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IoT Software Infrastructure for Remote Monitoring of Patients with Chronic Metabolic Disorders

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***Abstract*—Novel Information and Communication Technologies, such as Internet-of-Things (IoT), middleware and cloud computing, are providing innovative solutions ranging in different contexts. Smart health is one of these scenarios. Indeed, there is a rising interest in developing new healthcare services for remote patient assistance and monitoring. Among all, the main promised benefits consist on improving the patients' quality of life, speeding up therapeutic interventions and reducing hospitalizations' costs. This is also known as *Telemedicine*. In this paper, we present a novel distributed software infrastructure for remote monitoring of patients with chronic metabolic disorders: i) it collects and and makes available information coming from IoT devices, ii) it performs analysis to help medical diagnosis and iii) it promotes a bidirectional communication among the end-users (i.e. medical personnel and patients). In this paper, we also present our experimental results performed in a laboratory test environment to validate the proposed solution.**

***Index Terms*—Internet of Things, Distributed software infrastructure, Cloud, Smart Health, Telemedicine, Remote healthcare**

I. Introduction

In the last decades, we are witnessing to a demographic change characterized by a progressive lengthening of life expectancy and an increase in the elderly population. This is leading to an exponential growth of chronic metabolic disorders. In Europe, the percentage of over-65 raised from 14.6% in 1990 to 17.2% in 2005 and it is expected to be around 20.7% in 2020 [1]. In Italy, the percentage of over-65 exceeded the 22.3% in 2016 and around 88% of over-75 citizens is affected at least by a chronic pathology [2]. This lengthening of life expectancy implies an increase in healthcare spending and the inefficient management of resources (e.g. medical personnel, hospitals and technologies). In this scenario, the increasing demand of healthcare leads to rethink and change the organization of services that must be decentralized promoting solutions for remote assistance, also known as *Telemedicine*. The World Health Organization (WHO) defines Telemedicine as follows: *"The delivery of healthcare services, where distance is a critical factor, by all healthcare professionals using Information and Communication Technologies (ICT) for the exchange of valid information for diagnosis, treatment and prevention of disease and injuries, research and evaluation, and for the continuing education of healthcare providers, all in the interests of advancing the health of individuals and their communities"* [3], [4]. This highlights that Telemedicine and remote healthcare services are extremely useful for patients with stable chronic pathologies. Indeed, they allow medical personnel on having updated medical records for their patients avoiding unnecessary hospital admissions. The benefits of these decentralized healthcare services can be summarized as follows:

- improvement of patients' quality of life;
- speed up therapeutic interventions to solve serious metabolic disorders;
- increase patients' awareness on their illness;
- adapt therapies to patients daily life;
- improvement of the quality of the healthcare services;
- reduction of access to the emergency room for erroneous therapies or for therapies not adapted to changes in patients' medical records;
- reduction of hospitalizations and their costs;
- positive impact of patients on new e-health technologies.

In this view, novel ICT solutions are crucial to foster remote patient monitoring and healthcare services. Key rising technologies to move forwards along this direction are i) Internet-of-Things (IoT), ii) middleware and iii) cloud computing [5]. On these premises, we present a novel distributed software infrastructure, a.k.a. HEALTHIOT, for remote monitoring of patients with chronic metabolic disorders. In this paper, we focused on two types of patients: patients with diabetes disease (type 1 or type 2 diabetes) and patients undergoing house dialysis. However, we designed and developed HEALTHIOT to be extended taking into account also other medical pathologies. Thus, new healthcare services, post-process and applications can be developed following the needs of both medical personnel and patients. The proposed platform makes available i) vital patient's parameters to doctors in near-real-time and ii) post-processed information to help in doing medical diagnosis. In addition, HEALTHIOT promotes a bidirectional communication and information exchange i) between patients and their doctors and ii) among different experts and specialists (if authorized).

The rest of this paper is organized as follows. Section II reviews most relevant literature solutions. Section III introduces the proposed IoT software infrastructure for remote patients' monitoring. Section IV presents the laboratory tests we performed to validate proposed solution. Finally, Section V

discusses concluding remarks and future works.

II. Related work

Nowadays, rising ICT solutions are becoming key players to foster novel services for different context, such as Smart City, Smart Energy and Smart Health. As pointed out by [5], the Internet-of-Things, together with middleware technologies and cloud computing, is crucial to design and develop such new tools, platforms and applications, especially in the context of Smart Health and/or Telemedicine.

Fan et al. [6] proposed a smart rehabilitation systems based on IoT devices. The core of the system is an Ontology to help doctors i) in making quick diagnosis of patients and ii) in creating automatically a rehabilitation strategy based on the specific requirements of patients. Then, IoT devices are used to provide immediate information. VIRTUS [7] is an event-driven middleware that builds a multi-layered software architecture. It enables the interoperability among different devices and applications through XMPP protocol. In the context of Smart Health, VIRTUS has been used to implement a remote rehabilitation systems as case-study. UDA-IoT [8] is a cloud-based platform designed to collect and process information coming from IoT devices. It aims at sharing such ubiquitous information to improve the emergency medical services. In [9], authors present both a Smart e-Health Gateway for heterogeneous IoT sensors integration and a reference architecture for healthcare services. This architecture follows a fog computing approach where the intelligence is distributed among Smart e-Health Gateways that form an intermediary layer between IoT devices and the Cloud layer. Abawajy et al. [10] present a remote pervasive patient health monitoring framework. It combines both IoT devices and cloud computing to remote monitor health conditions of patients in real-time. Finally, iHealth [11] is a company that provides commercial IoT devices that send patient's vital parameters to its cloud, usually through a mobile phone. However, this cloud is limited in integrating only iHealth devices and it does not provide tools to post-process collected information.

The presented solutions are mainly focused on addressing a specific healthcare service. In addition, they lack on providing specific tools or modules to analyse and post-process patient's information for helping doctors in making medical diagnosis. Whilst, in our view an IoT platform for Smart Health and/or Telemedice should be customizable and extendible to provide general purpose healthcare services, hence to address different pathologies. In this view, we propose HealthIoT, a distributed software infrastructure for remote monitoring of patients with chronic metabolic disorders. It is a cloud-based infrastructure that i) integrates heterogeneous off-the-shelf IoT devices; ii) provides medical personnel with vital patient's parameters in near-real-time; iii) helps in making patients' diagnosis; iv) allows a bidirectional data exchange between patients and medical personnel. In this paper, we present healthcare services for two classes of patients: i) patients with diabetes disease (type 1 or type 2 diabetes) and ii) patients undergoing house dialysis. Such services have been developed following the requirements given by both diabetologists and nephrologists. However, HealthIoT is an open infrastructure that provides unified API and Web Services allowing the development of general purpose healthcare services. Hence, further services and applications can be developed for other pathologies and metabolic disorders.

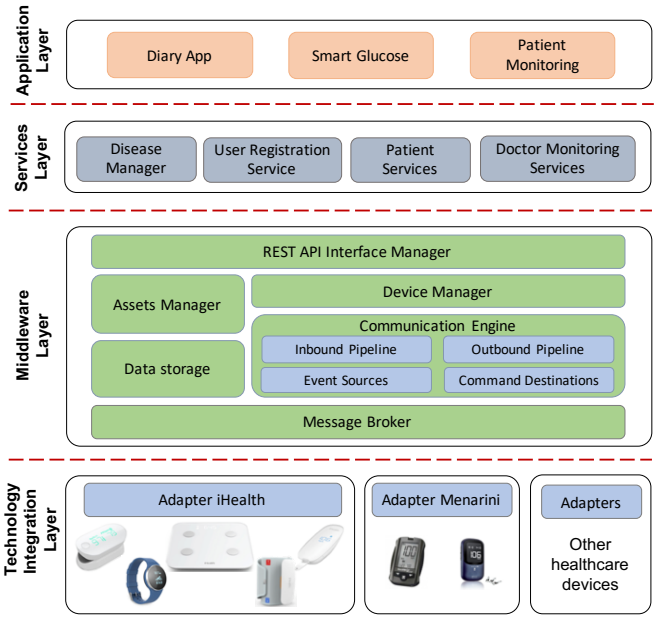

Fig. 1. Scheme of HealthIoT software infrastructure.

III. Software infrastructure for remote patients' monitoring

In this section, we present HealthIoT, our IoT software infrastructure for remote patients' monitoring. Its core has been developed starting from SiteWhere platform [12], which has been extended to address Telemedicine and remote healthcare objectives. HealthIoT allows a bidirectional communication and information exchange i) between patients and their doctors and ii) among different experts and specialists (if authorized). It has been designed to integrate heterogeneous IoT devices for healthcare monitoring by abstracting different underlying low-level technologies. It also enables the interoperability among such heterogeneous devices and offers a common data access to patients information. HealthIoT already integrates different technologies and protocols (e.g. IEEE 802.11 and Bluetooth) adopted by novel off-the-shelf IoT devices. Moreover, HealthIoT has been designed exploiting a microservice approach [13], [14] allowing the deployment on cluster of servers or in cloud systems. In addition, HealthIoT supports the multi-tenancy [15]. A tenant refers to a group of customers with shared common access and privileges to software instance. Multi-tenant software is a single instance of software that serves various tenants by providing a dedicated share of the same software instance avoiding data intermingling among different tenants.

HEALTHIOT multi-tenancy also allows separating data storage and processing pipelines.

As shown in Figure 1, HEALTHIOT consists of four layers: i) *Technology Integration Layer*, ii) *Middleware Layer*, iii) *Services Layer* and iv) *Application Layer*. The rest of this section describes each layer in more detail.

A. Technology Integration Layer

The *Technology Integration Layer*, the lowest in Figure 1, is in charge of integrating heterogeneous IoT technologies through *Technology Integration Adapters* (TIAs). TIA is a software component that abstracts features and functionalities of IoT devices following a methodology proposed in [16]. It acts as a bridge between HEALTHIOT and the underlying technology translating whatever kind of language the low-level technology speaks (e.g. IEEE 802.11 and Bluetooth) into common web interfaces. This is a crucial component because it allows to use each low-level technology transparently. In particular, we developed a TIA to integrate the iHealth [11] cloud, consequently all the iHealth IoT devices (i.e. activity trakers, smart scales, pulse oximeters, blood pressure monitors and glucometers), and another TIA for the glucometers produced by Menarini group [17].

B. Middleware Layer

The *Middleware Layer* is the core of HEALTHIOT. As shown in Figure 1, it consists of different components: i) to enable and guarantee a bidirectional communication with IoT devices through TIAs; ii) to store information and iii) to provide unified interfaces to access data and devices. The whole HEALTHIOT exploits the two main communication paradigms for information exchange: i) *request/response* and ii) *publish/subscribe* [18]. Request/response enables synchronous communication through REST web services [19]. Publish/subscribe allows asynchronous communication that complements request/response. It enables the development of scalable loosely-coupled event-based systems, services and applications that can react in (near-) real-time. In HEALTHIOT, we adopted the MQTT protocol [20]. In this view, the *Message Broker* (see Figure 1) manages the MQTT communication. It also routes all messages to the *Communication Engine* that manages the communication between HEALTHIOT and the IoT devices. In its core, the *Communication Engine* consists of four sub-modules: i) *Event Sources*, ii) *Inbound Pipeline*, iii) *Outbound Pipeline* and iv) *Command Destinations*. The *Event Sources* module receives measurements and alerts from devices (through TIAs) and checks message integrity before forwarding them to the *Inbound Pipeline*. The *Inbound Pipeline* module implements smart buffers to avoid data transmission spikes and congestions in storing information into the *Data Storage*. Similarly, both *Outbound Pipeline* and *Command Destinations* modules handles outcoming messages that have to be sent to IoT devices through MQTT. Hence, HEALTHIOT is ready to send commands back to IoT devices if required by applications and services. The *Data Storage* integrates different non-relational database models (e.g. document oriented or time series), where information are stored. The *Device Management* registers new IoT devices and the *Asset Manager* handles information of the assets (e.g. patients, doctors, places and things) and their associations. The *REST API Interface Manager* provides REST web services to applications and services for accessing data in HEALTHIOT. To access information and to verify permissions in performing certain operations, HEALTHIOT authenticates both services and users.

C. Services Layer

The *Services Layer* has a dual role: i) on the one hand, it provides modules to post-process patient's information; ii) on the other hand, it is the back-end for the HEALTHIOT's applications.

The *Disease Manager* is a sort of virtual box where different post-processing rules are executed as independent microservices. These rules analyse the healthcare information coming from IoT devices and provide output in terms of messages to be sent either to doctors or patients. Such rules and their parameters can be personalized and contextualized by doctors according to personal medical records of each patient. More details about the developed post-processing rules are given in Section IV. *User Registration Service* deals with both registration of users (either doctor or patient) and their access to the platform. *Patient Services* and *Patient Monitoring Services* consist of a set microservices to manage data exchange and data correlation of the applications for patients and doctors, respectively.

D. Application Layer

The *Application Layer*, the higher in Figure 1, offers API (Application Programming Interfaces) to develop novel applications for managing and accessing information coming from the underlying HEALTHIOT's layers. We developed specific applications for both patients and doctors. *Diary App* is a digital diary to report daily results of treatment and therapy. Thus, paper-based information is digitalized to foster remote patients' monitoring and to speed-up the information exchange among patients and doctors. For example, patients with renal insufficiency have to daily record the results of house dialysis and provide a complete report on it, usually, every 2 or 3 weeks. With *Diary App*, the daily report is immediately notified to doctors as soon as the patient fill it. *Smart Glucose* is an app for patients with diabetes disease i) to visualize trends of glucose and ketones in the blood over the time and ii) to provide possible messages from the doctor or from the system. *Patient Monitoring* is a mobile app suitable for Android-based tablets. It provides doctors with the medical record of their patients. This information is updated in (near-) real-time and comes from IoT devices, services or other applications (i.e. measurements, post-processed information and warnings). This allows a continuous remote monitoring and assistance of patients from both treatment and therapy viewpoints.

It is worth noting that the whole HEALTHIOT platform is opened on developing other novel applications, services and post-processing rules according to needs of both medical personnel and patients. HEALTHIOT is also ready to host machine learning algorithms to analyse patient health trends. Thus, it is not limited on those presented in this section.

IV. EXPERIMENTAL RESULTS

In this section, we describe the laboratory tests we performed to validate the HEALTHIOT platform and its services. For this purpose, we developed a special TIA that emulates different realistic patient conditions by injecting data in the platform. Every time a new data is received by HEALTHIOT, such information is post-processed by rules running on *Disease Manager*. The requirements of these rules come from the interviews we did to various doctors, both diabetologists and nephrologists. In the following, we describe each implemented rule and we discuss their experimental results. Each rule provides warnings as result of the computation. A warning is a message that is sent from the platform to the end-users, either patients or doctors. These warning messages help doctors in doing their medical diagnosis that can lead to further medical analysis or patient's hospitalization.

1) Variation of Body Mass Index rule: In general, maintaining a target weight is a good health habit for everyone. In particular, weight control for patients with diabetes disease and patients undergoing dialysis is crucial because most of them can also be affected by diseases related to body weight. *Variation of Body Mass Index* is a rule that analyses the Body Mass Index (BMI) trend of a patient. BMI results from the correlation of mass (weight) and height of a patient [21]. It is defined as the body mass divided by the square of the body height and it is expressed as kg/m^2. BMI quantifies the amount of tissue mass (muscle, fat and bone) and categorizes that person as underweight, normal weight, overweight or obese according to BMI ranges in Table I. Figure 2 shows the BMI trend of our emulated patient and the generated warnings for 90 days (one sample per day). In this case, the BMI of the emulated patient constantly decreases from $38kg/m^2$ to $18kg/m^2$ and the rule generates the right warnings according to BMI values. Only between day 58 and day 87, no warnings are generated because it is a normal weight condition.

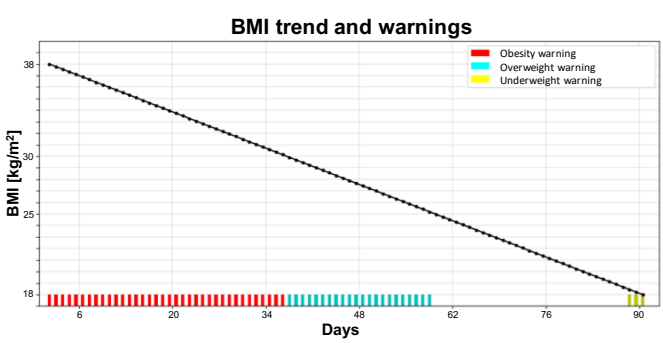

Fig. 2. BMI trend variation and generated warnings.

TABLE I
BMI RANGES FOR PATIENT CLASSIFICATION.

Classification	BMI ranges
Underweight	$16\ kg/m^2 \leq BMI < 18.5\ kg/m^2$
Normal weight	$18.5\ kg/m^2 \leq BMI < 25\ kg/m^2$
Overweight	$25\ kg/m^2 \leq BMI < 30\ kg/m^2$
Obese	$30\ kg/m^2 \leq BMI \leq 40\ kg/m^2$

2) Anomalous variation of body weight rule: The variation (increase or decrease) of weight in a short time period is to be considered an alarming condition. *Anomalous variation of body weight* (Δw) is a rule that compares the last body weight sample with previous values belonging to a pre-defined observation interval (SW), which is a sliding window. Figure 3 shows the body weight trend of our emulated patient and the generated warnings for 40 days (one sample per day). In this case, the rule generates a warning if $\Delta w \leq 8\ kg$ or $\Delta w \geq 8\ kg$ for an observation interval in the range of the previous 7 days and the previous 14 days. As shown in Figure 3, the body weight of the emulated patient is almost constant at $52kg$ for the first 9 days. Then, it constantly increases for the next 9 days reaching $61kg$. This generates the first type of warnings, anomalous increase of weight (red line), at day 18 by considering the information on the observation interval SW-1 (red dashed-line box in Figure 3). Then, the weight is almost constant at $61kg$ for few days before decreasing to $55kg$ at day 29. This triggers the second type of warnings, anomalous decrease of weight (violet line), based on the observation interval SW-2 (violet dashed-line box in Figure 3). This rule is very important because can help doctors in understanding how a new therapy impacts on the patient's metabolism and thus intervening promptly by modifying the therapy before the clinical conditions become critical.

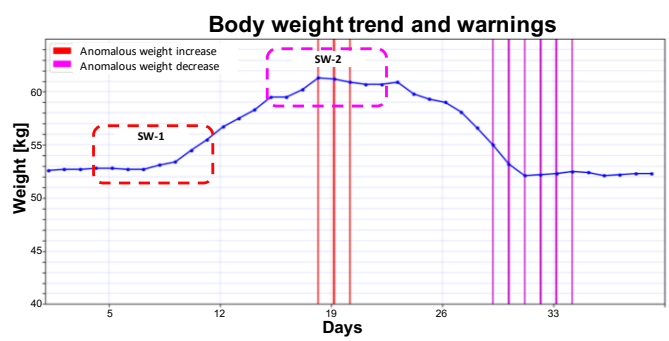

Fig. 3. Body weight trend variation and generated warnings.

3) Blood pressure warning rule: Hypertension is a clinical condition that often affects patients, especially older, with type 2 diabetes. Hence, *Blood pressure warning rule* analyses the incoming measurements on both systolic and diastolic pressure (SBP and DBP, respectively). It generates warning messages as soon as SBP is higher than $150mmHg$ or DBP is higher than $95mmHg$. Figure 4 shows a cloud of blood

pressure measurements for our emulated patient. It confirms that warnings are generated only when measurements are over the defined thresholds (red triangles in Figure 4).

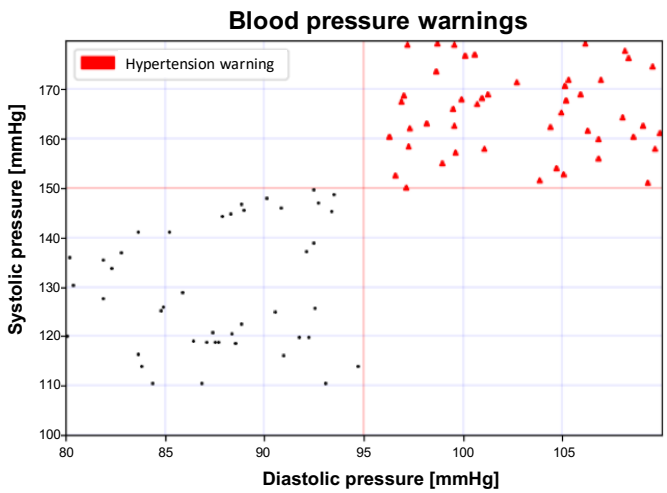

Fig. 4. Blood pressure and Hypertension warnings.

4) Blood pressure and oxygenation warning rule: This rule has been implemented to monitor patients undergoing dialysis. It generates a warning when the patient is in one of the following conditions: i) Hypoxaemia and Hypertension or ii) Hypoxaemia and Hypotension. Hypoxaemia occurs when the blood oxygenation is lower than 94%. Hypotension condition takes place when SBP or DBP are lower than $100mmHg$ or $70mmHg$, respectively. Finally for this class of patients, nephrologists suggested to consider Hypertension when SBP and DBP are higher than $160mmHg$ or $100mmHg$, respectively. To be correlated, measurements must be sampled in the same short time period, which must not be over the six hours. Figure 5 shows a 3D representation of the resulting warnings

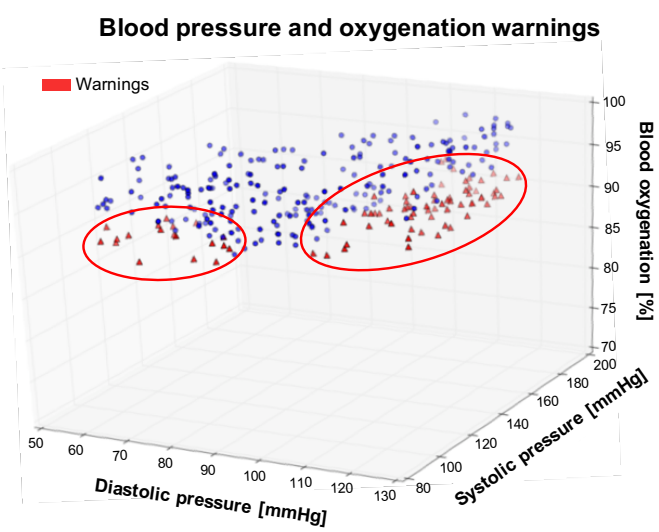

Fig. 5. Blood pressure and oxygenation warnings (3D representation).

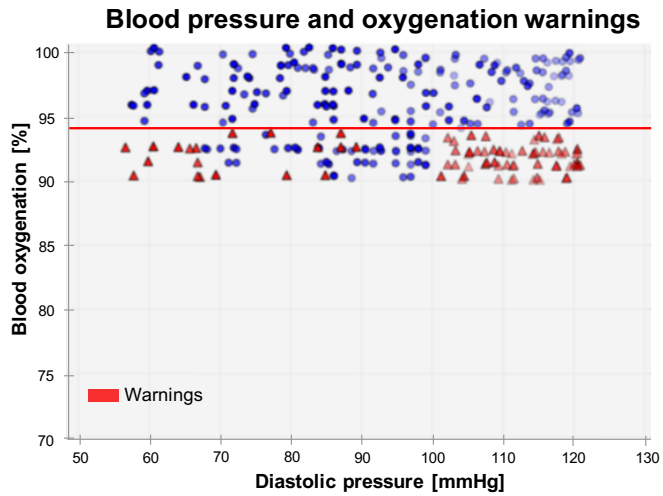

Fig. 6. Blood pressure and oxygenation warnings from blood oxygenation viewpoint.

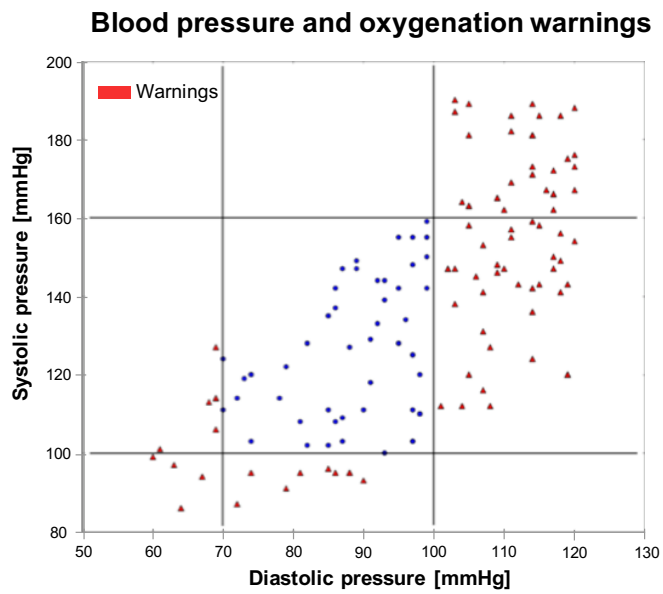

Fig. 7. Blood pressure and oxygenation warnings from systolic and diastolic pressure viewpoint.

(red triangles) for our emulated patient. Figure 6 and Figure 7 are two other representations of these results highlighting that warnings are generated only if correlated data are out of the given thresholds for blood oxygenation (Figure 6) and blood pressure (Figure 7).

5) Glycaemia warning rule: Analysing the blood glucose level (i.e. glycaemia) is also crucial for our patients, especially for those affected by diabetes. We can distinguish between two pathological conditions: i) severe Hyperglycaemia when glycaemia is higher than $250mg/dl$ and ii) Hypoglycaemia when glycaemia is lower than $70mg/dl$. It is worth noting that a severe Hyperglycaemia condition allows doctors in requesting an immediate patient's hospitalization. This has been

implemented as the *Glycaemia warning rule*. Figure 8 plots a cloud of glycaemia measurements of our emulated patient for almost 6 months (one sample per day). As expected among the total 170 samplings, only 39 of them generate warnings: 27 for severe Hyperglycaemia conditions (violet triangles on top of the plot) and 12 for Hypoglycaemia conditions (red triangles on bottom of the plot).

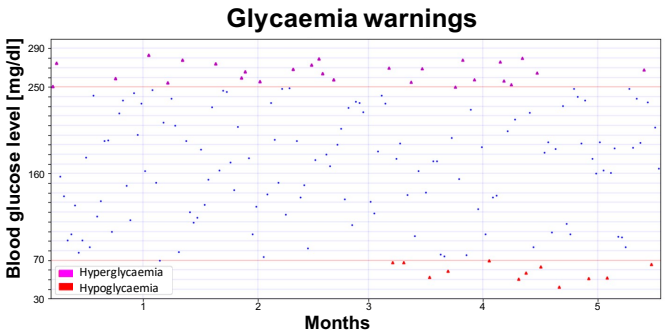

Fig. 8. Hyperglycaemia and Hypoglycaemia warnings.

6) Diabetic Ketoacidosis warning rule: The Diabetic Ketoacidosis is a very serious pathological condition that occurs mainly in patients with type 1 diabetes. This condition allows doctors in requesting an immediate patient's hospitalization. It is characterized by Hyperglycaemia and Hyperchetonemia. Dehydration is also an indicator of this condition. It is an effect of the Diabetic Ketoacidosis and not a cause. Thus, incoming information on dehydration is a trigger to control glycaemia and ketones, which will eventually generate warning messages. The developed *Diabetic Ketoacidosis warning rule* correlates information coming from glucometers (i.e. glycaemia and ketones) and from smart scales (i.e. total body water). To be correlated, measurements must be sampled in the same time period, which must not be over the two hours. To generate a warning, the rule considers: i) glycaemia higher than $250mg/dl$ (severe Hyperglycaemia), ii) ketones higher than $1.6mmol/l$ (Hyperchetonemia) and iii) total body water lower than 45% (Dehydration). Figure 9 and Figure 10 show the results of this rule for our emulated patient. Both figures highlight two type of warnings: i) warnings generated by Hyperglycaemia, Hyperchetonemia and Dehydration (red triangles), ii) warnings due to Hyperglycaemia and Hyperchetonemia (green triangles). Figure 10 omits the values of total body water confirming that Dehydration is an effect of the Diabetic Ketoacidosis as pointed by doctors during the interviews.

7) Glycaemia averaged trend rule: This rule analyses the glycaemia trend of patients undergoing dialysis. For each incoming glycaemia measurement, the rule retrieves all the previous samples received in the last 30 days from the *Data Storage* (see Section III) and averages them together with the new value. A warning is triggered if this average is over $120mg/dl$. This condition is a trigger for doctors to request more accurate medical analysis. For example, in case of fasting

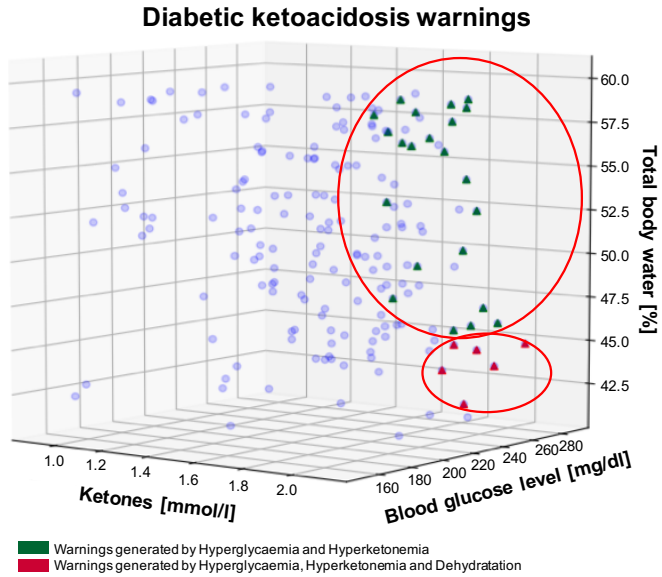

Fig. 9. Diabetic Ketoacidosis warnings (3D representation).

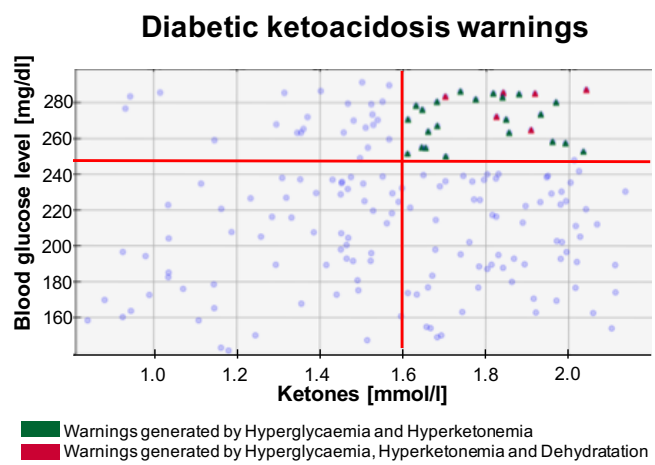

Fig. 10. Diabetic Ketoacidosis warnings (2D representation).

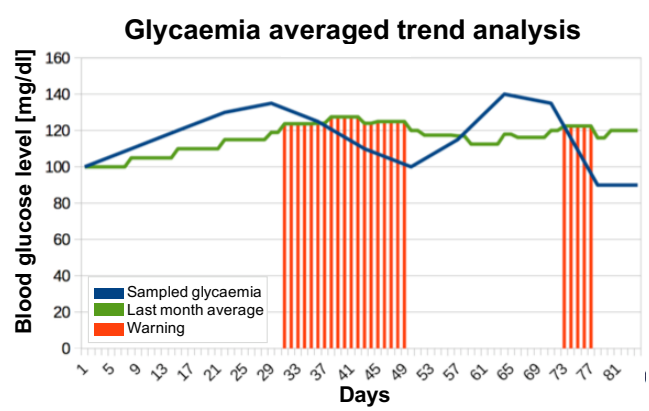

Fig. 11. Warnings triggered by *Glycaemia averaged trend rule*.

blood glucose higher than $120mg/dl$, the patient could also be affected by diabetes disease. Figure 11 shows the glycaemia trend (blue line) of our emulated patient and the post-processed average (green line) for almost 90 days. It confirms that the rule generates a warning only if the averaged glycaemia exceed the given threshold. This correctly occurred twice: i) between day 31 and day 50 and ii) between day 73 and day 77.

V. Conclusion

In this paper, we presented HEALTHIOT, a novel distributed software infrastructure for remote monitoring of i) patients with diabetes disease (type 1 or type 2 diabetes) and ii) patients undergoing house dialysis. It integrates different off-the-shelf IoT devices for healthcare monitoring and performs analysis on patient's health conditions. To perform such analysis, HEALTHIOT includes in its core a *Disease Manager*, which executes and orchestrates different post-processing rules. Such rules have been developed following the requirements given by doctors (both diabetologists and nephrologists) and they are customizable according to personal medical records of each patient. HEALTHIOT is also opened for future developments of new services, rules and end-user applications. In this paper, we also discussed the preliminary results to validate the proposed solution in a laboratory test environment.

As future work, we plan to extend the HEALTHIOT to other clinical pathologies and to perform tests in a real-world environment by involving real patients and doctors.

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