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Research Article

An IOT-based framework for providing preventive and intelligent healthcare in ICUs

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Abstract

Background and Objectives: Effective and continuous monitoring is one of the essential requirements of ICUs. In recent years, the advent of new technologies has led to the development of smart ICUs that automatically gather, store and analyze healthcare information. In this paper, we aim to design the information view of an IOT-based framework for smart ICUs to provide preventive and intelligent healthcare. In previous studies conducted to develop architectures for smart ICUs, data processing is done in a large centralized fashion by cloud computers. This approach may take a long time when dealing with a large amount of data. In this paper, we used the fog technique to bring some computation and storage resources to the edge of the network instead of relying on the cloud for everything.

Methods: A reference architecture model and new technologies such as IoT, cloud computing, fog computing and smart sensors were used to design the information view of a smart ICU architecture. This view consists of five layers of data acquisition, transfer, storage, process and presentation layer. The proposed framework gathers patients' health-related data continuously and provides real-time analysis.

Results: In this paper, training the models, that took a long time, was performed in the cloud. Instead, classifying the new records, which took much less time, was performed in the fog. This greatly increased the speed of operations (2 ms vs 13590 ms). In addition, conducting calculations in the fog intensely reduced the transmission delays (8 ms vs 108 ms for only SPO2 variable).

Conclusion: New technologies were used to provide the information view of a smart ICU framework. Instead of relying solely on cloud, this paper uses fog technology to bring some computation and storage resources to the edge of the network. This greatly reduced the transmission latency and provided real-time analysis.

Keywords: Smart ICU, IOT, framework, reference architecture

Background and Objectives

In intensive care units (ICUs), doctors are required to quickly make vital decisions while dealing with large amounts of sophisticated data. In order to solve this problem, it is required to automate activities such as data gathering and processing using modern technologies. In recent years, the emergence of the concepts of Internet of Things (IOT), mobile Internet, smart sensors, artificial intelligence and cloud computing has modified the process of gathering, storing and analyzing information in healthcare environments[1-6]. Networked sensors make it possible to gather health related information. The availability of a huge amount of health data, along with the artificial intelligence algorithms, can help early prediction, prevention and personalized treatment of diseases[7]. IOT can reduce the healthcare costs while improving the outcomes[2-8].

Given the importance of the problem, various studies have been conducted to develop efficient diagnostic systems. These systems should have properties such as:

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- **Large-scale data management:** Given the enormous volume of patient health data, the system should be able to manage, store and process this data.
- **Data security:** This feature ensures that services and tools are not accessible to unauthorized persons.
- **Scalability and flexibility:** Access to services and devices may be increased or decreased at different times. The system must have the flexibility to make such changes.
- **Accessibility:** This feature guarantees permanent access to devices and services.
- **Interoperability:** This feature enables one system to work with other systems.
- **Multi-users:** Different people with different roles should be able to use different system services.
- **Ease of use:** People with no specialized skills should be able to use the services easily.

Therefore, it is necessary to develop a framework for diagnostic systems capable of addressing the aforementioned problems and meeting the relevant requirements. In this regard, the current paper presents an information view of an IoT-based architecture for monitoring patients admitted to intensive care units using a reference model. This view of the architecture uses fog computing technology to perform real-time processing. The smart ICU architecture should be able to continuously monitor various events that are directly or indirectly related to patient health.

In the literature, some studies have been conducted to develop the appropriate context and architecture for smart ICUs. The authors in (9) and (10) have proposed frameworks for time-dependent monitoring of patients admitted to the ICU using IoT[9, 10]. In a series of articles (11), (12, 13), the authors attempted to explain the steps of developing smart ICUs[11, 12]. In (14), the authors proposed hybrid architecture for a patient monitoring system to automatically detect hazard and alert situations using cameras and medical sensor networks[14]. The authors' goal in (15) is to maintain ICU temperature and humidity and to monitor the heart rate. Regular monitoring of patients is done by sensors and the required messages are automatically sent to nurses[15]. The one-time password is used for security purposes when accessing messages. In (16), the authors investigated the feasibility of using pervasive sensors and artificial intelligence technology for automated monitoring in the intensive care unit. The authors examined anxious patients and their environmental conditions. Wearable sensors, light and sound sensors and cameras were used to collect the information of patients and their environment. The collected data were used to identify and recognize patients' faces, their position, head and face movements, body movements, sound pressure level, light intensity and frequency of visits[16].

In most of these architectures, the data processing is done in a large centralized fashion by cloud computers. When dealing with a large amount of data, executing user queries in this way may take a long time (17). Therefore, the presented results are probably a few hours old, which is not acceptable in delay-sensitive areas such as healthcare[17].

In this paper, we used the fog technique for real-time processing of ICU data. The fog brings some computation and storage resources to the edge of the network instead of relying on the cloud for everything[18-2].

The proposed subsystems of this study gathers patients’ health-related data continuously and provides real-time analysis, integrates these data sources with EHR data, enables timely interventions, reduces the staff’s workload and makes a significant reduction in human errors.

Designing IoT Architecture

The use of new technologies can help improve ICU health care processes. But identifying, testing, and implementing the information systems for ICU processes is often challenging and requires the involvement of interdisciplinary design teams that generally include various people including hospital management, clinical teams (consisting of physicians, nurses, pharmacists, infection control specialists, and other hospital staff) and the technical design team (consisting of engineers and other professionals including IT equipment experts)[13].

The design of IoT subsystems for the management of sensors and devices, so as to meet business needs and quality constraints, is of paramount importance. In this regard, we need mechanisms to standardize the processes of analysis, design, evaluation and evolution of the architecture of IoT subsystems[14-21].

Various approaches have been proposed so far for architectural design. The most important methods are Attribute Driven Design (ADD)[22], Siemens four views method[23], Rational Unified Process (RUP) methodology[24], business architecture process and architectural separation of concerns[25]. All of these methods have three common activities: Architecture analysis, construction and evaluation.

Architectural analysis and construction activities include identifying basic architectural needs, developing architectural scenarios, designing architectural elements using architectural patterns, and creating different views on architecture. Common methods of architectural evaluation include Architecture Trade-off Analysis Method (ATAM)[26], Software Architecture Analysis Method (SAAM) (27)and Quality-driven Architecture Design and Analysis (QADA) (28). These methods assess the strengths and weaknesses of the architecture, sensitivity, trade-off points and completeness of a given architecture with respect to specific qualitative features[27, 28].

The increasing complexity of software systems requires methods to provide reusable architectures. Hence, reference architecture (RA) methods have also been proposed for the design and analysis of architectures. A reference architecture may be used to standardize architectures or to provide an initial architecture for the development of final architectures[29]. A reference architecture, in addition to the various elements required for an architecture and different architectural views, also includes the process of designing, evaluating, and developing architectures. Figure 1 shows a picture of the process of analysis, design, evaluation and evolution of the architecture.

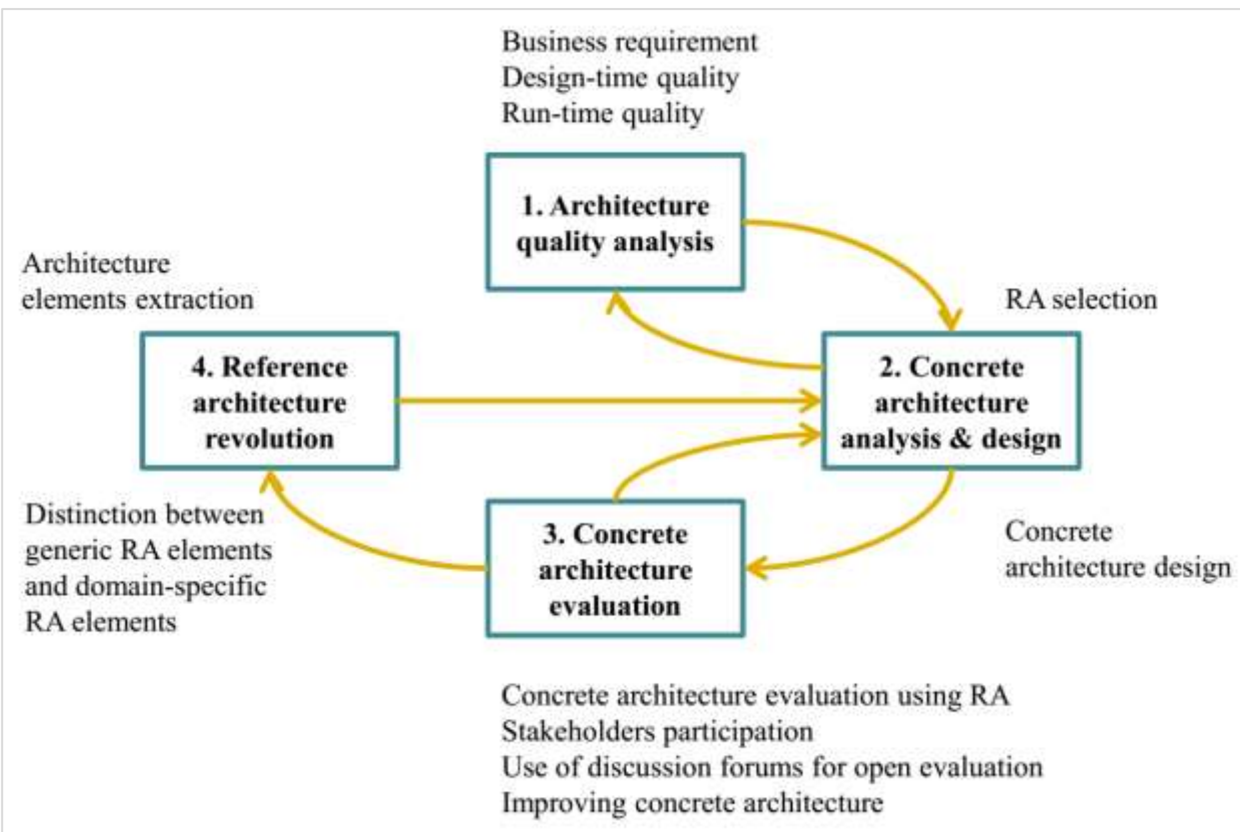


Figure 1: Architectural analysis, design, evaluation and development process[30]

The remainder of the paper is organized as follows: Section 2 describes the research method for developing a framework for smart ICU and explains its properties. Section 3 provides the obtained results using the proposed framework. Finally, Section 4 concludes the paper.

Method

In this section, the used reference architectural model and the proposed framework are explained.

reference architecture model

In this paper, was used the reference architecture model presented in (32) to design the proposed IoT architecture. In this model, the system architecture is developed based on different views[32]. The set of all views constitutes the overall architecture. A view represents one or more structural aspects of an architecture that illustrates how architecture has addressed the concerns of one or more stakeholders[33].

Figure 2 illustrates how the different views are linked to each other and how the overall architecture is created.

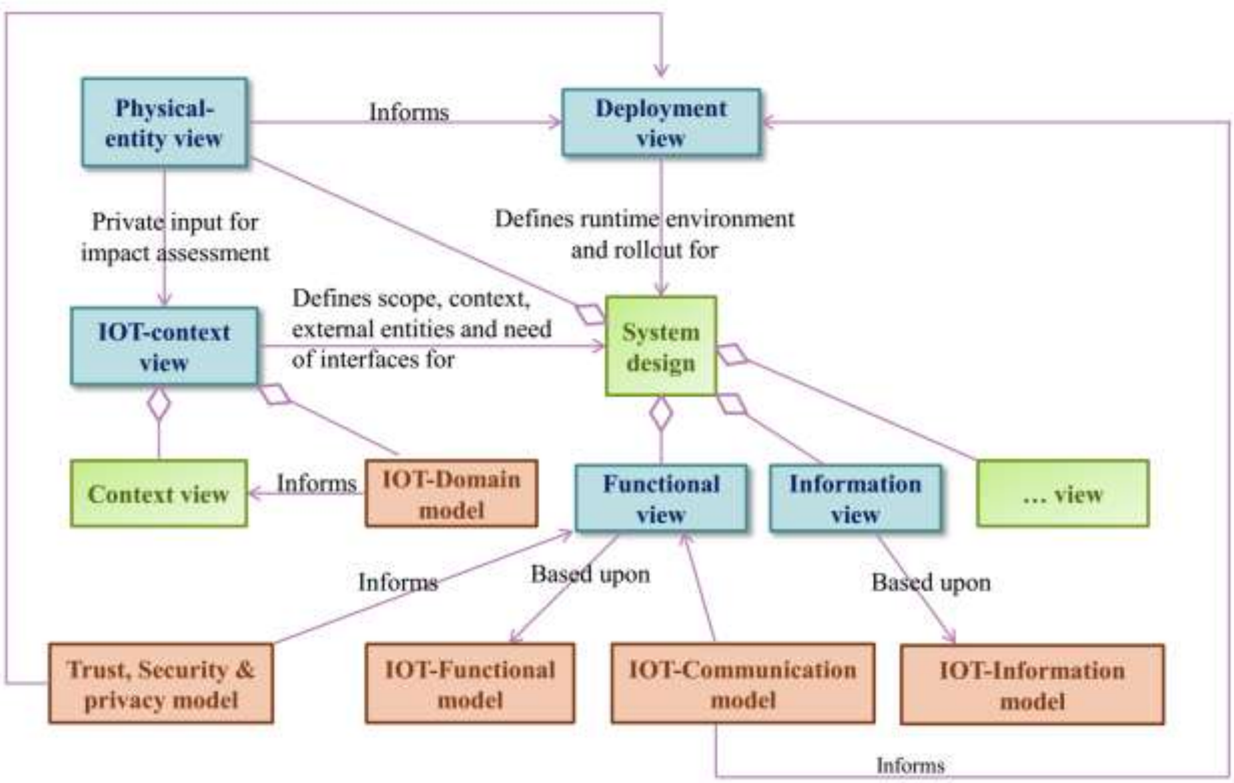


Figure 2: Relationship between different architectural views[31]

Different architectural views include:

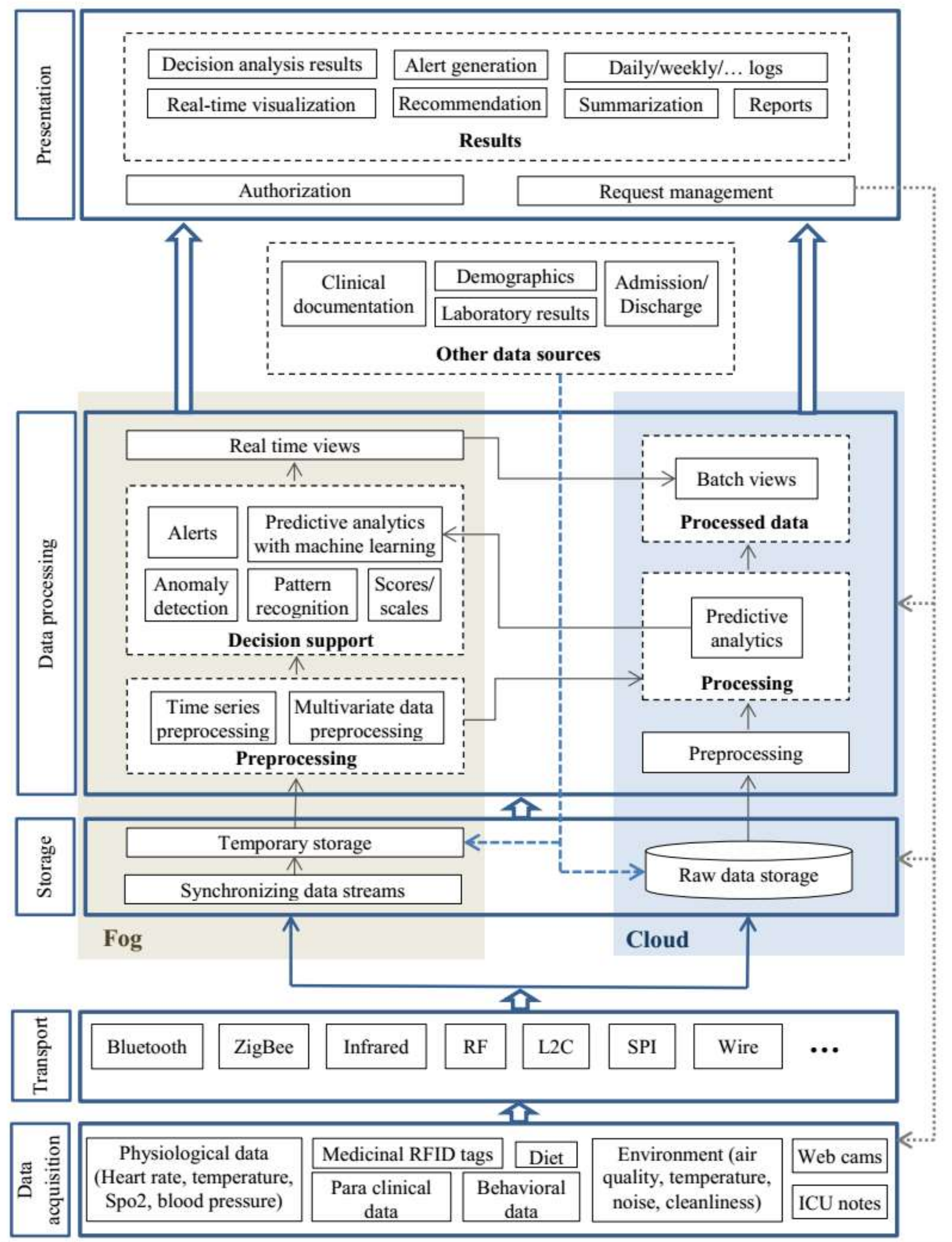
- **Physical Entity View:** This view refers to the physical entities of the IoT domain model. The physical entity is any physical object that is user-related or application-related.

- **IoT Context View:** This view describes the relationships, interdependencies and interactions between the system and its environment (the people, systems, and external entities it interacts with).
- **Information view:** This view describes how to store, manipulate, process, manage, and distribute architectural information. Information view helps to create a high level view of static information structure and dynamic information flow.
- **Functional view:** Functional view describes the functionality of the components at the time of system startup, the responsibility of the components, their default performance, the interfaces and the primary components' interactions.
- **Deployment view:** This view describes the system deployment environment and system dependencies at runtime. In this regard, the hardware environment, the technical environment, and the software elements required for each part of the execution environment are specified.

IOICU: The proposed information architecture for the intensive care unit

According to the above, designing the system's architecture is a complex process that would not be accomplished without the collaboration of individuals with different expertise to develop different architectural subsystems. In this paper, according to the research area and the expertise of the researchers, the reference architecture model was used to design the information view (information subsystem) of an IoT architecture for the intensive care unit. This view explains how to store, process, and distribute information. It also provides a high-level view of static information structure and dynamic information flow.

To design this architectural view, we have attempted to meet the key quality requirements of the IoT architecture. The proposed information view, called IOICU (Internet of ICU), consists of five layers including data acquisition, transmission, storage, data processing and presentation layer. IOICU uses fog computing technology to speed up real-time data processing[18, 32]. The general structure of the IOICU is shown in Figure 3. The details of each layer are explained at the following.



Figeure 3: IOICU, the proposed information view of an IOT-based framework for smart ICU

Data acquisition layer

In this layer, various data are acquired and integrated with the help of different devices and sensors embedded in the smart ICU. The collected data include textual data (pharmaceutical data, dietary data), graphical data (such as ECG and electroencephalography) and numerical data (such as blood pressure and body temperature). Therefore, the data is converted into a common format before transferring. These data can be divided into five general categories of patient's health data, behavioral variables, environmental variables, medicinal data and dietary data[10].

Patient physiological indicators include heart rate, blood pressure, respiratory rate, ECG, and so on. This data is collected by wearable smart sensors, body sensors, heart sensors and ECG monitors.

Patient drug data include information about the drug's strength, type of drug, dosage, date and time of use. Patient drug information can be collected using swallow sensors, wearable sensors, RFID tags, cameras image processing algorithms.

Patients with acute condition are sensitive to ambient conditions such as noise level, light, room temperature, air quality, toxic waste and so on. The room environment is therefore controlled by sensors related to light, air quality, noise, cleanliness, room temperature, chemical detectors and other things that can directly or indirectly affect patient health.

Numerous studies have shown that prolonged stay in the ICU may lead to some behavioral disorders among patients. In addition, high anxiety can sometimes make a patient's health worse. Therefore, data on behavioral aspects of the patient (stress, anxiety, restlessness) are collected and analyzed during the patient's stay in the ICU. Currently, psychologists widely use skin conductance sensors to receive stress and psychological responses from patients in medical centers and hospitals[33]. Patients' mental health data can be collected using biosensors, wearable sensors, and cameras.

In order to monitor the patient's health status, diet information should also be collected and analyzed. Oral sensors can be used for this purpose. The type and amount of food consumed by the patient can also be determined by cameras and image processing algorithms.

Transport Layer

Transport layer is responsible for transferring the data through wireless or wired networks and provides the networking support. It includes Bluetooth, infrared, ZigBee, radio frequency (RF), inter-integrated circuits (I2C), serial peripheral interface (SPI) technologies, and so forth. The sensor data is securely transmitted through this layer to the data storage layer.

Storage layer

The gathered data is stored in the cloud for future processing. In addition to the sensors data, the admission and discharge data, laboratory test results, clinical documentation, and EHR data are also stored in the cloud.

As previously mentioned in section 1, we used the fog computing technique to speed up real time processing. Several types of architecture such as layer-based, hierarchical and network-based are proposed by various researchers for the fog[34]. In this paper, we proposed a layer-based structure for the fog. The fog has some temporary memory, processing units, and some security features.

In IOICU, any new data is stored in the cloud, but it is also sent to the fog for preprocessing or real-time analyses. The fog synchronizes various data streams and stores them in a temporary memory. Since predictive models may need several hours of related data for predicting a special event, the temporary memory should have the capacity to store several hours of patients' data. The most recent multivariate data changes for ICU patients are stored in fog in order to avoid the time-consuming process of retrieving data from the cloud.

Data processing layer

Patient data is divided into two groups; some variables such as height and gender are recorded once and do not change over time, but others, such as vital signs, vary over time. Each group of these variables needs different pre-processing steps and analytical algorithms.

Pre-processing tasks should be performed on the data before conducting statistical calculations or data mining activities. In this layer, the new data preprocessed for any missing values, noise reduction, erroneous values, duplicates, correct data labeling and so forth in the fog. The preprocessing stage is performed differently for the two groups of multivariate data and time series. The pre-processed data is transferred from the fog to the cloud. Therefore, it is not required to repeat some pre-processing steps in the cloud. Hadoop service is used to process large scale data. Queries that are not sensitive to delay are performed with high accuracy in the cloud. The results are stored separately from the raw data and indexed for efficient accesses. These results gradually get updated with incremental updates based on the most recent data in the fog.

Operations such as calculating health scores/scales or generating alerts (when the values of the features exceed the acceptable range) are performed immediately in the fog on new data. If predictive analytic tasks are required, learning models that have been trained with the past data are used to classify new data. The trained models are available on fog to classify new data in real time. It should be noted that these learning models are not updated with the latest new data, because the process of updating and retraining learning models is a time consuming process. The predictive models in the fog are gradually updated with the results from the cloud.

However, if it is required to train some machine learning models using only recent data, the data will be acquired from the fog. In other words, small windows of data can be stored and processed in the fog.

Depending on the analytical need, supervised, semi-supervised or unsupervised algorithms may be used. When using supervised or semi-supervised models, the data label will be collected from the patient's electronic health record after being determined and recorded by physicians.

Presentation layer

In this layer, different requests are defined and the required instructions for generating the output are sent to the IOT sensors, storage layer and processing layer. The results are presented to the users after checking their permissions.

The results may be presented in the hospital information systems in the form of reports, alerts, recommendations, real-time visualization, summarization, etc. Authorized users can access the produced results through their mobiles, tablets and so forth in.

Users may be doctors, nurses, hospital staff, or the patient and his or her family. Access permissions for different users are defined in the hospital information system. For example, necessary warnings are automatically sent to hospital doctors and nurses; or the patient can receive the laboratory test results, graphs, and other health data from this integrated system. Patient's admission and discharge information, the status of empty beds, the weather and room cleanliness, the patient’s diet plan, etc. are also provided to the non-medical staff of the hospital.

The properties of IOICU

In addition to eliminating the delays of data transfer and providing real-time operation, other qualitative features are also provided with IOICU as follows:

Large-scale data management: The framework use cloud, fog and Hadoop technology in order to handle large scale data.

Data security: In this architecture, information is encrypted through communication channels and access levels are assigned to people, so that only authorized persons can access the information, therefore, data security is maintained.

Multi-users: Different people with different roles can use different system services. Determining access level is used to provide multi-user feature.

Scalability and flexibility: Since some parts of the processing operation are performed by the fog nodes in a decentralized and distributed manner, the scalability characteristics of the system are improved.

Interoperability: The tiered architecture helps to improve the interoperability feature of the system. In addition, using different types of fog nodes enables the system to respond to different devices with different hardware, operating systems and soft wares.

Ease of use: Different people with various roles including doctors, nurses, hospital staff, or the patient and his or her family can use the services easily.

Results

IOICU uses fog computing technology for real-time processing. As previously mentioned, all new patient data is stored in the cloud. Artificial intelligence algorithms are trained using this mass of data and are constantly updated with new data or retrained with all previous and new data. The model training process may take a long time, but after training a model, new data classification operations can be done in a short time. For example, in the authors' previous research (35), the time taken for training a model of cardiac arrest prediction and classifying new data to "normal" and "arrest" is as follows:

- Training algorithm: Stacking model,
- Software: IPython 5.1.0,
- The number of records used for training: 4611 records,
- The time taken for training the model: 13590 milliseconds,
- The time taken for classifying a new record: 2 milliseconds,
- Hardware specifications of the processing machine:

Processor: Intel(R) Core(TM) i5-3317U CPU @ 1.70GHz, 1701 Mhz, 2 Core(s), 4 Logical Processor(s).

RAM: 8 GB

As you can see, it takes a lot more time to train models than to classify new records. Given the sheer amount of data, model training operations may take a long time. Therefore, in the proposed architecture, models are trained in the cloud, which has huge computing and storage capabilities. But the classification of a new record is performed in the fog, because it does not require huge computational capabilities.

Moreover, classifying the new record must be done in real time. Performing the classification operation in the fog eliminates delays of transferring the data to the cloud and retrieving data from the cloud and allows real-time predictions. For example, in a simulation in iFogsim environment, the transfer delay for SPO2 variable is displayed in Table 1 . IFogsim simulation environment has modules and classes that are used to simulate fog calculations (36).

Table 1 :Transfer delay from one sensor to the cloud

Source	Transfer technology	Destination	Latency, ms
SPO2 sensor	Bluetooth	Data collection device	6
Data collection device	Wifi	Fog computing node (may be routers, gateways, switches or access points)	2
Fog node	internet	Cloud	100

In this example, the transfer delay from the sensor to the fog node is 8 milliseconds, while if we want to perform the processing in the cloud, the transmission delay will be 108 milliseconds, which is much longer. Performance of an application on the fog depends on latencies of the links connecting the fog node. Different kinds of devices have different latencies between them.

It should be noted that IOICU is a high-level view and more detailed subsystems should be developed for this view.

Evaluating the architecture

Evaluating software architectures plays an important role in examining the quality of software systems. A number of approaches proposed for software architecture evaluation activities include, but are not limited to ATAM[26], SAAM[27] and QADA[28]. Architectural evaluation activities should examine the compliance of IoT subsystems with qualitative and commercial requirements. Moreover, it should ensure that the choices made in the design of the different subsystems do not conflict. Therefore, stakeholders involved in designing an IoT subsystem should also contribute to the evaluation of other subsystems.

In this paper, given the scope of the research, only the information view of ICU architecture has been presented; therefore, it is not possible to fully evaluate it. In order to evaluate the architecture, other views and necessary subsystems should be designed with the help of specialists with relevant expertise. Views and subsystems should then be evaluated in order to confirm the qualitative and commercial requirements and examine the inconsistencies between different subsystems.

Conclusion

In this paper, the information view of an IoT-based architecture was proposed for smart ICUs. New technologies such as IoT, cloud computing, fog computing and smart sensors were used for designing this view. According to this view, the proposed architecture collects patient health data continuously, combines it with other patient health record data, and performs real-time analysis. The proposed view consists of 5 layers of data acquisition, transmission, storage, processing and presentation. In order to design this architectural view, fog computing technology was used to accelerate real-time processing and time series analysis. Since this paper provides only the information view, it is not possible to fully evaluate the proposed architecture.

The following activities are recommended as future studies:

- In order to accurately evaluate the architecture, other views and subsystems of the smart ICU architecture must be developed with the participation of expert groups with different expertise.
- The proposed architecture should be evaluated using standard methodologies and with the involvement of all stakeholders and designers in order to assess the quality and business requirements.
- The proposed architecture should be simulated in an appropriate environment in order to evaluate the performance.
- The ppproposed architecture should be implemented and evaluated in the real world to evaluate its effectiveness and applicability.

Abbreviations

ADD: Attribute Driven Design; ATAM: Architecture Trade-off Analysis Method; I2C: Inter-Integrated Circuits; ICU: Intensive Care Unit; IOICU: Internet of ICU; IOT: Internet of Thing; RA: reference architecture; RF: radio frequency; RUP: Rational Unified Process; SAAM: Software Architecture Analysis Method; SPI: Serial Peripheral Interface; QADA: Quality driven Architecture Design and Analysis.

Competing interests

None

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