Getting of the human and environment information
2. Filtering the imperfect or insignificant information
3. Storing data to database
4. Time and space based human and environment data fusion
5. Decision making by using data fusion and knowledge base access

6. Send commands for execution by actuators
7. If the result is unsatisfactory, return to step 5
8. End the decisional process

5 Conclusions

The proposed human-centered architecture for a MCPS work on the principles of event based classification and interpretation. By introducing the concept of local and global awareness the method can achieve higher understanding between the physical world and the cyber world. On the other hand, correlation of environment data from sensors (in particular from the body area networks) and information from the human perception system guarantees an improvement of the decisional process, primarily by reducing the computation time and storage, secondly by enabling performance improvement by iterative feedback adjustments.

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