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PROPOSAL FOR A SMART HOME BASED ON FUZZY LOGIC SMART HOME PROPOSAL BASED ON FUZZY LOGIC

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Abstract: This research work explores an advanced solution in smart home automation, using a Raspberry Pi 4B as a central server and operating through Home Assistant, an open source automation platform. The research aims to develop an efficient management interface for home devices, using ZigBee technology for energy efficient integration. With special focus on temperature regulation, gas leakage monitoring and safety, the methodology employs Fuzzy Logic for advanced processing of sensory data and precise actuation on actuators. The implementation of this system seeks to demonstrate adaptive operability and greater personalization in home automation, providing an accessible and low-cost solution that improves autonomy and comfort. The conclusions highlight the effectiveness of the proposed approach, evidencing its applicability and underlining the potential of open technologies in overcoming barriers in traditional automation.
Keywords: Internet of Things, Smart Home, Artificial Intelligence, Home Assistant, ZigBee.

INTRODUCTION

Rapid technological development has revolutionized several spheres of human life, transforming the way we interact with our environment. One of these transformations has been the conceptualization and implementation of what we know as smart homes. These use automation systems and Internet of Things (IoT) devices to simplify daily tasks and improve the quality of life of their occupants (Noura, Atiquzzaman, & Gaedke, 2019). The use of smart technologies such as sensors, actuators, and artificial intelligence (AI) in homes, buildings, or environments can positively affect quality of life, well-being, productivity, energy savings, and safety. The term "smart" is becoming a trend to improve the built environment, including home, building, transportation, construction and city (Sepasgozar et al., 2020). For this reason the Internet of Things (IoT) represents a world in which billions of objects can sense, communicate and share information through interconnections on public or private networks using the Internet Protocol (IP) (Cook, 2004, pp. 623-626).

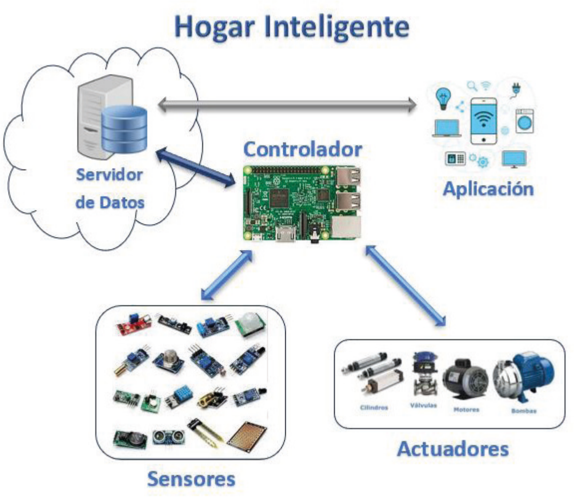

Figure 1. Smart Home Environment (Own Design).

To achieve precisely this interconnection between devices and the autonomy of the environment created by them, artificial intelligence plays a fundamental role. This involves not only understanding how intelligence works, but also designing and programming systems that can learn and improve their performance over time. AI is a discipline that aims to emulate human intelligence in machines and computer systems, and is relevant to any task that requires cognitive or intellectual skills (Russell & Norvig, 2021). Among the most common artificial intelligence techniques can be found Fuzzy Logic. This is widely used in Internet of Things (IoT) applications due to its ability to model complex systems with uncertainty and variability in the input data. It focuses on imprecise reasoning, uncertainty and the use of fuzzy sets, which allow representing vague or ambiguous concepts. It is used in a variety of applications such as automatic control systems, pattern recognition, decision making and data analysis. Examples of practical applications of Fuzzy Logic include temperature control of a furnace, collision detection in an autonomous car, and credit risk assessment in the financial industry (Zimmermann, 2011). In the context of IoT, Fuzzy Logic is mainly used to make decisions and control processes in real time, such as: lighting and temperature control, air quality monitoring, traffic control, facial recognition, among many others (Zadeh, 1965).

In Mexico, it is estimated that in 2021 there were 24.3 million homes with internet access, equivalent to 66.4% of all homes in the country (INEGI, 2022). In addition, during the period between 2022 and 2023, there was a notable growth in sales of smart home hardware, especially in devices such as security cameras, switches, light fixtures and locks.

The smart home phenomenon is revolutionizing the way Mexicans live, especially in large cities. However, although significant progress has been made in the implementation of smart solutions in various sectors, such as industry and public services, there is still a gap in the field of residential automation.

In order to address this problem, the research focuses on the development of a proposal for a smart home based on Fuzzy Logic.

MATERIALS AND METHODS

The design of the smart home proposal was carried out following ISO standards (ISO 9001 Processes, n. d.). The figure below illustrates the result.

The architecture presented structures a Smart Home through processes and subprocesses. The "inputs" are the signals from the sensors, while the "output" corresponds to the actions executed by the Smart Home system, such as activating a gas valve or adjusting the

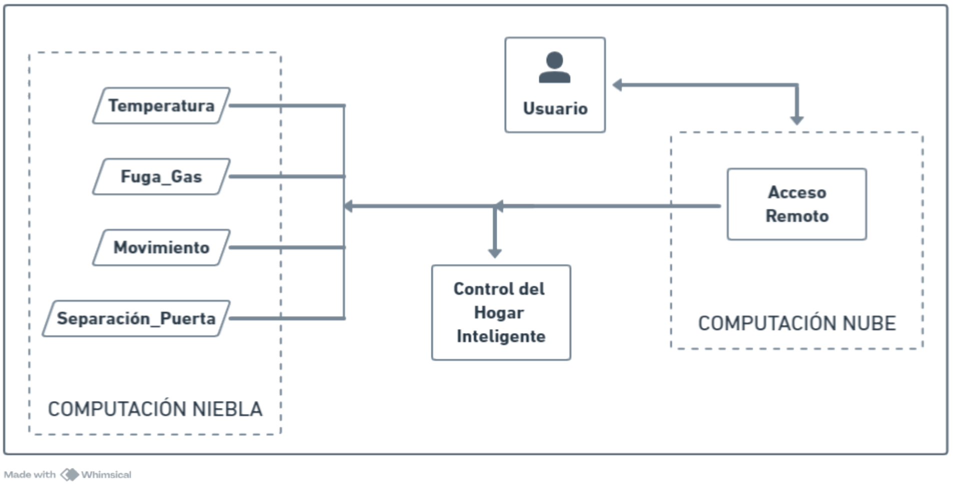

Figure 2. ISO-based Smart Home architecture.

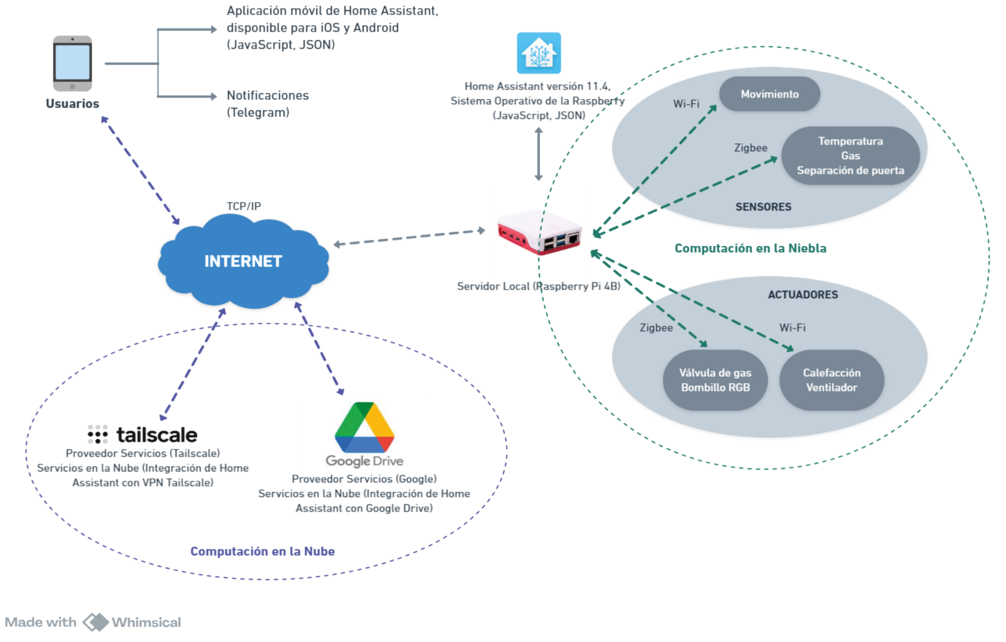

Figure 3. Architecture of the Smart Home (*House*) based on Fuzzy Logic (Own design).

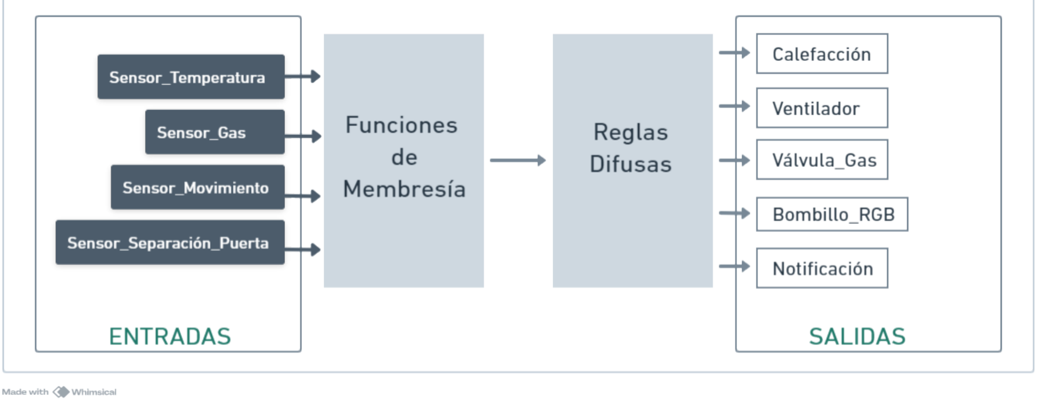

Figure 4. *House* control system with built-in Fuzzy Logic.

RGB lighting. These operations fall within the scope of fog and cloud computing, being interpreted as the “resources” referred to in the ISO standard. The “Remote Access” component through cloud computing aligns with the need for processes that meet the demands of the customer, represented here by the user who controls the system remotely, which is critical for system feedback and improvement.

In accordance with the ISO standard, it is crucial to map processes and their interrelationships to ensure that each activity contributes to the overall purpose of the quality management system. The architecture of the Smart Home shows a clear procedural scheme, where the interaction between the different elements and their collective functioning aim at the efficient and safe control of the home.

The following image shows the architecture of the smart home (which we will call Casa), highlighting the infrastructure and communication between devices.

In the center left, a cloud is shown, symbolizing Internet connectivity and the ability to remotely access the home network. Cloud services are referenced, enabling daily system saves through the integration of Home Assistant with Google Drive, and the use of the VPN that enables remote connection via web and mobile app.

The central server, represented by a *Raspberry Pi 4B,* runs the *Home Assistant* automation software as the Operating System; it is also connected to a *Wi-Fi Network,* consisting of an IP camera and two smart plugs that control the Heating and Fan, and to a *ZigBee Network*, consisting of a temperature sensor, a door separation sensor, a gas sensor, a gas valve and an RGB bulb, all connected through bidirectional dotted arrows, suggesting wireless communication. The ZigBee network coordinator, which is the gateway needed to connect the ZigBee devices to the Raspberry Pi (in this case the *Sonoff ZigBee 3.0 USB Dongle Plus* coordinator), is connected to it, although it is not illustrated in the image.

Finally, in the upper left part of the image, a smartphone is shown representing the application with a user interface. This application allows monitoring and controlling the home network and displays indicators such as temperature and the current status of the devices. In addition, Telegram is used as a messaging system to send notifications about the operation of the home, which facilitates immediate and effective communication of any relevant event within the smart home system.

FUZZY LOGIC IN THE CASA SYSTEM:

The following diagram illustrates the operating scheme of the Fuzzy Logic based *Home* control system.

The system inputs, represented by different sensors, are processed by membership functions to convert real data into fuzzy values. These values feed a set of fuzzy rules that, in turn, dictate the actuators’ responses as well as the issuance of notifications. This control approach, detailed in the diagram, although seen as a whole, in reality, due to the nature of each control flow itself, it was decided to split into three control subsystems for better configuration: *Temperature*, *Gas_Leak_Control* and *Intrusion_Detection*.

SIMULATION IN MATLAB:

MATLAB offers a specific Fuzzy Logic Toolbox that is designed to facilitate working with Fuzzy Logic systems. This allows designing, tuning and simulating fuzzy systems efficiently (MathWorks, n.d.). For this reason this software was chosen to reinforce the conceptual basis of the proposal.

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Figure 5. View (from the Fuzzy Logic Designer of Matlab) of the three control subsystems with Fuzzy Logic incorporated.

As evidenced in the previous illustration, the implementation of the *Casa* control system in MATLAB was supported by the precision of Fuzzy Logic, whose mathematical foundation was extracted from the work of Ross (2017). The choice of specific membership functions for each subsystem is explained below:

Gaussian functions: used for temperature control, these functions are defined as:

$$G(x) = e^{\frac{-(x-c)^2}{2\partial^2}} \quad (1)$$

Where:

x is the input variable, c the center of the curve, and $\boldsymbol{\sigma}$ the standard deviation.

Its smooth, symmetrical profile is ideal for shaping thermal response, allowing fine regulation that mimics the natural dynamics of the environment.

Trapezoidal functions: used in the inputs of the *Gas_Leak_Control* subsystem and to model the outputs in terms of time ranges, these functions are characterized by the equation:

$$T(x;a,b,c,d) = \max\left(\min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), o\right) \quad (2)$$

Where:

(***a, b, c, d***) define the key points of the trapezoidal shape.

Its usefulness is highlighted in the definition of action thresholds, providing clarity in the limits of operation.

Triangular Functions: In the *Intrusion_Detection* and *Gas_Leak_Control* subsystems, the triangular functions are used for the inputs and are expressed as follows:

$$Tr(x; a, b, c) = \max\left(\min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), o\right) \quad (3)$$

Where:

(***a, b, c***) are the vertices of the triangle.

These functions are valuable for their simplicity and effectiveness in representing clearly defined states with sharp transition points.

Sigmoidal Functions: were chosen for outputs that require a binary decision, such as turning a device on or off, and are defined as follows:

$$S(x) = \frac{1}{1+e^{-k(x-x_0)}} \quad (4)$$

Where:

k is the slope of the curve and x_0 the mean value where the function is 0.5.

Its 'S' shape provides a clear transition between 'on' and 'off', 'true' and 'false' states, essential for immediate decisions.

After careful selection of the membership functions for each subsystem in MATLAB, the Mamdani inference system was chosen over Sugeno. The choice of the Mamdani system was due to its ability to model human decisions intuitively and its ease of interpretation, crucial aspects for a system intended to automate a living environment (MathWorks, n.d.). Sample of this are the following images:

Although Sugeno may offer advantages in terms of computational efficiency and ease of implementation, Mamdani aligns better with the goal of creating rules that reflect human reasoning and preferences, especially in home automation applications where decisions directly affect occupant comfort and safety (MathWorks, n.d.).

This MATLAB simulation not only validated the effectiveness of the selected Fuzzy Logic rules and membership functions, but also served as a cornerstone to reinforce the theoretical basis of the project. This process ensured that the transition from theory to practice was solid and consistent, establishing a bridge to the actual implementation of the *Casa* system in the Home Assistant environment using Node-RED.

IMPLEMENTATION IN NODE-RED:

Node-RED, configured as an add-on in Home Assistant, offers a visual programming environment that facilitates home automation through flows composed of different nodes according to specific needs. This allows a flexible and dynamic management of connected devices, favoring an efficient interaction between sensors and actuators (Node-RED, n.d.). For this project, a dedicated flow was designed for each control subsystem, thus ensuring specialized management, as shown in the following image:

THE NODES SELECTED FOR THIS IMPLEMENTATION WERE THE FOLLOWING:

Event: State: this node listens to the events and status changes of all devices connected to the Home Assistant system, being fundamental to capture sensor data in real time. Its ability to react to specific variations in the data makes it the mainstay of automatic monitoring and control.

Function: function nodes are used to apply custom logic, such as the evaluation of conditions for *Fuzzy_Rules*, *Membership_Functions*, *Counter* and *Timer*. These nodes allow scripting, facilitating direct manipulation of input and output data.

Join: this node is essential to combine data coming from multiple sources or sensors, such

	Rule
1	If (Temperatura is Baja) then (Calefacción is ON)(Ventilador is OFF) (1)
2	If (Temperatura is Confortable) then (Calefacción is OFF)(Ventilador is OFF) (1)
3	If (Temperatura is Alta) then (Calefacción is OFF)(Ventilador is ON) (1)

Fuzzy Rule Set defined in Matlab for *Temperature*.

	Rule
1	If (Fuga_Gas is Nula) then (Válvula_Gas is Abierta)(Bombillo_RGB is Blanco) (1)
2	If (Fuga_Gas is Baja) then (Válvula_Gas is Abierta)(Bombillo_RGB is Blanco)(Notificación is Falsa_Alarma) (1)
3	If (Fuga_Gas is Moderada) then (Válvula_Gas is Abierta)(Bombillo_RGB is Blanco)(Notificación is Fuga_Moderada) (1)
4	If (Fuga_Gas is Alta) then (Válvula_Gas is Cerrada)(Bombillo_RGB is Rojo)(Notificación is Alerta_Crítica) (1)

Fuzzy Rule Set defined in Matlab for *Gas_Leak_Control*.

	Rule
1	If (Detección_Movimiento is Bajo) and (Intrusión is True) then (Bombillo_RGB is Azul)(Notificación is Intrusión) (1)
2	If (Detección_Movimiento is Bajo) and (Intrusión is False) then (Bombillo_RGB is Blanco)(Notificación is Movimiento_Bajo) (1)
3	If (Detección_Movimiento is Moderado) and (Intrusión is True) then (Bombillo_RGB is Azul)(Notificación is Intrusión) (1)
4	If (Detección_Movimiento is Moderado) and (Intrusión is False) then (Bombillo_RGB is Blanco)(Notificación is Movimiento_Moderado) (1)
5	If (Detección_Movimiento is Alto) and (Intrusión is True) then (Bombillo_RGB is Azul)(Notificación is Intrusión) (1)
6	If (Detección_Movimiento is Alto) and (Intrusión is False) then (Bombillo_RGB is Azul)(Notificación is Movimiento_Elevado) (1)

Fuzzy Rule Set defined in Matlab for *Intrusion_Detection*

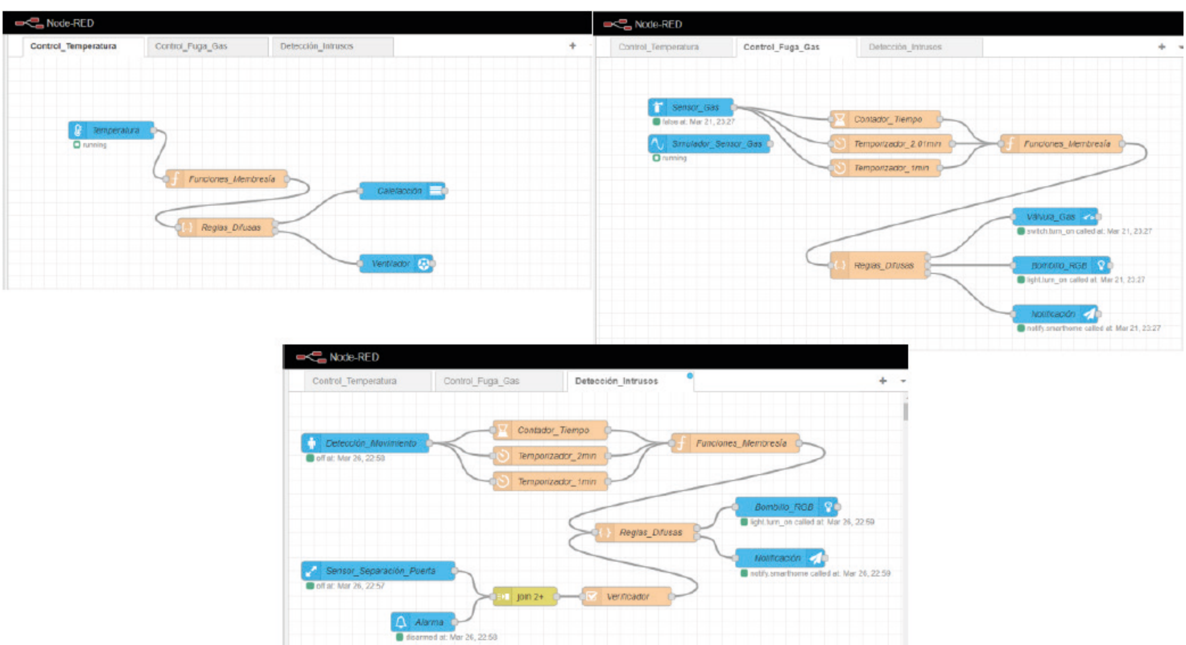

Figure 9. View (from Node-RED in Home Assistant) of the three control subsystems with Fuzzy Logic incorporated.

as the integration of *Alarm* and *Door_Sensor_Separation_door* activation signals, allowing a more complex management of conditions and events inside the home.

Call Service: through these nodes, direct actions are performed on the devices, such as turning on the *Heating*, turning off the *Fan*, changing the color of the *Bulb_RGB* or sending *Notifications* via Telegram. They represent the command interface that translates Fuzzy Logic decisions into physical interactions with the environment.

The configuration of these nodes within Node-RED is facilitated by intuitive interfaces that allow defining complex logic and behaviors without the need to write code from scratch. However, for those cases where more sophisticated logic is required, Node-RED allows the insertion of JavaScript code directly into function nodes, providing unprecedented flexibility in customizing automation tasks (Node-RED, n.d.).

USER INTERFACE:

Home Assistant is positioned as a leading smart home automation platform, standing out for its open source nature and its ability to seamlessly integrate with a wide range of technologies and communication protocols. This versatility allows users to connect devices from different manufacturers, creating a highly customizable and efficient smart home ecosystem. Home Assistant's user interface, known for its visual appeal and intuitive navigability, offers an exceptional user experience, both in web browsers and in its dedicated apps for Android and iOS (Home Assistant, n.d.).

Within this platform, dashboards can be fully customized from the administrator account, allowing users to define and tailor the interface to their specific needs. Whether it's arming or disarming an alarm system, changing the color of a smart bulb, or monitoring various aspects of the home, Home Assistant facilitates these tasks through a local interactive web interface (Home Assistant, n.d.).

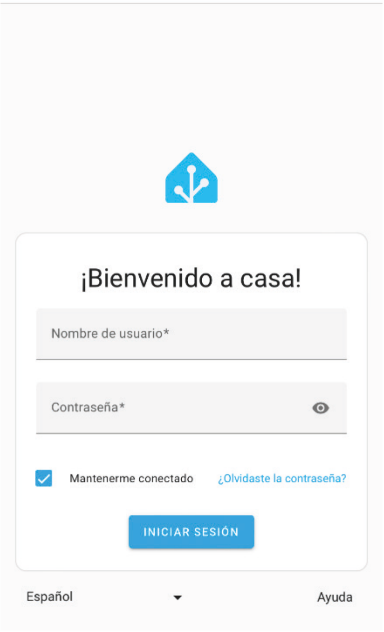

Figure 10. View of the mobile application login.

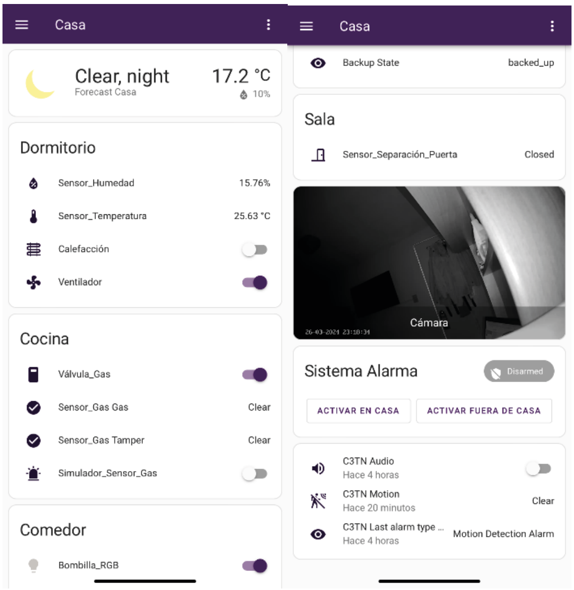

Figure 11. View of the Summary dashboard in the mobile application.

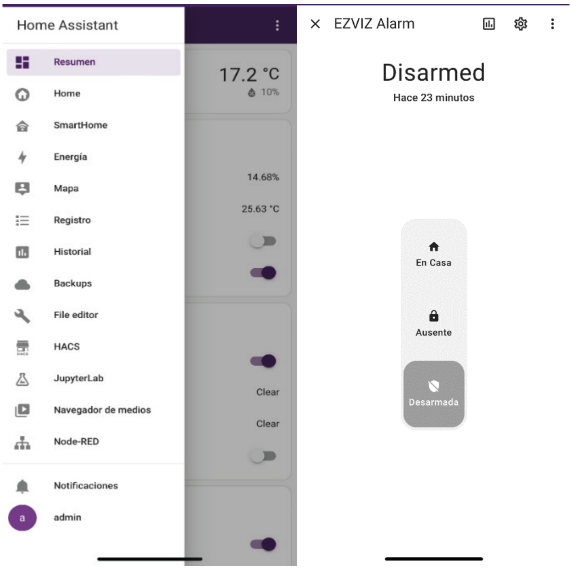

Figure 12. View of settings and add-ons within the admin account in the mobile application.

Figure 13. View of alarm arming and disarming and RGB bulb configuration in the mobile application.

Another vital component of this intelligent ecosystem is the integration with messaging services for notification management. A tangible example of this functionality is the use of Telegram's bot, called *SmartHome*, specifically designed to send critical alerts and updates directly to users. This bot becomes an essential communication channel, especially for managing significant events such as gas leak detection and intruder identification, ensuring that occupants are informed in real time about the security conditions of their home.

The two images below illustrate the interaction with the *SmartHome* bot in Telegram, showing how users receive instant notifications upon alert situations.

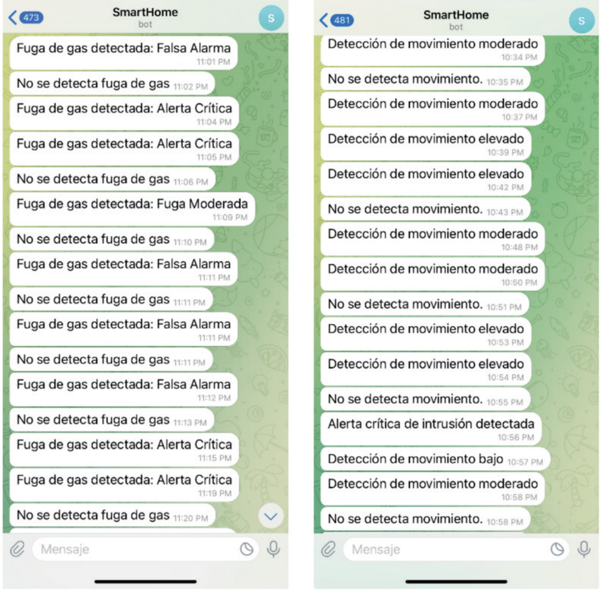

Figure 14. Interaction with the *SmartHome* bot in Telegram for the *Gas_Leak_Control* and *Intrusion_Detection* subsystems.

This notification method complements the user experience by providing a rapid response mechanism to critical events, enabling effective management of the home environment even from a distance.

RESULTS AND DISCUSSION

After the practical implementation of the *House* automation system based on Fuzzy Logic, the need arose to validate its effectiveness. With this objective in mind, three specific data sets were extracted, corresponding to the *Temperature*, *Gas_Leak_Control* and *Intrusion_Detection* subsystems. These data are not mere theoretical assumptions; they were obtained from actual readings from sensors located in the home, under simulated scenarios to gather accurate information. With the

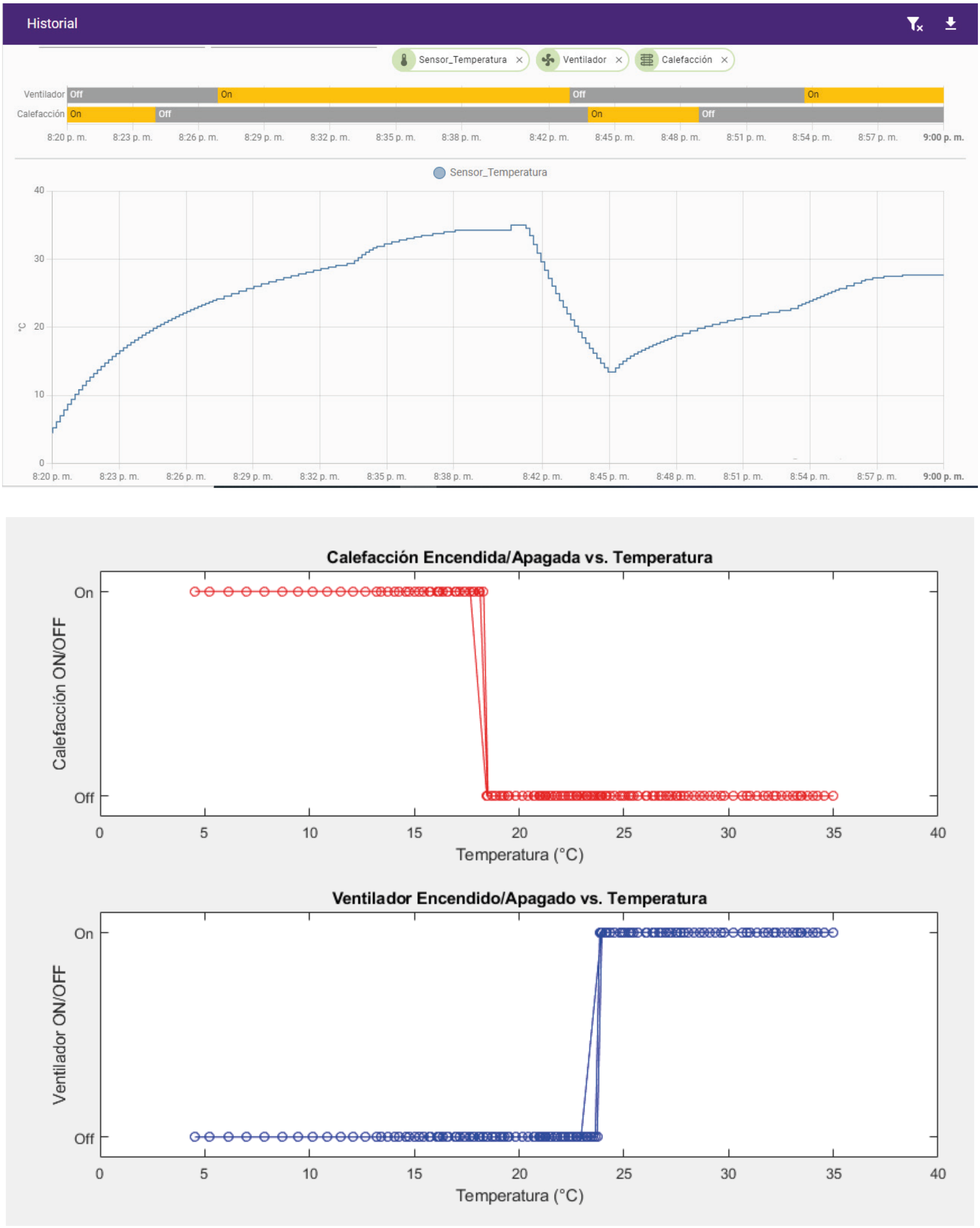

Figure 15. Comparison of results in the *Temperature* subsystem using Node-RED implementation and MATLAB simulation.

Figure 16. Behavior of the *Temperature* subsystem in the PPP.

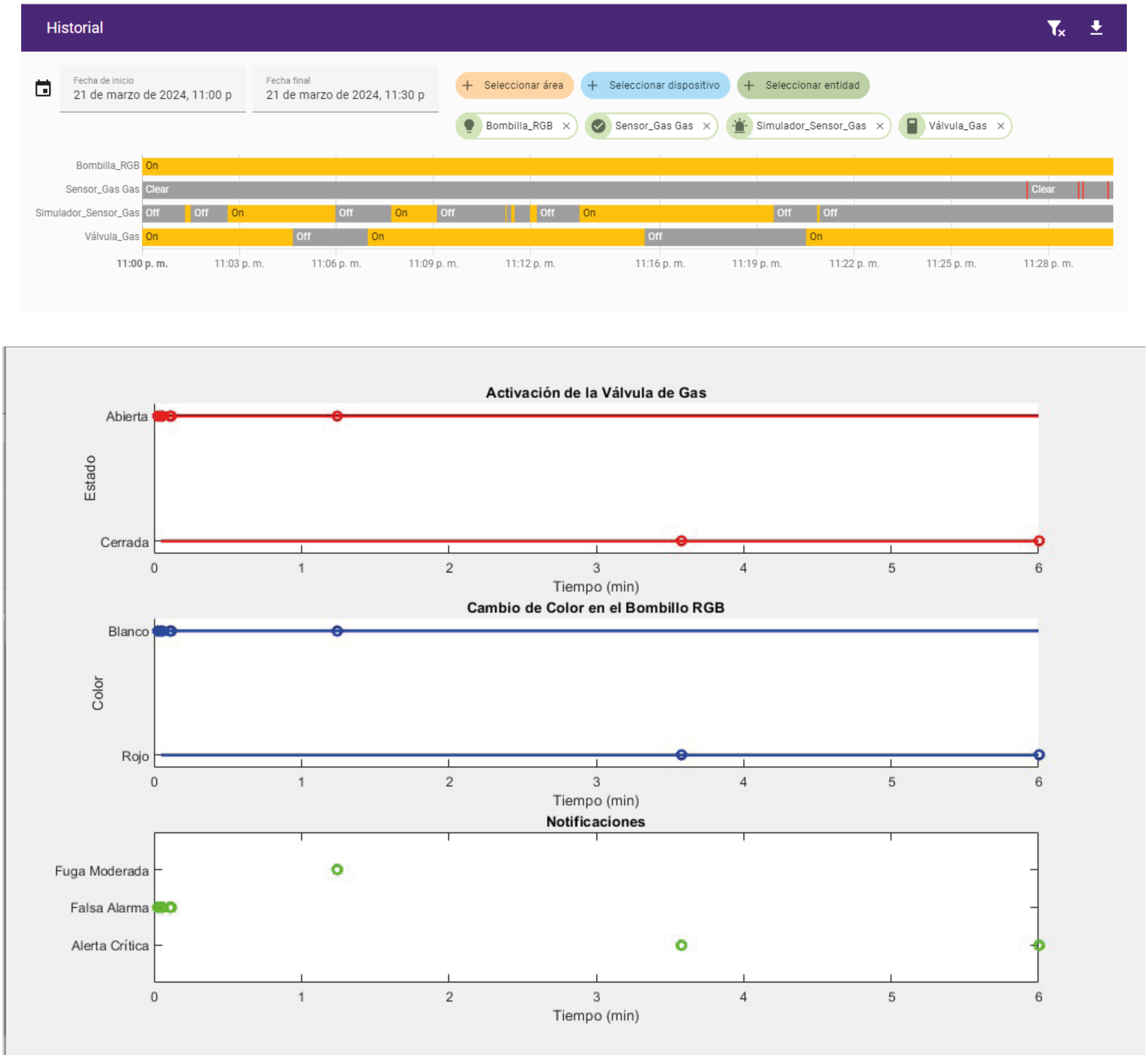

Figure 17. Comparison of results in the *Gas_Leak_Control* subsystem using Node-RED implementation and MATLAB simulation.

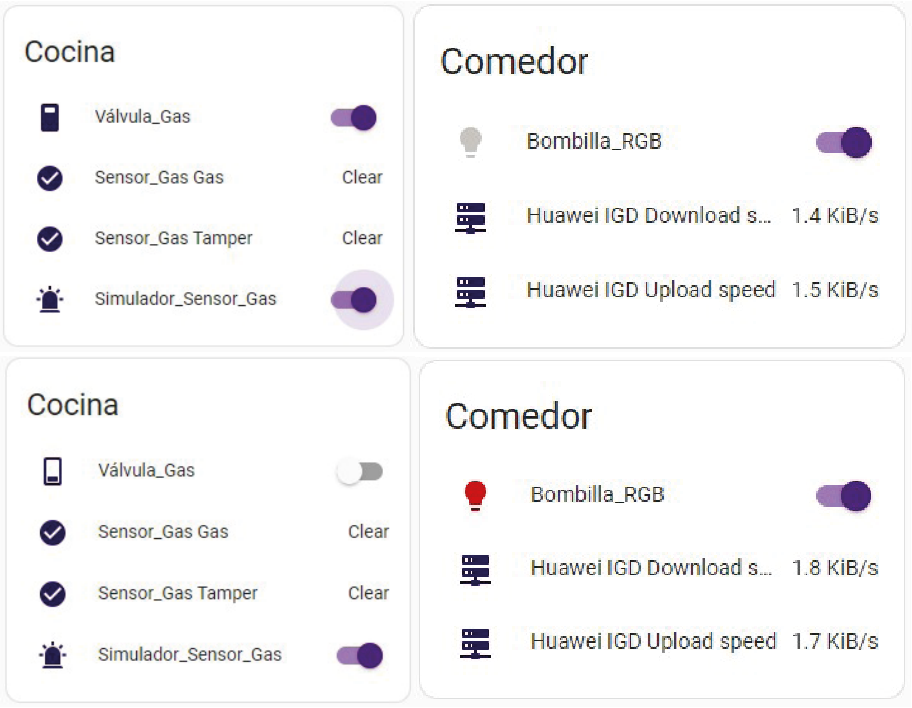

Figure 18. Behavior of the *Gas_Leak_Control* subsystem in the PPP.

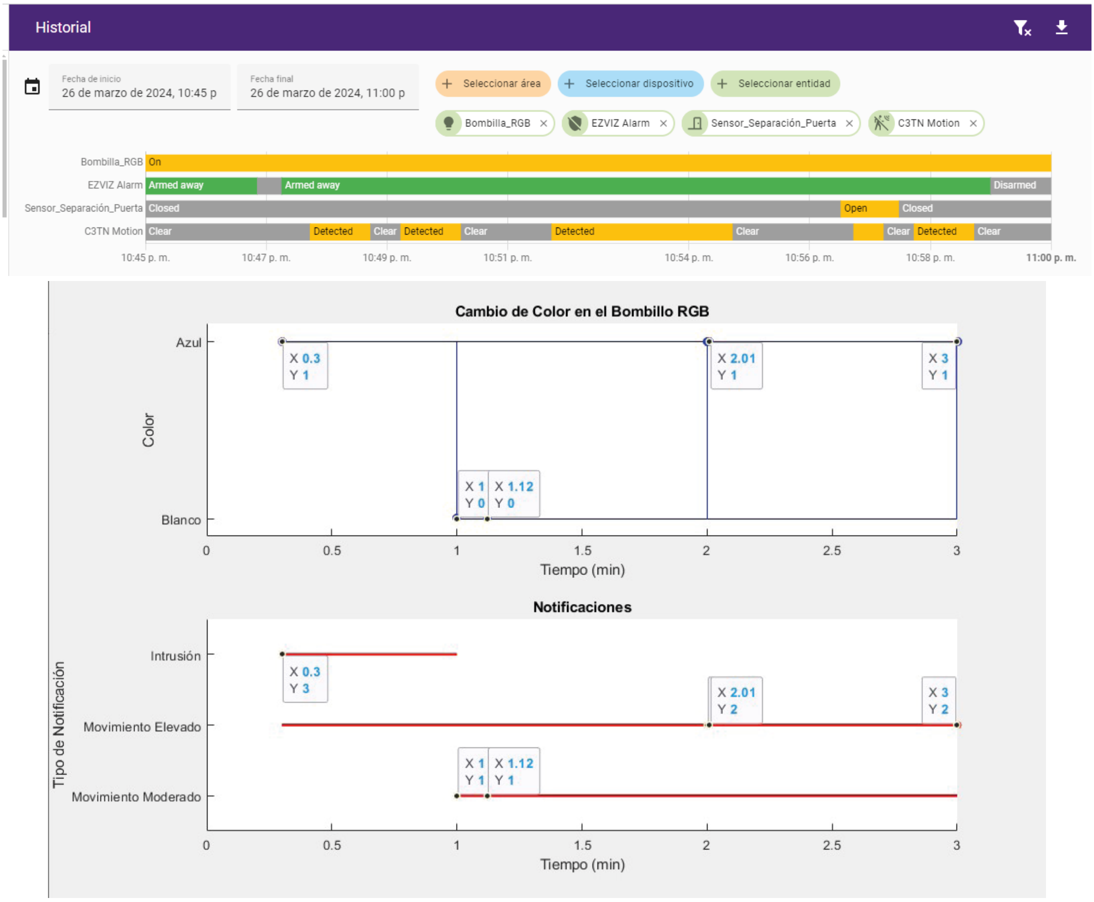

Figure 19. Comparison of results in the *Intrusion_Detection* subsystem using Node-RED implementation and MATLAB simulation.

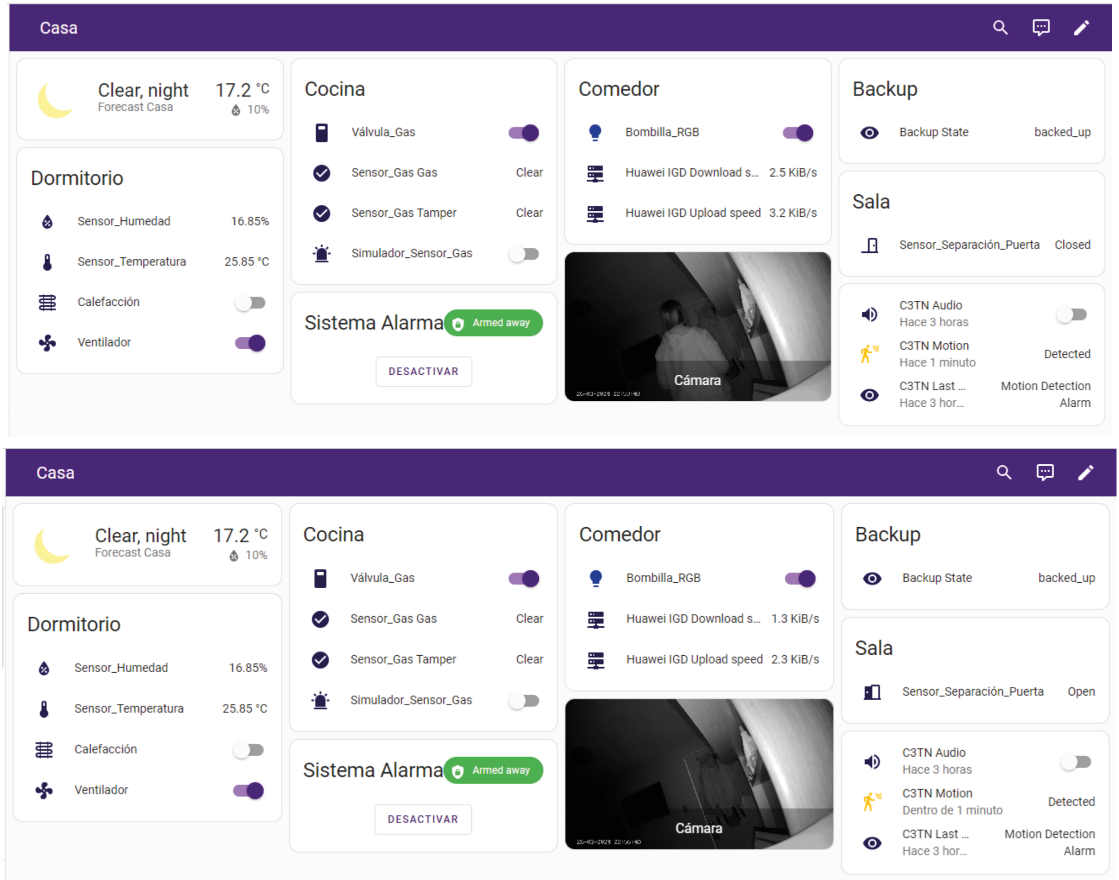

Figure 20. Behavior of the *Intrusion_Detection* subsystem in the APP.

datasets in hand, we observed the behavior of the implemented system and proceeded to feed the same information into the simulated versions of MATLAB. The results showed significant correlations between the practices and simulations, as evidenced in the various graphs presented below.

In terms of temperature management, the system properly activated and deactivated the fan and heating according to the requirements of the temperature ranges. For gas leakage control, the valve responded in a timely manner, closing and opening at crucial times, and notifications were delivered without delay. Similarly, in intrusion detection, the system not only provided timely alerts, but also effectively managed visual signaling via the RGB bulb, prioritizing critical events such as the detection of a door opening.

This consistency between practice and simulation confirms the soundness of the mathematical foundation behind the applied Fuzzy Logic. It also validates the correct installation of the intelligent devices and the Node-RED programming of the workflows.

CONCLUSIONS

This research highlights the significant contribution of Fuzzy Logic in home automation, demonstrating with concrete data how this technology improves the efficiency and personalization of home automation. Through the implementation of Home Assistant and the integration of IoT technologies, a measurable increase in home comfort and functionality has been achieved. Although not formally hypothesized, the results corroborate the premise that interoperability and accessibility are crucial in home automation.

The findings suggest new avenues of exploration in the use of open source software for smart home personalization, pointing toward the creation of spaces that dynamically adapt to users' needs.

The research raises a promising path towards the integration of more complex workflows and advanced Fuzzy Logic systems, opening perspectives for future innovations that could bring even more to the field of home automation. The applicability of these results is immediate and offers a framework for the continuous improvement of home automation in Mexico.

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