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Mathematical models for uncertainty control in internet of things sensors

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Abstract
The Internet of Things (IoT) connects devices over the internet to solve specific problems, using sensors to collect data and actuators to execute tasks. Uncertainty in data, caused by sensor inaccuracy, affects decision making. This study proposes mathematical models based on fuzzy logic to manage this uncertainty.
Five systems with six representative sensors were designed, simulated in MATLAB and developed on ESP8266/ESP32 microcontrollers using edge computing. The physical implementations demonstrated accuracy similar to the simulations, validating the use of fuzzy logic to address uncertainty. It is suggested to extend the study to sensors in critical processes and explore neurofuzzy systems for autonomous learning.

Keywords: IoT, fuzzy logic, sensors, actuators, fuzzy inference

Introduction

The Internet of Things (IoT) faces significant challenges due to uncertainty and variability in data collected by sensors, caused by measurement errors, noise, and changing environmental conditions (Hu, 2016; Krushnan *et al*., 2023 [6]; Bakar, 2022). Although statistical approaches exist to manage these problems, they are not flexible enough to address the inherent vagueness of data (Hillar, 2016; Prasetyo *et al*., 2023; Maulana *et al*., 2023) [3].
Fuzzy logic, proposed by Zadeh (1965) [1], is a mathematical tool that addresses imprecision and uncertainty by extending analysis to ambiguous data (Klir and Yuan, 1995; Mohammed and Bahjat, 2023) [2]. This study seeks to develop fuzzy logic-based models that allow the interpretation and processing of sensor data in IoT systems, improving decision-making and accuracy in dynamic environments (Prasetyo *et al*., 2023 [3]; Xiao, 2018).
The main objective is to formulate mathematical models that manage uncertainty in IoT sensor data, using simulations in MATLAB and edge computing to physically implement such models. The central hypothesis states that the principles of fuzzy logic, combined with tools such as MATLAB and microcontrollers, allow the efficient management of uncertainty in IoT systems, achieving consistent results between simulations and physical tests.

Materials and Methods

We have the background of the doctoral thesis entitled "Design of level and temperature control of a mixing system for the textile industry using fuzzy logic" by Utrilla Mego Limberg Walter (2020), Universidad Nacional San Agustín de Arequipa, proposed to design a system that optimizes mixing processes in the textile industry through level and temperature control. To do this, three types of controllers were developed and compared: proportional-integral (PI), proportional-integral-derivative (PID) and one based on fuzzy logic. The results showed that the fuzzy controller presented high performance indices, such as zero overshoot, shorter settling time and zero stationary error, thus validating its superiority for this type of applications (Utrilla, 2020) [11].
On the other hand, the study entitled "Design and Development of Efficient Water Management for Agriculture using IoT and Fuzzy Logic" by Dekka *et al.* (2020) [10], carried out in India, addressed the problem of efficient water management in agriculture. A fuzzy logic and IoT-based system was proposed to control water supply using a smart motor, which enabled water consumption to be balanced and pipeline leaks to be prevented. The results showed that the implementation of these technologies not only solved the leaks but also optimized agricultural productivity in an economical and sustainable manner (Dekka *et al*., 2020) [10].
The research is based on fuzzy logic and the Internet of Things (IoT), essential elements for developing a mathematical model that addresses problems with imprecision and uncertainty.

1. **Fuzzy Logic:** Introduced by Lofti Zadeh in 1965 [1], fuzzy logic extends the concepts of classical sets and functions to fuzzy sets and membership functions. This theory allows representing degrees of truth between completely false and true, facilitating reasoning in imprecise and vague contexts. It is widely used in applied mathematics, engineering, and domains with uncertainty.

2. **Uncertainty:** It refers to the lack of sufficient information to deterministically describe or predict the behavior of a system. This phenomenon is frequent in everyday activities and disciplines such as engineering, medicine, or commerce, where traditional mathematical methods are insufficient.

3. **Linguistic Variables:** These variables take values that are words instead of numbers. For example, temperature can be represented as "cold", "warm" or "hot". Linguistic variables are better suited to describe uncertainty and imprecision, as they capture subjective interpretations.

4. **Fuzzy Sets:** A fuzzy set associates each element of a reference set with a membership degree between 0 and 1, which represents its level of identification with said set. This approach allows modeling ambiguities and vagueness in mathematical systems.

5. **Membership Functions:** These functions assign each element of a set a value in the interval [1], indicating its membership degree to a fuzzy set. If the values are limited to 0 and 1, the classic or crisp sets are obtained.

Fuzzy logic, by allowing work with uncertainty and membership degrees, constitutes a fundamental tool for modeling complex problems and imprecise systems.
The research adopts a quantitative approach based on the collection and analysis of numerical data generated by sensors. These data allow measuring the variable "uncertainty" and evaluating its relationship with mathematical models based on fuzzy logic. An experimental method was used, which involved the evaluation of uncertainty in sensor data by applying various mathematical models.

The research followed the following steps
Definition of variables
Independent: Mathematical models to control uncertainty in sensor data.
Dependent: Uncertainty in sensor data, measured by specific metrics.
- Sample selection: Representative sensors in IoT applications were chosen.
- Implementation of the experiment: Application of mathematical models to analyze uncertainty.
- Data analysis: Comparison of results using statistical techniques to evaluate accuracy and effectiveness.
- Interpretation of results: Evaluation of the usefulness of the models to manage uncertainty, identifying limitations and proposing improvements.

The population and sample consisted of the different types of sensors used in IoT applications; and the sensors relevant to environmental control, including those that measure humidity, temperature, pressure, among others; respectively.

Operationalization of variables
- **Independent variable:** Mathematical models.

Conceptual definition: Abstract representations for analyzing real systems.

Operational definition: Includes stages such as problem formulation, model development, computational implementation, validation, and analysis. Indicators evaluate precision, stability, robustness, and computational efficiency.

- **Dependent variable:** Uncertainty in sensor data.

Conceptual definition: Lack of precision in the data collected.

Operational definition: Dimensions such as measurement precision, stability, reliability, calibration, and sensitivity to environmental conditions. Indicators include mean absolute error, standard deviation, and error rate.

Data collection techniques and instruments
Various techniques were used, such as:
- Operation of sensors to obtain data in real time.
- Detailed data recording and direct observation.
- Pilot tests to validate mathematical models under controlled conditions.

Results
1. Sensor Selection and Implementation
Selected sensors
The sensors used measure key variables for IoT systems: temperature, ambient humidity, soil moisture, gas concentration, distance and movement. The chosen sensors are:
DHT22 (temperature) and DHT11 (humidity): They measure environmental variables.
Soil Moisture: Automated irrigation control.
MICCS-5524: Pollution monitoring.
HC-SR40: Proximity-based gate automation.
HC-SR501: Movement for surveillance systems.

Implementation Methodology
Digital twins: Platforms such as Wokwi and Tinkercad were used to simulate and adjust the sensors before physical implementation.

Physical and logical connection: The sensors were integrated into microcontrollers such as ESP32. The logical configuration was developed in Arduino IDE.

Data storage and management: The data collected was stored in Arduino Cloud and managed through relational databases in HeidiSQL.Data storage and management: The data collected was stored in Arduino Cloud and managed through relational databases in HeidiSQL.

2. Mathematical Models Based on Fuzzy Logic
Fuzzy Systems Evaluated
Environmental Control: Relates humidity and temperature to the speed of a DC motor.

Irrigation Control: Manages the speed of a water pump based on soil humidity.

Gas Control: Optimizes the speed of an air extractor based on gas concentrations.

Door Automation: Determines the angle of rotation of servomotors based on proximity.

Surveillance: Activates alarms depending on the detected movement.

Implemented Mathematical Models
For each system, fuzzy sets, membership functions (triangular, trapezoidal, L and gamma), and Mamdani-type inference rules were defined.
The development of the systems included simulations in MATLAB and implementation in edge computing environments.

3. Evaluation of the Models
Accuracy: The sensors maintain a precision level of ±0.5%.

1. Errors
Average error: ~0.2%.
Error rate: 0.05.

2. Simulated vs. Edge Computing Results

The systems showed consistency on both platforms, validating the viability of the models.

Veamos el gráfico de Funciones de membresía para la Humedad**:** Representa los niveles difusos (Bajo, Normal y Alto) basados en los valores de humedad del sensor. Esto ayuda a entender cómo se interpretan los datos para sistemas difusos

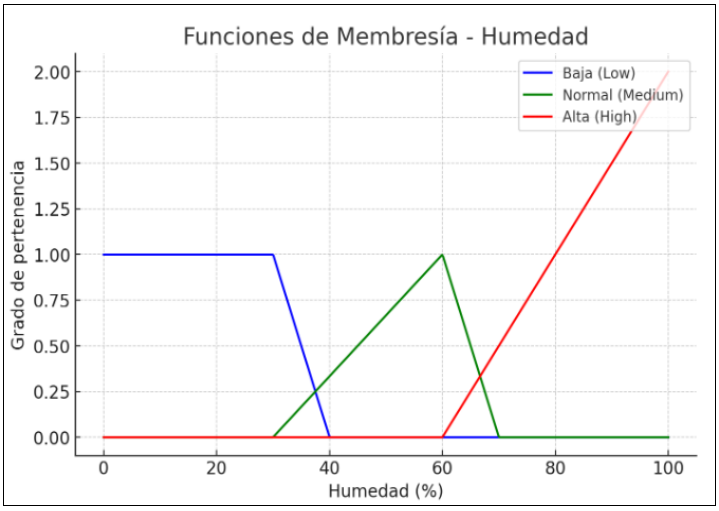

Fig 1: Membership Functions for Humidity

Now let's look at the Simulation Results vs. Edge Computing graphs for the environmental control, irrigation and gas systems.

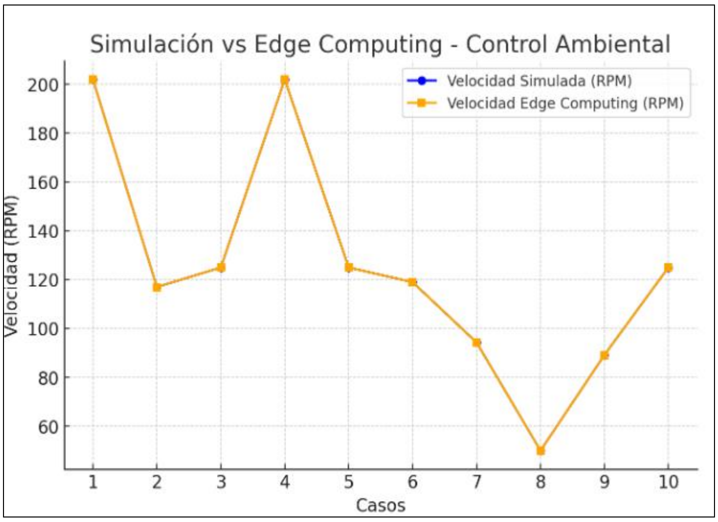

Fig 2: Simulation Results vs. Edge Computing - Environmental Control

Simulation vs. Edge Computing Comparison (Environmental Control): Shows that the simulated and edge layer results are consistent, validating the implemented models.

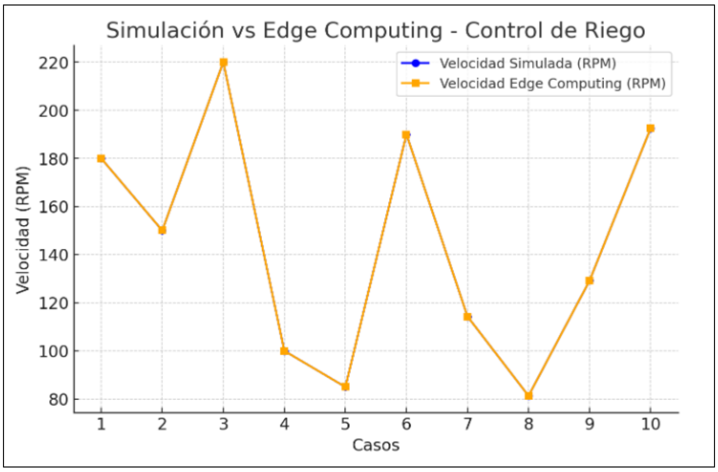

Fig 3: Simulation Results vs. Edge Computing - Irrigation Control

Irrigation Control: Comparison between simulated speed and edge computing speed
Simulation vs. Edge Computing- Irrigation Control: Comparison of the speeds generated by the fuzzy system in simulation and edge computing, based on soil moisture.

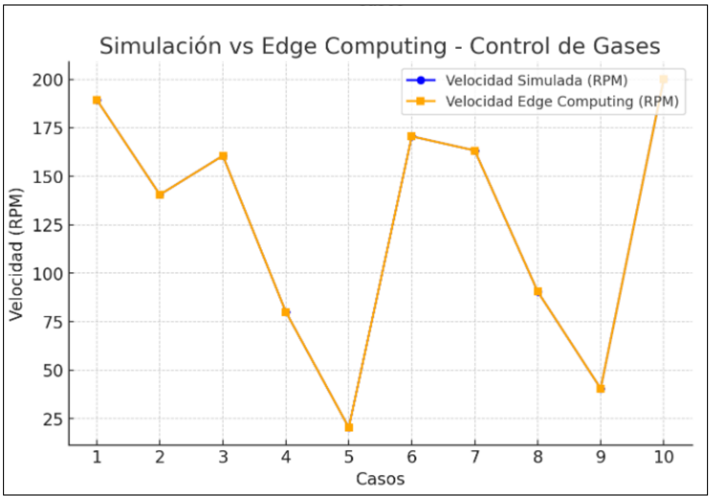

Fig 4: Simulation Results vs. Edge Computing - Gas Control

Simulation vs. Edge Computing - Gas Control: Shows the consistency in the results when managing gas concentration.

Flowcharts of the implementation method and logical connection

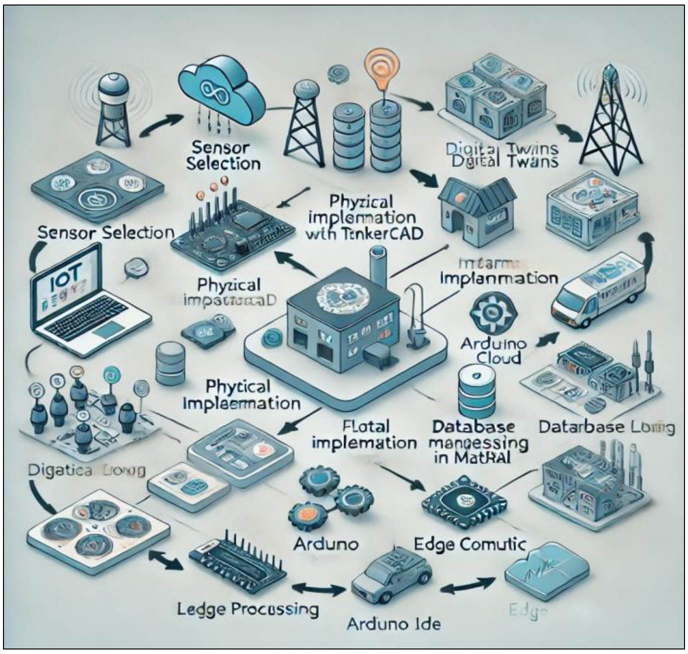

Fig 5: Complete Process: From Sensor Selection to the Implementation of Mathematical Models with Fuzzy Logic

Fig 5 shows the generated flow diagram that illustrates the complete process, from the selection of sensors to the implementation of mathematical models using fuzzy logic.
To detail the most important stages, we can focus the adjustments on the following key points of the flowchart:

1. Sensor selection and implementation
Detail the sensors used (e.g. DHT22, DHT11, etc.) and their measured variables (temperature, humidity, etc.).
Include calibration decisions based on datasheets.

2. Simulation with digital twins
Highlight the platforms used such as Wokwi, Tinkercad, and Proteus.
Indicate how the configurations are validated and adjusted before physical implementation.

3. Cloud storage and local processing
Differentiate between storage in Arduino Cloud and database management in HeidiSQL.
Show how these platforms connect to the local server (PHP, HTML, JavaScript).

4. Mathematical models and fuzzy systems
Include membership functions, inference rules, and simulations in MATLAB.
Mention the implementation in edge computing with Arduino IDE.

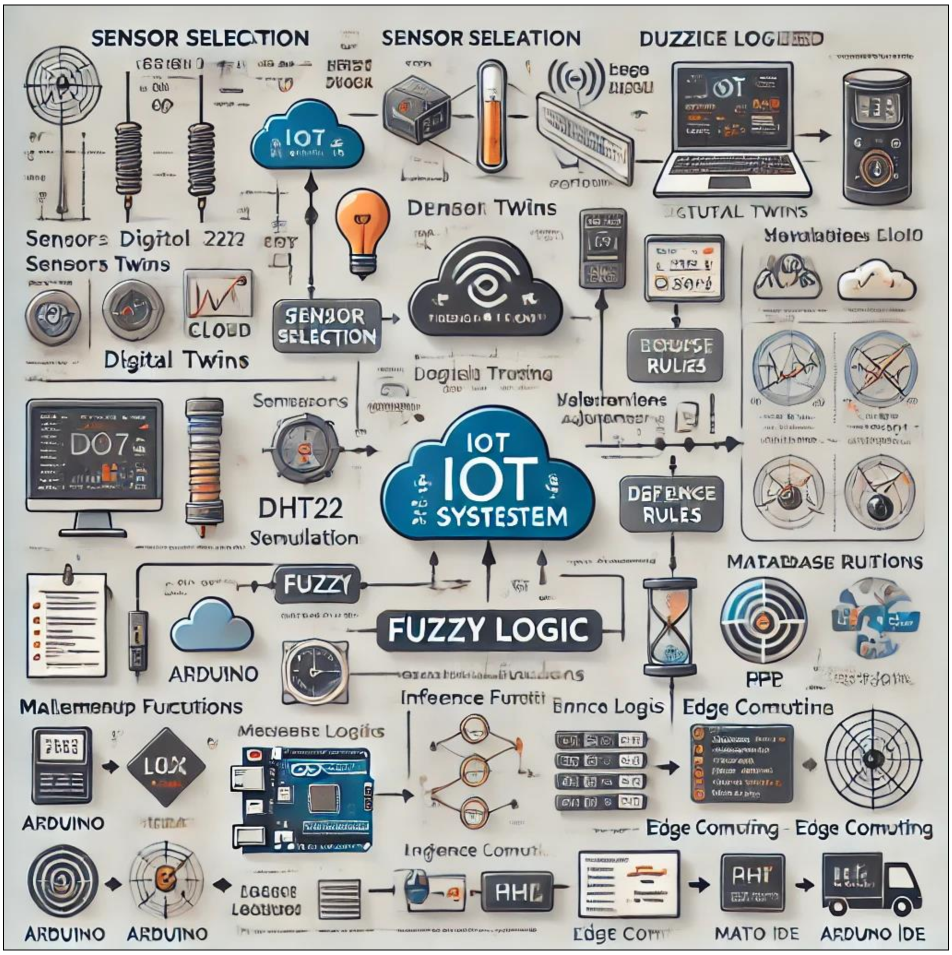

Fig 6: Integrated Implementation Process for IoT Sensors and Fuzzy Models

Here is the adjusted flowchart that emphasizes the most important stages of the project, such as sensor selection, simulation with digital twins, cloud storage, and mathematical modeling with fuzzy logic.

Conclusions

1. Fuzzy logic is an efficient tool to manage uncertainty in data captured by IoT sensors, especially in environments with high variability (Zadeh, 1965) [1].
2. The proposed mathematical models are effective in both simulation and physical implementation, validating their applicability in real situations (Klir & Yuan, 1995).
3. Edge computing allows practical implementations without the need for expensive additional devices, facilitating the adoption of this technology in various sectors (Dipali *et al*., 2023) [4].
4. It is recommended to expand research to critical areas such as medicine or transportation, incorporating neuro-fuzzy systems to achieve greater autonomy and adaptive learning (Tabatabaei, 2023) [5]

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