Systems-of-Systems Framework for Providing Real-time Patient Monitoring and Care

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ABSTRACT

While the importance of System-of-Systems (SoS) is widely recognized, today's missing support for real-time and reliability requirements limits the realization of SoS in safety-relevant real-time applications. Today's reliable embedded real-time architectures are not suited to deal with the openness, dynamic nature and lack of global control in SoS. This paper describes a framework for providing scalable and effective monitoring services for patients' health and conditions to help them to rehabilitate and recover from their illnesses. Different from most of the proposed work in the literature, this framework utilizes the concept of systems-of-systems approach in sensing, analyzing the patients' information data, and issuing real-time alert messages to the healthcare monitoring center and proposes mechanisms to efficiently deal with the reliability and real-time data delivery challenges that are very essential in healthcare monitoring and reporting process.

Keywords

System-of-Systems, E-health, Healthcare monitoring, Real-time communication, Scheduling, Reliability, Time Triggered Ethernet, Wireless communication

1. INTRODUCTION

In recent years, the number of people suffering from multiple chronic conditions is growing. An important demographic fact is the increase in percentage of people with chronic conditions that depend on the healthcare system and require costly long-term care, especially with elderly people. In order to provide an integrated system that can monitor and report the conditions of people as they travel through their everyday life, and then to make informed decisions on their care, based on this information, an integrated healthcare system supported with robustness, reliability and real-time capabilities is needed to ensures smooth patients' rehabilitation and recovery.

The potential benefits of Systems-of-Systems (SoS) in healthcare applications are already clearly recognized, and societal trends indicate that they will be attractive to a large and increasing number of people. As a part of the medical SoS, the elderly people environment will be equipped with sensors to obtain a range of normal and abnormal medical data (e.g., cardiac sensors, pulse oximetry sensors). If the analysis of the sensor data indicates that anything abnormal is happening, an alert will be generated to enable a safe, timely and efficient handling of the patient. Building such a medical SoS is challenging due to the fact that the system monitors patients in different ambient assisted living spaces (homes, and care centers for elderly) as well as the development of distributed embedded system architecture for constantly evolving and dynamic SoS with support for verifiable real-time, reliability and safety properties.

This paper provides a SoS framework for patients' healthcare monitoring and reporting, that takes into account data delivery reliability and real-time assurance among several patients, each represented by a Constituent System that can be either locally distributed (in different rooms in a hospital for example) or regionally distributed (in different houses for examples) within certain geographical area. The remainder of this paper is structured as the following. Section 2 reviews related work. In Section 3, we describe our proposed framework and approach. Finally, the paper concludes with a road-map towards future research in Section 4.

2. RELATED WORK

The SoS paradigm is getting increasing attention in the design of large systems such as healthcare systems.

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The authors in [1] provided a comprehensive literature review of some solutions that aim at building platforms for real-time health monitoring that use wearable wireless sensors to monitor the patients' health information. Examples of these platforms are: Mobihealth [4], Telemedicare[1], Osiris-SE[2] and PhMon[3]. The clinical safety and effectiveness for a medical application platform is addressed in [2]. Modelling and tooling was addressed in the VAALID[4] project.

There are, however, critical challenges that must be tackled in order to leverage the results from these initiatives; system robustness, reliability and real-time capability are not addressed in the state-of-the-art architectures. In this paper, the system architecture is introduced to support reliable closed loop control with stringent real-time requirements for applications such as medical monitoring and therapeutic support.

3. FRAMEWORK ARCHITECTURE

In this section, a general description of the SoS framework will be given, then it will be customized to the context of patients' monitoring and healthcare. As depicted in Figure 1, the SoS framework comprises Constituent Systems (CSes), each of which consists of a set of the medical devices and actuators connected to each other through wirebound or wireless communication networks. We distinguish between the behavior within CSes and the coordination between them. To support this interaction, it is planned to deploy in each CS a Constituent System Manager (CSM) and an Inter-Domain Gateway (IDG). In fact, this architecture is inspired from the Internet network hierarchical architecture where there are two levels of networking and communications, the intra-domain level where nodes communicate within the same domain specified by the Autonomous System (AS) using specific communication protocols such as the Open Shortest Path First (OSPF) intra-domain routing protocols for example, while inter-domain communication process takes place between different AS domains and run another suit of communication protocols such as the inter-domain Border Gateway Routing Protocols (BGP). Such a hierarchal architecture proved itself to be both efficient in reducing the communication overhead and reducing the end-to-end delay, and extremely scalable in the Internet context, which is quite applicable to our SoS framework that requires both high efficient communication processes and scalable, flexible and extensible capabilities. Further, an IDG is used to manage the communication process between different CSes, especially when each CS may have different communication media and protocols, such as the case of having a wireless communication media and protocols within the CS and wired media and protocols between the CSes or vice versa. In what follows, a description of the proposed SoS in the context of healthcare monitoring is provided. As depicted by Figure 1, the CSs can be represented as patients who need healthcare monitoring and follow-up. Notice that each CS has a group of medical sensors and actuators connected to a processing units that report their measurements and communicate with the Analysis and Notification Unit (ANU) using an intra-domain communication protocol. A detailed description of the CS components is provided in the next subsection.

3.1 Constituent System Components

This subsection presents a description of the CS components and functionalities, followed by two main mechanisms used to assure real-time delivery and reliability to the patients' captured data.

3.1.1 Monitoring Sensors and Actuators

The main purpose of these components is to provide timely and accurate information about the monitored events. In our case, the patients' health information. For example, blood pressure, skin temperature, heart monitoring, oximeter, glucose level, etc. Each sensor is attached to a processing element; a microcontroller for example [5], with a wireless transceiver that enables the sensor to send its information over the wireless channel to the ANU for further analysis and processing.

Notice that in some scenarios, where sensors' physical locations are close to each other, several sensors can be directly connected to a single microcontroller. For example, a skin temperature sensor and a blood pressure sensor are normally close to each other and can be both connected to a single processing element, while a video monitoring sensor, which is normally placed far away from the patient, will be connected directly to another processing element. In this configuration, the processing element has several crucial roles in managing the sensors' communication and data dissemination process, which in turns will result in a better usage of the wireless spectrum, less communication overhead, less interference, and fast transmission. These roles can be summarized as follows:

- Early data analysis and recording

  The processing element can analyze the sensed information values and if it is below or above certain thresholds, then it will send it to the ANU. This is much more efficient compared with the other schemes where the sensors continuously access the wireless channel and always send their information to the ANU, which may cause interference and collision especially in cases where there are large numbers of sensors and monitored patients.

- More efficient media access mechanisms and scheduling

  Access to the wireless media channel is very crucial in providing real-time data transmission and dissemination. With the existence of distributed scheduling algorithms (discussed later), different sensors can access the wireless channel more effectively without loading the wireless channel with collided and resent packets.

[1]Telemedicare project

[2]OSIRIS-SE project, "Runtime Environment for Data Stream Management in Healthcare"

[3]PhMon project, "Personal Health Monitoring System with Microsystem Sensor Technology"

[4]Accessibility and Usability Validation Framework for Ambient Assisted Living (AAL) Interaction Design Process, FP7

[5]With the extensive spread of smartphones, the processing element can be also a smartphone with the proposer applications designed for that purpose.

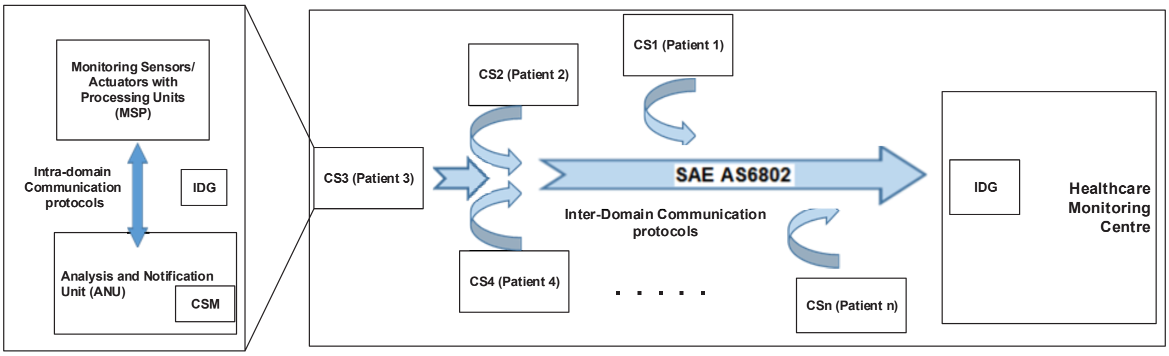

Figure 1: Healthcare Monitoring SoS

Further, each sensor can have a different priority for accessing the channel.

- Power and energy saving in sensors batteries

  In this design, sensors' do not need to continuously send their information via the wireless channel, which requires significant amount of energy, especially for long distances, instead, sensors will convey their data to the processing element that is close to it.

3.1.2 The Analysis and Notification Unit

The ANU described earlier as the Constituent System Manager is the brain of the CS where critical data sent from various sensors via their processing elements is analyzed and a decision is made and sent to the healthcare monitoring center, where emergency doctors look at the sent alert messages and take appropriate actions. In addition, this unit also receives the sensors' log data and sends it to the healthcare center for archiving and later viewing and analysis.

3.1.3 The Inter-Domain Communication Protocols

In order to send the captured and analyzed data to the ANU, a communication protocol is provided that is responsible for providing the appropriate communication media and access among all sensors' processing elements. In this proposed system, this communication protocol has the major role of delivering the patients' data in real-time to the ANU.

Real-time assurance on delivering the patients' information, especially when an emergency case happens, is extremely important and it is a lifesaving process. In the proposed framework, the sensors' processing elements have to send their information to the ANU in a timely manner, which in turn will be sent to the healthcare center for further processing and response. As such, several mechanisms have to be deployed to assure real-time delivery for this information. In the following subsections, two mechanisms that are still under development are described to achieve that purpose: scheduling and data protection and prioritization.

1. Scheduling

   The goal of the scheduling mechanism is to develop distributed algorithms for online scheduling in a healthcare SoS consisting of multiple CSes each with a time-triggered communication network.

It is important to mention that the scheduling mechanism will be managed within the single CS (with different sensors belonging to one patient) and between different CSes (between different patients). The static control structure of present-day systems with time-triggered protocols is not suited for SoS. While several protocols improve flexibility with additional event-triggered communication primitives (e.g., rate-constrained and best-effort communication in TTEthernet), the time-triggered schedule is built off-line and remains fixed at run-time. Off-line scheduling and schedulability analysis of time-triggered systems have been intensively studied during the past years (e.g., OSIRIS-SE and PhMon projects). [3] presents an algorithm to handle event-triggered sporadic tasks based on offline schedules. The use of a plug-in approach to add functionality to existing scheduling schemes is proposed in [6]. However, online scheduling and reconfiguration in time-triggered communication networks based on real-time and reliability requirements is an open research problem. Furthermore, the heterogeneous natural of the SoS is another challenging aspect that should be taken into account, when designing the scheduling algorithms, since within the CS, some sensors may have time-triggered capabilities, especially the one with wired connection, while other sensors may not have such capabilities (wireless sensors for example), which may require a gateway device that interfaces the wireless devices with the time-triggered network.

The conventional scheduling problem involves the definition of an input model that describes the scheduling problem, followed by the search for a feasible schedule using a scheduling algorithm and the adoption of the feasible schedule [7]. During the search, the input model remains fixed. In a SoS, this assumption of a strictly sequential process is unrealistic. Rather, further change requests for the input model must be incorporated while the scheduling is ongoing. The concurrent processing of change requests with consistent scheduling results is a novel research problem. For example, when adopting a new schedule for a given set of change requests in one CS, the other CSes should adopt corresponding schedules to satisfy the dependencies between CSes. Also, when new change requests arrive, intermediate schedule results must be mapped to new input models in order to prevent the invalidation of prior search results.

To achieve that, we will extend previous scheduling algorithms for time-triggered systems [7] to support distributed scheduling with constrained knowledge about other CSes, as well as concurrent change requests to the scheduling problem. The scheduling results will include the configuration parameters for the CS as well as the configuration parameters for the interaction between them. We plan to support standard Internet and Ethernet protocols (e.g., IEEE 802.1 standards) where scheduling results include parameters for traffic shaping, priority assignment and clock synchronization (e.g., 802.1Q, 802.1AS). A candidate for a wire-bound protocol within constituent systems is Time-Triggered Ethernet (SAE AS6802) [8], for which the computation of a time-triggered communication schedule will be performed. Candidates for wireless protocols are WiFi, Bluetooth and Zigbee. However, with the existence of different communication media, one should take into account that the overall communication architecture needs to be heterogeneous.

2. Data protection and prioritization

   Delivering data without any errors and in a real-time manner is of high importance in the proposed SoS framework, especially in the case of wireless media channels. In order to provide the sensors with access control to the media channel, as described above, a scheduling mechanism will be proposed that takes into account the time constraints for each sensor. This scheduling mechanism will be designed while also considering reliability issues. QoS assurance and reliability are very important in wired and wireless media, and it is more urgent in wireless media due to the fact that data is prone to both packet loss and bit errors. The framework will be designed in conjunction with the scheduling algorithm to assure delay constraints of the sensors and to support suitable error protection and correction mechanisms. In the literature, there are many data transmission frameworks proposed to protect data from transmission errors using different mechanisms such as error correction and detection code, the prime example of such code is the Reed Solomon Forward Error Correction codes [5].

3.2 Healthcare Center Unit

After describing the CS components and communication requirements, it is important to complete the cycle and describe the Healthcare Center Unit (HCU) and its role in communicating with the CSs.

As can be seen in Figure 1, each CS represented by its ANU needs to send its information to the HCU Inter-Domain Gateway for further processing and decision making. The IDG is simply a processing node that accepts the sent information from the ANU which may be from a different communication network such as the wireless media, and relays it to the HCU network, which is normally a wired network. Normally, physicians and healthcare personnel monitor these notifications and may take actions for their patients. To achieve that, an inter-domain communication protocol is used which has similar functionalities to the intra-domain protocol in terms of scheduling, real-time data assurance, and data protection and correction. However, here the scheduling will be among different CSes utilizing the TTEthernet technology.

4. CONCLUSION AND FUTURE WORK

This paper presented a SoS framework for healthcare monitoring service, with particular focus on the real-time data assurance and reliability. As this is an ongoing research project, we are currently designing the proper scheduling algorithms and data protection and prioritization mechanisms. Besides, we are investigating other important factors such as security and privacy.

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