Advanced Home-Based Diabetes Monitoring System: Initial Real-World Experiences.*

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Abstract. Diabetes is a disease that requires monitoring of healthy habits for its treatment. A recent study suggests that sensor-based activity recognition approaches are a suitable tool for monitoring such habits that are established between clinical personnel and the patient through a therapeutic contract. To date, there is no fully described system architecture for implementing a sensor-based activity recognition approach to monitor healthy habits. In this paper, we present the advanced architecture of a system for monitoring healthy habits of multiple diabetes patients in their homes. The presented system, called AI2EPD, features a complex architecture that encompasses from the sensor devices deployed in each patient's home to persistence in the central server and visualisation in the technical and clinical interface. The system has been deployed in the municipality of Cabra in Córdoba (Spain) in collaboration with the Cabra Health Centre. The approach for sensor installation in the patient's home, as well as the issues and challenges encountered during system deployment, are presented in this section.

Keywords: sensor-based activity recognition · monitor healthy habits · diabetes patients · complex architectures with sensors

1 Introduction

Individuals diagnosed with diabetes face an increased risk of developing severe health complications, leading to high healthcare costs, decreased quality of life, and increased mortality [5]. As such, optimising diabetes management is a crucial

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public health priority [10]. According to the International Diabetes Federation's (IDF) diabetes atlas, there were an estimated 451 million people worldwide between the ages of 18 and 99 with diabetes in 2017 [4]. The IDF predicts that by 2045, this number will rise to 693 million. Lifestyle modifications such as maintaining a healthy diet, engaging in regular physical activity, not smoking, and maintaining a healthy weight are essential in the fight against diabetes [12].

Another crucial aspect of managing diabetes is patient involvement, with recommendations tailored to individual needs and therapeutic objectives agreed upon by the patient and healthcare provider. Individualised interventions have shown long-term beneficial clinical outcomes in patients with diabetes [14, 7].

In this context, human activity recognition has advanced significantly in recent years, enabling a wide range of applications such as healthcare, smart homes and manufacturing. There are two main types of human activity recognition systems: video-based and sensor-based [9, 1]. The former use cameras to capture images or videos of people's behaviour, while the latter rely on body or environmental sensors to detect details of movement or traces of activity. Due to the privacy concerns posed by cameras in personal spaces, sensor-based systems are more commonly used to monitor everyday activities [15]. In addition, the proliferation of smart devices and the Internet of Things has made it possible to embed sensors in a variety of objects, such as phones, watches, cars, walls and furniture, providing a ubiquitous and non-intrusive record of human motion information [11, 8].

In the literature, there is a new study that propose sensor-based activity recognition approaches to empower patients with diabetes to improve healthy habits due to the fact that these approaches have the ability to record and analyse people's behaviours [14]. To this end, a therapeutic contract is proposed between the clinician and each patient with diabetes, agreeing on the healthy habits that each patient should have. These habits include, among others, the number of hours the patient should sleep or the time the medication should be taken.

A home activity monitoring system (Beprevent) was initially proposed for the treatment of patients with type 2 diabetes mellitus [14]. Beprevent [6], was a multipurpose home activity control system that provides information about people's routines through a mobile application; its target population is mainly made up of elderly, dependent, chronically or mentally ill people or people with some kind of physical and/or mental disability who live alone. For this purpose, it provides a central device with a power cable and 5 adhesive labels, which are attached to everyday objects. Through a mobile app, the routines under study are reported with these 5 labels.

Due to the major challenges addressed inter by this extension for patients with diabetes in a clinical setting, this extension was not ultimately carried out. Therefore, there is currently no real system with a detailed description of its architecture that implements a sensor-based activity recognition approach to monitor healthy habits in the therapeutic contract prescribed by the clinician.

Due to this gap, this paper presents the advanced architecture of such system, entitled AI2EPD, to monitor the behaviours of multiple patients at home, following the protocol and the experimental design proposed in their study *Feasibility of an Activity Control System in Patients with Diabetes: A Study Protocol of a Randomized Controlled Trial* [14]. Thus, this work presents the proposal of the integral technical architecture that includes the devices with sensors used to collect the information, the data collection in each home, the persistence in the database and, finally, the visualisation of the data from both the technical role and the clinical role.

The proposed system has been implemented in collaboration with the Cabra Health Centre and deployed in the municipality of Cabra in Córdoba, Spain. This paper also presents the approach used for sensor installation, as well as the challenges and issues encountered during system deployment.

This contribution is structured as follows: Section 2 reviews the importance of the therapeutic contract in the diabetic context. Section 3 presents the set of sensor devices to monitor therapeutic objectives. Section 4 presents the architecture of AI2EPD to monitor the behaviours of multiple patients at home. Section 5 presents the deployment experience of the system . Finally, Section 6 presents the conclusions.

2 Therapeutic contract to monitor diabetic patients

Diabetes mellitus is a chronic condition that poses a significant burden on healthcare systems worldwide. Patients with this condition face a higher risk of developing severe health problems that could be life-threatening. The management of diabetes requires significant lifestyle modifications, including regular physical activity, healthy diet, and blood glucose monitoring. Despite the availability of effective treatments, patients with diabetes often struggle to adhere to their prescribed treatment regimen. Non-adherence can result in poor health outcomes, increased healthcare costs, and reduced quality of life.

To address this issue, the study presented in [14] aimed to evaluate the feasibility of a multipurpose activity control solution for home activity (home activity control system) in improving treatment adherence in diabetic patients. The system was designed to provide real-time information on the activities of daily living carried out outside the home, enabling clinicians to monitor patients' behaviour and adjust their treatment regimen accordingly. By incorporating patient data into treatment plans, clinicians can develop tailored interventions that address each patient's unique needs, improving the likelihood of adherence to therapeutic objectives.

The therapeutic objectives for each patient are established in a therapeutic contract, which outlines the activities to be performed and their frequency. The contract also sets the frequency of follow-up visits to the healthcare centre to monitor the patient's condition. The therapeutic contract is reviewed at each follow-up visit, and any necessary adjustments are made in collaboration with the patient.

The importance of the therapeutic contract lies in its ability to enhance communication between healthcare providers and patients, promote collaboration and active patient participation in their own healthcare, and improve treatment adherence. By establishing clear and measurable goals and specifying the activities required to achieve them, the therapeutic contract helps ensure that patients receive appropriate and personalised treatment.

This paper presents the advanced architecture to monitor the therapeutic contract of diabetic patients. In collaboration with the Cabra health centre, the activities that will be included for monitoring and their frequency are as follows:

- Physical activity: walk at least 30 minutes in the morning and 30 minutes in the evening every day.
- Rest: the patient should sleep for a minimum of 5 hours each night.
- Self-care:
  - Tooth brushing: at least 3 times a day after main meals.
  - Shower: once a day.
- Nutrition: eat at least X times a day.
- Medication: take at least X times every X hours.

The X variables will be configured in a personalised way between the clinician and the patient.

3 Sensor devices to monitor therapeutic objectives

The prototype presented here is composed of a variety of sensors and devices, as shown in Figure 1. These include intelligent nodes, among which central nodes are distinguished, responsible for managing the sensors, and anchor nodes, which determine the location.

The following section outlines the necessary sensors required to carry out the monitoring of the activities previously established. In order to ensure accurate measurement, specific devices have been selected for each activity.

For physical activity monitoring, the use of an activity bracelet, as well as a sensor for opening and closing the main door, has been chosen. In this way, the time dedicated to performing physical exercises, as well as access to the dwelling, can be precisely recorded.

For monitoring rest, a motion and light sensor will be employed to supervise sleep patterns, thus enabling analysis of sleep habits.

Regarding tooth brushing activity, the location of the toothbrush will be taken into consideration to select the appropriate sensor. If the toothbrush is located within a cabinet, an opening and closing sensor will be used. Conversely, if it is located in an accessible place, a motion sensor will be employed.

In terms of shower monitoring, a combination of a temperature and humidity sensor, as well as a motion sensor, will be used to collect information about shower duration and water temperature.

For food consumption, a motion sensor will be used to record meal times. This will allow for monitoring of feeding schedules.

Fig. 1: Sensors and devices. **1** Temperature and humidity sensor. **2** Motion and light sensor. **3** Open and close sensor. **4** Activity tracker. **5** Nodes (Raspberry Pi). **6** Bluetooth adapter. **7** Conbee 2.

Lastly, for medication activity, an opening and closing sensor has been chosen. It will be placed on the medication container to record the moment when medication is taken.

4 Architecture of AI2EPD system

The architecture of the system, consisting of a home layer and a server layer, is illustrated in Figure 2.

4.1 Home Layer

The home layer is composed of each of the homes that will be monitored.

Within each home, there is a Raspberry Pi configured to act as a central node in an IoT device network. The central node hosts the MQTT (MQ Telemetry Transport) broker [4], which is a subscription and publication messaging protocol used for communication between IoT devices. The MQTT broker allows connected devices in the IoT network to efficiently and reliably send and receive messages. Through this protocol, the rest of the nodes in the network in that home, called anchors, will send the information related to the RSSI of the activity tracker in that home.

The central node of each home also collects data from the activity tracker, as the node is linked to the tracker. In this sense, the information collected from the activity tracker is published on a topic, to be processed later in the MQTT client hosted on the same node. Furthermore, the Raspberry Pi is configured

[4] https://mqtt.org/

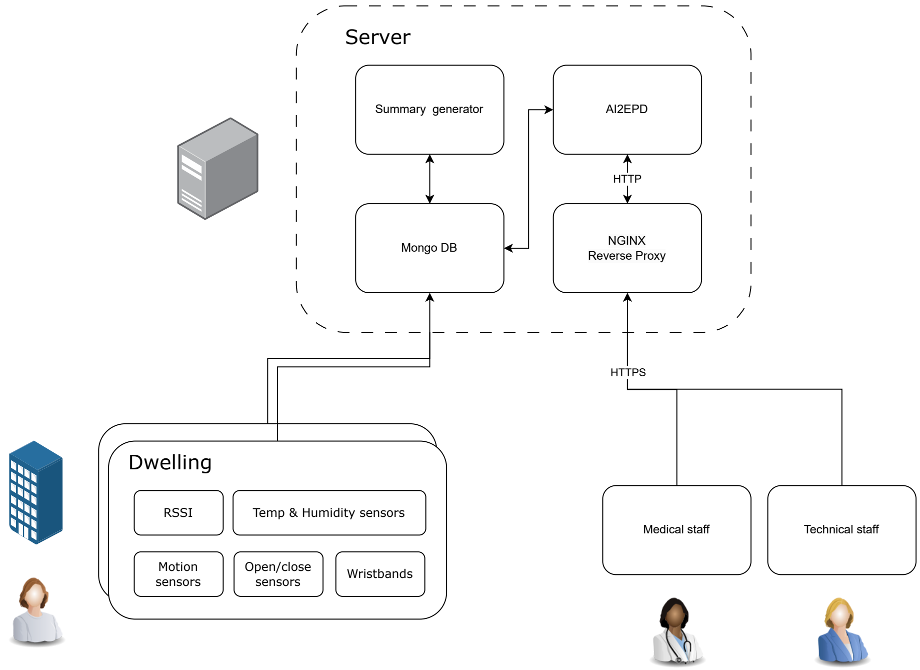


Fig. 2: System architecture.

with the installation of Home Assistant [3], an open-source home automation platform.

The Home Assistant platform is necessary to manage the previously described sensors from the central node, which in combination with the Zigbee module, allows it to act as a Zigbee coordinator. The information received through this protocol is dumped to topics, where the MQTT client will process them.

Once the client receives information from the different topics, it inserts the information into the database collection associated with the assigned home.

4.2 Server layer

General description This layer is responsible for carrying out all intelligent processing while providing information of interest to both technical and health-care personnel.

The process begins when the home layer sends data to the server. This data is stored in a specific database on the server, which also stores the therapeutic contracts that have been previously defined for each patient.

With the data streams collected at the patient's home and therapeutic contract, compliance summaries are generated. These summaries are generated using automated algorithms and processes that analyse the data and compare it with the defined therapeutic contracts, using the methodologies proposed in [2, 13].

To begin with, the location of the monitored patient within the home is determined. This is done by using the Received Signal Strength Indication (RSSI) between the anchors and the patient's activity tracker. Based on the strength, the patient's location in the environment can be determined approximately [2]. In addition, the combination of RSSI data with data from sensors distributed throughout the home allows inference of the patient's activities, such as walking, showering, sleeping, among others [13].

Once the compliance summaries have been generated, the inferred information is stored in the same database. Subsequently, healthcare personnel can access the dashboard and consult the compliance summaries to evaluate treatment progress and make informed decisions about the treatment plan for each patient.

Reverse proxy Data security is a crucial issue in any context, especially in the field of healthcare. For this reason, special emphasis has been placed on implementing measures that ensure adequate protection against potential threats.

One of the measures adopted to guarantee data security is the use of a reverse-proxy [5]. This method involves using a web server, specifically NGINX, that sits between the application and clients. The main function of the reverse proxy is to provide HTTPS(HyperText Transfer Protocol Secure) to clients, which encrypts communications, serves the static content of the application, and offers mitigation's against certain types of attacks, such as DDoS (Distributed Denial of Service).

The use of a reverse-proxy helps to increase the level of application security by providing an additional layer of protection.

Database In a monitoring system, it is common to generate large volumes of data of different types and formats due to the large number of sensors and devices involved. These data may be of a heterogeneous nature, which makes their storage and management using traditional databases difficult.

In this regard, a non-relational database, specifically MongoDB [6], has been chosen as the solution for storing and managing the data generated by the system. MongoDB is a document-oriented database that allows for the storage of unstructured or semi-structured data, making it ideal for storing heterogeneous data generated by various sensors and devices.

Web system In order to ease the management of the system and allow healthcare professionals to monitor patients, a web application has been developed using Django, a high-level web development framework in Python. This application has been specifically designed to meet the needs of technical and healthcare personnel responsible for managing the system.

[5] https://www.cloudflare.com/learning/cdn/glossary/reverse-proxy/
[6] https://www.mongodb.com/

The web application has an authentication system using credentials, which ensures that only authorised users can access the different functions of the system. Each user has different types of access to the system's functions, depending on their role. This allows for greater security and more precise control over who can access what information and functions within the system.

As a result of this application, technical staff are able to effectively manage the system, while healthcare staff can oversee and monitor the status of patients.

- Technical view. The application designed for technical staff enables them to carry out important tasks for the proper functioning of the platform. Firstly, they can register and edit sensors, activity bracelets, and homes, among other devices and elements necessary for patient monitoring. In addition, it provides the possibility of consulting the status of the monitored homes, which allows for detecting possible faults in the devices and solving them quickly. It also makes it possible to retrieve the information recorded by the sensors and devices in the homes and visualise it through the use of graphs, Figure 3, which enables analysis and decision-making by the technical staff.
- Clinical view. The application for healthcare staff consists of a main page that provides information on patients, medical staff and compliance with the therapeutic contract. In addition, it allows healthcare professionals to consult summaries indicating the degree of compliance with the activities established in each patient's individual therapeutic contracts, including details on the objective of each activity and the percentage of compliance within the planned schedules, Figure 4. The application also allows the creation, modification and consultation of therapeutic contracts, including information on the date of entry into force, the author of the modification and the number of modifications made. Finally, it provides the option of downloading in CSV format the activities carried out by patients in a given date range for subsequent analysis.

5 Real-world implementation: Issues and challenges

The home-based patient monitoring system for diabetes proposed in this contribution has been deployed in a patient's home in Cabra de Córdoba (Spain) in collaboration with the Cabra Health Centre.

This section outlines the approach used for sensor installation in the patient's home, along with the issues and challenges encountered during system deployment.

5.1 Home deployment approach

The process of deploying a system in a real-world setting is a critical activity that requires a well-defined series of steps.

Prior to deploying the system in the patient's home, a thorough interview is conducted to gather detailed information about the patient's habits in relation

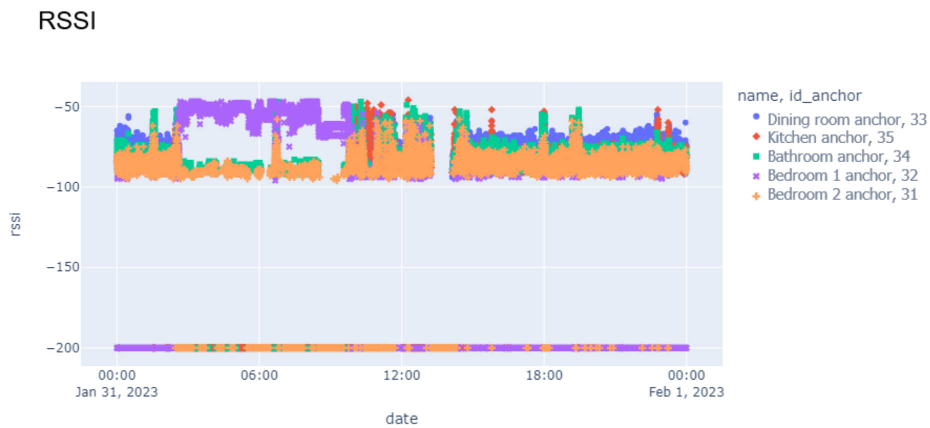
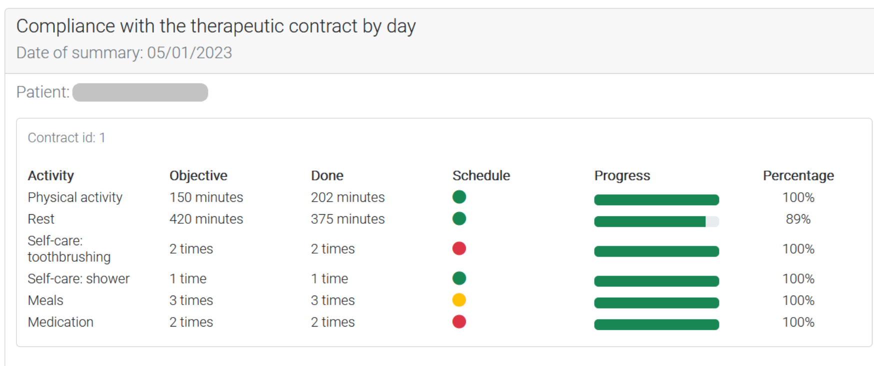


Fig. 3: RSSI of the anchors installed in the home.



Compliance with the therapeutic contract by day

Date of summary: 05/01/2023

Patient: [redacted]

Contract id: 1

Activity	Objective	Done	Schedule	Progress	Percentage
Physical activity	150 minutes	202 minutes			100%
Rest	420 minutes	375 minutes			89%
Self-care: toothbrushing	2 times	2 times			100%
Self-care: shower	1 time	1 time			100%
Meals	3 times	3 times			100%
Medication	2 times	2 times			100%

Fig. 4: Summary.

to their daily activities. Details are collected about the activities performed, approximate schedules, and the most common locations where these activities are carried out. In addition, a detailed analysis of the spatial distribution in the home is conducted to determine the most suitable locations for the sensors and devices.

During this stage, it is important to verify whether the home has access to the internet. If not, a mobile access point with a SIM card is provided for data transmission. Once the initial interview has been conducted and appropriate locations for the sensors and devices have been determined, the system is deployed in the home.

During the initial deployment of the system, a technical team travels to the patient's home to perform the installation. First, the central node, as shown in Figure 5a, is installed, which contains the MQTT (Message Queuing Telemetry Transport) broker, Zigbee module, and Home Assistant necessary to interconnect the rest of the sensors and nodes. After installing the node, it is accessed through SSH (Secure Shell) to update it if necessary and to verify that it has started correctly.

Subsequently, the anchors are installed in the designated position, as shown in Figure 5b. It is necessary to verify that the WiFi reception signal is adequate since they may need to be relocated if they are further away from the access point.

Once the anchors are installed, the sensors are installed in the previously defined locations, and a series of tests are carried out. It is verified from the online platform or from the Home Assistant installation whether the sensors are sending data.

As an additional check for the motion sensors, a verification is carried out to determine if the range and vision of the sensor are adequate and only detect the desired motion patterns. If not, the parameters are adjusted from the platform.

As the last step of the system deployment, the activity bracelet is linked, and it is verified that the anchors experience a variation in the RSSI signal strength as they move closer or further away from them.

(a) Central node. (b) Anchor.

Fig. 5: Nodes installed in the home.

Once the installation process described above is completed, the system will be properly configured and ready for use in the patient's home. This way, the patient can continue with their usual daily activities while the system constantly monitors their therapeutic goals.

5.2 Issues and challenges

The deployment of a patient's home monitoring system brought to light a number of issues and challenges that are presented in this section.

Firstly, it was observed that some sensors and devices stopped operating correctly spontaneously due to a variety of factors, such as power loss and sensor disconnection. In the event of power outages, the devices have automatic reset functions, although occasionally they need to be manually disconnected and reconnected. Sensor disconnection, on the other hand, requires in-person reconnection.

Secondly, the energy cost associated with the operation of the system is a concern for some patients, even though the energy consumption is low and results in low operational costs. Therefore, it is important to evaluate compensatory measures for patients who may be affected financially.

Finally, remote updating of the smart nodes can be a complex process that affects the system's operation. During critical updates that involve changes to the project's code as well as third-party services and applications integrated with the system, remote updating of the smart nodes can be a complex process that affects the system's operation. In such cases, a team of technical experts, including some members present in the patient's home, is necessary to assist with the updates. It is crucial to carefully plan and communicate the update process to avoid any disruptions to the system's operation and ensure prompt resolution of any issues that may arise.

6 Conclusions

A fully defined system architecture for implementing a sensor-based activity recognition approach to monitor healthy habits in diabetic context. In this study, we have presented the advanced architecture of the AI2EPD system, which is used to monitor the healthy habits of multiple diabetes patients in their homes. This complex architecture encompasses devices with sensors deployed in each patient's home to data persistence in the central server and visualisation in the technical and clinical interface. Additionally, this system has been implemented in collaboration with the Cabra Health Centre in Córdoba, Spain. This section has outlined the methodology employed for the installation of the sensors in the patient's home, along with the problems and challenges encountered during the deployment of the system.

The proposed system represents a significant advancement in the management of diabetes by providing clinicians with accurate and up-to-date information on patient behaviour. By enabling real-time monitoring of patient activity, the system can facilitate early intervention and prevent complications associated with non-adherence. Further research is needed to assess the long-term effectiveness of the system and its impact on patient behaviour and treatment adherence.

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