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Article

Embedded Intelligence in IoT - Based Mixed-Criticality Connected Healthcare Applications: Requirements, Research Achievements and Challenges

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Abstract: Technology advancements are evident in the healthcare field; numerous new opportunities and applications have emerged during the last years based on embedded intelligence and related to real-time diagnosis of medical issues, tele-care and telemedicine, remote monitoring of patients, computer-assisted "smart" transportation in case of emergencies, as well as new types of remotely controlled surgical operations. This paper aims to provide an overview of the application of embedded intelligence in the field of healthcare; it gathers the main critical requirements, related technologies and research advancements up to date, and it presents the most important challenges that are yet to be faced. The main focus is given in the development and optimization of Body Area Networks (BANs) based on advanced embedded sensing devices, the optimization of smart gateways in such networks, and the provision of holistic scalable and secure solutions in the healthcare domain. In addition, the paper presents two principal use cases that stem from the combination of novel information and communication technologies with classic healthcare practices, explaining the functional and non-functional requirements, as well as the mixed criticality characteristics of the associated systems.

Keywords: Embedded Intelligence, Body Area Networks, Healthcare applications, Remote Elderly Monitoring, Smart Ambulance System

1. Introduction

In our modern era, the Internet governs almost every aspect of our daily lives. In recent years in particular, Internet-based solutions have been applied in the sensitive domain of healthcare and medicine. The advent of the Internet of Things (IoT), the rise of the Cloud and on-demand computation and storage, as well as the proliferation of sensors and ubiquitous wireless communication are expected to drive revolutionary approaches in healthcare activities such as: real-time diagnosis of medical issues, tele-care and telemedicine, remote monitoring of patients, computer-assisted "smart" transportation in case of emergencies, as well as new types of remotely controlled surgical operations. Such approaches can be implemented via new types of systems-of-systems (SoS), which are mainly composed of hardware (e.g., sensors, smartphones) and software (e.g., specialized OSes, Cloud services) that can execute several applications of different criticality. Healthcare is traditionally a domain requiring mostly safety-critical core systems and functionalities, since human lives can be jeopardized by a faulty implementation.

Moreover, the complex information and communication technology (ICT) systems involved may also include mission-critical or non-critical peripheral components.

Towards this direction, one of the key technology advancements is related to embedded intelligence, which can provide significant possibilities for the field of healthcare. Intelligent wireless networks can assist patients and their caregivers by providing continuous medical monitoring, memory enhancement, control of appliances, medical data access, and emergency communication. The IoT is in the revolutionary road and it will remodel the healthcare sector on the way in terms of social benefits and penetration as well as economics. Enabled by ubiquitous computing, all the healthcare system entities (individuals, appliances, medicine) can be monitored and managed continuously [2]. The IoT's connectivity provides a way to monitor, store and utilize health and wellbeing related data on a 24/7 basis [2] and enable the IoT related data and services to be ubiquitous and customized for personal needs [3].

In the light of the above, the contribution of this paper is manifold. In particular, the paper provides an overview of the application of embedded intelligence in the field of healthcare through outlining the main critical requirements and related technologies, presenting the research advancements up to date, as well as through discussing on the most important challenges that are yet to be faced. To do so, the main focus is given in the development and optimization of Body Area Networks (BANs) based on advanced embedded sensing devices, the optimization of smart gateways in such networks, and the provision of holistic scalable and secure solutions in the healthcare domain. Moreover, the paper presents two principal use cases that stem from the combination of novel ICT technologies with classic healthcare practices, explaining the functional and non-functional requirements, as well as the mixed-criticality characteristics of the associated systems. The rest of the paper is structured as follows. The next section discusses materials and methods focusing on embedded intelligence in healthcare, and specifically on its requirements, research achievements and challenges. Section 3 exemplifies the above by describing the results focusing on two indicative related use cases, namely the Remote Elderly Monitoring System (REMS) and the Smart Ambulance System (SAS), followed by the relevant discussion. Finally, the last section contains some concluding remarks and outlooks for future work.

2. Materials and Methods

2.1. Introduction: challenges and requirements for embedded intelligence in healthcare

Healthcare is expected to significantly change the way it is provided during the next 10 years; moving from hospital-centered, first to hospital-home-balanced in 2020th, and then ultimately to home-centered in 2030th [1]. This upcoming change is directly related to the fact that the convergence and overlap of the IoT technologies for healthcare domains and smart spaces in general need to be more actively considered. Towards this direction, body/personal/local area networks have been evolving. In a Body-Area Network (BAN), various sensors are attached on clothing or on the body or even implanted under the skin [13]. This new communication approach can be used to continuously monitor health features such as physical activity, heartbeat, body temperature, blood pressure, ECG (electrocardiogram), EEG (electroencephalography) and EMG (electromyography) and therefore improve human health and the quality of life. BANs provide a technological infrastructure for remotely streaming sensor data to a medical doctor's site for a real-time diagnosis, to a medical database for record keeping, or to a corresponding technological equipment that, pro-actively and autonomously, can issue an emergency alert or intelligently manage this information for taking suitable actions and improving the quality of human life [14].

For such networks, that may for example be implemented and linked with a smart hospital, gateways can play a key role. Gateways in these applications act as a hub between such networks and a remote health center. These gateways, being usually static, are non-resource constrained in terms of processing power, power consumption and communication bandwidth. This luxury may be exploited by outsourcing some burden of resource-constrained sensors to be performed on the gateways, and on the other hand, it can be used to add some levels of intelligence to its basic functionalities and extend its role to an intelligent embedded server [25]. The optimization of these gateways remains a critical requirement and challenge these days; at the same time the efficient operation of BAN is also a critical challenge. The rapidly advancing electrical sensing techniques and organic electronics have contributed to significant progress in the development of flexible pressure sensors, which possess unique advantageous properties such as outstanding flexibility, low cost, and compatibility with large-area processing techniques [7][8][9]. Through large-area integration of flexible devices, active sensing matrices have been fabricated which tend to be ideal candidates for electronic skin (e-skin) applications. Interest in integrated networks of sensors is also motivated by the promising applications in intelligent robotics, which greatly promote the advancement of embedded intelligence systems. Mobile biomonitoring in medical diagnostics and healthcare is another attractive application for embedded sensors; at the same time, the advent of organic material based flexible pressure sensors offers a novel potential opportunity to develop these applications [10]. But these implementations impose numerous challenges, including the transmission protocols, data privacy and security and others.

Finally, many smart phone apps are becoming readily available for physiological status monitoring [2][3][4]. However, despite being an important step towards personalized medicine, these solutions often suffer from scalability, security and privacy issues. Furthermore, such solutions are only able to provide a snapshot of physiological conditions rather than a continuous view of the overall health over the course of many years. With recent advances in sensor networks research we are already embarking on the path of revolutionary low-cost health care monitoring systems embedded within the home and living environments [5] [6]. Ambient intelligence technology can be used to monitor the health status of older adults or people with chronic diseases, and it can provide assistive care for individuals with physical or mental limitations. It can be used for developing persuasive services to motivate people to lead a healthier lifestyle. It also can be used in rehabilitation settings or in general in enhancing the wellbeing of individuals. Ultimately, it can support the health care professionals in terms of providing innovative communication and monitoring tools. These systems will provide health monitoring in a transparent and unobtrusive way; but it is critical to ensure holistic scalable and secure solutions in order for these systems to be efficiently applicable.

2.2. Research Achievements

Numerous research achievements have tried to deal with the challenges and requirements presented in the previous sections. These challenges and their relative technology advances are summarized in Figure 1. The overall implementation required the definition of healthcare applications (e.g. product monitoring, care plans improvement, disease detection etc.), the technical integration (including virtualization, low latency applications, proximity optimization etc.), the industry collaboration realization (focusing on standards and IoT applications based on cloud facilities) and the business transformation (including revenue generation, time to market minimization and new markets creation).

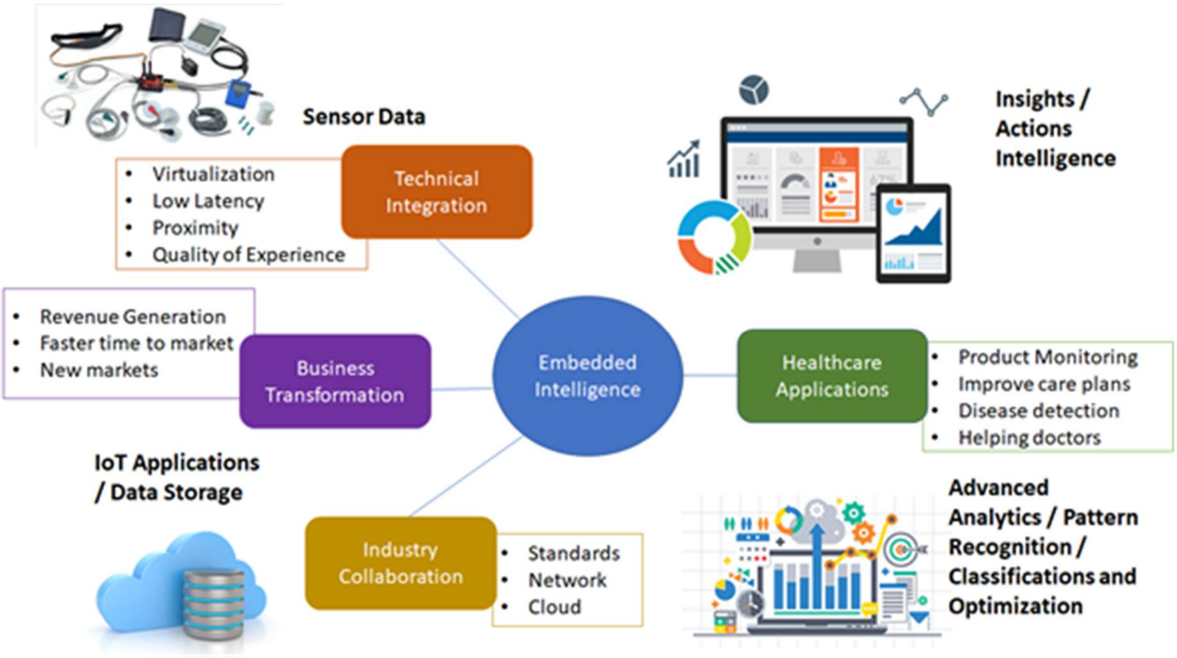


Figure 1: Summary of Challenges on applying Embedded Intelligence in Healthcare

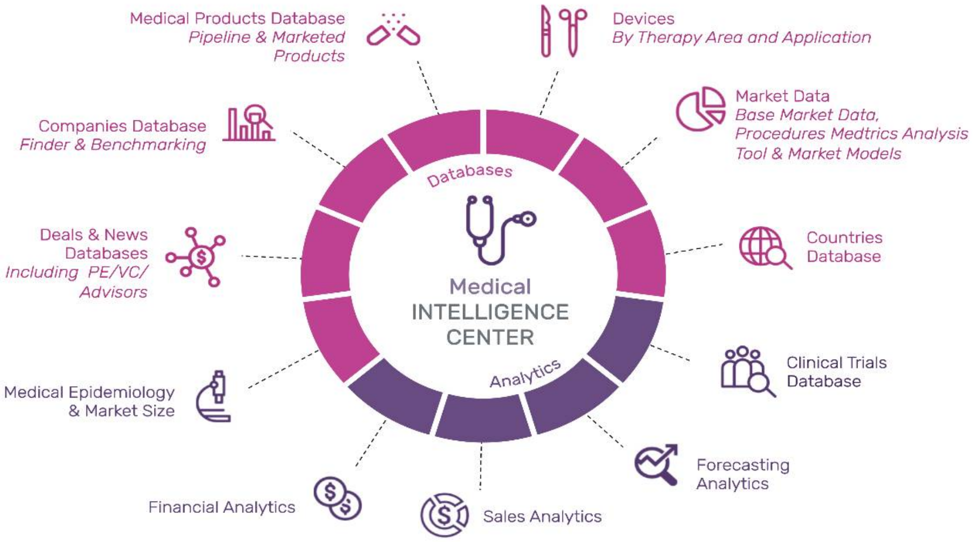


Figure 2: The Medical Intelligence Center [11]

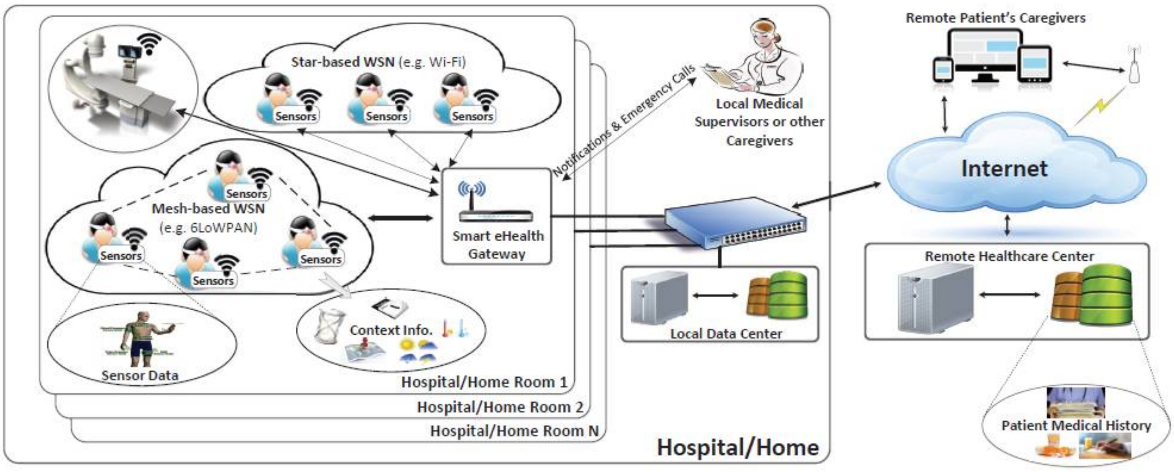


Figure 3: Smart eHealth Gateway [24]

A number of solutions have been proposed towards this direction; The goal is to move towards a holistic framework like the “medical intelligence center”. A medical Intelligence Center platform delivers a number of complementary services through the same interface, with combined search, browse and alert functionality. In such a platform, Pharmaceutical and Medical insight is provided across the Healthcare value system, helping end-users to get ahead of the curve through unique data, surveys and trackers, and analytical tools, as it has been discussed in [11] and is presented in Figure 2.

In addition to the above, such an Intelligence Center offers a mix of data visualization, analytical and export tools to slot insight seamlessly into any end-users’ workflows. Medical Intelligence Centers ensure Ease of Access, through (i) Highly powerful data access and mining application; (ii) Intuitive data search and advanced filtering functionality to find the right information quickly and (iii) Easy ways to download and export content to the formats you need (data, charts, images and text). They also comprise Embedded Analytics, including (i) Big data manipulation tools for power users; (ii) Strong in-tool analytical capabilities and (iii) Direct access to our analyst teams; and they provide Tailored Data Visualization via (i) Leading edge visualization tools for different users and (ii) Clipping and report building functionalities [11].

Another critical issue regarding such applications is about “Smart Gateways”. A Smart e-Health Gateway should be capable of enhancing IoT architectures used for healthcare applications in terms of energy-efficiency, performance, reliability, interoperability, just to mention a few. A Smart e-Health Gateway serves as a bridge for medical sensors and home/hospital building automation appliances to IP based networks and cloud computing platforms. By exploiting the unique strategic position of gateways in IoT architectures, a Smart e-Health Gateway can tackle many challenges in ubiquitous healthcare systems such as energy efficiency, scalability, interoperability, and reliability issues.

In regards to that challenge, Jong-Wan et al. [25] present a sensor network system comprising of a main server and several sensing servers acting as gateway and connecting with different sensor networks. In a work presented in [26], a plug-configurable-play service-oriented generic gateway is proposed in order to provide simple and rapid employment of various external sensor network applications. Guoqiang et al. [27] propose a smart general-purpose gateway which provides i) pluggable architecture enabling the communication among different communication protocols, ii) unified external interfaces fitting for flexible software development, and iii) flexible protocol to translate different sensor data. In order to save energy and reduce the cost of smart home, Bian et al. [28] present a new type of intelligent home control system, using Android Phone as a temporary home gateway instead of the default home gateway. Finally, in the work presented in [29], authors propose a prototype of a smart 6LoWPAN (IPv6 over Low Power Wireless Personal Area Networks) border router which makes local decisions of health states using a Hidden Markov Model.

A thorough solution has been described regarding that challenge in [24]; overall architecture of that system is shown in Figure 3.

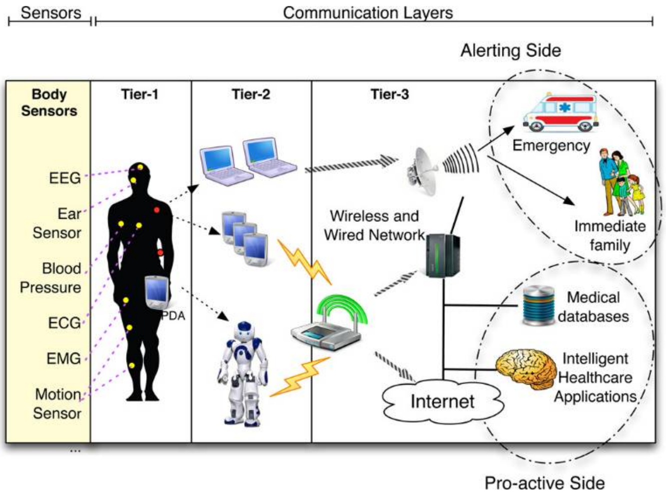


Figure 3: Body Area Networks Architecture [18]

Finally, the widespread use of wireless networks and the constant miniaturization of electrical devices has empowered the development of Body Area Networks (BANs), as already stated in the previous section [12]. Significant research efforts have been realized the last years, in order to optimize the operation of wireless BANs in health care applications, mainly related to *communication efficiency* and *cost-effectiveness*. Indeed, physiological signals obtained by body sensors can be effectively processed to obtain reliable and accurate physiological estimations. At the same time, the ultra-low power consumption provision of such sensors makes their batteries long-lasting. Moreover, with the increasing demand of body sensors in the consumer electronics market, more sensors will be mass-produced at a relatively low cost, especially for medical purposes. Another important benefit of BAN is their scalability and integration with other network infrastructure. BANs may interface with Wireless Sensor Networks (WSNs), radio frequency identification tags (RFID) [15], [16], Bluetooth, Bluetooth Low Energy (BLE, previously called WiBree) [17], video surveillance systems, wireless personal area network (WPAN), wireless local area networks (WLAN), internet, and cellular networks. All of these important benefits are opening and expanding new marketing opportunities for advanced consumer electronics in the field of ubiquitous computing for health care applications.

Figure 3 better depicts BANs' communication architecture in terms of three different layers: *Tier-1-Intra BAN*, *Tier-2-Inter BAN*, and *Tier-3- beyond-BAN communications[18]*. These architectural layers cover multiple aspects of communication that range from low-level to high-level design issues, and facilitate the creation of a component-based, efficient BAN system for a wide range of applications.

3. Results

3.1. Remote Elderly Monitoring System (REMS)

REMS as an IoT Service

In the context of this work, a remote health care monitoring system [19] is a platform that enables the doctor(s) (or in general health care provider) to monitor the health status of a patient remotely, reducing the number of times a patient has to travel for a regular check at a health care facility premises.

Medical information from the patient, e.g., stemming from embedded sensors, is electronically transmitted via a secure channel to the health care provider in a different location (e.g., a hospital) for further assessment and recommendations. The doctor(s) should be alerted if there is a cause for concern, e.g., inferred symptoms of a health problem which requires immediate medical attention. The proposed system consists of a variety of diagnostic tools and devices, used for monitoring physiological signs and health parameters of the elderly in real-time, from a health care personnel located at a remote facility [20]. REMS architecture is composed of three (3) subsystems: the home (where the elderly patient resides), the data repository (where data is stored and processed) and the remote facility (where the health care personnel is located). Table 1 summarizes the basic services REMS offers.

Table 1: REMS – Services

Basic Services and Applications		
Subsystem	Service	Object of Service
Home	Record	Vital Signs Sleep Safety
	Transmit	Collected data
Data Repository	Storage	Collected data
Remote Facility	Detection	Abnormal Signs Abnormal Behavior Incidents
	Health Care	Monitoring Emergency Support Communication Expert recommendation

REMS Criticalities

Figure 4 illustrates REMS with its components (red colored) as a mixed-criticality system with safety (dark yellow colored), mission (blue-colored) and non-critical (green-colored) criticalities. Criticalities considered as both safety and mission-critical are illustrated with the light-yellow color. In the following, we discuss the identified criticalities grouped related to each discrete subsystem:

Home. All the sensors (e.g., Electrocardiogram (ECG)) are safety-critical, since failure to operate and record patient-related vital signs may result in serious harm. Lacking the appropriate redundancy on a hardware level is important. It is critical that the set of sensors should operate correctly 24/7 even in the face of individual sensor failures. The safety critical factor applies to the gateway layer, as the real-time collection and transmission of data should be redundant with tolerance to transient failures. The gateways are responsible for the robust real-time identification and management of sensor data flows stemming from remote monitoring devices. Also, it is critical for them to possess the efficiency and technical capabilities in order to encapsulate a large number of functions (e.g., receive data from all sensors, preprocess, send data, etc.) within their system. Time is a safety-critical factor for both sensors and gateways. The results have to be generated and transmitted within a given time interval or the real-time behavior of the system is jeopardized and considered faulty. The security is mission-critical as it may affect the credibility of the remote facility. There is a need of communications between devices that ensure the confidentiality and integrity of transmitted data without any fault or modification by an adversary. Finally, the low power consumption of all devices can be considered as non-critical. The problem with low power consumption protocols, like Bluetooth Low Energy (BLE) 4.0, is that the security criticality might be affected in a negative way. Another non-criticality is the Size, Weight and Power (SWaP) [21] that helps ensure that devices are easier to carry and have larger autonomy.

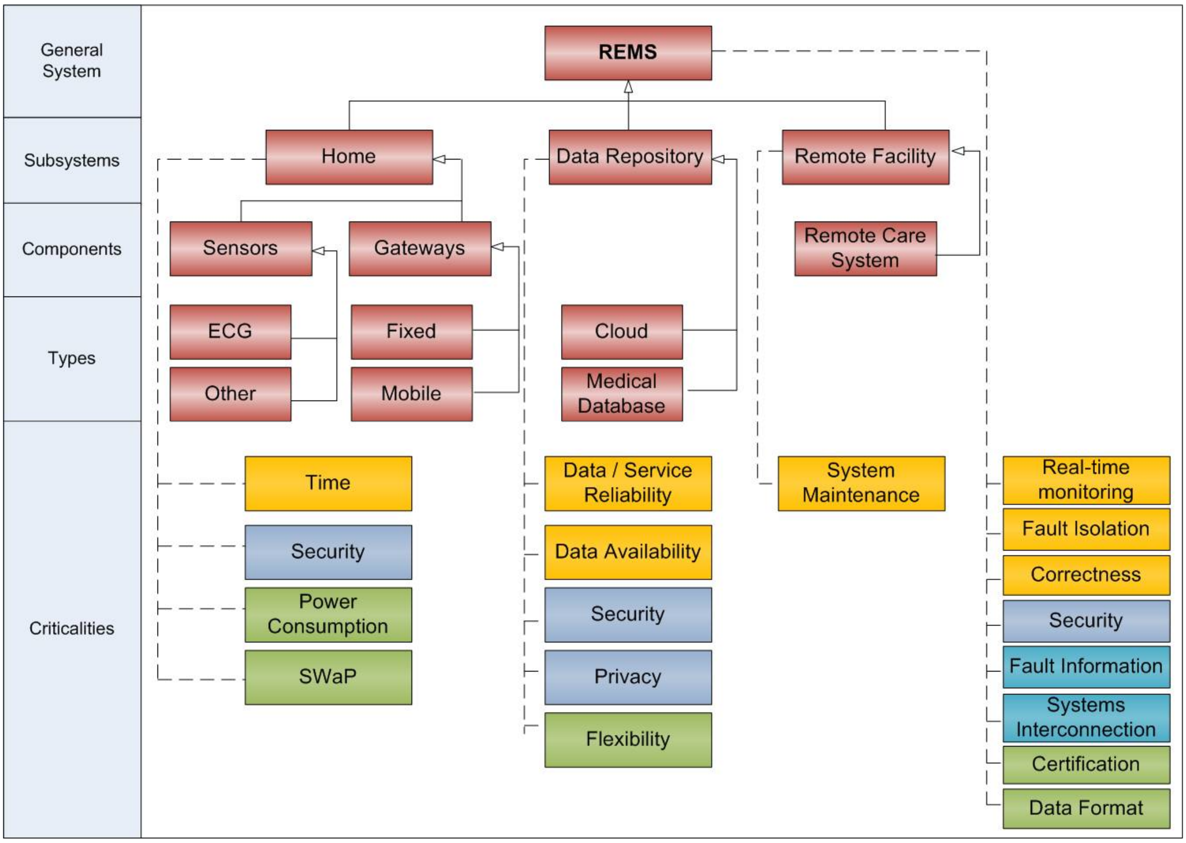
Data Repository. The challenge in this subsystem is the management of medical data. It is critical to protect patients' sensitive medical data, from the sensors to the data repository and then to the remote facility). Therefore, the following must exist, with greater weight being placed on the clouds side. Data / Service Reliability is safety-critical. Cloud service providers need to provide excellent reliability of services over the cloud, especially in the health care industry [22]. The availability of the data is considered as safety-critical. The health care system cannot operate without availability of services and patients' sensitive data. Moreover, privacy is mission-critical. It must be guaranteed so that the health care organization can safely shift to cloud-based solutions, because of the sensitivity of the patients' data. HIPAA [23] has some very strict regulations about the privacy of medical data. Finally, flexibility is non-critical in a data repository. The cloud services should be flexible and configured according to the user requirements. Adding new services as needed should be accommodated.

Remote Facility. First, the operation and maintenance of the facility's medical database is safety-critical with a very high significance as it holds all patients' sensitive medical data and history. In practice it involves similar criticalities as in the cloud-based data repository section. Secondly, the remote care system, as a basic part of the remote facility, is safety-critical. The operation and visualization of the patients' medical data in real-time to the health care personnel is very important. The received bio-signals must be presented in textual or graphical waveforms for visualization and diagnosis purposes. In addition, it is critical for the system to support multiple different platforms for the data visualization as it is a viable market policy. As there are not any mission and non-critical factors in the remote facility, it is characterized as safety-critical with a high significance in the REMS.

REMS as whole. In general, the REMS inherit the criticalities of its subsystems (home, data repository, remote facility). In this section, we expand on the criticalities of the REMS as an integrated system of systems. First, the real-time monitoring process is safety-critical. The REMS has functions that must react in real-time and provide time predictable communication among different networked devices. A failure to perform an operation within a given time may result in serious harm. The significance of the real-time monitoring is very high. Secondly, the fault isolation is also a safety-critical. Faults in an application / device must not propagate to other. Any fault must be handled by the failing application itself or by the system, while cascading failure effects should be highly improbable. The significance is between medium and high. Safety-critical can also be the temporal isolation / correctness. The real-time behavior of an application must be correct, independently of the execution of other applications. The significance is medium / high.

The security is mission-critical. Communications between devices shall be confidential. Moreover, due to high significance of the data, the traffic leaving the devices must be encrypted, while ensuring their integrity. It is critical to avoid errors or intentional modification to the data being transmitted. For example, false measurements cannot be injected by an adversary using packet spoofing or Denial of Service (DoS) attacks. In order to meet this criticality, well-known network security protocols and software suites can be employed. The fault information is both safety and mission-critical. The REMS platform must provide fault information to the devices, applications (lost data) and system. Information about faults occurring at the lower levels can be sent, in order to take corrective actions. Single points of failure should be avoided, and the integrated system should be distributed and highly redundant to reduce the criticality of such faults in the first place. The significance is high.

Another highly significant safety / mission-critical is the systems interconnection. All the devices (e.g., sensors, connected devices, etc.) must interact and cooperate with external services. As for the non-critical, the system should be developed while considering health care certifiability (e.g., HIPAA standards), for higher applicability in the health care domain. Moreover, data should have a robust and extendable standard format to be readable more or less indefinitely.



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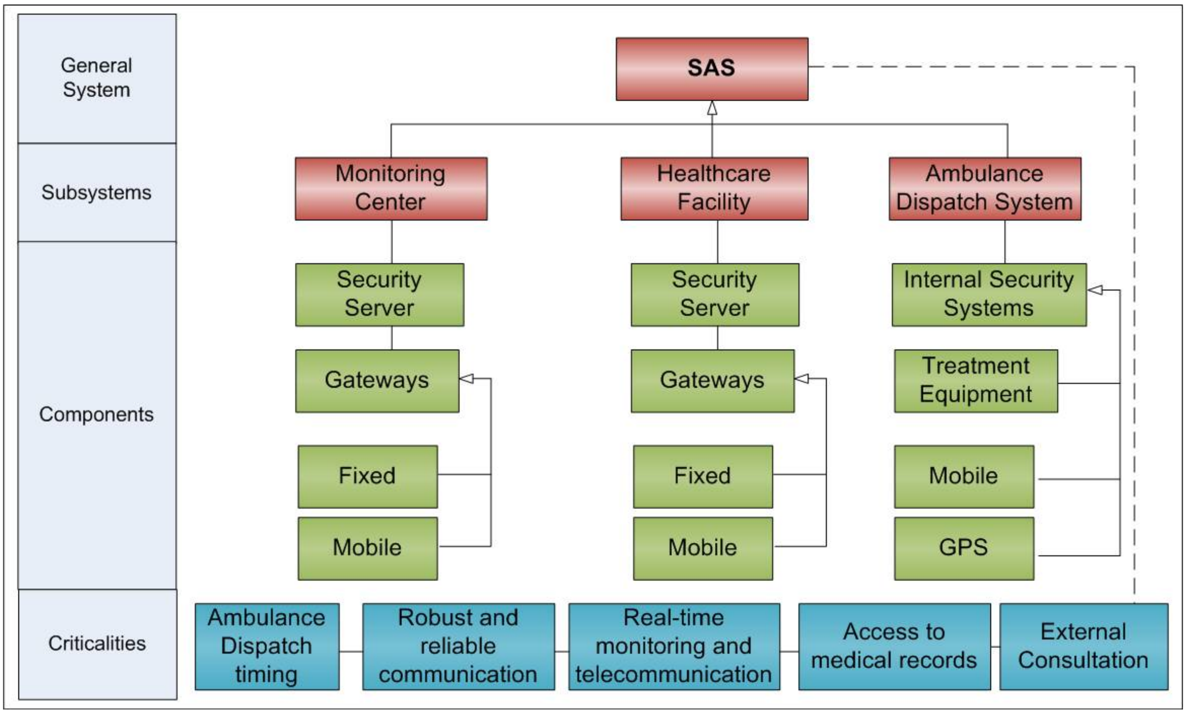
283 **Figure 4: REMS criticalities**



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285 **Figure 5: SAS Criticalities**

286 *3.2. Smart Ambulance System (SAS)*

287 The Smart Ambulance Systems targets two primary services:

a) Dispatching the nearest available ambulance to an incidents location and b) provides on-line monitoring of patients and sends patient's data to the health-care facility. SAS architecture is composed of three (3) subsystems:

Ambulance Dispatch System-Monitoring Center, which finds and dispatches the nearest available ambulance to an incidents location.

Health-Care Facility. It can be a hospital, a clinic or any medical facility.

Ambulance, which responds to an emergency and provides health care to a patient enroute to the health-care facility. Its basic functionality is the real-time monitoring of a patients' medical data inside the ambulance via telecommunication services and the provision of consultation, medical advices and support. In addition, it can track the ambulance and its route. Note that in the most common scenario, the monitoring center and the ambulance are considered as components of a healthcare facility and thus belong to its infrastructure.

SAS Criticalities

Figure 5 illustrates SAS as a mixed-criticality system with subsystems in pink color and components in green color. In such a system, the following criticalities (in blue color) can be identified:

Ambulance Dispatch timing. This is characterized as safety-critical, since it depends on a fast-as possible dispatch, response and arrival (to either the incidents location or a healthcare facility) of the ambulance.

Robust and reliable communication. As both a safety and a mission-critical factor, it is important for the connection between an ambulance and a healthcare facility to be always on. Moreover, the communication should be secure and redundant against non-authorized adversaries.

Real-time Monitoring and Telecommunication. This is a safety-critical factor and constitutes the most important criticality for the SAS. Healthcare personnel needs to monitor and supervise the collected patients' vital signs (such as heart rate, blood pressure, body temperature, etc.) in real-time, using small-factor diagnostic tools, like sensors, and transmit these data to a remote healthcare facility or to a remote data repository for storage and further analysis. Further, it is necessary to monitor the patient using video and images. The vital signs of the patient are measured and placed within acceptable ranges; alarms are activated and displayed both to the ambulances screen and the healthcare personnel's monitoring system in the case of patients' signs are outside the specified limits. Another safety-critical factor is the emergency access to the patients' medical record. In case of emergency situations, the healthcare personnel might need to gain full access to a patients' medical record and history in order to appropriately treat them.

Support of external consultation. It can be treated as a safety-critical factor if it involves the immediate consultation for the treatment of a patient as well as a non-critical factor in case the patient has already reached the facility and the initial emergency has been dealt with successfully.

4. Discussion

Embedded intelligence is intelligence within large systems. However, this definition does not reflect its attractiveness, considering the fact that being located inside large systems, embedded intelligence spans a wide range of system requirements. Its attractiveness and unifying characteristic is that the design goals are often wildly at odds. For example, most portable communication devices require super computer class processing capabilities for audio, imaging, and video processing, but must run on a very limited battery power supply and fit in a pocket-friendly form. Simultaneously, cost constraints and very aggressive time-to-market requirements are also there. These conflicts are why embedded intelligence presents such interesting research and commercial challenges. Embedded intelligence is often associated with the execution of real-time code and the existence of complex hardware accelerators attached. The real-time software often has gaps or holes in its schedule that a programmer can exploit to reimplement the complex hardware accelerators in software.

Cache coherence is another classic problem in multiprocessor computer architecture, but the heterogeneous processing typically employed in embedded intelligence applications provides new challenges. Nowadays, designers can develop inexpensive and specialized embedded intelligence solutions using hybrid chips containing both CPU and Field Programmable Gate Array (FPGA) components. The exploitation of their full potential presents an interesting challenge for system developers, who could also try to apply reuse best practices that reduce cost and time to market.

Overall, the prevalence and development of embedded intelligence face several challenges ranging from humancentric sensing/sampling, heterogeneous data collection and uncertainty management, to complex intelligence modeling/learning issues, which will definitely pose numerous challenges and opportunities to industry and academia. In the particular domain of healthcare and well-being, embedded intelligence has found several sub-areas to revolutionize starting from the design of treatment plans through the assistance in repetitive jobs to medication management or drug creation. In more detail, and in relevance with the results presented in the previous section, cases could be directly related to (i) mining medical records; (ii) Designing treatment plans; (iii) assisting repetitive jobs; (iv) getting the most out of in-person and online consultations, (v) Health assistance and medication management; (vi) precision medicine, as well as (vii) drug creation.

5. Conclusions

In conclusion, embedded intelligence constitutes a huge field of research, aiming at revealing the patterns of human/group behaviors, space contexts, as well as social and urban dynamics, extracted from the digital traces that are based on interactions with trillions of deployed smart devices. A great variety of innovative applications are enabled by embedded intelligence, in areas like mobile social networking, real-world search, city resource management, and environment monitoring.

This paper has provided an in-depth view of embedded intelligence as applied on healthcare related applications. To do so, it first went through healthcare embedded intelligence fundamentals, presenting specific requirements, research achievements and challenges. To exemplify those issues, it then presented two use cases, focusing on remote monitoring and smart ambulance services. Based on this review, several exciting work areas are opened. Indicatively, the use of modeling environments for the visualization of the aforementioned applications / systems will be studied, resulting in application level models with their functional specifications, and ultimately to a thoroughly developed system model, which will be implemented on an embedded multi-core platform.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Figure S1: title, Table S1: title, Video S1: title.

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