Available online at www.ijournalse.org

Emerging Science Journal

(ISSN: 2610-9182)

Vol. 9, No. 1, February, 2025

Mechatronic System Based on Bluetooth Communication with a Mobile Application for Automatic Irrigation in Greenhouses

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Abstract

Non-automatic irrigation in greenhouses presents significant disadvantages, such as waste of water and loss of time, although they are highly widespread and low cost. Research highlights the importance of rationally managing and using water through information technologies to improve crop quality, recommending the use of automated irrigation systems, although challenges are faced in the proper integration of electronic devices in agricultural environments. For this reason, it is considered that the use of drip irrigation, the integration of embedded systems with Bluetooth connection, and mobile applications facilitates its use. This paper describes the design and implementation of a prototype mechatronic system to manage greenhouse irrigation, using an embedded system based on a microcontroller. In this case, temperature and humidity sensors are used that control a water pump, monitor environmental factors, and display data in the mobile application connected via Bluetooth, activating the water pump automatically. The results show that the prototype is functional, meets the stated objectives, and proposes improvements related to the range of Bluetooth communication and the implementation of a solar panel for use in areas without electricity supply.

Keywords:

Automatic Irrigation;
Greenhouses;
Mobile App; Bluetooth;
Microcontroller;
Drip Irrigation.

Article History:

Received:	15	July	2024
Revised:	12	October	2024
Accepted:	04	December	2024
Published:	01	February	2025

1- Introduction

Non-automatic irrigation of greenhouses is common worldwide due to its low cost and easy implementation. This implies that people carry out irrigation activities manually and at inappropriate times that directly affect the growth of crops [1, 2]. In underdeveloped countries and with low technological integration in agriculture, manual irrigation is used in almost all crop areas without optimizing the use of water, generating loss of time during the irrigation process and inaccuracies in the irrigation of the plantation [3]. In this way, it is necessary to use automatic irrigation, which generates advantages such as efficiency in water distribution, saving people's time, and preventing plant drought by staying constantly hydrated [4, 5]. Furthermore, in non-automatic irrigation processes, rational use of water is not made, and people are unaware of the appropriate time to irrigate a certain crop. On the other hand, the installation of an automatic irrigation system in home greenhouses is necessary because of the benefit it would provide to people and small farmers by optimizing resources and improving crops [6, 7].

Despite advances in automated irrigation technologies and their advantage over traditional irrigation in terms of efficient use of water resources, the literature presents several research gaps related to the fact that although automated irrigation has been found to offer benefits, there is no clear consensus on which specific technologies maximize water efficiency in different agricultural contexts, limiting their general applicability [8, 9]. For example, drip irrigation has been documented to be highly efficient in minimal water use, particularly in greenhouses, but there is a lack of studies

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DOI: http://dx.doi.org/10.28991/ESJ-2025-09-01-02

evaluating its performance in open fields with significant environmental variability or comparing its effectiveness with other irrigation methods such as sprinkler or gravity irrigation under similar conditions [10-12].

Another gap in the literature is the integration of information technology into automated irrigation systems, which have the potential to improve water management, but research is limited on how these systems can be adapted to different crop types and environments [13, 14]. Furthermore, there is a lack of studies exploring how IT-based automated irrigation solutions can be scalable for different farming operations or dynamically adjust to external factors such as climate variations or soil quality. On the other hand, although some research has pointed out the economic benefits of drip irrigation in greenhouses, there is a lack of economic analyses comparing the costs and benefits of its implementation in other crop types or larger plots [15, 16].

Other aspects not investigated in the papers deal with the development of prototypes based on devices such as the Raspberry Pi and the TIGO development board to capture and process temperature and humidity data. In these cases, an evaluation of devices with hardware limitations and the evaluation of their behavior and the useful life of the electronic components is still lacking [17-20]. Another area that lacks study is the integration of mobile or web applications for remote monitoring [21, 22]. Likewise, wireless technologies such as Bluetooth, although widely used in these systems, have not been systematically compared with other more robust communication options, such as LoRa or ZigBee, in terms of scalability and coverage in large greenhouse environments [23, 24].

Regarding the drip irrigation method, this has been identified as the most efficient and economical [25, 26], and there are still studies that analyze its performance in different types of crops and climatic conditions [27, 28]. Most studies have focused on crops under controlled conditions, but how it adapts to crops that require different levels of humidity or in areas with more extreme climates has not been investigated [29, 30]. Although the potential of integrating advanced sensors with Internet of Things (IoT) technologies to automate irrigation accurately and in real time is recognized, the literature reviewed does not address the review of standard protocols to ensure interoperability between devices from different manufacturers [31, 32].

Therefore, the following question arises: How can the irrigation of home greenhouses be managed by using a mobile application on a smartphone? Therefore, this study focuses on the design and implementation of a mechatronic system that manages the irrigation of domestic greenhouses through a mobile application via Bluetooth, differentiating itself from existing literature by specifically addressing small-scale urban gardening environments and how technologies available in consumer electronics can be used to contribute to the improvement of crop care processes. The main objectives are to develop an intuitive application for real-time irrigation control and to evaluate the integration of low-cost electronic components and sensors in the prototype for the optimization of water use.

The motivation for this paper arises from the need to generate automated solutions for monitoring and control in greenhouse contexts. Therefore, the integration of low-cost digital transformation technologies is sought based on compliance with the design, development, and evaluation objectives of the prototype of a mechatronic system. The article is structured in the following way: the introduction; section 2 of materials and methods, where the methodology is described; section 3, which presents the results; section 4, focused on the discussion; and, finally, the conclusions.

2- Material and Methods

The research is based on theoretical approaches related to mechatronic technology and system automation. In this case, the mechatronic stage is manifested in the design and implementation of the system, where temperature and humidity sensors provide data that allow the automatic activation of the water pump. In addition, the phased design approach (which includes electronic circuit analysis, irrigation algorithms, and application development, whose theoretical approach) provides a flexible environment for the creation of automated solutions in urban agriculture.

The developed system allows managing the irrigation of homemade greenhouses according to the values of the detected temperature and humidity sensors. This management is based on the control of a water pump, monitoring of environmental factors, and visualization of this data in a mobile application (connected via Bluetooth to the PIC 18F4550 microcontroller) and on an LCD screen with 16 characters in 2 rows. With respect to electronics, the sensors located in the home greenhouse capture the variables of ambient temperature and soil humidity. After that, electrical signals are sent to the microcontroller, which is responsible for processing them in integer format, storing them in its memory, and evaluating the activation of the water pump. Finally, the water pump of the homemade greenhouse is activated if the ambient temperature exceeds 29°C and if the soil humidity exceeds 70% (Figure 1).

Regarding the development of the mechatronic system and the mobile application, four phases are considered. Firstly, in the design phase, the analysis of the electronic circuit, the irrigation algorithm, and the design of the mobile application, as well as the design of the mechanical structure, are considered. Then, in the development phase, the circuit is implemented on a Bakelite plate along with the mechanical structure made with wooden slats and the mobile application. Later, in the evaluation phase, these elements are integrated, both electronically and mechanically, and the operation of the mechatronic system and mobile application is verified, considering the desired water pump activation parameters (Figure 2).

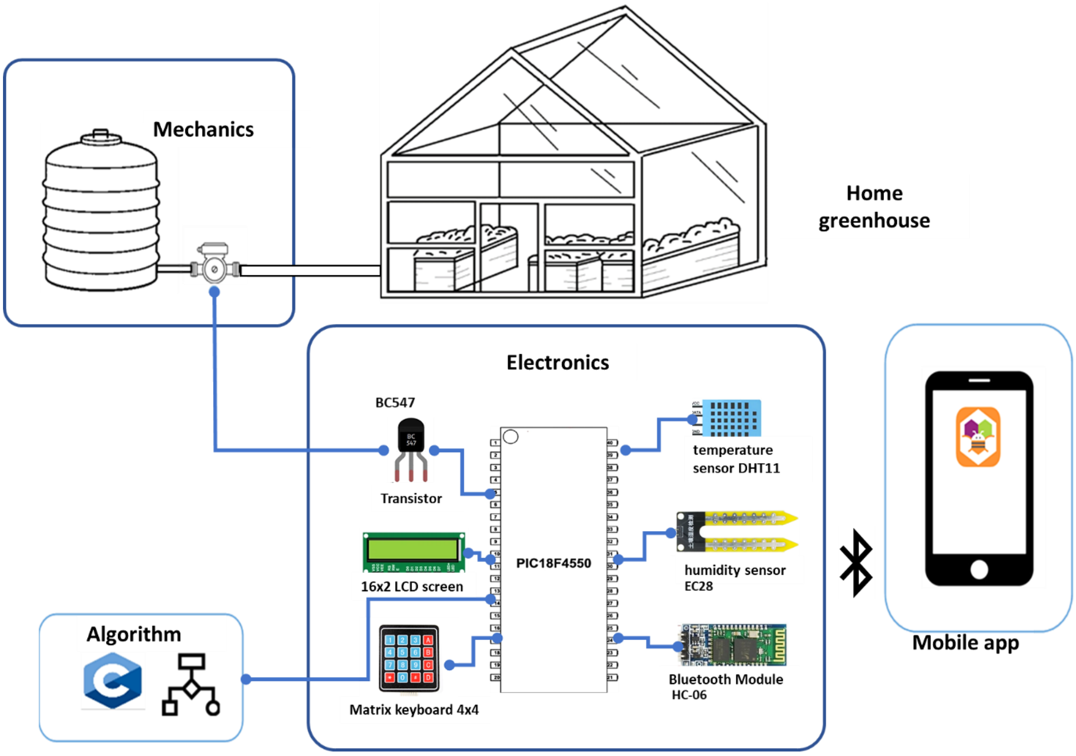


Figure 1. **General Scheme of the Mechatronic System for Automatic Irrigation Control**

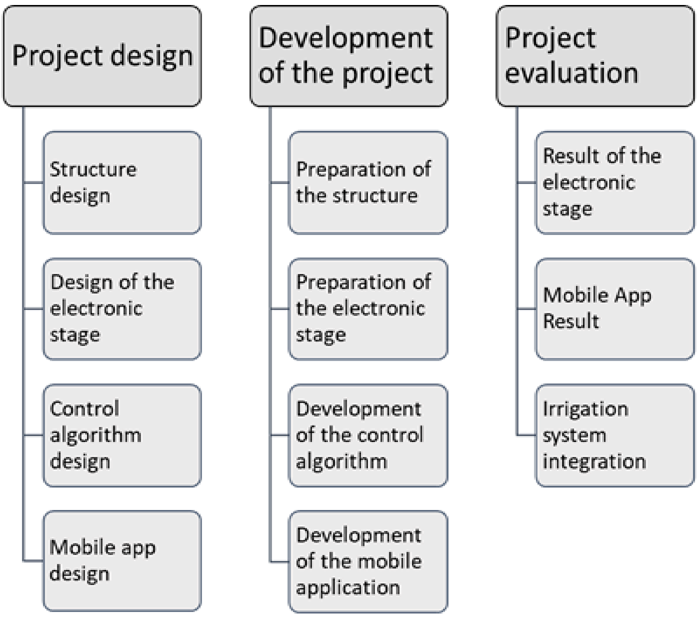


Figure 2. **Phases of the Design of the Mechatronic System for Automatic Irrigation in Greenhouses**

The operation of the prototype begins with the ignition of the electronic circuit, where the temperature and humidity sensors capture the data. Then, the mobile application is opened, and pairing is made with the HC-06 Bluetooth module.

Once connected, the temperature and humidity values are displayed. After that, to manage the water pump, if the temperature exceeds the desired value (default 29°C) and the humidity exceeds the configured value (default 70%), the pump turns on automatically. Likewise, if you enter manual mode, you can configure the desired temperature and humidity value with which you want to activate the pump (Figure 3).

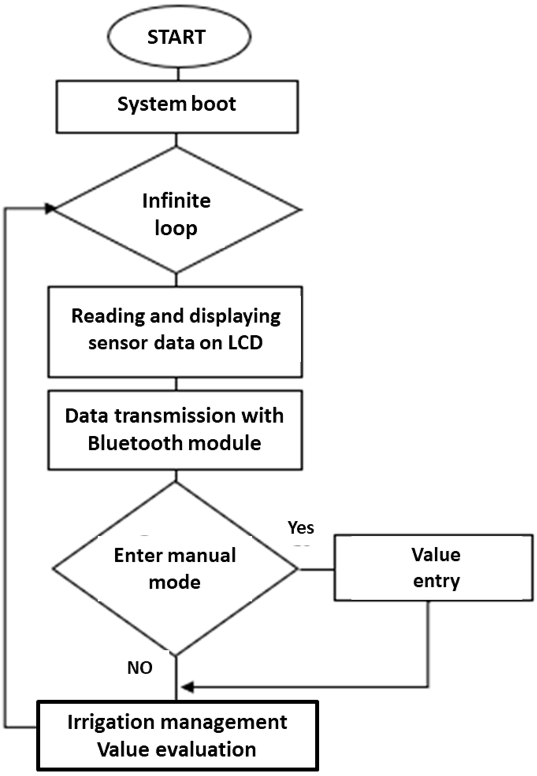


Figure 3. General Block Diagram of the System considering Sensors, Actuators, Microcontroller

2-1- Electronic Stage

The fundamental components include a microcontroller, storage memory, control software and algorithm, and input and output devices. In addition, for the electronic design, the digital and analog inputs used for the sensors, the matrix keyboard, the LCD screen, the Bluetooth module, and the water pump are determined (Figure 4).

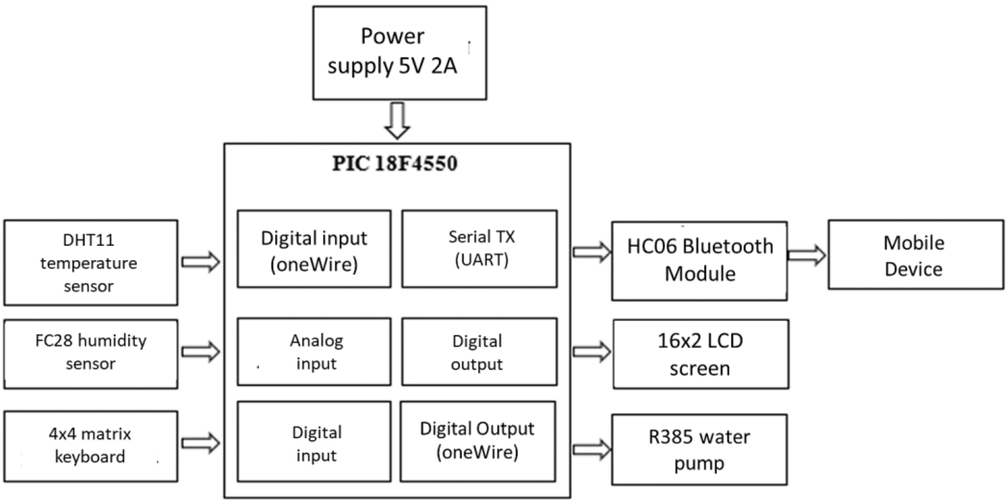


Figure 4. Block Diagram of the Electronic Stage of the Automatic Irrigation System

The stages to carry out the electronics design are:

a) Selection of the control unit. The control device is low cost, easy to transport and install, with analog and digital input/output ports. The PLC was discarded due to its high cost and complex applications, and the 16F28A microcontroller due to its low number of ports. Finally, the PIC18F4550A is chosen for its low cost, easy transportation and installation, extensive documentation, and several input and output ports.

b) Identification of inputs and outputs. The PIC microcontroller is responsible for reading the temperature and humidity, controlling the LCD screen, and sending data via Bluetooth to a mobile device. Furthermore, when the evaluation conditions with the sensor data are met, the water pump is activated. The GPIO pins are used to control a keyboard for access validation and manual control. In the case of PORTA, this is configured as input (humidity sensor, data logging indicator LED, manual/automatic control); PORTB is for the matrix keyboard, PORTC for the temperature sensor and data transmission, and PORTD is for output (LCD screen control, water pump).

c) Circuit design in PROTEUS. Figure 5 shows the electronic diagram, where the PIC18F4550A microcontroller uses the clock frequency of 20 MHz. The DHT11 temperature sensor is used, connected to a pin on port C. For initial validation of the simulation operation, it is considered that the humidity sensor is represented by a 1KΩ potentiometer connected to an analog input. The control of the water pump is based on automatically evaluating the temperature and humidity values programmed in the microcontroller, without direct user intervention (Figure 5).

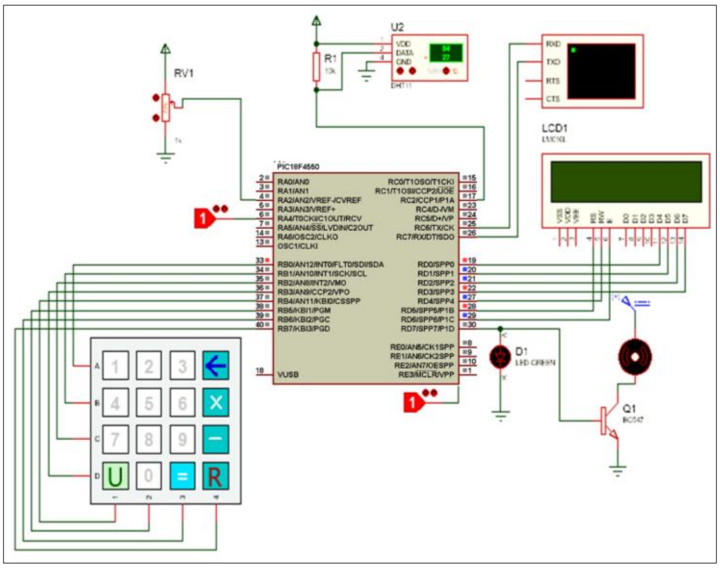


Figure 5. **Design and simulation of the electronic circuit in PROTEUS**

To build the circuit, the PROTEUS PCB designer is used and then the Bakelite board is built to integrate the components, including the microcontroller. The design of the PCB was carried out considering the size of the structure, the number of layers (1), width of the specific tracks for voltage supply and data transmission. In addition, points are displayed to solder the terminal blocks that belong to the PIC, matrix keyboard, power supply input, voltage regulator, Bluetooth module, LCD screen, sensors, etc. (Figure 6).

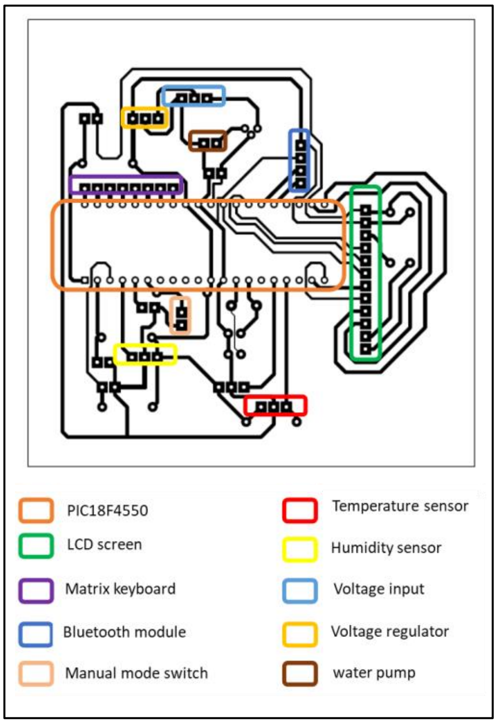


Figure 6. **Layout of Electronic Elements on the PCB for the Automatic Irrigation System**

Before construction, the PCB is observed in 3D to visualize and validate the location, size, and arrangement of the electronic components. This allows the protection structure used for the electronic card to be adequately defined (Figure 7).

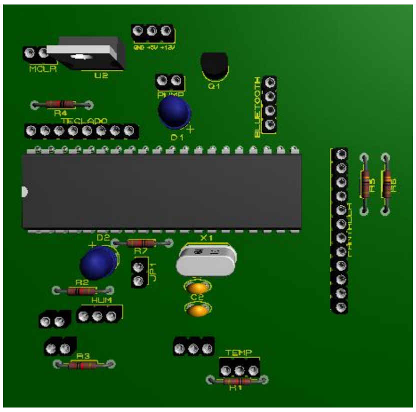


Figure 7. Three-dimensional representation of the printed circuit board with integration of sensors, actuators and Bluetooth communication module

2-2- Mobile Application

Figure 8 shows the conversion diagram of the acquired data to a text-type format that is displayed on an LCD screen, which is then transmitted through the serial output of the microcontroller. The serial port is connected to the Bluetooth module operating at a communication speed of 9600 bps.

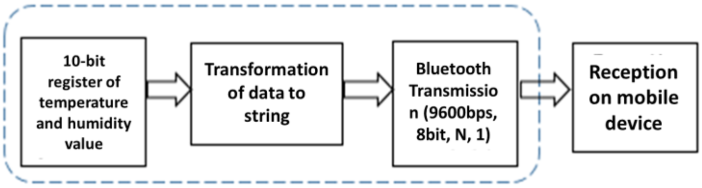


Figure 8. Design of the communication and mobile application stage

Figure 9 shows the flow chart of the mobile application. Its operation begins with the wireless connection process using the button called "connect with Bluetooth" to select the item that corresponds to the HC-06 module. The data received by the mobile application is displayed in the visual components related to temperature and humidity in text form without the need to perform data conversion.

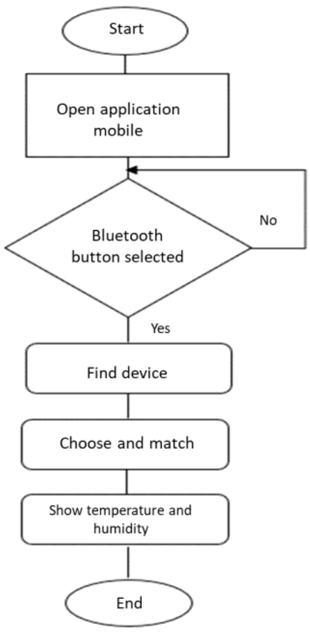


Figure 9. Interaction Sequence between the User, Bluetooth Communication and the Greenhouse Management System

Using MIT AppInventor, the programming of the mobile application is carried out considering that there is a connection button and sensor data display screens. A 500-millisecond timer is integrated, which is responsible for updating the data received from the microcontroller corresponding to temperature and humidity (Figure 10).

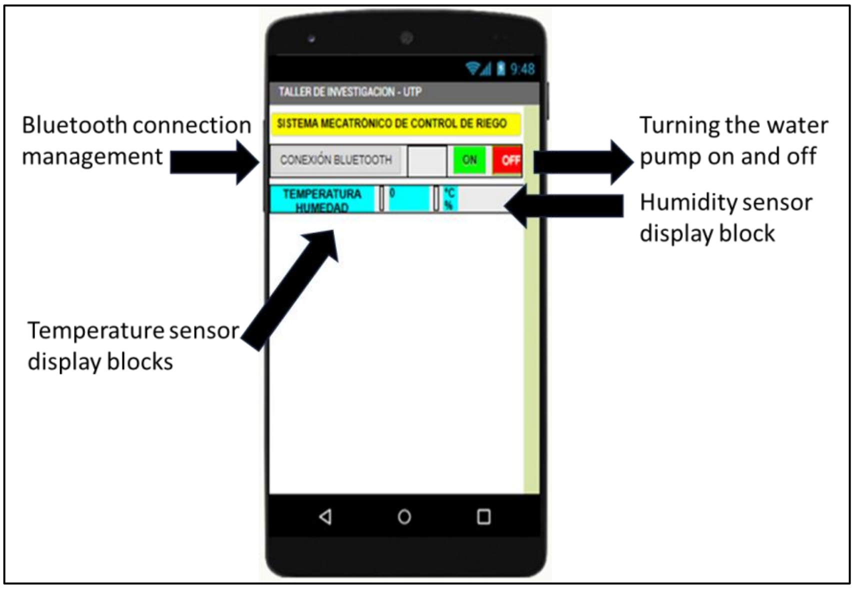


Figure 10. Main screen of the mobile application

2-3- Water Irrigation Management Algorithm

The irrigation management process is carried out in the microcontroller and is responsible for receiving data from the sensors and evaluating them with predetermined values to activate the water pump. The algorithm evaluates the set temperature value (default 29°C) and humidity (default 70%) and, using branching processes, activates the pump automatically. Likewise, if you enter manual mode, you can set the temperature and humidity value to activate the pump (Figure 11).

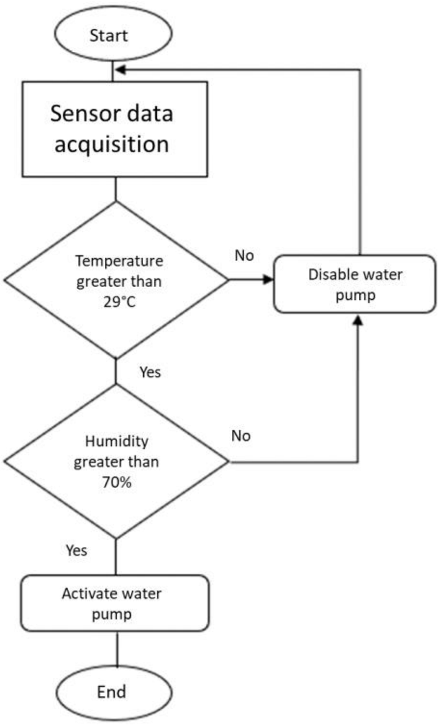


Figure 11. Irrigation Management Algorithm Design for Automatic System in Greenhouses

To develop the management algorithm, libraries are integrated into the microcontroller to control the sensors, the LCD screen, the keyboard, and the water pump. The XLC.C library is used to control the LCD screen, allowing you to organize ASCII characters, clear the screen, and position characters. Data transmission through the PIC serial terminal was handled with the UART library, which configures the baud rate and data type. The matrix keyboard was controlled with the KEYBOARD.C library, which receives binary data, determines the key pressed, and sends the value in string format.

2-4- Mechanical Structure

The structure is built using 39 × 89 mm wooden slats, with a base of 500 × 800 mm and a ceiling height of 800 mm. The greenhouse is divided into three sections for planting and irrigating crops (Figure 12).

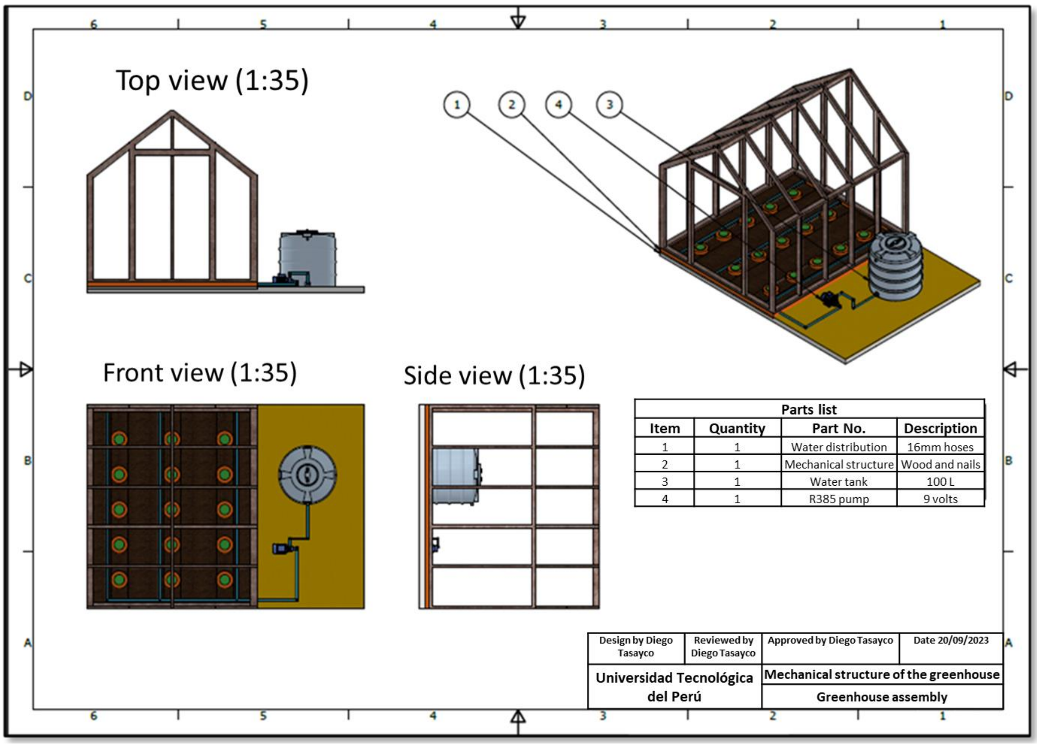


Figure 12. Structural design of the homemade greenhouse

Figure 13 shows the structure of the finished homemade greenhouse, where a plastic cover and the hoses installed internally are displayed.

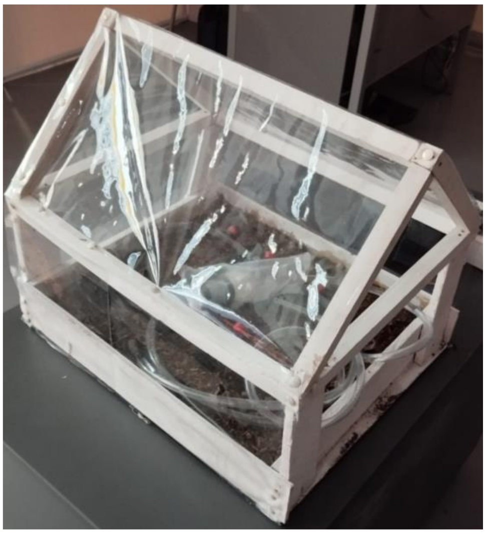
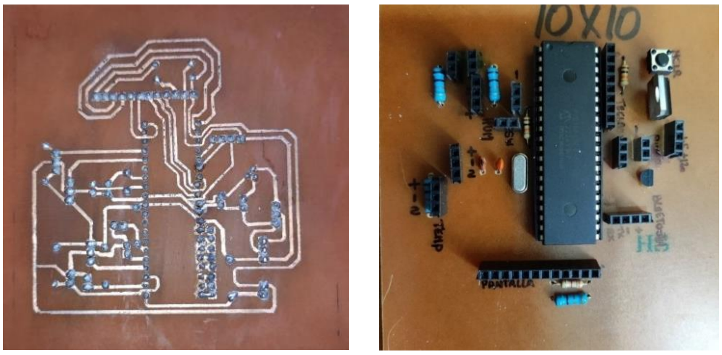


Figure 13. Greenhouse Prototype Structure with Integrated Components

3- Results

3-1- Result of the Electronic Stage

In Figure 14, the components installed in both the top (Figure 14-a) and bottom (Figure 14-b) of the Bakelite card are observed.



(a) (b)

Figure 14. Top (a) and bottom (b) view of the electronic card

Figure 15-a shows the project control box with the manual mode selector, LED indicators, a matrix keyboard, and the LCD screen. On the other hand, inside the components connected to the electronic card are shown, such as the 9V battery, the On/Off switch, and the voltage regulator.

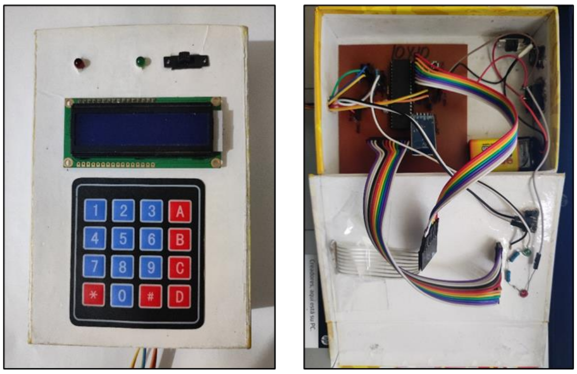


Figure 15. Exterior view (a) and interior view (b) of the electronic box

Figure 16 shows the data on the LCD screen related to the different states that the system may be running, such as initial activation, actual greenhouse temperature and humidity values. You can access manual mode, which requires password entry. The maximum temperature and humidity values are then requested to activate the pump.

Figure 16. Operation of the Electronic Circuit for the Automatic Irrigation System

3-2- Communication with Mobile Application

Access to the mobile application and its pairing with the HC-06 Bluetooth module connected to the microcontroller was carried out appropriately by observing the data in real time in the visual controls. (Figure 17).

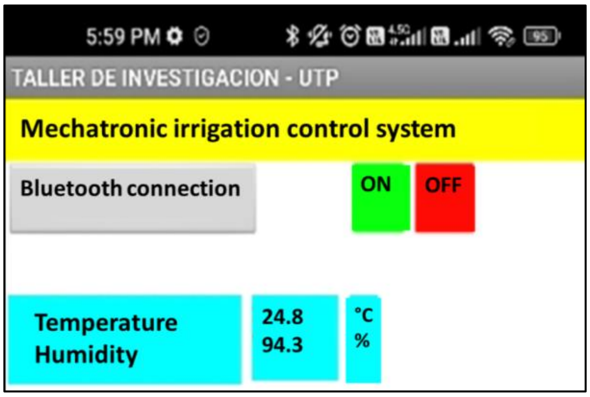


Figure 17. Communication between the Automatic Irrigation System and the Mobile Application

3-3- System Integration

Figure 18 shows the irrigation channels with their respective drippers. The water pumps are activated automatically depending on the values of soil humidity and ambient temperature.

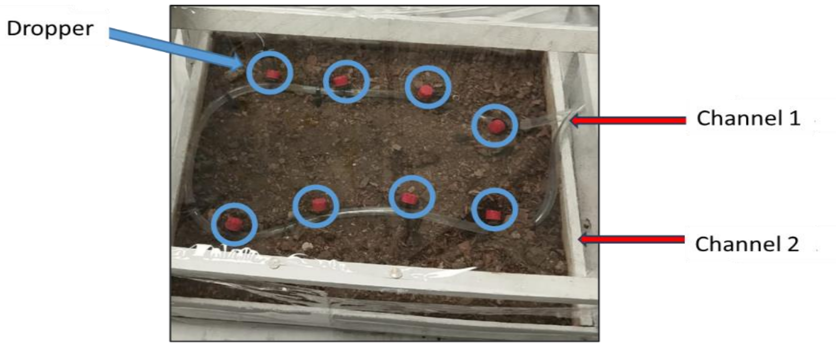


Figure 18. Location of Irrigation Channels in the Automated Irrigation System

The integration of all the components of the system was carried out to evaluate its operation in a laboratory environment, demonstrating the total functioning of the project and meeting the objectives set as it is a descriptive type of research (Figure 19).

Figure 19. Integrated Irrigation Management System with Components for Optimizing Water Control in Greenhouses

3-4- Discussion

The electronic cardboard worked properly and was built considering that the copper tracks can withstand currents close to tens of milliamps for data transmission. In the case of the mobile application, it acquired and displayed the values of the ambient temperature and soil humidity. These are recorded according to the format sent from the microcontroller, respecting the maximum communication distance range (10 meters) and displaying the information on the LCD screen.

The evaluation of the prototype was carried out in a laboratory environment, observing that the system responded accurately and efficiently to the conditions programmed for automatic irrigation, which validates the correct integration of the sensors, the microcontroller, and the interface of the user. The results to infer that the system is viable for application in real environments, providing an effective and low-cost solution for automated irrigation monitoring and control.

4- Conclusion

The prototype of a mechatronic system was implemented and deployed, performing automatic irrigation management through Bluetooth communication. The mobile application allowed intuitive real-time control, aligning with the goal of improving crop care in small-scale urban gardening environments. This system differs from other studies by integrating consumer electronics technologies to optimize water use.

In the case of the Mobile Application, algorithms based on event-oriented flowcharts were designed, which facilitated the programming of both the microcontroller and the mobile application. These diagrams allowed the creation of the APK, which was installed and tested on a smartphone, complying with the intuitive control specification. Additionally, low-cost electronics integrated into the prototype demonstrated functionality, accurately monitoring key parameters and validating readings with local instruments. Furthermore, the system automatically activated the water pump, optimizing water use according to the measured values.

The prototype met the stated objectives, proving to be functional, the measurement of the monitored parameters being accurate, validating its reading by other local instruments. It is recommended to use a Bluetooth module with a range greater than 10 meters to improve communication with the mechatronic prototype in environments that have objects that may interfere. In addition, it is suggested to implement a power stage with a light-tracking solar panel for use in agricultural spaces without electricity supply.

Future research could focus on optimizing energy consumption and expanding the system's functionalities to improve its adaptability to different growing conditions, considering connectivity with remote services on the Internet.

5- Declarations

5-1- Author Contributions

Conceptualization, R.Y., J.T., and A.V.; methodology, R.Y.; software, J.T. and A.V.; validation, R.Y., J.T., and A.V.; formal analysis, R.Y.; investigation, R.R., J.T., and A.V. ; resources, J.T. and A.V.; data curation, R.Y.; writing—original draft preparation, R.Y.; writing—review and editing, R.Y., J.T., and A.V.; visualization, R.Y.; supervision, R.Y.; project administration, R.Y., J.T., and A.V.; funding acquisition, R.Y. All authors have read and agreed to the published version of the manuscript.

5-2- Data Availability Statement

Data sharing is not applicable to this article.

5-3- Funding

The author received no financial support for the research, authorship, and/or publication of this article.

5-4- Institutional Review Board Statement

Not applicable.

5-5- Informed Consent Statement

Not applicable.

5-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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