Extending and Instantiating a Software Reference Architecture for IoT-Based Healthcare Applications

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Abstract. The Internet of Things (IoT) is making possible the development of applications in many markets, such as buildings, home, industrial and healthcare. Concerning the healthcare market, there are a lot of challenges in the design, development, and deployment of these applications, such as interoperability, availability, usability, and security. To contribute to solve the aforementioned challenges, we proposed a software reference architecture, named *Reference Architecture for IoT-based Healthcare Applications (RAH)*, to systematically organize the main elements of this domain, its responsibilities and interactions, promoting a common understanding of these applications' architecture. RAH presents software architectural solutions (i.e., architectural patterns and tactics) documented using architectural views. This work aims to present RAH and instantiate it to design the software architecture of an IoT-based healthcare platform for intelligent remote monitoring of the patient's health data.

Keywords: Internet of Things (IoT) · Healthcare · Reference architecture · Software architecture

1 Introduction

New technologies can change lives! That is what is happening with the use of the Internet of Things (IoT). The IoT denotes a trend where a large number of embedded devices employ communication services offered by Internet protocols. Many of these devices, often called "smart objects" or "things", are not directly operated by humans but exist as components in buildings or vehicles, or are spread out in the environment [1]. Thus, the basic idea of this paradigm is

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the pervasive presence, around all users, of a variety of things - such as Radio-Frequency IDentification (RFID) tags, sensors, actuators, mobile phones, etc. Through unique addressing schemes, things are able to interact with each other and cooperate with their neighbors to reach common goals [2]. It is estimated that by 2025, 80 billion IoT devices will be online, creating 180 ZB of data [3]. This myriad of connected things, the data captured by them, and the connectivity between them is making possible the development of IoT applications in various markets, such as transportation, buildings, energy, home, industrial, and healthcare.

Concerning the healthcare market, this paradigm is reshaping modern healthcare, connecting everything to the Internet, shifting "from anytime, anyplace connectivity for anyone" to "connectivity for anything". The IoT can be the main enabler for distributed healthcare applications, thus having a significant potential to contribute to the overall decrease of healthcare costs, while increasing the health outcomes. Moreover, IoT-based healthcare applications are projected to provide the biggest economic impact. These applications, such as mHealth and telecare, which help to afford medical wellness, prevention, diagnosis, treatment and monitoring services to be delivered efficiently through electronic media, are expected to create about \$ 1.1–\$ 2.5 trillion annually in global economy growth by 2025 [4].

There are a lot of challenges in the development and deployment of this kind of application, such as (i) **interoperability** [5,6]: there are heterogeneous sources of data, the devices' protocol is not open, so a given device cannot be integrated to another (or multiple) applications, and there are also different studies and proposals for patient monitoring at hospitals or personal monitoring at home; (ii) **availability** [5]: several applications do not provide a way to ensure that they are available when needed; (iii) **usability** [7]: most existing home healthcare systems have drawbacks, such as simple and few functionalities, weak user interaction, and poor mobility; (iv) **security** [5]: many existing systems lacks of permission control, privacy, and data anonymity, etc; (v) **flexibility** [8]: existing products cannot autonomously adapt to usage scenarios, such as assisted living, intelligent buildings, smart transportation, energy, healthcare, or entire supply chains; (vi) **productivity** [8]: IoT-based healthcare services need to extend toward predictive maintenance and proactive enhancements, improving uptime and, thus, productivity.

In short, the complex and heterogeneous nature of the IoT-based healthcare applications makes their design and development difficult. It also causes an increase in the development cost, as well as hampers interoperability among existing systems. Thus, a strategy to design a software reference architecture to systematically organize the main elements of IoT-based healthcare applications, its responsibilities, and interactions, promotes a common understanding of these applications' architecture. A reference architecture (RA) is used as a basis to design concrete architectures in multiple contexts, serving as an inspiration or standardization tool [9]. Nowadays, the increasing complexity of software, the need for efficient and effective software design processes, and the need for high levels of system interoperability, demands for reference architectures to systematically organize the software design process, applying an architecture-centric development approach.

Considering the challenges associated to the development of IoT-based healthcare applications, the main objective of this paper is to present and instantiate a reference architecture, named *Reference Architecture for IoT-based Healthcare Applications* (RAH) [10], designed to improve the common understanding and systematization of the IoT-based healthcare applications' architectural design, and to offer guidelines for the development of these applications. The Reference Architecture presented in this paper is an extension of an initial version presented by Barroca and Aquino [10].

The rest of this paper is organized as follows: in Sect. 2, related works are reviewed. RAH reference architecture is described in Sect. 3. Section 4 describes the case study used to apply RAH to design and develop an IoT-based healthcare application, named PAR, for intelligent remote monitoring of patients in critical situation. Finally, the final remarks and future works are presented in Sect. 5.

2 Related Work

This section discusses about the existing reference architectures for the Internet of Things (IoT). These architectures were identified through the conduction of an exploratory review. Currently, to the best of our knowledge, there is no specific reference architecture for IoT-based healthcare applications. Identifying and structuring an architecture or model is a long and tedious process with much effort to abstract from specific needs and technologies. Such a reference can serve as an overall and generic guideline [8].

In the IoT context, the applications have been based on fragmented software implementations for specific systems and use cases, and usually they do not follow reference architectures. The need for reference architectures in industry has become tangible with the fast-growing number of initiatives working toward standardized architectures. These initiatives aim to facilitate interoperability, simplify development, and ease implementation [8]. There are three major reference architectures found in the literature for IoT: IoT-A [11], IIRA [12], and WSO2 [13]. These reference architectures work with concepts, such as IoT domain and IoT service, trying to address as many IoT applications scenarios as possible.

IoT-A Reference Architecture is, among others, designed as a reference for the generation of compliant-IoT concrete architectures that are tailored to one's specific needs [14]. It is an abstract framework that comprises of a minimal set of unifying concepts, axioms and relationships for understanding significant connections among entities of the IoT domain. IIRA is a standard-based open architecture for Industrial IoT (IIoT) systems. IIRA maximizes its value by having broad industry applicability to drive interoperability, to map applicable technologies, and to guide technology and standard development. The architecture description and representation are generic and at a high level of abstraction to support broad applicability in industry. IIRA distills and abstracts common characteristics, features and patterns from use cases defined in the Industrial Internet Consortium (IIC), as well as elsewhere. The WSO2's reference architecture consists of a set of components organized in layers and cross-cutting layers [13].

IoT-A RA argues the need to address the following quality attributes: interoperability, availability, security, performance, and scalability. However, it does not present the components defined to meet these attributes and, it does not present an evaluation in a real system. IIRA is at a level of abstraction that excludes architectural elements and requirements whose evaluation requires specificities only available in concrete systems, not presenting what are the addressed quality attributes. The WSO reference architecture highlights the scalability and security quality attributes mapping them into proprietary components of the WSO2 platform. Moreover, it was not found examples of how to instantiate these reference architectures into concrete architectures, and their evaluation.

Finally, the idea to address as many IoT applications requirements and scenarios as possible, without specifying the quality attributes required for the IoT-based healthcare applications or the components that address these requirements, make it difficult to use these reference architectures as guidelines for the development of these applications. Moreover, these reference architectures for IoT-based applications are too generic and abstract, and they do not focus on IoT-based healthcare applications. Therefore, currently, to the best of our knowledge, there is no reference architecture for the IoT-based healthcare domain.

3 A Reference Architecture for IoT-Based Healthcare Applications

As presented in Sect. 1, there are a lot of challenges related to the development and deployment of IoT-based healthcare applications, such as interoperability [5,6], availability [5], usability [7], security [5], flexibility [8], and productivity. Regarding interoperability, the overview of the papers presented by Barroca and Aquino [15] showed that 93% of the described new solutions would demand a change in the existing healthcare hardware and software. Although, there are many proposed protocols and different studies about IoT-based healthcare applications [15], a shared goal to produce an interoperable system adopting open standards for healthcare, for example HL7 [16], and a seamless framework to be easily deployed in any given scenario for healthcare is still missing [6]. In this scenario, the current state-of-the-art comprises independent IoT-based healthcare applications that do not interoperate and communicate with other applications. With the perspective of expanding these applications market and consequently the development of new solutions, this problem will grow significantly.

In this context, one of the possible cause for the lack of interoperability and communication between IoT-based healthcare applications is the absence of a software reference architecture (SRA) to serve as a guideline for the design of their architectures. SRA facilitates the development process, acting as a means of standardization and making modular configuration and interoperability with IoT-based healthcare solutions from different suppliers possible. Finally, its existence would provide a standardized view for these applications architecture which facilitates communication between the potential stakeholders (business professionals, software developers).

Therefore, we designed a software reference architecture for IoT-based healthcare applications, named *Reference Architecture for IoT-based Healthcare Applications (RAH)*, to serve as a guideline for the design of these applications' architectures [10]. It systematically organizes the main elements of these applications, its responsibilities and interactions, promoting a common understanding of these applications' architecture. RAH is defined based on a set of functional and nonfunctional requirements (quality attributes) related to IoT-based healthcare applications. These requirements were extracted from existing publications collected through the study presented by Barroca and Aquino [15]. This SRA was previously presented by Barroca and Aquino [10], but it is updated and instantiated in this work.

This section presents the proposed software reference architecture for IoT-based healthcare applications. It is structured as follows: in Sect. 3.1, it is described the requirements of a reference architecture for IoT-based healthcare applications, specifying the functional and nonfunctional requirements (quality attributes). Section 3.2 describes RAH, the software reference architecture for IoT-based healthcare applications.

3.1 Requirements of a Reference Architecture for IoT-Based Healthcare Applications

In this section, it is discussed the functional and nonfunctional requirements that must be addressed in RAH. The functional requirements express the functionalities that must be supported by an IoT-based healthcare application. The study presented by Barroca and Aquino [15] was used to define these requirements. The nonfunctional requirements must be addressed in the development of an IoT-based healthcare application. To define the nonfunctional requirements of a reference architecture for IoT-based healthcare applications, it was used the list of quality attributes of information systems presented by Bass et al. [17], as well as the existing publications presented by Barroca and Aquino [15]. Based on these list of requirements, the first version of RAH was defined. In this section, a set of extended functional and non-functional requirements of IoT-based healthcare applications is presented.

Functional Requirements. According to Bass et al., the functional requirements state what the system must do, and how it must behave or react to runtime stimuli [17]. Thus, the functional requirements of IoT-based healthcare applications consist of monitoring the patient's body and environment [15]. Regarding the body monitoring, the applications use sensors attached to the patient's body and capture data from: *Electrocardiogram (ECG)*, *Blood pressure*, *Blood glucose*, *Heart rate*, *Oxygen saturation*, *Temperature*, and *Breathing rate*. To monitoring the environment, the applications use sensors deployed in the patient's environment to capture data from *temperature, light, humidity, location, body position, motion data,* SpO_2*, atmospheric pressure and* CO_2 [15]. They are important because the environment conditions can directly affect the patient's treatment.

Quality Attributes (Nonfunctional Requirements). The quality attributes or nonfunctional requirements are qualifications of the functional requirements or of the overall product. A qualification of a functional requirement is an item such as how fast a function must be performed, or how resilient it must be to erroneous input. A qualification of the overall product is an item such as the time to deploy the product or a limitation on operational costs [17]. Thus, the main nonfunctional requirements/quality attributes of IoT-based healthcare applications are [15]: *Availability*, *Interoperability*, *Performance*, and *Security*.

3.2 RAH - Reference Architecture for IoT-Based Healthcare Applications

From the requirements of a reference architecture for IoT-based healthcare applications, which were previously defined, RAH was designed. The stakeholders for this reference architecture are systems analysts, software architects and developers of IoT-based healthcare applications. RAH is presented in the layered view in Fig. 1. The layered view is based on the layered style, which reflects a division of the software into layers that represent a group of modules offering a cohesive set of services [18]. More information about its views and services can be found in https://par.imd.ufrn.br/services.

This reference architecture is composed of five layers: **Sensing**, **Middleware**, **Services**, **Applications** and **Quality Attributes**. Interacting with the Sensing Layer, there are patients with devices to capture their biometrics and environment data. Interacting with the Applications Layer there are the users, such as physicians, hospital administrators, nurses, family, patients, pharmaceutical and clinical staff, that can be using an IoT-based healthcare application.

The *Sensing Layer* is responsible for monitoring the patient's body and environment, and is composed of the following components:

1. *Devices*: it is a hardware component that represents the devices used for monitoring the patient's body and environment. For instance, for the patient's body monitoring sensors to capture heart rate, temperature, etc, and for the environment monitoring, the devices are sensors that capture data related to temperature, light, humidity, SpO_2, pressure, and CO_2.
2. *Gateway Component*: it is a software component that receives data from the *Devices* and makes them available to the *Middleware Layer*. This component is composed of the *Raw Data Receive Service, Raw Data Send Service, Filter Service, and Network Service.*

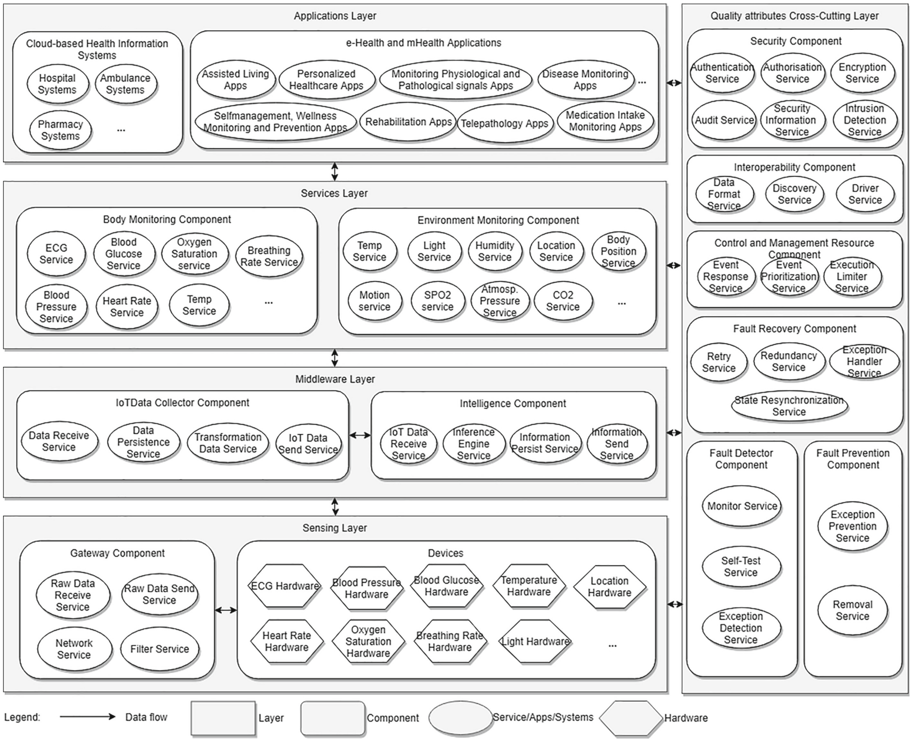

Fig. 1. Layered view of the RAH reference architecture.

Regarding the *Middleware Layer*, it is responsible for receiving the patient's sensors and environment data from the *Sensing Layer*, processing it, persisting it and making it available for the *Services Layer*. This layer is composed of the following components:

1. *IoTDataCollector Component*: it is a software component that receives the raw data sent by the *Gateway* component. It is composed of *Data Receive, Data Persistence, Transformation, IoT Data Send* services. Thus, this component is responsible for persisting, processing and transforming the raw data in a data format that are understandable by the *Intelligence* component.
2. *Intelligence Component*: it is a software component that receives data from the *IoTDataCollector* component and uses inference engines to classify and persist the intelligent information in a repository. This intelligent information can be specific alerts configured by the clinical staff for the patients, or automatic alerts detected by the use of Artificial Intelligence techniques. This component also sends information to the *Services Layer*, and it is composed of *IoT Data Receive, Inference Engine, Information Persist and Information Send* services.

The *Services Layer* is responsible for establishing a set of available operations related to the consumption of the patients monitored data (body and environment) by the applications. It centralizes access to data providing a bridge between the applications in the *Application Layer* and the *Middleware Layer*. Thus, this layer is composed of the following components:

1. *Body Monitoring Component*: it is a software component composed of services that provides information about patients' biometrics data. This component is composed of *ECG, blood glucose, oxygen saturation, breathing rate, blood pressure, heart rate, and temperature* services.
2. *Environment Monitoring Component*: it is a software component composed of services that provides informations about patients' environment data. This component is composed of *light, humidity, location, body position, motion,* SpO_2*, atmospheric pressure,* CO_2*, and temperature* services.

Thus, the data about patients' biometrics and environment are available to the *Applications Layer*. The *Applications Layer* contains the primary usage scenarios of IoT-based healthcare applications. Therefore, these examples of applications are grouped in cloud-based health information systems, e-Health, and mHealth applications. The cloud-based health information systems are for hospitals, ambulance, and pharmacy systems. The e-Health and mHealth applications are for the assisted living, personalized healthcare, self-management, wellness monitoring and prevention, disease monitoring, medication intake monitoring, telepathology, and rehabilitation.

The *Quality Attributes Cross-Cutting Layer* is responsible for features that make IoT-based healthcare applications secure, interoperable, available, and efficient. Its components address availability, interoperability, performance, and security. It is important to emphasize that because of the responsibility of this layer, it interacts with the *Applications*, *Services*, *Middleware*, and *Sensing* layers. Therefore, it is composed of the following components:

1. *Security Component*: it is a software component responsible for protecting patients data and information from unauthorized access while still providing access to people (patients, clinical staff, family, and physicians), systems and services that are authorized. It is composed of *authentication, authorization, encryption, audit, security information, and intrusion detection* services.
2. *Interoperability Component*: it is a software component responsible for allowing the IoT-based healthcare applications to have the ability to exchange data (syntactic interoperability), and also to interpret the data being exchanged (semantic interoperability). It is composed of *data format, discovery, and driver* services.
3. *Control and Management Resource Component*: it is a software component responsible for the performance of IoT-based healthcare applications. This performance regards to the response time and IoT-based healthcare applications ability to meet timing requirements. It is composed of *event response, event prioritization, execution limiter* services.

4. *Fault Recovery Component*: it is a software component related to availability and faults recoveries of IoT-based healthcare applications. It is composed of *retry, redundancy, exception handler, and state resynchronization* services.
5. *Fault Detector Component*: it is a software component related to availability and faults detections of IoT-based healthcare applications. It is composed of *monitor, self-test and exception detection* services.
6. *Fault Prevent Component*: it is a software component related to availability and faults preventions of IoT-based healthcare applications. It is composed of *exception prevention and removal* services.

4 A Case Study of Development of an IoT-Based Healthcare Application

This section presents the evaluation of RAH. For this evaluation a case study was conducted aiming to search evidence to test the hypothesis that RAH can be used to design an IoT-based healthcare application. For this, the case study research process presented by Runeson and Host [19] was followed.

4.1 Case Study Design

To assess RAH, the software architecture of PAR was designed as an instance of such reference architecture. PAR is an IoT-Based healthcare platform to integrate patients, physicians and ambulance services [20] in order to promote better care and fast preventive and reactive urgent actions for patients in a critical situation. It is composed of five modules: *Remote Patient and Environment Monitoring, Patient Healthcare Data Management, Patient Health Condition Management and Emergency and Crisis Management.* This platform was developed considering the need to transfer the healthcare from the hospital (hospital-centric) to the patient's home (home-centric) and is based on RAH (Reference Architecture for IoT-based Healthcare Applications).

Objective. The main objective of this case study is to validate the suitability of RAH to support the software architecture design of IoT-based healthcare applications capable of addressing their requirements.

Research Question (RQ). Can a software architecture of an IoT-based healthcare application be designed by using RAH?

4.2 Collecting Evidence

Nine people participated of this case study during its conduction: (i) The software architect of RAH, in charge of verifying the correct conduction of the instantiation process of RAH, and responsible for collecting and analyzing the evidence to answer the RQs; (ii) the software architect of PAR, responsible

Table 1. Functional requirements of PAR and RAH's components and services.

Id	Functional requirements	RAH's component and services
FR01	Remote body monitoring of patients: ECG, heart rate, oxygen saturation, temperature, breathing rate	RAH's body monitoring component: ECG, heart rate, oxygen saturation, temperature, and breathing rate services
FR02	Remote environment monitoring of patients: temperature and humidity	RAH's environment monitoring component: temperature and humidity services
FR03	Patient healthcare data management: records data of patients, physicians, nurses, health insurance, health condition, history of monitoring and emergency alerts	RAH's cloud based health information systems: Hospital systems
FR04	Patient's health condition management: definition of critical levels for the values read by the sensors	RAH's cloud based health information systems: Hospital systems
FR05	Emergency and crisis managements: patient's health condition and the services that should be alerted in case of emergency	RAH's cloud based health information systems: Ambulance systems; RAH's e-health and mhealth applications

for conducting and documenting the instantiation process; (iii) five developers responsible for supporting the requirements elicitation and implementation of PAR; and (iv) two registered nurses assisting the domain analysis activity. The remainder of this section presents the information collected at conducting each procedure described in Sect. 4.1.

Procedure 1 - Documenting the Platform Software Architecture Design. In this procedure, the scope and architectural design of PAR were established. PAR is an IoT-based healthcare platform for intelligent remote monitoring of patients in a critical situation and was developed considering the necessity to transfer the healthcare from the hospital (hospital-centric) to the patient's home (home-centric). This platform integrates patients, physicians, and ambulance services to promote better care and provide fast preventive and reactive urgent actions. It addresses challenges like interoperability, performance, security, and availability.

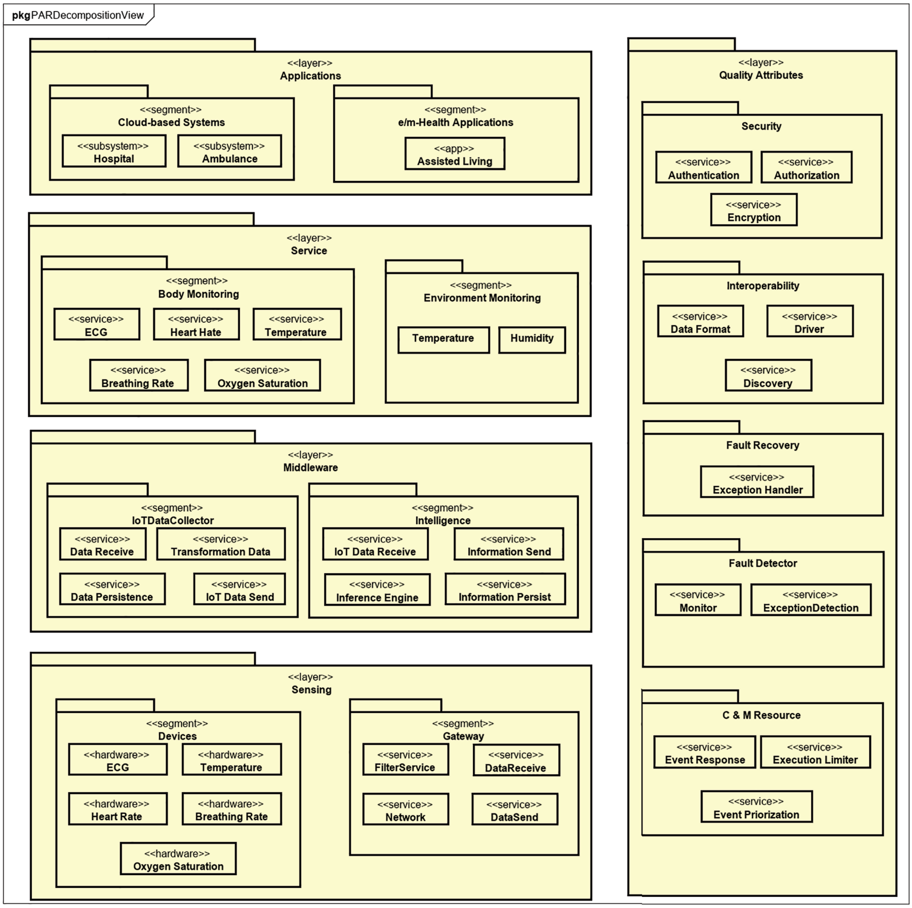

Fig. 2. PAR decomposition view as an instance of RAH.

The two registered nurses involved in the case study were responsible to define with the developers and architects the requirements of PAR. In total, 05 functional requirements and 12 nonfunctional requirements were defined for PAR. These functional requirements are summarized in Table 1. The software architecture of PAR identified what are RAH's services and components that address these functional requirements. Stakeholders identified in the context of PAR are the patient, family, physician, nurse, hospital and ambulance operators.

Regarding non functional requirements (quality attributes), the software architecture of PAR identified what are RAH's services and components that address these requirements. Thus, the non functional requirements and RAH's components and services are summarized and presented in Table 2. The number of monitored patients (19) proposed in NFR12 is based on the current capacity of the Intensive Care Unit (ICU) of the Onofre Lopes Hospital of the Federal

Table 2. Non functional requirements of PAR and RAH's components and services.

Id	Non functional requirements	RAH's component and services
NFR01	The platform must be able to interface (exchange data and interpret it) with an OMNI 612 Multiparametric Monitor using HL7 v2.6, and an eHealth Shield using a hashmap (interoperability)	Interoperability component: driver service
NFR02	Each device of the platform must be able to be located by its type, protocol, and IP (interoperability)	Interoperability component: discovery service
NFR03	The platform must allow standard communication between participating services (interoperability)	Interoperability component: data format service
NFR04	The platform must allow access to patient data only for authorized users (security)	Security component: authorization service
NFR05	The platform must authenticate users and participating services (security)	Security component: authentication service
NFR06	The platform must offer authorization mechanisms for users and participating services (security)	Security component: authorization service
NFR07	The platform must respect patients privacy and protect its data with confidentiality and integrity (security)	Security component: encryption service, authorization and authentication services
NFR08	The platform must detect failures in the participating services (availability)	Fault detector component: Exception detection service
NFR09	The platform must provide errors handling (availability)	Fault recovery component: Exception handler service
NFR10	The platform must monitor the participating services and devices (availability)	Fault detector component: monitor service
NFR11	The platform must be aware of its situation, and prevent and correct internal faults and failures (availability)	Fault detector component: monitor service
NFR12	The platform must be able to monitor 19 patients and to handle 133 transactions per second (performance)	Control and management resource component: event response, prioritization and execution limiter services

University of Rio Grande do Norte. The nurses participating in this case study work at this hospital, and suggested that this platform should be able to handle the current capacity of this ICU. The number of transactions (133) proposed in NFR12 is based on the 19 patients and the necessity of PAR to monitor ECG, heart rate, oxygen saturation, temperature, breathing rate, temperature, and humidity (NFR01 and NFR02). This results in 19 patients with 7 monitored data per second (one for each sensor).

Based on the requirements documents and RAH reference architecture, PAR's software architect designed PAR architecture instantiating the identified elements of RAH. Figure 2 presents PAR decomposition view. This view presents PAR in a fragmented way, beyond the layers and components of PAR Layered View, it details the PAR's services. This view was created by the PAR software architect following the requirements, and selecting which services of RAH would be instantiated for PAR. The importance of PAR decomposition view is the simplicity of the presentation of PAR fragmented in services, without showing its relationships, that are the focus of the following architecture views, designed from this decomposition. The services of RAH selected for the components are necessary to achieve the functional and nonfunctional requirements of PAR.

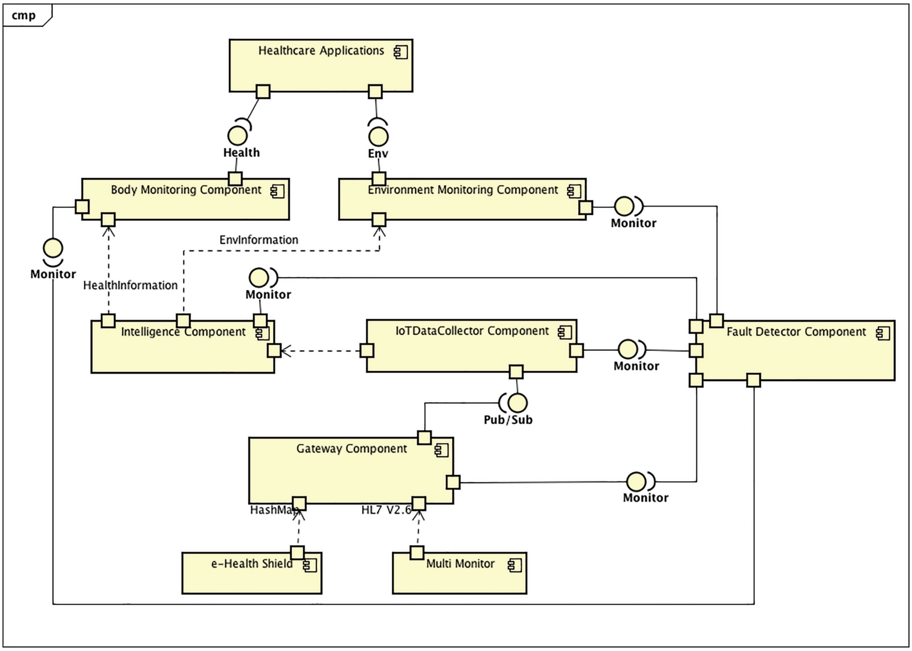

Fig. 3. PAR component and connector view.

PAR component and connector view is presented in Fig. 3. In this view, it is possible to note the following PAR quality attributes: interoperability and availability. Interoperability can be achieved in the communication between the devices and the Gateway component, which allows connection with different device types and different data flows. Availability can be achieved through the presence of the Fault Detector component, which monitors the PAR components, to identify any anomalies in their behavior. Regarding the data flow presented in this view, it starts with the devices sending the raw data (HL7 V2.6 and

HashMap) to the Gateway. The Gateway packages the data, it defines the packet headers and sends them to the IoTDataCollector (IDC). The IDC will receive the data packets, persist and treat them so that the output to the Intelligent Component is like IoTData.

Therefore, the Intelligent Component will apply its rules of inference about the IoTData, so that this data is semantically understood and presents information about the health status of a patient. The service layer components (Body and Environment Monitoring) act as interfaces that abstract the requests for information about patients' health and the environment in which they are accommodated. Finally, this information reaches the applications and is presented to the end users of PAR.

Resources - This procedure took 118 h:

1. Nine persons, of which two were nurses, one was the RAH's software architect, one was the PAR's software architect and five were developers, were involved in the PAR's requirements and use cases specifications and documentations. This activity took 26 h to be completed.
2. Two persons, the software architect of PAR and the software architect of RAH were involved in the identification of what are RAH's services and components that address the defined requirements. This activity took 9 h to be completed.
3. Two persons, the software architect of PAR and the software architect of RAH were involved in the design of PAR's services and components to attend the defined requirements, based on RAH's instantiation. Most of the work made in this activity was under responsibility of the architect of PAR. The PAR's software architect spent 67 h to complete this activity. The RAH's software architect spent 16 h in this activity, to resolve doubts and in the reviewing meetings made jointly with the software architect of PAR. Considering the time spent by both architects, this activity demanded 83 h to be completed.

4.3 Analysis of Collected Data

In this section conclusions are derived based on the collected evidences in Sect. 4.2. For the research question, conclusive statements are proposed offering evidence to support or refute the related hypothesis.

To answer the RQ - *Can a software architecture of an IoT-based healthcare application be designed by using RAH?*, time and people required to conduct and document the instantiation of RAH was registered. Therefore, at the end of the Procedure 1, presented in Sect. 4.2, information about time spent and people involved to design software architecture of PAR was detailed.

To support the hypothesis that *RAH allows to design software architectures of IoT-based healthcare applications*, the concrete software architecture of PAR was designed, as an instantiation of RAH. In this procedure, presented in Sect. 4.2, the requirements and architectural elements of PAR were mapped into requirements and architectural elements of RAH. This mapping, presented in Tables 1 and 2, shows that each requirement of PAR is under the responsibility of at least one component and service of RAH. Figure 2 presents the services and components instanced of RAH for PAR.

Moreover, the architectural views of PAR were created following the guidelines and views of RAH, as presented in Figs. 2 and 3. With these evidences, it is possible to affirm that RAH allowed the design of the software architecture of PAR, an IoT-based healthcare application. However, additional instantiations of RAH for the design of concrete architectures of IoT-based healthcare applications must be performed to offer more evidence to support this hypothesis.

Finally, as presented in the Procedure 1, the RAH's software architect spent 16 h to resolve doubts and in the reviewing meeting made jointly with the software architect of PAR. The PAR's software architect spent 67 h to complete this instantiation of RAH and documentation of PAR. It is possible that this time could be less if there were a specific instantiation process to use with RAH. A video presenting PAR is available in https://par.imd.ufrn.br/video, and its architectural views are presented in https://par.imd.ufrn.br/views. The source code of PAR is available in https://projetos.imd.ufrn.br/iothealthcareplatform/.

5 Conclusions and Future Works

This paper presented an extended version of an initial proposal of RAH. This new consolidated version is instantiated in this paper through a case study involving 9 specialists in grounding the application using RAH as a basis for the development process. RAH was designed mainly using as input a systematic mapping study presented by Barroca and Aquino [15]. This study allowed us to extract the main characteristics (functional and nonfunctional requirements), protocols and challenges related to healthcare applications.

The applicability of RAH was assessed using evidence by conducting an instantiation process to design and implement PAR, an IoT-based healthcare application for intelligent remote monitoring of patients in a critical situation. Although the obtained results were positive, replications of the case study can be conducted in different types of applications. The components and services developed for PAR can be reused in new IoT-based healthcare applications. Thus, the update of RAH to support code generation of the instanced software architectures, providing common components and services can help in the instantiation of new applications.

Finally, many opportunities for research emerged during the development of this work. They represent perspectives of future research that can contribute to the areas of e-Health, IoT-based healthcare applications, and software architecture. Some of them are described as follows: development framework for IoT-based healthcare applications; RAH as middleware for IoT-based healthcare applications; and RAH as a product line architecture.

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