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Hospital and home environments automation for Amyotrophic Lateral Sclerosis patients: Building Information Modelling and Internet of Things in digital environments

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Abstract

In this work, we present a novel distributed software platform for patients with neuro-degenerative diseases that affect motor-neurons. The linking point between this wide range of diseases is the strong social impact they have, degrading the freedom of action of the patient: the loss of functionality of motor neurons, caused by progressive degradation, makes the body unable to move. Thus, our solution aims at making patients more autonomous in their daily activities and at improving remote healthcare monitoring for medical staff by combining Virtual Reality, Building Information Modelling (BIM), Internet of Things (IoT) and Eye-Tracking technologies. Starting from the 3D parametric BIM model, patients can virtually explore the surrounding environment (through eye' movements) and can control the environment by interacting with IoT smart devices, thus performing different tasks.

Keywords**:** Building Information Modelling, Virtual Reality, Internet of Things, Digital Twin, Amyotrophic Lateral Sclerosis, Eye-gaze, Telemonitoring, Telemedicine

Introduction

The most aggressive and progressive diseases affecting motor neurons. [1][2]. It affects 1 in 3 people per 100,000 inhabitants worldwide, with an index of 1.5 per 100,000 in Europe [1][2]. Typically, ALS occurs around the age of 50 – 65 years old and as a progressive disease, it is fatal and incurable, with a life expectancy of approximately 5 years after diagnosis [1] [2]. The combination of asymmetry and spasticity of movements, atrophy of muscles, dysphagia and failure to breathe [2] contributes to the progressive decrease in patients' quality of life.

For these reasons, research has focused on the need to define a specific technology for neuro-degenerative diseases, on the optimization of life quality and on maintaining patients' autonomy as much as possible [2]. The crucial point is the strong social impact this disease has, dramatically reducing the patient's freedom of action [3] [5]. On one hand this condition leaves the patient's consciousness intact, while on the other hand she/he cannot make movements or communicate, due to a complete paralysis of almost all voluntary muscles in the body, except for the eye muscles. Individuals cognitive functions remain intact enough to understand and to communicate by eye movements [3] [5]. In this scenario, patients interface with devices that allow them to regain in some way the ability to communicate. Most common devices are Speech Generating Devices (SGDs) or devices for Eye-Tracking and Eye-Gaze detection [3]. Generally, eye-detection can be used by any type of patient with a movement inability, and they are mainly based on infrared systems that hit the eye illuminating it. In this way, cornea movements can be traced by using the corneal centre pupil reflection (PCCR) [3] [4]. Eye-tracking devices can be used to allow users with ALS to interact with BIM (Building Information Modelling) models, a modelling methodology that allows for scalable management of building data, as will be better described later. Eye-tracking devices also allow models to be easily navigated using Virtual Reality (VR) according to the paradigms described in [15]. The healthcare sector is characterized by a higher degree of complexity in terms of space, patient worker management. Good organization and design of the healthcare environment are the basis for ensuring health for citizens and proper coordination for workers [9]. Lately, to ensure optimal management of hospital buildings, the construction industry has extended into healthcare with the introduction of Building Information Modelling (BIM). It is defined as "*a digital representation of physical and functional characteristics of a facility. It serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward*" [11]. The system implementation uses the BIM model as a database of the building's assets to enable virtual navigation and interaction with the ecosystem. In recent years, BIM methodology for the design and management has brought great benefits to those working in the construction sector, leading to increasing development and research into applications for BIM models in other sectors [10]. The standard exchange format able to achieve these objectives is the Industry Foundation Classes (IFC) [16]. Given these opportunities, the medical industry has also approached BIM methodology with a view to manage articulated buildings, following the National Healthcare Facility Benchmarking Program (NHFBP) [11]. After the COVID-19 pandemic, the need to invest resources and technologies for telemonitoring has become even more evident. Healthcare has relied as much as possible on telemedicine to treat and follow patients who do not need hospital equipment or nursing homes. In this way, even patients who require a constant doctor-patient relationship, such as those with ALS, can be regularly followed from a medical and psychological aspect while staying at home. Several studies have led to the emergence of technologies that base their architecture on a Cloud-Based system to support telemonitoring and to provide technologies for diagnosis [7] [8]. Some of these have involved Virtual Reality (VR) to produce communication systems and simulations that combine BIM and VR for healthcare design [9]. With the support of additional technologies such as VR, it is possible to complete the use of BIM, enriching it also from a communicative and cognitive point of view.

Healthcare also represents one of the most fascinating areas for application of the Internet of Things (IoT), bringing with it numerous improvements. IoT includes a wide range of devices capable of connecting consumer and/or industrial objects on the Internet, bringing together information and managing the devices via software to increase efficiency, create new services or bring health benefits and safety [12]. These types of "things" can be deployed anywhere, on any network and are readily available. Sensors, diagnostic devices, medical devices are all a springboard for IoT, since they can be exploited to improve the quality of life, to reduce costs, to facilitate the transmission and reception of medical data but also the interoperability between different stakeholders [12] [13]. With the latest innovations, numerous software infrastructure-based technologies have been proposed to monitor and provide inclusive service in terms of remote care for frail patients suffering from diseases with the aim of shorten the distance between physicians and/or caregivers and patients through analytics and aggregation [13].

Although virtual reality, BIM and IoT have been widely studied, there are not many studies describing their connection. In this paper, we propose an innovative distributed software infrastructure that ties IoT to BIM to provide autonomy in ALS patients in indoor automation during their daily life.

Based on the concepts expressed by Milgram in [15] there are several ways to interact with virtual reality environments including conventional non-immersive computer graphics simulations with monitors and immersive simulations with Head Mounted Displays. In our solution, VR is used in a Desktop visual display system [17] using eye-tracking device for the user interactions. Combining a BIM model with the IoT devices installed in the building, data updates the model and makes possible several applications that exploit the concept of Digital Twin technology. Its concept model is characterized by three main parts "*physical products in Real Space, virtual products in Virtual Space, and the connections of data and information that ties the virtual and real products together*" [14]. Our solution extracts the information contained in the BIM model and creates a scalable system that controls indoor automation through IoT devices. Patients suffering from motor neuron degradation can thus interact with the virtual representation of smart objects in the real-world environment (e.g., IoT devices, windows, etc.) navigating within the BIM 3D model by using an Eye-Tracker to, then, act in the real-world. So, they can regain more control over actions that have been lost and they interact with the environment, breaking routines to which they had to adapt to. On the one hand, our solution improves the monitoring of patients and environments, allowing patients to become more autonomous, control home automation devices and leads to quality of life improvements. In addition, doctors can monitor patients by checking their health parameter over the time, administrating pharmaceutical therapies, managing diagnoses and updating follow-ups [3].

The article describes the challenges of technological innovation that places the patient at the centre of the social ecosystem, defining some connections between the construction world and the healthcare sector. In the section titled distributed software platform for ALS patients, the process followed for the development of the care platform is described, followed by a description of the hardware prototype developed for the first testing phases with a focus on the technologies used. Then, some considerations are made regarding the impact the described technology may have on frail users and the conclusions drawn during the research work. In the future work, the next goals and collaborations that will be pursued with the research activity are described.

Distributed software for ALS patients

The proposed distributed software infrastructure in Figure 1 consists of three layers: i) *Digital Twin Layer*, ii) *Services Layer* and iii) *Application Layer.* Every communication between Layer modules is based on REST requests. The *Digital Twin Layer* connects heterogeneous IoT technologies with BIM methodology. The *Services Layer* includes all the main actors that govern the technology proposed here and that allows the data interchange and the connection between the BIM and IoT devices using Unity[1] as rendering engine. Through the created applications, the *Application Layer* provides the necessary services to patients in the first instance to improve their quality of life and to facilitate their monitoring and the useful applications for medical staff.

[1] https://unity.com/

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A similar type of micro-services application was described in [18], where, using questionnaires, the services and devices most of interest to frail users were identified. Each layer is described in more detail in the following section.

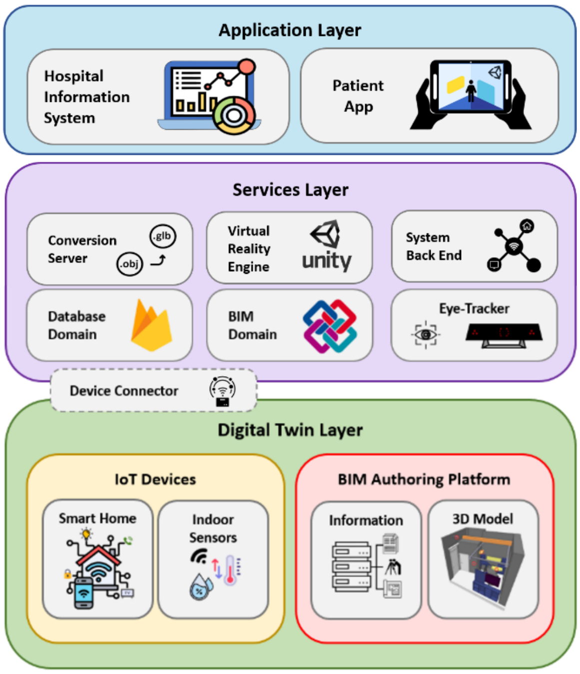

Figure 1. Schema of the proposed distributed software platform for ALS patients.

Digital Twin Layer

At the basis of Figure 1 there is the *Digital Twin Layer*. It consists of the *IoT devices* and *BIM Authoring Engine*, fundamental parts to achieve the Digital Twin of the environment where the patient lives. IoT devices, both for sensing and actuating, are part of the building and therefore they must be included within the BIM model i) to link virtual IoT devices with the corresponding object in the real-world, and ii) to allow data integration with external databases for communication. To allow the recognition of IoT devices, the BIM model must be enriched with additional metadata reporting both the unique identifier and the type of the corresponding IoT device in the real-world. In this way, it will be possible to perform the paring operation and automation of any kind of IoT device with all building spatial data. The steps for the creation of the BIM 3D model, and consequently the development of the digital twin, are illustrated in Figure 2 and they will be explained in detail below.

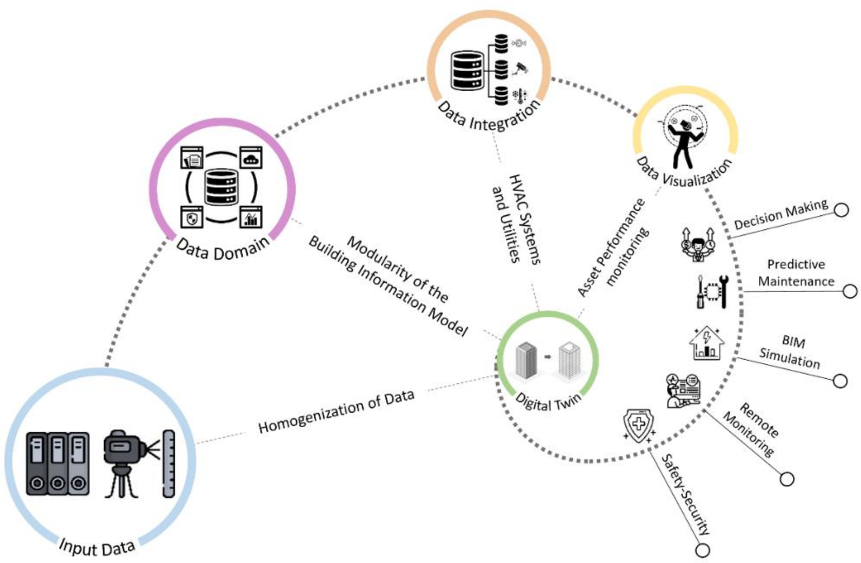

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Figure 2. Digital Twin process.

The modeler takes data inputs from Design, Construction and Maintenance phases of the building and it homogenizes them to build a unique and reliable database. After the input data collection, the creation of a real environment reproduction enriched with data, such as material information or unique codes useful for room management in a building, must be performed. Thanks to the parametric approach of the BIM methodology, models can be modified and updated at any time. In our solution, the *BIM Authoring Engine* creates the BIM 3D model. In particular, we used Dynamo[2], a visual language programming tool integrated in Autodesk Revit® BIM software, both i) to create a high-quality BIM model, and ii) to integrate data from the different IoT devices in the environment. Through a Graphical User Interface (GUI) has been created to enable the model uploading process in the *BIM Domain*, to produce a reliable, updatable and evolvable BIM model. The *Device Connector* is a software component in our solution to integrate heterogeneous IoT devices and to enable the interoperability among them and other platform software components. In this view, the *Device Connector* is in charge of i) managing connections with IoT devices, and ii) periodically sending environmental information and patient parameters to the *Database Domain*. The integration of BIM 3D models is performed by the *BIM Domain*, which provides web services for their upload, store and download. The *Conversion Server* translates the original BIM model, converting the model from the original .ifc dataformat to .glb (more derails in next Section - Service layer). These actions must be performed manually by technicians, before the model is downloaded by the *Patient App* deployed in computer device equipped with Eye-Tracker. Finally, all the data collected by the entities in the platform are available to develop additional applications, even third-party, for different healthcare stakeholders [15].

Services Layer

The *Services Layer* forms the core of the proposed solution, and it is in the middle of the system diagram showed in Figure 1. It contains all those software entities that make possible the virtual model navigation and the interactions with IoT devices, giving access to their data and control.

All BIM models necessary for the proper running of the application are loaded into the *BIM Domain*, a server designed explicitly to contain and read BIM models in .ifc format. A BIM based server is essential to manage models in the correct way and it allows the updates/changes, replacement and implementation of the models, the checking of files versions to understand what changes have been made and their the approval or rejection. To navigate the model in a VR environment, it has to be managed by the proposed *Patient App* which is based on Unity3D library. However, Unity3D does not provide support for .ifc data-format management. For this reason, the the .ifc BIM 3D models must be processed by the *Conversion Server* before landing on the *Patient App*. Thus, the *Conversion Server* is in charge of converting each BIM 3D model first into .obj, and then into .glb. This double conversion is necessary to maintain building and sensors information. IfcConverter.exe (open-source software provided by IfcOpenShell) binds object names that make up the 3D model with the BIM model hierarchy.
During all processing phases, each step is recorded in the *Database Domain*, a Realtime Database that manages files and connects them with the *Virtual Reality Engine* and *IoT devices*. Applications are connected through *Database Domain*, which exposes REST web services to access and update data. *Database Domain* consists of three different databases, as follows:

- *IoT4SLA*: it is the main database where data are collected depending on the framework used. It is compiled with data ranging from the unique ID for each patient to geospatial information related to their placement within the facility and the IoT devices active in the room.
- *User Database*: it manages logins within the platform and contains information about users (logged in, last access and details).
- *Statistical Database*: it collects historical data used for Data Analytics processes. It is important to calculate how much the patient uses the application and consequently an increase in his/her autonomy. The data deriving from data collection and data analytics are then stored in the IoT4SLA.

The *Virtual Reality Engine* is the rendering engine that was used to create interactive patients' application from collected data. To develop our prototype, as previously mentioned, we chose Unity, a real-time 3D rendering software that comprises thousands of functions and features to develop games for cross-platform computer systems. We used it to develop the proposed *Patient App* (more details in the next Section – Application layer). The *Virtual Reality Engine* communicates with the *Device Connector* to access IoT devices and, eventually, change their status. In addition, the *System Back End* manages the requests sent by the applications providing common unified interfaces and web services to platform software entities, making them able to bidirectionally communicate with the other various actors. While the navigation of the patient into the application is due to the *Eye-Tracker* from the time that a patient in the advanced stages of ASL can only move their eyes.

[2] https://dynamobim.org/

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Application Layer

The *Application Layer* is the highest layer reported in Figure 1 and it includes all the final visualization and interaction blocks of the system. Starting with low resources windows devices, to respond to ASL patients' inputs and to render the VR model, the *Patient App* arises thanks to the *Virtual Unity Engine*. Figure 3 shows the front-end of *Patient App*. To perform actions on buttons, into *Patient App* the cursor position is used: if the cursor remains over an interactive object for more than a set threshold, the system considers that as a click [3]. Within it, patients can navigate a virtual environment that represents the reality that surrounds them. An example of an action that a patient can perform is to turn on/off the light. This operation is possible through the user's REST web services that start thanks to the *Virtual Reality Engine*. Communicating with the *Database Domain* and the *Device Connection*, the *Virtual Reality Engine* changes the status of the lamp. *Patient App* has been specifically designed to provide user friendly Graphical User Interface (GUI) to address ALS patients' needs and, thus, to integrate Eye-Tracking devices to navigate in this virtual environment (see icons with arrows in Figure 3 (a)). Action Commands provides interactions with the external environment through HTTP-REST web services provided by the Device Connector integrating the heterogeneous IoT devices deployed in the real-world environment. There is a Call Nurse button that sends an HTTP-REST Request to trigger an audio signal calling the nurse. A Service Command button (home icon in Figure 3 (a)) opens a widget providing a list of all the IoT devices (either sensors or actuators) deployed in the real-world environments (see Figure 3 (b)). From this widget, the patient can send actuation commands and read data sampled by IoT devices.

a **b**

Figure 3. (a) Overview Game Interface. (b) Action Buttons [3].

Figure 4 shows the Sequence Diagram of the *Patient App*, highlighting all the interactions with the other software entities in the distributed platform to allow patients in navigating the BIM 3D model and in accessing IoT devices.

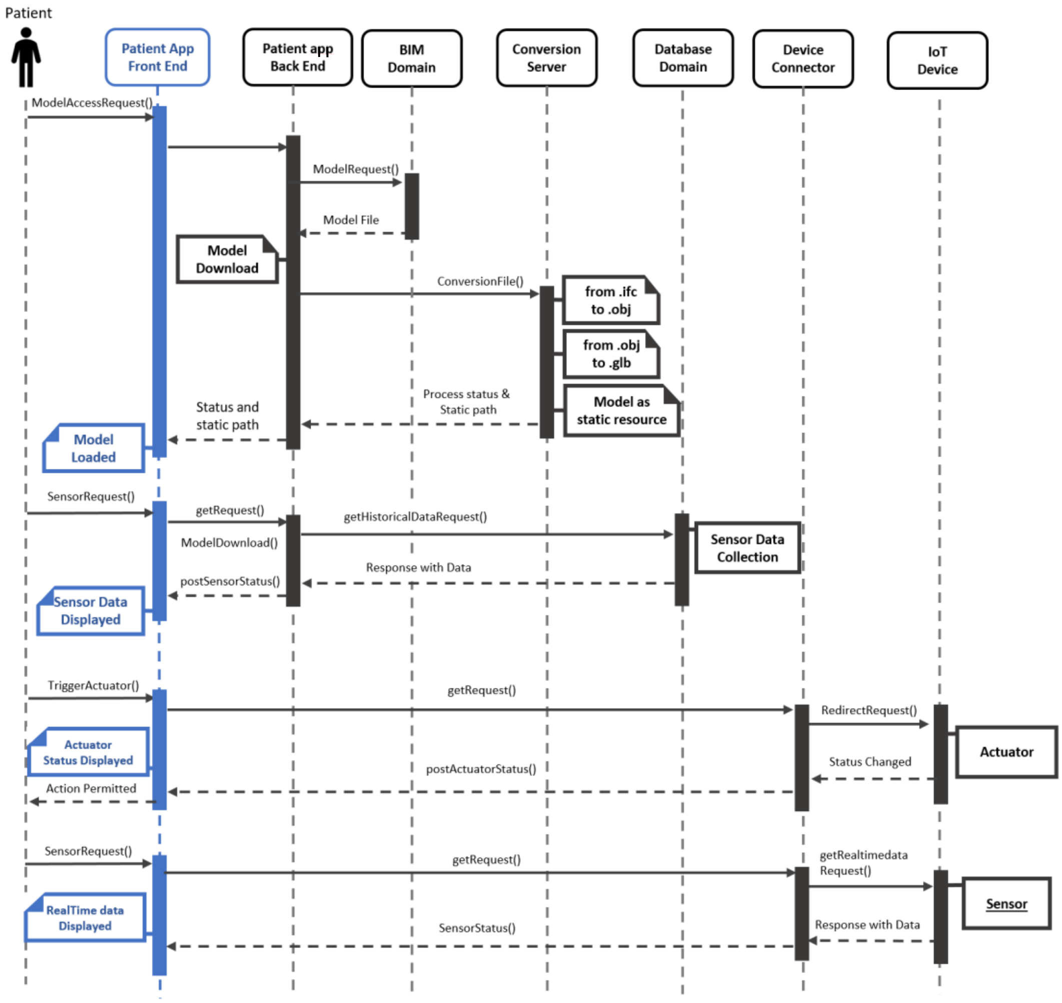

Figure 4. Patient Action Sequence Diagram.

The user must first Login by entering their credentials. The activities that he/she can perform are possible because of the interaction with the BIM model that is visualized in the *Patient App*. A GET request diverts the operation request and groups them in a payload to send it to *BIM Domain*. In turn, *BIM Domain* generates a *Token* if the Login is successful, so the user can proceed with further actions. If the patient wants to access a specific BIM model, he/she has to choose it in the *Patient App*, at that point a GET request starts for *BIM Domain*. Here, the 3D model is sent back to the *patient app Back End* allowing download of it into a protected folder. Before loading the model into the Unity scene, the model's double format conversion is done. So, BIM and IoT data matching is performed. Once the model is converted, the file can be downloaded and uploaded with a static path to Unity. Then the user can choose between obtaining historical information about IoT devices or changing actuators status and query a specific sensor in real time. *Patient Back End* acts as a link with *Database Domain* and allows the display of historical data in the Front End part of the system. Requests sent to the *Device Connector* instead act directly on actuators and sensors. Sensor data and actuator status are then returned to *Patient App* and are readable to the patient.

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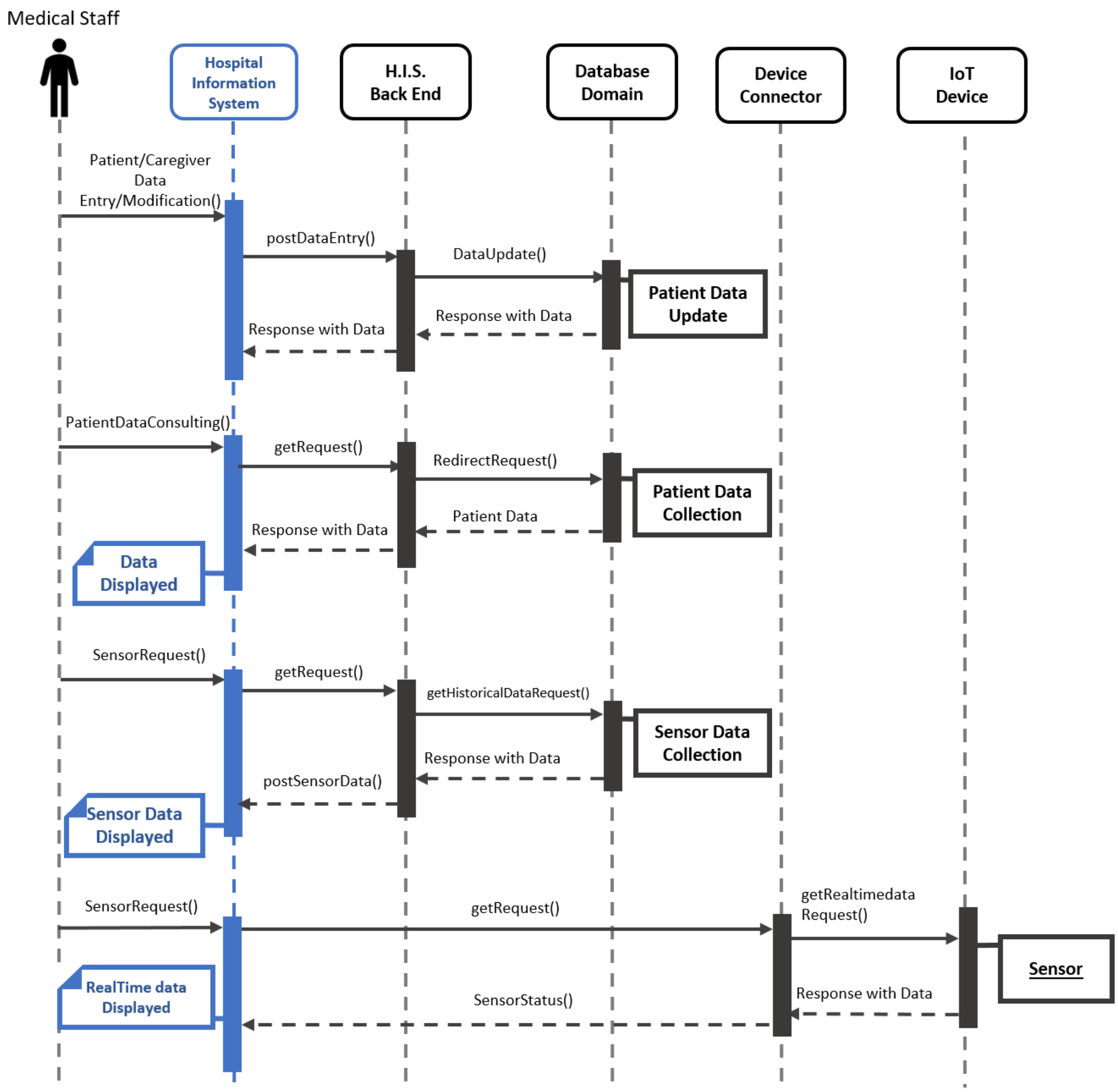

Figure 5. Doctor/ Nurse Action Sequence Diagram.

The second component of the *Application Layer* is the *Hospital Information System*, specifically created to manage patients, monitor their treatments, follow-ups and all related documentation, as showed in Figure *5*. Research of common communication systems can help identify deficiencies in the health care system and decrease the gaps between doctors and patients. The *Hospital Information System* presents a division between the framework intended for the doctor and the one for the nurse. It is possible to visualize and modify patients' data under treatment, while in the second case it is possible to monitor their presence inside the hospital structure. The availability of this information is possible thanks to the *Database Domain*. The medical staff can also send a request to the *Database Domain* to display the historical data collected by sensors, or send a request to a specific sensor, through the *Device Connector*, to display Real Time sensor data.

Hardware prototype

The software solution described in the previous sections was created with the aim of integrating with hardware devices already present on the market and used daily by people with ALS. The authors, not intending to bind themselves to any specific hardware, decided therefore to create a prototype with the basic components necessary for the operation of the application. Through access to specific APIs of already existing devices, however, it is possible to integrate the solution on any device.

The hardware prototype consists of a series of components that collect information and expose it to the end-user. Figure 6 shows the System Prototype that has been developed specifically for patients in all its hardware parts. A Windows OS Tablet displays the BIM 3D model and runs the *Patient App*. The user actions to the interface are triggered with the *Eye-Tracker*, a Tobii Eye Tracker 4C version. The IoT system is based on: the Raspberry Pi Model B+, the DHT11 sensor by Mouser Electronics for

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temperature and humidity, the Motion Controller that exploits PIR Motion Sensor by Adafruit and the Pi Relay Board v1.0 for actuators' switch. The Raspberry Pi, deployed at patient premises, executes the *Device Connector* software to integrate the IoT devices with the rest of the proposed distributed software platform.

Figure 6. System Prototype composed of a main PC, (a) a Tablet PC with the Patient App, (b) Eye-Tracking device (Tobii Tracker), (c) a Relay single board, (d) a Breadboard with PIR Sensor and DHT11, (e) a Raspberry Pi 3 Model B+ and (f) a Lamp [3].

Impact on remote ASL patients' assistance

Currently, the management of patients with motor neuron degeneration is faces several critical challenges. The difficulty in understanding the progress of the disease prevents effective communication between doctor and patient. Applying tools that allow continuous monitoring of the environment and the actions that the patient can perform would allow the doctor to better understand the patients' behavior. Medical records also have deficiencies for data collection, preventing the optimization of the statistical analysis of these diseases. Patients suffering from these diseases lose the ability to interact with their caregivers and their surroundings and they have few tools to regain their autonomy. Using a tool that connects the environment of the patient to that of the health care sector, will allow patients to interact more efficiently with the environment and their caregivers and providers.

With the proposed platform based on microservices approach, we aim to provide ALS patients with a novel solution to autonomously perform different tasks in a home and/or hospital environment thanks to non-immersive VR. By increasing patient autonomy, caregiver intervention decreases. This is also reflected in the healthcare system with the introduction of a leaner management model for the individual patient. Teleconsultation to request assistance from the healthcare team remotely improves the service given to the patient, it allows efficient data collection and generates cost savings by reducing home visits by medical personnel. Finally, the adoption of the BIM methodology offers a high level of accessibility to local data and an innovative experience compared to classic communicators. The development of BIM models related to public and private facilities, in fact, will grow and therefore the management of real estate assets will be optimized thanks to the generation of information models also used in the hospital sector by the various stakeholders.

Conclusion

In this paper, we presented an innovative solution aiming at increasing the level of autonomy of patients suffering from ALS. Especially in the most advanced disease stages, patients can only interact with the surrounding world through their eyes. Our solution provides on the one hand the navigation of a BIM 3D model in VR by the patient through an eye-tracker, allowing him/her to perform actions such as turning on/off the light, or monitoring parameters status (e.g., temperature). This is possible thanks to the integration of IoT devices deployed in the real-world environment where the patient lives. On the other hand, a dashboard designed for doctors, nurses and caregivers allows them to monitor the patient, also providing a platform that encapsulates the patient's history, diagnoses and treatments.

Future Work

The software functionalities of the proposed prototype will be increased through the connection to several additional services such as: the possibility to navigate the cultural heritage remodelled through BIM methodology, the use of artificial intelligence to exploit the users' creativity, and the possibility to connect several users in the same virtual environment in order to improve the people's social aspect.

Regarding the hardware of the device, taking advantage of the patent protection related to the work set out in [3], strategic partners in the industry are being sought to develop more stable prototypes. In addition, solutions using more complex IoT devices such as those based on Ambient Assisted Living (AAL) will be integrated into the proposal [19].

Collaboration is also underway with the University of Neurology of Turin, with whom we are working to test the software prototype and assess the increase in autonomy and quality of life of patients while protecting their privacy.

Finally, trials are currently in progress to evaluate how users use the proposed assistance system in order to create metrics that highlight the types of devices and services that are most important for improving the quality of life and autonomy of people with ALS.

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