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Do-Care: A dynamic ontology reasoning based healthcare monitoring system

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A B S T R A C T

Healthcare remote monitoring applications dominate the market of new technologies due to their valuable aid to patients, families, and medical staff. They provide ubiquitous remote health services for patients with chronic diseases or specific conditions and can provide ubiquitous communication between patients and caregiver(s). This paper presents an ontology reasoning-based healthcare monitoring system called Do-Care. The proposed system supports the supervision and follow-up of outdoor and indoor patients suffering from chronic diseases. Collected data, from *wearable*[1], *nearable*[2] or *usable*[3] devices forms the instances for entities from the proposed Do-Care ontology used by the reasoner when applying a set of SWRL[4] rules to determinate the health situation of a patient as Normal, Abnormal or Wrong. The main contribution in this paper is a modular and dynamic ontology composed of FOAF[5], SSN[6]/SOSA[7] and ICNP[8] ontologies with a scalable set of inference rules. The proposed rule based methodology is dynamic and adjustable to meet possible changes in the medication market, medical discoveries, and personal users' profiles. The presented experimental results show the efficiency of the proposed DO-Care system.

1. Introduction

Nowadays, it is clear that four unprecedented trends will shape the future of the healthcare industry. These trends include the increasing population of the elderly worldwide, the proliferation of chronic diseases, the emerging of new strains of viruses causing worldwide epidemics, and the recent and continued advances of information and communications technologies. The trend of a growing elderly population has been supported by studies from the WHO[9] and UN.[10] The WHO foresees that by 2030, older adults will comprise 13% of the total population (one in eight people will be 65 or older [1]. While the UN estimates that by 2045, the number of adults, 60 years and older, will outnumber children under the age of 15 [2]. The continuous increase of chronic diseases was shown in a study conducted by the WHO in 2001. This study indicates that chronic diseases cause approximately 60% of the 56.5 million of the total reported deaths worldwide and contributed to approximately 46% of the global financial burden due to diseases [3]. The some study also shows that the proportion of the financial burden is expected to increase to 57% by 2020. The most notably rapidly spreading chronic diseases are diabetes, heart diseases, breast cancer, COPD,[11] stroke and obesity. However, the effectiveness of healthcare systems worldwide has been recently challenged due to the outbreak of the Novel Coronavirus (Covid-19) which

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1 Worn or implanted in the patient's body.
2 Ambient and physiological sensors distributed in patient's environment.
3 Mobile, tablets and laptops.
4 Semantic Web Rule Language.
5 Friend of a Friend Ontology.
6 Semantic Sensors Network.
7 Sensor, Observation, Sample and Actuator Ontology.
8 International Classification Nursing Practices Ontology.
9 World Health Organization.
10 The United Nations.
11 Chronic Obstructive Pulmonary Disease.

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was declared as pandemic by the WHO in March 2020. Such new strains of viruses has been shown to defeat all expectations of any healthcare system.

Based on these findings, there are extensive research and development efforts to harness the potential of new technologies such as IoT,[12] Blockchains, autonomous reasoning, decision support systems, and mobile computing, to provide cost-effective, ubiquitous and efficient care for the growing numbers of chronically ill people and during an epidemic or a pandemic. IoT has been increasingly utilized in the healthcare industry to create potential and appealing changes and improvements to the healthcare ecosystem [4]. More than 40% of the total investments on IoT have been dedicated to mobile health referred to as mHealth[13] [5–8]. The GOe[14] defines mHealth as the medical and public health services carried out through mobile devices like cellphones, patient monitoring devices, PDA[15]s, and other wireless devices [9]. IoT-based mHealth systems development is still in its infancy and few IoT-based healthcare modeling, monitoring and reasoning systems have been proposed. Dealing with data and device heterogeneity coupled with the need for user context and situation awareness requires semantically modeled and designed solutions. Semantic models are based on ontologies that are effective for sophisticated context modeling [10]. Accordingly, many proposed healthcare monitoring systems are ontology-based. However, one main shortcoming in these systems is the lack of continuous updating of their knowledge bases. The used rule base methodology is such systems is predefined and thus does not adapt to related frequent changes and incidents. Moreover, these systems focus only on data modeling, data measurement, analysis, and decision making and overlook the agility and reliability of devices and the quality of measured data. Hence, this paper proposes a semantic-based healthcare monitoring system with a seamless integration of several intricate existing knowledge, ontologies and technologies. The proposed system is a dynamic rule-based system, which infers information and medical recommendations based on interactions among IoT input captured data, subjective and objective knowledge and a dynamic rule based approach. The major innovative contributions of this paper are as follows:

- Develop a system based on one modular and extended ontology. This ontology integrates three different ontologies, namely, ICNP medicine ontology, SSN/SOAS ontology sensor network ontology, and FOAF personal profile ontology.
- Propose a user personalized rule based methodology, which considers two types of knowledge, objective and subjective. The set of rules is dynamic and may be refined according to proofed predictions and health area changes.
- Investigate the reliability of data and devices.

The remaining of the paper is structured as follows: Section 2 presents the background and related work. Sections 3 and 4 provide respectively an overview of the DO-Care system and the reasoner engine. Section 5 describes the general diagnosis procedure. The proposed Do-Care ontology is described in Section 6. The Dynamic Medicine Rules Inference Process is detailed in Section 7, where Section 8 evaluates the proposed system and discussed the obtained experimental results. Finally, the paper is concluded along with future work.

[12] Internet of Things.

[13] Mobile Health.

[14] Global Observatory for eHealth.

[15] Personal Digital Assistant.

2. Background and related work

An ontology is a conceptual model that consists of classes, properties and relations between classes within a specific domain. A class represents a concept, while properties represent its attributes [11,12]. Ontologies represent knowledge in a semantic and interoperable model that encourages knowledge reuse and simplify problem-solving in various fields.

2.1. Ontology

This research work integrates three different classes of ontologies, namely, medicine ontologies, sensors ontologies, and personal profile ontologies. Medicine is one of the complex fields that benefit from applying ontologies, and there are various types of medicine ontologies [13–15].

Medicine ontologies can be divided into three groups according to the knowledge used [16]. The first group represents the standard medicine terminologies which aim to achieve consistency in various medicine information systems such as ICD[16] ontology [17,18], SNOMED-CT[17] [19], the FMA[18] [20], and the ICNP[19] [21]. The second group represents declarative knowledge related to constant concepts and relationships within a medical organization or medical research field such as the Actor profile ontology which identifies positions and responsibilities in healthcare. The third group represents procedural knowledge which identifies the terms, decisions and processes of managing the clinical workflow such as instruction ontologies in evidence-based clinical decision support systems. Ontologies for standard medicine terminologies are considered the most widely used ontologies in related research. Some of these commonly used ontologies are ICD, SNOMED-CT, FMA and ICNP [22]. ICD consists of standardized terminologies and diseases knowledge base, their symptoms and health problems associated with the variant conditions such as the health status influencing factors. ICD is mainly used in semi-automatic smart diagnosis systems. It is one of the earliest medicine standardization with its eleventh version being the latest [17,18]. SNOMEC-CT consists of the core terminologies in health records and aims to enhance the effectiveness of clinical data recording [19]. FMA represents the declarative knowledge of body anatomy [20]. ICNP includes the terms and definitions of the nurses' statements considered in patients' diagnosis. It is worth mentioning that nursing science has a significant contribution in healthcare services since nurses' statements play and important role in systemizing and prioritizing healthcare services [23].

The integration of wearable and implanted body sensors represents a medical body area network, which can record different human body functions, vital signs and environmental factors for specific purposes, either medical or others [24–26]. The W3C SSN[20] is one of the essential ontologies used in describing sensors. It describes the sensors' capabilities, actuators' observations and other related concepts and attributes [22,27]. WSSN[21] is the extended SSN version that includes the wireless data communication policy. SOSA[22] is the lightweight core of SSN which provides a general-purpose specification model for interaction between sensors. SOSA does not replace SSN, but it expands the targeted audience in the semantic web community by providing a flexible framework and easy to use vocabulary [28]. As the patient

[16] International Classification of Diseases.

[17] Systematized Nomenclature of Medicine — Clinical Terms ontology.

[18] Foundational Model of Anatomy.

[19] International classification for nursing practice.

[20] Semantic Sensors Network.

[21] Wireless SSN.

[22] Sensor, Observation, Sample, and Actuator.

plays the most crucial role in medical research, defining patients' profiles is a mandatory process in such projects. In that regard, general ontology can be used to declare patients' profiles and empower this process. FOAF[23] is a general ontology which became the standard ontology for declaring personal profiles in different fields such as health, finance, and law [29]. FOAF classes describe a person, his activities and his relations with others in general. It has four main categories, including basic information such as name and title, personal information such as age and interests, online accounts such as bank account and email account, and documents, and images such as personal photos and logos [30].

2.2. Healthcare reasoning

Smart healthcare applications rely on smart objects that monitor changes in the physical environment or/and the human body and actively contributes to the overall healthcare process creating what is known as ambient intelligence [31]. Today, patients' have high expectations from healthcare systems; they are looking to live a convenient and safe independent life with minimal human interventions [32]. Modern healthcare applications should ensure greater autonomy and give patients human-servant-like assistance in case of any problem. Several studies have been conducted in this regard by various researchers based on different healthcare reasoning techniques [32] such as rule-based [33], case-based [34], Fuzzy logic [35] and ontology-based Reasoning [16,36–38]. Rule-based and case-based reasoning are the earliest healthcare reasoning techniques. In [33], a rule-based expert system was proposed for a heart failure telemonitoring system based on the patient's weight, blood pressure, heart rate, and symptoms. Valijo et al. [34] proposed a case-based reasoning system called InNoCPR for nosocomial infection[24] detection and classification. Kumar et al. [35] proposed a system for monitoring and diagnosing diseases by utilizing IoT devices and cloud computing to collect and store data and a Fuzzy rules algorithm for the diagnosis process. Hybrid-based reasoning systems combine two or more reasoning methods and they have been the interest of recent research studies [39–41]. Ahmed [39] proposed an intelligent healthcare system to monitor elderly vital signs daily using IoT for data collection and rule-based and case based reasoning for patient's diagnosis. Malathi et al. [41] proposed a disease prediction support system using a combination of fuzzy set theory, k-nearest neighbor and case-based reasoning. Applying reasoning methods on ontologies are widely used in healthcare systems. Hristoskova et al. [36] proposed an intelligent ambient framework to monitor a congestive heart failure patient. The novelty of the framework was in personalizing the real-time monitoring process of the patient's health status and risk stage and sending an alert to the specialized physicians accordingly. Moreover, it considered the physician's location and intervention time in emergency cases. The framework consisted of wireless medical devices, sensor networks to specify the location of the physicians, patient monitoring application, and an ontology for congestive heart failure reasoning. The framework was based on utilizing a combination of IoT and ontology based technologies, but was limited to congestive heart failure patients. Zhang et al. [16] proposed an ontology-driven decision support system to monitor and follow up chronic disease patients outside the hospital to provide a continuous assessment and chronic disease management. The proposed ontology adopted SNOMED-CT and consisted of three-knowledge types: patient data, medical domain knowledge, and patient assessment criteria for chronic diseases. The decision support system (DSS) was adopted to automate the selection of a patient's assessment program. DSS collected required data from different sources such as the patient's electronic health record, the patient's mobile application, and medical devices composing a patient's database. The framework was applied for type 2 diabetes and achieved 99.93% accuracy and 95 completeness. Rhayem et al. [37] proposed an ontology-based system for patient monitoring with connected objects consisting of three modules. The first module was for connecting and managing objects using a Health IoT ontology, the second module was for diagnosis and detection to allow physicians to assist patients remotely, and the third module was for alert distribution to inform patients about their status and list of their medical prescriptions. The use of ontology in this system was limited to IoT and medical devices only, while the vital signs analysis and decision making needed human intervention. A physician could assist the patient remotely, but this process was not automated and that might had affected the treatment response time. Shen et al. [38] proposed an ontology-driven clinical support system (IDDAP) for the diagnosis of infectious disease and prescription of antibiotics. The system helps prescribe the related antibiotic as a first line therapy. It specified the infection based on the patient's self-description of body temperature, symptoms, complications, antibacterial spectrum, contraindications, and drug-drug interactions and then proposed the appropriate infection therapy. The system consisted of 507 infections and their therapies and the proposed infection ontology was considered as the most complete ontology compared to others at the time of the publication. One of the main shortcomings about these systems was the fact that no IoT technologies were applied for data collection to enhance the accuracy of obtained results. Farman et al. [40] proposed an IoT based system for monitoring patients' health and recommended diet and medicine for the treatment of chronic diseases. The system applied semantic web language (SWL) rules, and fuzzy logic on the ontology to automate the recommendation process and (SPARQL) queries to evaluate the ontology.

3. Do-Care overview

The Do-Care system is a ubiquitous and continuous remote monitoring system for patients with chronic diseases which is equipped with a decision support system for care givers such as physicians and nurses during medical examinations and diagnosis. The proposed system can determine the health situation of a patient and generate an appropriate alert accordingly to be sent to care givers. The health situation is inferred from the human body, environmental and patient history factors, and a dynamic knowledge base, including general medicine rules. In the following subsection, we present a set of terms and definitions used throughout the paper. Then, we present the Do-Care system: general overview, features, architecture and main components.

3.1. Terms and definitions

The Do-Care System considers a set of followed patients denoted by $\mathcal{P}$ equipped with a set of applied Sensors $\mathcal{S}$. It distinguishes between three health situations for each patient ($\mathcal{ST}_p$): *normal*, *abnormal* and *wrong*. The health situation is determined by different *environmental* $\mathcal{E}$*Sign* and *vital* $\mathcal{V}$*Sign* signs representing the context and the health profile of a patient and defined by a set of *observations* noted by $\mathcal{O}$. *Environmental* signs are associated with contextual observations as the ambient temperature, the location, the level of humidity, etc. However, *vital* signs are a set of human body observations as the blood pressure, the body temperature, the heart rate, the respiratory rate [42] and also the oxygen level.

23 Friend Of A Friend.

24 Nosocomial infections referred to infections from the hospital environment during the patient treatment in the hospital.

Any *observation* has three characteristics: a *measurable* value v in a given *time* t which belongs to a patient p and originates from a sensor s. It is denoted by $\mathcal{O}_t^{s,p}$. Three possible descriptions can be associated with any Observation, $\mathcal{O}_t^{s,p} \in$ [*normal*, *abnormal*, *wrong*], which are respectively associated with three possible value ranges of any measurement also classified as *normal, abnormal* and *wrong* ranges. The normal and abnormal ranges are defined using a set of observation possible values for each of an observation for a patient noted by $\mathcal{R}_o$. However, impossible values of an observation fall within what we refers to as the wrong range denoted by $\mathcal{W}_o$. In this case, the corresponding sensor s is considered as unreliable source. The Boundaries of the three ranges are defined as per general medicine practices and depend on the patient's profile (i.e. the blood pressure depends on the age and gender of the patient).

The health situation of any patient is deduced from the set of observed *environmental* and *vital* signs as follows: The situation of a patient is *normal* if all the observations associated to all his *signs* are classified as *normal observations*. An *abnormal* status is declared if at least one observed signs was found to be an *abnormal* observation. Similarly, a *wrong* status is declared if at least one of the observed signs was deemed as a *wrong* observation.

While *normal* and *abnormal* are representing the health situation of a patient, however, the description *wrong* is in general a representation of a fault during the observation of a sign. The Do-Care system generates two types of alerts: *risky* and *wrong*. The alert *risky* is activated for patients with a health situation of *abnormal*, the alert *wrong* is activated for patients with a faulty observations. Even though a *wrong* observation does not have any medical interpretation, it still should be considered.

A patient's medical *history* containing previous recordings of his vital signs can help interpret his current health situation. For patients with chronic diseases and patients who need continuous medical attention, the medical history is not only analyzed and used for personal healthcare, but it can be also used to detect possible new medical conditions and better course of treatments, etc.

3.2. General overview

The proposed Do-Care system is a combination of a set of smart *devices* interconnected through the Internet. Devices can be sensors, medical devices, mobiles, tablets, laptops, etc. And, they are classified as: *wearable, nearable and usable* devices. Wearable devices are usually worn or implemented body sensors by the patient. Nearable devices are sensors or devices part of the patient's environment such as ambient sensors, a mobile, a tablet, etc. Usable devices are any smart medical device connected to the Internet like medical machines in the hospital, or any device used by the medical staff as laptops, mobiles and tablets. All devices are interconnected and able to communicate through the Internet. The system collects real-time data for environmental and vital signs current observations. All collected data concerning current or previous observations, should be securely saved. The data is used to provide an ubiquitous monitoring healthcare by determining the current health situation of a patient and providing all related and necessary services. The health situation is deduced based on current observations and using a knowledge database, which is a set of general medical specifics. The main contribution of the proposed Do-Care system is the dynamic updates of its knowledge data base using different sources of new specifics such as: the medical history of a patient, the direct intervention of a medical staff, etc. Table 1 compares the proposed system with the different ontology healthcare systems cited in Section 2.

3.3. Do-Care features

The patient interacts with the Do-Care system through a mobile application installed on his/her attached device, such as a Personal Digital Assistant while collected data is available online for caregivers and medical staff. The system features can be used by three defined types of users: patient, doctor, and caregiver. Each patient is monitored by at least one doctor and is getting the care from at least one caregiver, which can be a family member or a professional care-provider such as a nurse. The Do-Care system provides different services: common, for all users, and specific, depending on each user's role. For instance, patients can see their own personal environmental and vital signs only. A caregiver or a doctor can inquire about all vital signs from all associated patients. The Do-Care system should efficiently support a set of functional and nonfunctional requirements [43,44]. Functional requirements are main operations and activities that users expect from the software, often documented via use cases diagram. The different use cases for the proposed Do-Care system are presented in Fig. 1. However, non-functional requirements represent the list of criteria according to which the operation of a system may be judged as detailed below.

i Ergonomic and minimalist design: should be simple, easy to use and pleasant to look for a very particular type of users as elderly people.
ii Flexibility and efficient use: must provide the ability to accomplish the intended tasks (view and store health record in a dedicated database, track the patient, exchange secure messages between the actors...) smoothly and efficiently. It must use a comprehensive plain language.
iii Availability and continuous operations: must operate reliably and ubiquitously regardless of the time and context. Connectivity disruption must be vigorously avoided.
iv Safe store health records and personal information: supports data (diagnostic, laboratory tests, medications, etc.) collecting, storing, monitoring, provisioning and sharing with a guarantee of availability and privacy.
v Easy communication and collaboration tools: supports calls, emails, instant messages, alerts, etc.
vi Health knowledge services: supports customized inferring and matchmaking algorithms to develop and make suitable recommendations and statistical data for the patient as well as for the doctor.
vii Privacy and trust management: ensures user's right to control the collection, use, and disclosure of his/her personal health information and/or personal information.

3.4. Do-Care general architecture

The proposed system, as shown in Fig. 2, is composed of five layers explained as follows:

i Sensing Layer: a set of wearable and nearable sensors connected directly to the user. Their role is to collect context data: health data, ambient data, location, motion, personal information, etc. This set of sensors are managed by one platform and related to one user.
ii Networking Layer: a set of networking devices to facilitate the communication between the different physical elements and the connection to the Internet. Networking elements also allow the data exchange between the sensing layer and the knowledge component.
iii Data set Layer: a server hosting all data; current data collected in real-time and saved information about the user. It provides instances enriching ontologies from the knowledge component. The dataset is composed of collected data

Table 1
Summary of a comparative study between the Do-Care system and existing related works.

Reference	Ontologies	Patient profile attributes	Dynamic knowledge	Medical purpose	Additional reasoning techniques
[36]	Specific	Health situation and location	No	Heart failure	No
[16]	SNOMED-CT	Health situation and assessments	No	Assessments	No
[37]	Specific	Health situation and treatment	No	Medicine prescription	No
[38]	Specific	Health situation and self prescription description	No	Infection disease and antibiotic prescription	No
[40]	Specific	Health situation	No	Diet including food and medicine	Fuzzy logic
Do-Care	FOAF, SSN/SOAS and ICNP based ontology	Patient context, personal and health profile	Yes	General Healthcare Monitoring	No

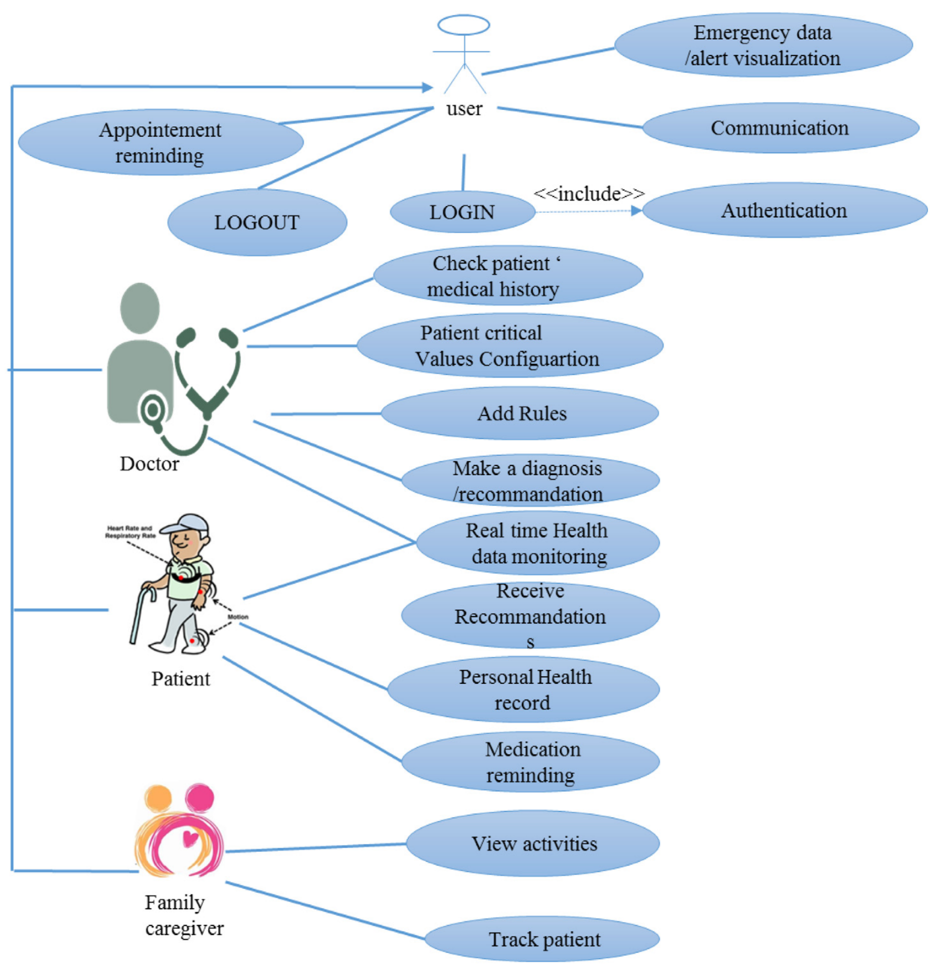

Fig. 1. Uses cases diagram for Do-Care system.

from all sensors. It contains the various values of vital signs per patient and per time.

iv Application Layer: an implementation of all features of the healthcare application needed to provide prescribed services for an ubiquitous and continuous medical monitoring. This is an MVC application separating data, presentation, and control.

v Knowledge Layer: This layer is the primary entity of this system architecture. It is composed of a three multidisciplinary knowledge and a reasoner. It is composed of four ontologies and a reasoner engine. The dataset layer feeds the ontology with instances about the health profile of patients, which enables reasoning on those instances and hence inferring new facts about a patient's current clinical situation. Ontologies enrich the data set layer semantically by allowing a reasoning capabilities to conclude the patient's current situation (wrong, normal or abnormal). The reasoning capability is due to a set of rules which can be used by an inference engine to determine the patient's situation.

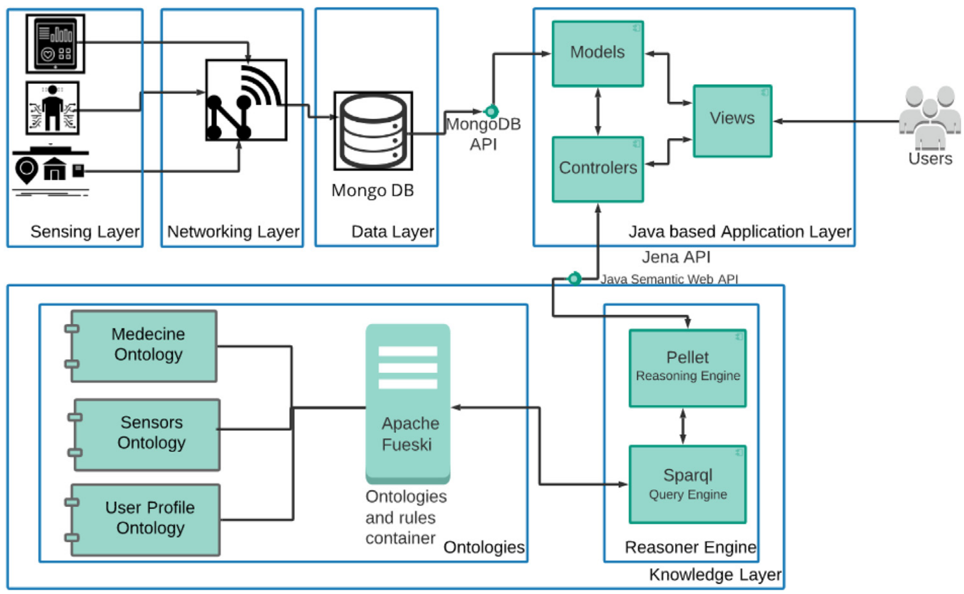

Fig. 2. System architecture.

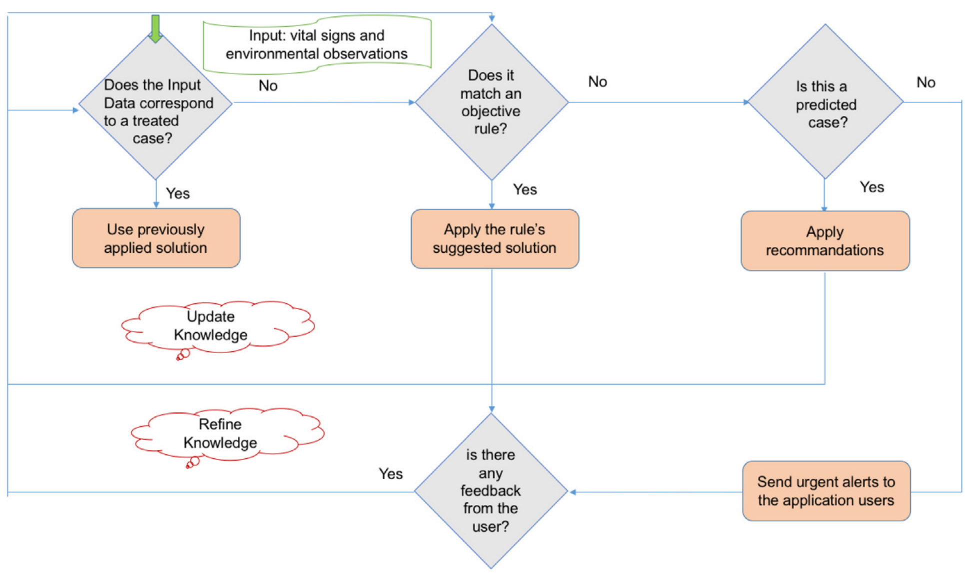

Fig. 3. Do-Care system reasoner engine.

4. Reasoner engine

The reasoning engine analyses the gathered data reasons with all available knowledge for situation assessment and prediction. It generates recommendations according to the reasoning process results. The Do-Care system engine deals with two types of knowledge; subjective and objective. Objective knowledge presents general medical rules, which are known by major doctors and can be found in textbooks. Subjective knowledge is related to the patient profile and context such as prior medical history, genetic diseases, personal lifestyle, etc. In these cases, all rules are stored in forms of predictions. If the forecasts are approved the predicted recommendation is applied and the approved predictions are stored onto the subjective rules database. Fig. 3 shows the Do-Care system reasoned engine, when it receives the patient personal data, it checks if the current situation has occurred in the past. If so, it recommends the previous treatment (i.e. the same medication). Otherwise, if the captured data does neither correspond to an existing objective rule or a subjective or predicted case, the system alerts the doctor asking for the appropriate recommendation. In all cases, the patient is informed of the feedback about the recommendation results to improve the two types of knowledge and mainly the system efficiency.

5. General diagnosis procedure

The Do-Care System provides real-time alerting and enacts effective recommendations to rescue patients in risky or wrong situations. For example, a measurement value 38 °C is a *normal observation* of the vital sign body temperature for an adult patient which requires no actions where, a measurement value 40 °C is considered as an *abnormal observation* requiring a risky alert to be activated and associated with the corresponding patient. However, a measurement value 48 °C of the body temperature for an adult patient is a wrong observation. Thus, in this case, a wrong alert is activated and associated with the corresponding patient. The general procedure of the diagnosis of a patient is summarized

Table 2
Body temperature ranges per age.

Age	Range bounds (°C)	Range situation
Under 18	36.6–37.5	Normal
Under 18	Under 36.6 or Over 37.5	Abnormal
Greater than 18 and Under 65	36.5–37.5	Normal
Greater than 18 and Under 65	Over 37.5 or Under 36.5	Abnormal
Over 65	35.6–36.3	Normal
Over 65	Under 35.6 or Over 36.3	Abnormal
Any	Under 14.2 or Over 46.5	Wrong

Table 3
Resting heart rate ranges per age.

Age	Range bounds (beats per minute bpm)	Range situation
1–12 months	110–160	Normal
1–12 months	Under 110 or Over 160	Abnormal
1–2 years	100–150	Normal
1–2 years	Under 100 or Over 150	Abnormal
3–5 years	95–140	Normal
3–5 years	Under 95 or Over 140	Abnormal
6–12 years	80–120	Normal
6–12 years	Under 80 or Over 120	Abnormal
13–18 years	60–100	Normal
13–18 years	Under 60 or Over 100	Abnormal
18–30	100–170	Normal
18–30	Under 100 or Over 170	Abnormal
30–40	95–162	Normal
30–40	Under 95 or Over 162	Abnormal
40–50	90–153	Normal
40–50	Under 90 or Over 153	Abnormal
50–60	85–145	Normal
50–60	Under 85 or Over 145	Abnormal
60–70	80–136	Normal
60–70	Under 80 or Over 136	Abnormal
70–80	75–128	Normal
70–80	Under 75 or Over 128	Abnormal
80–90	70–119	Normal
80–90	Under 70 or Over 119	Abnormal
Greater than 90	65–111	Normal
Greater than 90	Under 65 or Over 111	Abnormal
Any	Under 50 or Over 200	Wrong

by the Algorithm 1. Tables 2–5 resume all the considered ranges per vital sign and per age.

Algorithm 1 Patient health diagnosis.

Data: vital signs and environmental observations
Result: patient health diagnosis
$\forall \mathcal{O}_t^{s,p}$ **if** $(\mathcal{O}_t^{s,p} \notin \mathcal{R}_o)$ **then**
    $(\mathcal{ST}_p) \leftarrow$ *rong*
    $s \leftarrow$ *unreliable source*
    send Alert (s is wrong)
else
    if $\mathcal{O}_t^{s,p}$ == *abnormal* **then**
        $(\mathcal{ST}_p) \leftarrow$ *abnormal*
        send Alert (p is in a risky situation)
    else
        $(\mathcal{ST}_p) \leftarrow$ *normal*
    end
end
Update p's medical history

6. Do-Care ontology

The Do-Care ontology, as shown in Fig. 7, is a multidisciplinary modular ontology built by merging, mapping and extending three predefined ontologies. This section presents the general procedure of building the Do-Care ontology, then, it details its main components: the predefined and extended concepts, are described in details. Finally, the validity of the proposed ontology is discussed. Fig. 4 presents the main components and development steps of the Do-Care ontology.

Table 4
Resting blood pressure ranges per age [45].

Age	Range bounds (diastolic/systolic) mmHg	Range situation
1–12 months	50/75–70/100	Normal
1–12 months	Under 50/75 or Over 70/100	Abnormal
1–5 years	50/80–78/112	Normal
1–5 years	Under 55/80 or Over 78/112	Abnormal
6–12 years	55/85–80/120	Normal
6–12 years	Under 55/85 or Over 80/120	Abnormal
13–18 years	62/94–88/140	Normal
13–18 years	Under 62/94 or Over 88/140	Abnormal
18–60 years	90/60–120/80	Normal
18–60 years	Under 90/60 or Over 120/80	Abnormal
Greater than 60	121/83–147/91	Normal
Greater than 60	Under 121/83 or Over 147/91	Abnormal
Any	Under 70/40 or Over 190/100	Wrong

Table 5
Resting respiratory rate ranges per age.

Age	Range bounds (breaths per minute)	Range situation
Birth to 6 weeks	30–40	Normal
Birth to 6 weeks	Under 30 or Over 40	Abnormal
6 months to 3 years	25–40	Normal
6 months to 3 years	Under 25 or Over 40	Abnormal
3–6 years	20–30	Normal
3–6 years	Under 20 or Over 30	Abnormal
6–10 years	18–25	Normal
6–10 years	Under 18 or Over 25	Abnormal
10–18 years	17–23	Normal
10–18 years	Under 17 or Over 23	Abnormal
18–65	12–18	Normal
18–65	Under 12 or Over 18	Abnormal
65–80	12–28	Normal
65–80	Under 12 or Over 28	Abnormal
Greater than 80	10–30	Normal
Greater than 80	Under 10 or Over 30	Abnormal
Any	Under 4 or Over 50	Wrong

6.1. Design and conception

This subsection explains the general architecture of the Do-Care ontology in two main steps. The first step is a discussion about the interest and motivation for a modular architecture. The second step is a presentation of the basic steps to build the Do-Care ontology.

6.1.1. Modular ontology

The modularity of an ontology is highly recommended in multidisciplinary applications such as the proposed Do-Care system making its extension and management easier. For this reason, the Do-Care ontology is the composition of three different ontologies: personal profile ontology, sensors ontology and medicine ontology. The personal profile ontology represents the user's attributes, such as personal account, personal information, contacts and a medical history. The sensors ontology accounts for the different devices of the system, the different features of interest such as the different vital signs, all the observed property for each sensor and the time of each observation. Finally, the medicine ontology states the different medical and clinical terminologies. However, to fit the features of the proposed environment, there is a need to extend it with new concepts. The following subsection presents the three modules of the proposed ontology and its extensions. Since predefined ontologies are being used, the names of any predefined class is prefixed by the name of the corresponding

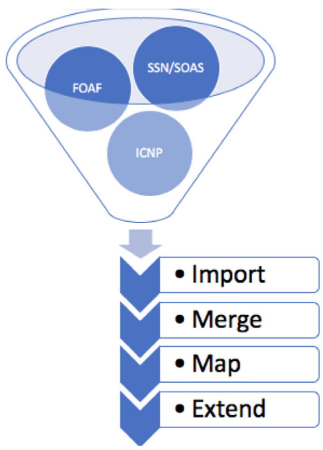

Fig. 4. The main steps of the development of Do-Care ontology.

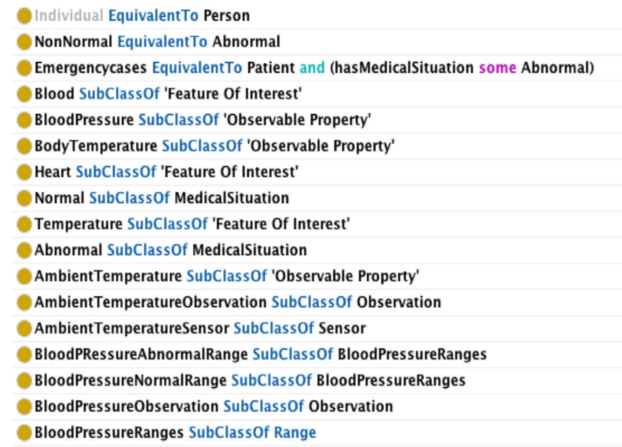

Fig. 5. Do-Care axioms.

ontology, i.e. if the name of the class is not prefixed, it means that the corresponding class is being specially created for the Do-Care ontology.

6.1.2. Merging, mapping and extending ontologies

As aforementioned, the proposed Do-Care Ontology is composed of three ontologies: a personal profile ontology, a sensors ontology and a medicine ontology. Three operations are performed to get all the required entities: a monolingual mapping, a merging then an extension. The monolingual mapping makes the correspondence between each two entities having the same name. This procedure cannot provide a complete association between all equivalent entities from all ontologies. For the simple reason that in many cases a one entity may have different names from one ontology to another. The mapping is followed by a merging operation based on a set of axioms expressing the equivalence or the membership. For instance, the entity Individual from the medicine ontology is equivalent to the entity person from the personal profile ontology. The equivalence is expressed by the two first axioms from Fig. 5, so the equivalence relation between those two entities is shown in Fig. 6. The mapped and merged ontology need to be extended to achieve some specific requirements. For example, to express that a result is observed by a sensor and this sensor is worn by a particular patient, two objective properties should be defined to express the relations between an observation and a sensor then between a sensor and a patient. A set of personalized data properties, objective properties and inference rules, provided in Section 7.1, is proposed to express all the requirements.

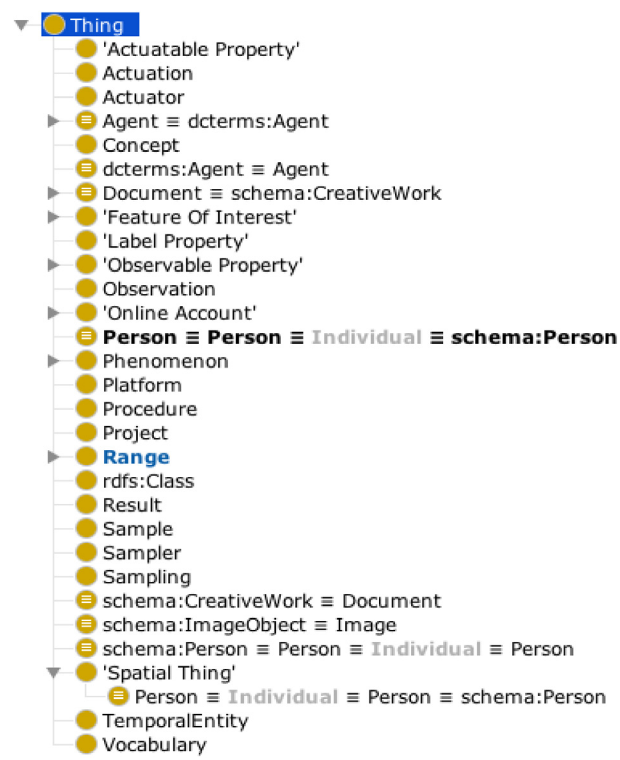

Fig. 6. Do-Care merged ontology.

6.2. Components

6.2.1. FOAF based personal profile ontology

FOAF ontology includes all possible aspects of a general profile of a user. The class *FOAF:Person* represents a one user's profile and associates with it different data properties, such as, name, gender, account, phone, age, etc. However, new medical concepts and properties are also need to be added as a physical dimension status to fit the features of the proposed environment defined by the medicine ontology ICNP. The class ICNP: PhysicalDimension-Status defines the following properties as weight, height, blood, etc, as sub-classes.

6.2.2. SSN/SOSA based sensors ontology

The class *SOSA:Observation* is to estimate or calculate a value of a property of a feature of interest. The class *SOSA:Feature Of Interest* is the feature whose property is being estimated or calculated in the class of an *SOSA:Observation*. For example, the class *BloodPressureObservation* is a sub-class of *SOSA:Observation* representing all the observations of the pressure of the feature of interest *Blood* which is a subclass of *SOSA:FeatureOfInterest*. The set of features of interest in Do-Care are: blood, oxygen, temperature, glucose and heart. Each feature of interest is measurable using an observable property represented by the class *SOSA:Observable Property*. For instance, the class *Pressure* is a

Table 6
Table of notations.

Notation	Signification
Patient	Set of Patients
Alert	Set of Alerts
Doctor	Set of Doctors
CommminicableDiseaseRate	Rate of patients with communicable disease
CommunicableDiseasethreshold	The threshold of number of patients with a communicable disease if it is reached all patients should be alerted
RiskyCases	Sub set of patients having as a health situation risky
hasPotentialityState	A relation between the set of patients and timing associating time to the health situation of patient
AlertDescription	Description of (causes of) Alert
ActualNegativeMedicationInteraction	The case when the prescription of Medication does not give any positive results
ActualNegativeMedicationSideEffect	The case when the prescription of a medication is accompanied by side effects
ActualNegativeDrugRules	The case when the prescription of a medication does not give any positive results
ActualNegativeDrugMedicationAllergy	The case when the patient has an allergy of one medication

subclass of *SOSA:Observable Property* of the class *Blood*. In the Do-Care ontology, the following set of observable properties is defined: *Pressure*, *Level*, *Rate* and *Value*. Any observation *is made by* a sensor, i.e. a sensor *observes* an observation. The set of sensors are represented by the entity *SOSA:Sensor* containing two sub-classes *BodySensors* presenting sensors worn by the patient and *AmbientSensors* presenting sensors around the patient. *BodySensors* are decomposed per observable properties: *BloodPressureSensor, GlucoseSensor, HeartRateSensor, OxygenSensor* and *TemperatureSensor*. All sensors, devices, actuators, or other platforms belonging to one user are hosted by, *is hosted by*, the same *SOSA:Platform*. Relation between a user and associated platform is represented by the relation *has Platform*. The value result made by a sensor, i.e. value of an observation, is represented by the class *SOSA:Result* and they are related using the relation *SOSA:is result of*. To each *SOSA:Result* is associated a *Range* expressing the situation of the corresponding observation: *normal, abnormal* or *wrong*. Tables 2–5 give examples about the ranges per vital signs per age per gender as it is defined in medicine.

6.2.3. ICNP based medicine ontology

ICNP:Individual defines all the possible human actor in a healthcare or clinical system: *ICNP:Doctor, ICNP:Nurse, ICNP:Patient, ICNP:Pharmacist, ICNP:CareGiver, ICNP:CareProvider, etc.* For each individual is defined *ICNP:Development Period* depending on its age. Moreover, this ontology contains the class *ICNP:Sign* and its sub-class *ICNP:VitalSign* which defines the different vital signs of the human being and having the following subclass *Blood Pressure Sign, Glucose sign, Heart Rate Sign* and *Body Temperature Sign*. In general, each phenomena in ICNP can be judged Negative or Positive depending on its presence. For a patient, an infection is judged positive in case of its presence. The class *ICNP:AbsoluteJudgedState*, having two subclass: *ICNP:NegativeJudgedState* and *ICNP:PositiveJudgedState*, is for all the phenomena that are absolutely judged, as infection. The objective property *ICNP:hasAbsoluteJudgeState* is expressing the state of each phenomena including vital signs and the objective property *ICNP:hasPotentialityState* is associating time to the phenomena. For instance, a patient in a risky case if his blood pressure sign is judged negative and the potentiality of this state is actual, i.e *ICNP:hasAbsoluteJudgeState some ICNP:NegativeJudgedState and ICNP:hasPotentialityState some hasPotentialityState:Actual.*

6.3. Validation

Even though three validated ontologies are being used: FOAF, SSN/SOSA and ICNP, there is no guarantee that the Do-Care Ontology is validated because of new created concepts and facts. Fig. 8 shows the validation of the proposed Do-Care Ontology.

7. Dynamic medicine rules inference process

7.1. General process description

The main contribution of the proposed Do-Care proposed system is its dynamic knowledge whenever it is objective or subjective. The objective knowledge is refined according to the withdrawal or the appearance of some drugs from the market and the appearance of a new unrecognized virus or a seasonal epidemic (influenza). The complete process of refinement is described by the pseudo-code in Algorithm 2 where Table 6 explains the used notations.

Algorithm 2 Refine Knowledge.

```
Data: Objective Knowledge and General Health Conditions
Result: Refined Objective Knowledge
if (CommunicableDiseaseRate > CommunicableDiseasethreshold) then
    for all patient perform GuidingAct
end
if ∃ Patient has ImmunisationRate < Immunisationthreshold then
    define new rules (symptoms Communicable Disease, Prescription)
end
if (∃ Drug has withDrawlStatus) then
    for Patient do
        PrescribingMedication equivalent Drug
    end
end
if (∃ new Drug with Low SideEffectRate ) then
    for Patient and AbsenceOfMedicationSideEffect do
        PrescribingMedication new Drug
    end
end
```

The Do-Care system updates are considered subjective knowledge according to the medical personal profile of each patient. Precisely, the subjective knowledge may be updated if: the patient exhibits an allergic reaction to some medications, the prescribed medications did not produce results, has worsening health conditions or the prescribed medications have negative drug to drug interactions. New inference rules can be interpreted from the medical history of a patient: the history of the different vital signs observations and the previous prescriptions. The process of the knowledge update is presented as a pseudocode in Algorithm 3.

Algorithm 3 Update Knowledge.

Data: Subjective Knowledge and Historic Context Awareness Personal Profile
Result: Updated Subjective Knowledge
for *Alert received by Doctor* **do**
  if *(Patient in RiskyCases and Patient hasPotentialityState(Potential)* **then**
    send(recommendation, patient)
  end
  (Patient in QueryCases and Patient hasPotentialityState(Actual)) **switch** *AlertDescription* **do**
    case *ActualNegativeMedicationInteraction*
      update rule(prescription, new Drug)
    end
    case *ActualNegativeMedicationSideEffect*
      new rule(prescription, new Drug)
    end
    case *ActualNegativeDrugUse*
      new rule (TeachingAboutNegativeDrugUse, same Drug)
    end
    case *ActualPositiveMedicationAllergy*
      Edit(ProhibitedDrugs,Patient); new rule(prescription, new Drug)
    end
  endsw
end

7.2. Dynamic inference rules

The set of inference rules for the proposed Do-Care system is composed basically of three main sub-sets of rules: Medicine Inference Rules, Sensors Rules and Merging Inference Rules. The Medicine Inference Rules is composed of rules necessary for medicine related purposes used to determinate the current situation of the patient. The Sensors Rules are the set of inference rules related to sensors and theirs observations. The Merging Inference Rules (MIR) are used to create the appropriate links between the different ontologies.

Medicine inference rules. The main aim of this set of rules is to determinate the health situation of a patient. The Fig. 9 presents all medicine rules considered in the Do-Care system.

Sensors rules. The main role of the sensors rules is to arrange the value observed in its appropriate range depending on the corresponding feature of interest. The Fig. 10 presents the different SWRL rules belonging to sensors and observations.

8. Evaluation and experimental results

In this section, the development and implementation of the Do-Care system are presented. The Do-Care system is tested using an arbitrary data set.

8.1. Implementation framework

The Do-Care system is a web based application, as shown in Fig. 2, composed basically of three components: view, model and control. Views are all web pages, i.e. graphical interfaces which are basically provided for the users. Models are all java classes associated with entities of the data set, i.e. with each class of the ontology, it is associated a java class. The control components are implementing of the following features:

- retrieve the ontology and the reasoner (the set of SWRL rules)
- recuperate the data set containing the collected data from patients
- feeding the reasoner with the instances from the data set of the patients to deduce new facts
- show result consistency in alerts

8.1.1. Servers

The Do-Care system, as a web application, needs two servers:

Apache Tomcat Web server which is a web server containing the web pages. The web container used is Apache Tomcat which contains, besides the web pages, all necessary APIs for the Do-Care system, for example the Jena API and mongoDB API.

MongoDB server a data server containing the collected data. The data should be ubiquitous, i.e. real-time collected from the patient's body sensors. The NoSQL data server: MongoDB, has been chosen to save the collection of data from the different body sensors.

Since, the main contribution of the proposed system is its dynamic ontology, thus, the **server Apache Fuseki** was chosen to contain the proposed ontology and allow for its update.

8.1.2. Pellet based reasoner

The Do-Care's reasoner is implemented based on the reasoner Pellet. It is an open source java reasoner that uses Jena and OWL-API interface in ontology reasoning. It supports expressive description logics and bugs explanation. Pellet is allowing reasoning in the data set using the proposed set of rules specified using SWRL.

8.1.3. Do-Care ontology development

The proposed ontology is developed using Protégé [46,47] which is a free, open source ontology editor and a knowledge management system. It allows for the defining both, the ontology and the set of SWRL rules.

The general procedure for the development of the Do-Care ontology is as follows, and as is shown in Fig. 11,:

- Import FOAF, SSN/SOAS and ICNP ontologies in Protégé
- Use the feature merging ontologies in Protégé
- Define the set of mapping axioms
- Extend the ontology to fit the feature of Do-Care system

8.2. Do-Care views

This subsection presents different views from the developed prototype Do-Care for the following scenario: default dashboard for the three users: patient, caregiver and doctor; alerts for risky and wrong cases; add a new rule based on his medical history; and denying a medicine prescription because of allergy.

Default dashboard. Any user should authenticated to get access to the different functionalities of the Do-Care system. Fig. 12 gives an example of the login interface, in its left side, and the dashboard for a connected user, in its right side. Since the user in Fig. 12 is a doctor, the right side is showing the list of his patients scrolled one by one. For each patient, the doctor can see all details about his current healthcare situation with the values of his vital signs as body temperature, blood pressure, etc.

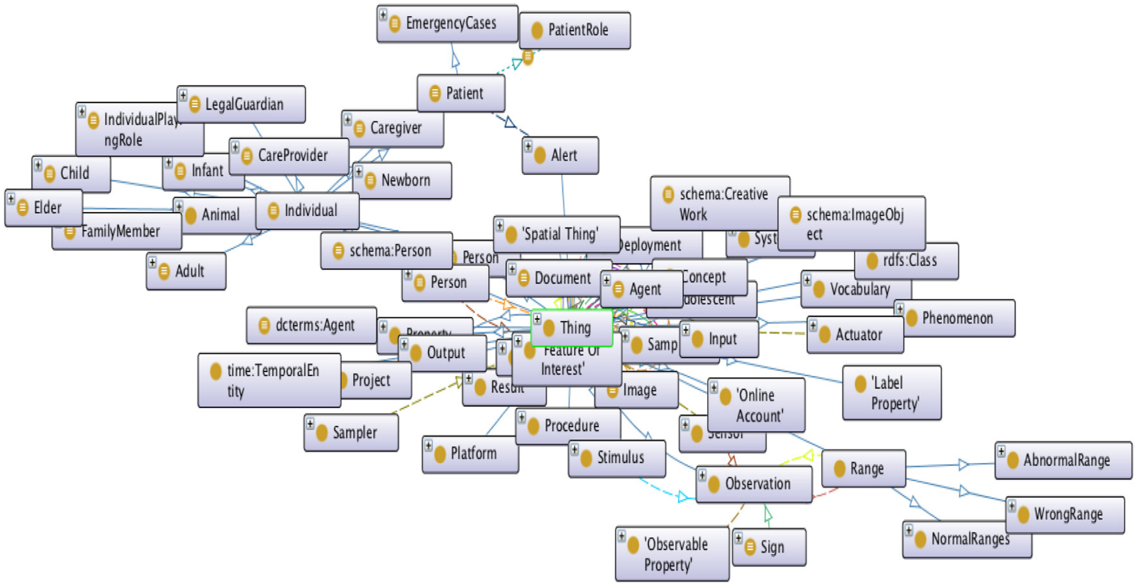

Fig. 7. Do-Care ontology.

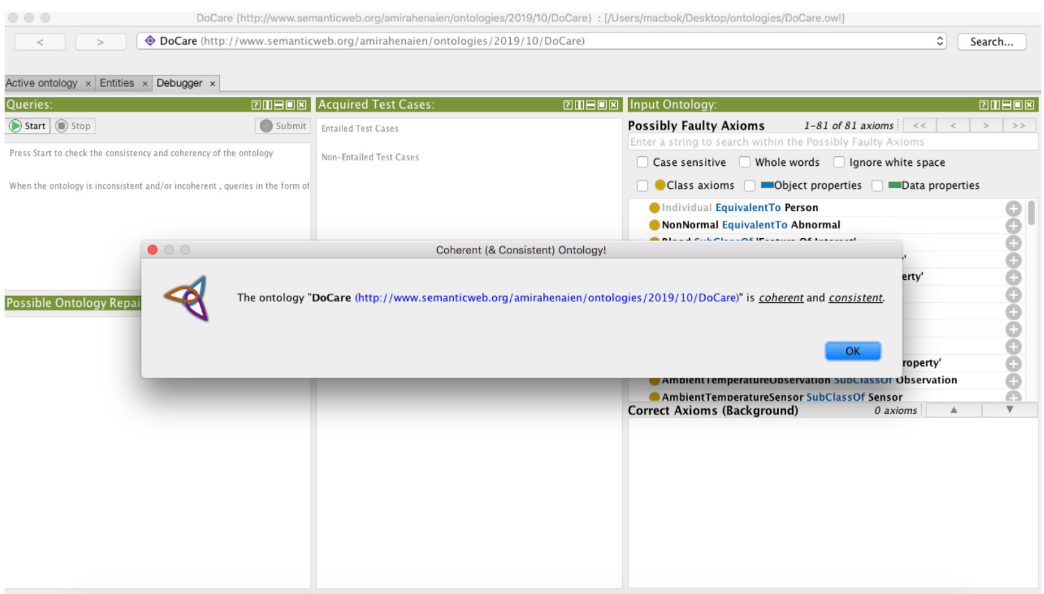

Fig. 8. Do-Care ontology validation.

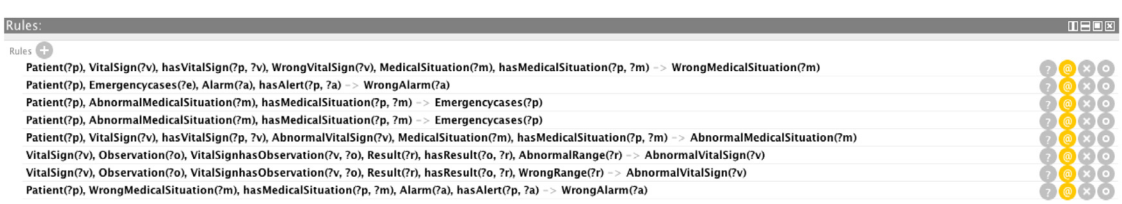

Fig. 9. Medicine SWRL rules.

Alerts. Alerts will be sent for emergency cases. For each doctor or care giver, the system highlights the alerted cases. The Fig. 13, presents one alerted case, highlighted with red color. The patient has 40 °C as a body temperature which belongs to the abnormal range as it is mentioned in Table 2. The corresponding SWRL rule that is able to deduce an emergency case is: $icnp : Patient(?p) \wedge autogen0 : AbnormalMedicalSituation(?m) \wedge autogen0 : hasMedicalSituation(?p, ?m) -> autogen0 : Emergencycases(?p)$.

New medicine rule base on predict case. The definition of a new medicine rule is assisted by a doctor. As shown in Fig. 14, the doctor can consult all previous medical situations and select any one of them that is a potential emergency case. The selected

```
3BPRAN612 EquivalentTo (BloodPressureNormalRange and ((Diastolic some xsd:integer[> 80]) or (Diastolic some xsd:integer[< 55]))) or ((Systolic some xsd:integer[> 120]) or (Systolic some xsd:integer[< 85]))
3BPRN612 EquivalentTo (BloodPressureNormalRange and ((Diastolic some xsd:integer[> 55]) or (Diastolic some xsd:integer[< 80]))) and ((Systolic some xsd:integer[> 85]) or (Systolic some xsd:integer[< 120]))
4BPRAN1318 EquivalentTo (BloodPressureAbnormalRange and ((Diastolic some xsd:integer[> 88]) or (Diastolic some xsd:integer[< 62]))) or ((Systolic some xsd:integer[> 140]) or (Systolic some xsd:integer[< 94]))
4BPRN1318 EquivalentTo (BloodPressureNormalRange and ((Diastolic some xsd:integer[> 62]) or (Diastolic some xsd:integer[< 88]))) and ((Systolic some xsd:integer[> 94]) or (Systolic some xsd:integer[< 140]))
5BPRAN1860 EquivalentTo (BloodPressureAbnormalRange and ((Diastolic some xsd:integer[> 120]) or (Diastolic some xsd:integer[< 90]))) or ((Systolic some xsd:integer[> 80]) or (Systolic some xsd:integer[< 60]))
5BPRN1860 EquivalentTo (BloodPressureNormalRange and ((Diastolic some xsd:integer[> 90]) or (Diastolic some xsd:integer[< 120]))) and ((Systolic some xsd:integer[> 60]) or (Systolic some xsd:integer[< 80]))
6BPRANplus60 EquivalentTo (BloodPressureAbnormalRange and ((Diastolic some xsd:integer[> 147]) or (Diastolic some xsd:integer[< 121]))) or ((Systolic some xsd:integer[> 91]) or (Systolic some xsd:integer[< 83]))
6BPRNplus60 EquivalentTo (BloodPressureNormalRange and ((Diastolic some xsd:integer[> 121]) or (Diastolic some xsd:integer[< 147]))) and ((Systolic some xsd:integer[> 83]) or (Systolic some xsd:integer[< 91]))
```

Fig. 10. SWRL ranges axioms.

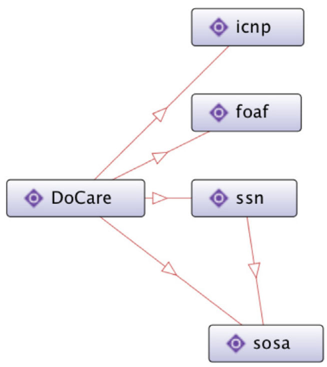

Fig. 11. The development of Do-Care ontology using Protégé.

situation is transformed to a new rule and inserted in the set of medicine rules for future uses.

Denying a medicine prescription because of allergy. The system Do-Care make a doctor aware of the different allergies a patient may have. For example, as shown in Fig. 15, the prescription of ACE-inhibitors is denied because the patient has already an oral allergy. The corresponding rule, $Patient(MedBen) \wedge hasAllergy(MedBen, Oral) \wedge Hypertension(?h) \wedge hasDiagnosis(anas, ?h) -> deniedprescription(MedBen, ACE - inhibitors)$.

9. Conclusions and future works

Ubiquitous healthcare monitoring and effective decision support systems are among the most prevalent IoT-based health applications. Remote health monitoring systems aim to collect raw data from heterogeneous devices, extract useful information and present that information in a form of comprehensive medical prescriptions and recommendations. Obviously, such systems have to ensure personal context, situation and dynamic health area changes awareness. However, this is not taken into account in existing proposed systems. This paper proposes an ontology reasoning based health-care monitoring system called Do-Care. The proposed system is designed to support the supervision and follow-up of out and in door patients suffering from chronic diseases. Decision-making approach tailoring is based on a dynamic SWRL rule based reasoning engine and a subjective and objective knowledge bases. In this regard, both rule bases are adaptable to medication market, health incidents and discoveries and personal patient profile reactions. The system is developed and its efficiency is tested as well as its ontology and reasoning engine. As a future work, the integration of the Decision Tree Learner algorithm seems to be efficient in the prediction of diseases and to provide additional support for doctors in preventive medication recommendations. The Decision Tree algorithm is intended to match the patient profile, his medical history, the system feed-backs, and the developed ontology that define subsumption relations between concepts to derive the decision tree leaves and continuously improve the Do-Care SWRL base.

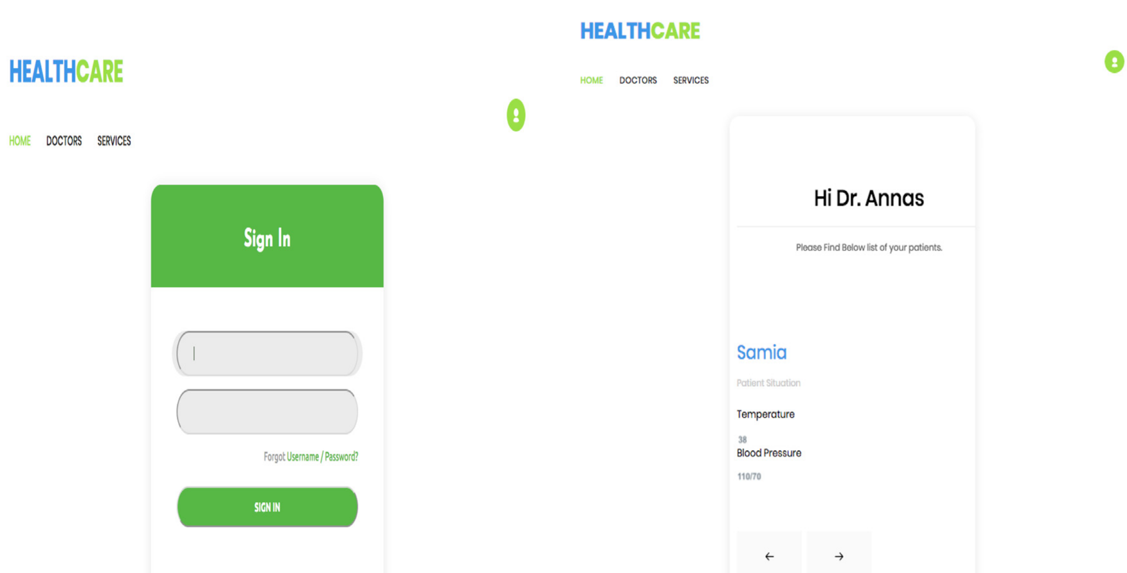

Fig. 12. Dashboard for a Doctor.

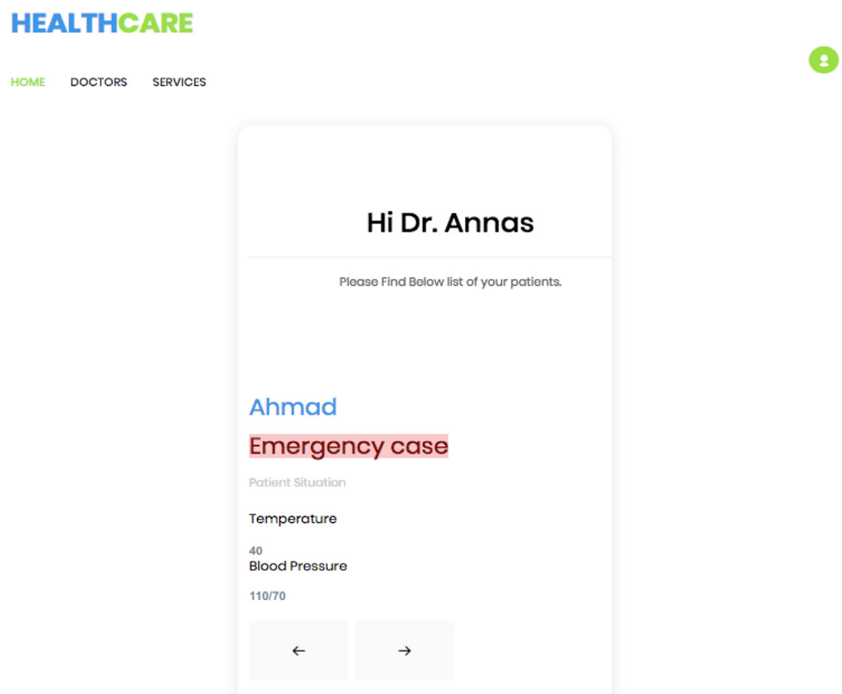

Fig. 13. Alert example of an emergency case.

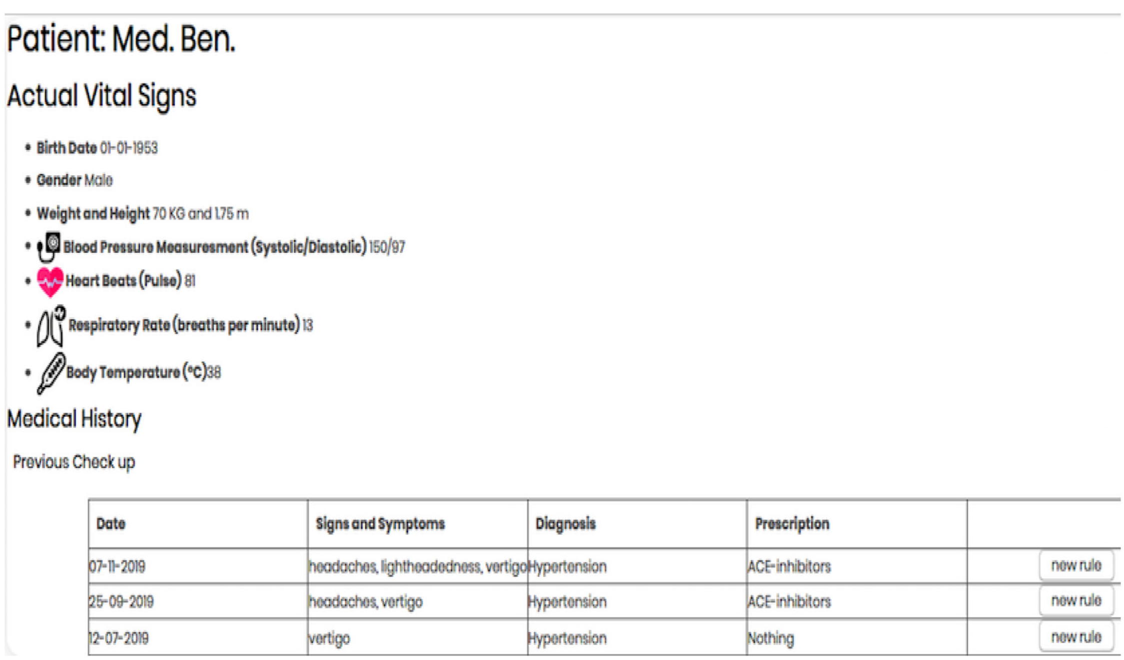

Fig. 14. Doctor's interface to add a new rule.

CRediT authorship contribution statement

Hadda Ben Elhadj: Conceptualization, Validation, Investigation, Supervision. **Farag Sallabi:** Conceptualization, Validation, Writing - review & editing, Project administration, Funding acquisition. **Amira Henaien:** Methodology, Software, Investigation, Writing - original draft. **Lamia Chaari:** Conceptualization, Validation. **Khaled Shuaib:** Validation, Writing - review & editing, Funding acquisition. **Maryam Al Thawadi:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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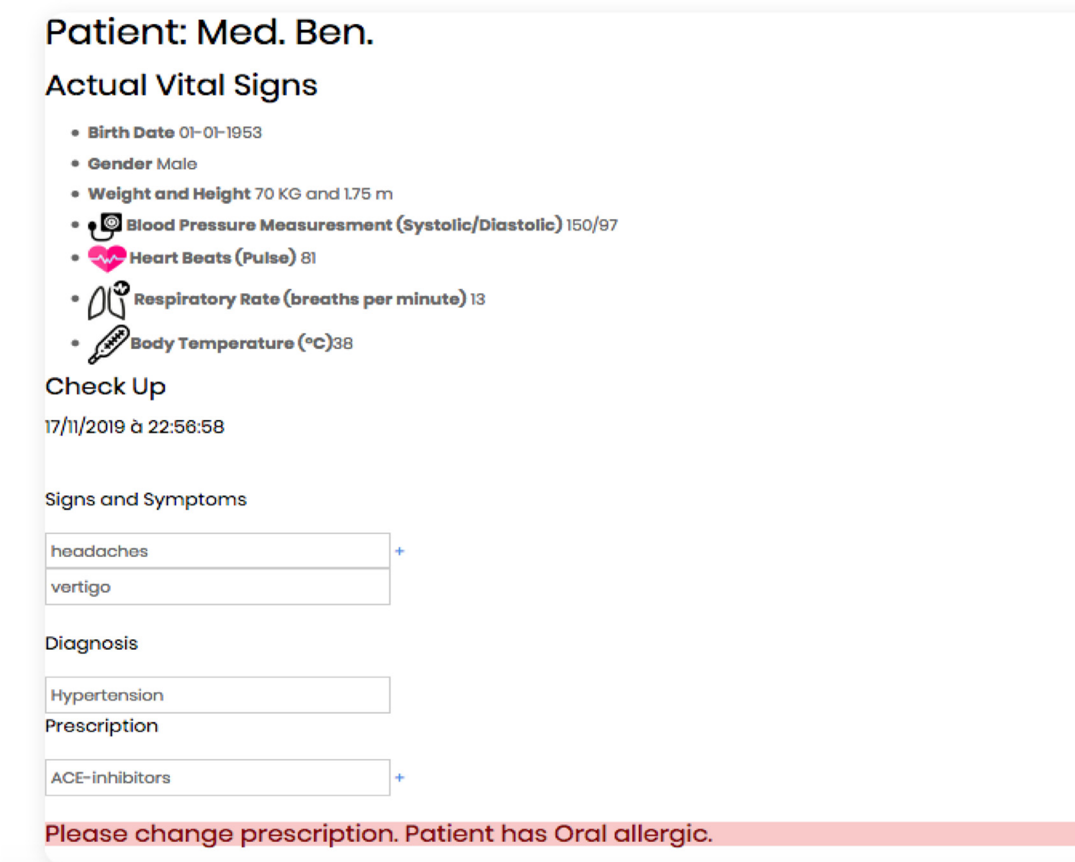

Fig. 15. Example of prescription denied because of patient's allergy.

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