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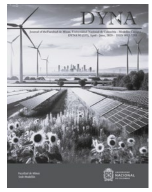

UNIVERSIDAD NACIONAL DE COLOMBIA

Development of a water level monitoring and control system for pumping stations in agricultural systems

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Abstract
Monitoring water levels in reservoirs and suction pipes is essential to avoid failures in pumping and agricultural systems. This study aimed to develop an intelligent system for automated monitoring of water levels in irrigated agricultural reservoirs, ensuring safer operation of pumping stations and aiding decision-making. The system enables visualization, water level management, and protection of motor pumps. After assembly and programming, the prototype was installed in a reservoir. Tests showed a difference of less than 5 mm between manual and system measurements. Google Sheets was used for accurate data analysis. The control system includes a contactor, thermal relay, bipolar circuit breaker, simple control relay (activated by the ESP32), and two buttons — one normally closed and one normally open. The proposed intelligent system proved effective for automated water level management in reservoirs.

Keywords: agriculture; water management; limnigraph; ultrasonic sensor.

Desarrollo de un sistema de monitoreo y control del nivel de agua para estaciones de bombeo en sistemas agrícolas

Resumen
El monitoreo de los niveles de agua en los reservorios y tuberías de succión es esencial para evitar fallos en los sistemas de bombeo y en los sistemas agrícolas. Este estudio tuvo como objetivo desarrollar un sistema inteligente para el monitoreo automatizado de los niveles de agua en reservorios de riego agrícola, garantizando un funcionamiento más seguro de las estaciones de bombeo y apoyando la toma de decisiones. El sistema permite la visualización, gestión del nivel de agua y protección de las motobombas. Tras el montaje y la programación, el prototipo fue instalado en un reservorio. Las pruebas mostraron una diferencia de menos de 5 mm entre la medición manual y la realizada por el sistema. Se utilizó Google Sheets para el análisis preciso de los datos. El sistema de control incluye un contactor, relé térmico, disyuntor bipolar, relé de control simple (activado por el ESP32) y dos botones, uno normalmente cerrado y otro normalmente abierto. El sistema propuesto demostró ser eficaz para la gestión automatizada del nivel de agua en reservorios.

Palabras clave: agricultura; gestión del agua; limnígrafo; sensor ultrasónico.

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1. Introduction

The use of technology is currently necessary to assist in the management of natural resources, as well as to support decision-making in agricultural systems. Scientific research applied to agriculture generally requires the use of devices to measure and collect data, which often implies significant costs for project development. However, when technology is developed in a more simplified way, it becomes an ally to the producer, providing greater efficiency and economy.

Although there is no universally accepted definition of what "low-cost" instrumentation is, it refers to any type of sensor, data collector, and data storage device that costs less than conventional instrumentation [1]. The construction of a data logger-sensor set develops skills and competencies that enhance creativity and facilitate the understanding of physical principles and their interactions with the studied phenomena [2–4].

The application of instrumentation for process automation in agricultural systems with more readily available and easy-to-handle components can potentially revolutionize the field of agricultural instrumentation and environmental monitoring, providing high-density spatial-temporal data [5], helping in processes such as the measurement of environmental variables [6], or in the monitoring of soil moisture [7,8], among others [9–13].

Farming systems can be automated using the Internet of Things (IoT), allowing tasks like water distribution verification via irrigation channels and alert systems for low levels [14]. However, implementing these intelligent systems requires qualified technicians for installation, operation, and maintenance [15].

To have an IoT, connected intelligent objects are necessary, where the 'objects' (things) must be designed with embedded hardware, and the term 'intelligent' in turn requires software programming with instructions for the hardware, to provide intelligence to the objects; finally, 'connected', using communication architectures and models to interact with other objects through the internet. For example, [16] proposed an IoT system for monitoring and controlling irrigated systems and found that this system reduced human intervention and wasted water and energy. [17] stated that IoT uses the principles of precision agriculture and can be used to manage water resources in agricultural systems, such as irrigation management and monitoring the water level of reservoirs in real time.

It is crucial to highlight that the availability of water in irrigation projects represents one of the main challenges faced in a pumping system, especially in irrigated areas that do not have a security system in case of water scarcity. In this context, the monitoring system has the purpose of solving this issue, in addition to providing data for more effective planning of water availability and the implementation of low-level alert systems [18]. The monitoring system is one of the main tools, with its real-time control and data generation that enable more efficient analysis and operation [19].

Monitoring the water level in suction pipes is very important to avoid the occurrence of undesirable phenomena in the pumping system. Nowadays, intelligent water supply systems in irrigation projects, especially with long channel lengths, are necessary, as their use can bring numerous advantages for farmers, if they are well implemented [20]. In this sense, the aim of this study was to develop an intelligent system for automated monitoring of water levels in reservoirs within irrigated agricultural systems, to ensure safe operating conditions in pumping stations and support decision-making by managers.

2. Methodology

2.1 Study area

The work was developed to meet the demands of rural producers in the Irrigated Perimeter of the Formoso Project, located in the municipality of Bom Jesus da Lapa, Bahia, Brazil. The perimeter is managed by the Formoso Irrigation District, which performs operation and maintenance of the common and collective structures of the irrigated area. In this case, the District is responsible for the abstraction, diversion, pumping, adduction and distribution of water to the fields.

The Formoso Irrigation Perimeter has a total area of 19,500 hectares, with 12,100 hectares of irrigable area. This area was implemented by the Federal Government, through Codevasf, on the banks of the Corrente River, in the region of the municipality of Bom Jesus da Lapa, with the goal of promoting agricultural and livestock development in the region [21].

2.2 System design

The methodological procedure for the development of the system is divided into several stages, from the conception of the project to the collection and analysis of the obtained data. The procedure follows a simple flowchart of task execution, but each stage is important to ensure the successful observation of the data at the end of the study. Fig. 1 shows the flowchart that outlines the methodological sequence of tasks, using an adaptation of the methodology proposed by [15].

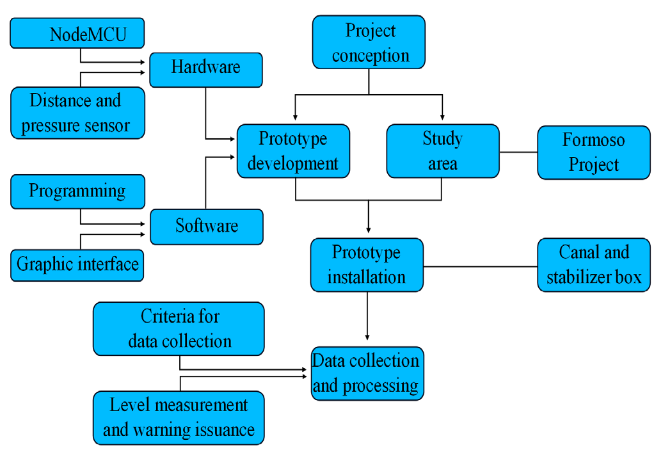

Figure 1. Project design flowchart.
Source: Adapted from [15].

The water level monitoring system in channels and safety conditions in pumping stations is designed to visualize and manage available water depth while protecting pumps. This system is particularly useful in locations where managing water levels and detecting failures is challenging.

With an intelligent meter, this monitoring work can allow automation with a simple, relatively low-cost system. This makes it possible, through the prototype, to have quick decision-making regarding how to manage the available resources, or even to automate the decision-making process by integrating the meter with some type of intelligent management system. The system is composed of the water storage unit where the ultrasonic sensor and the processing unit will be placed, a web server that will store the data, internet and a cell phone that will receive the measured data through a spreadsheet. The prototype is composed of two main devices: the ESP32 and the ultra-sonic sensor.

2.3 Prototype development

To develop the prototype of the water level monitoring system in channels and safety in pumping stations, it will be necessary to divide the stage into two parts: hardware and software.

The hardware part comprises the physical components of the prototype, which are: the ESP32 board, ultrasonic distance sensor, set of indicator LEDs, relay and magnetic switch, in addition to some other peripheral components, with a power supply, cables and others, which help in visualizing some information at the time of installation. The methodology suggested by [15] and [22] was used. The adaptation presented were simplicity in design, assembly, and management, transmission to the internet via Google Sheets, ultrasonic sensor calibration, and control system.The ESP32 (Fig. 2a) is a prototyping board that has integrated WIFI, capable of receiving information from external sensors, through analog and digital ports, and processing this data according to the user's needs. To read the data, an ultrasonic sensor, model JSN-SR04T (Fig. 2b), was used.

The software is the logical part of the prototype, and through it the information is received, processed and stored. Through the software, it will be possible to develop projects, from the simplest to the most complex, as long as the user has sufficient knowledge in programming in the language used by the ESP32. This programming is developed within the Arduino IDE environment, which is the environment of the Arduino platform, another line of prototyping boards, but which integrates the ESP32.

As one of the most widespread prototyping boards in the world, Arduino has a more user-friendly environment for the programmer, with more updates and ease, especially in the programming language, which is compatible with the ESP boards, which is why its IDE was used to develop the project.

The data obtained by the prototype needs to be remotely accessible, for this the Adafruit website is used, which provides an IoT (Internet of Things) Cloud Service platform for users to send and store the data obtained in projects.

For this project, the water depth in the reservoirs and the occurrences of water shortage activation were sent. Adafruit IO allows up to 30 data points to be sent per minute to the site, but for this project it will not be necessary to make so many readings. The received data is organized into a table in Google Sheets, with the date and time of receipt.

2.4 Prototype installation

After completing the prototype assembly and programming stages, it was in-stalled in a reservoir. For this, the board was placed inside a container, to avoid humidity, as well as the sensor, which is pointed in the direction of the water depth.

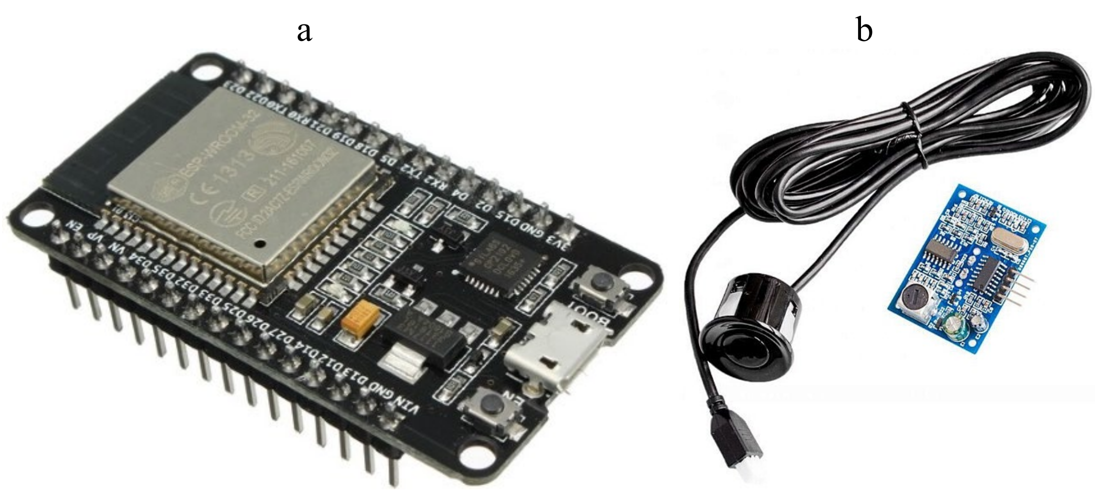

Figure 2. NodeMCU prototyping board (a) and ultrasonic sensor (b).
Source: https://bit.ly/3UUqeXn (a) and http://bit.ly/4be4coo (b).

The installation of the prototype was fixed by a support, positioned at the top of the reservoir to facilitate the installation. For the installation, a power outlet was necessary, so that the ESP32 is connected to the power through the 5V power supply, and a nearby WiFi point, so that the board can connect to the internet and send the obtained data.

2.1 Data collection and processing

Since it is a device in a development system, the prototype may present some in-accuracies in the readings, so it is necessary to process the collected data through software. The distances obtained by the system will be verified and analyzed through correlation verification with the data obtained from manual measurements. These values may come from a reading failure by the sensor or something that has crossed in front of the sensor.

After the data has been processed, the information on the water level and the water shortage alert system will be sent to the Adafruit IO cloud, where graphs and a de-tailed history of water storage in the channel will be generated.

2.2 Sensor validation

In general, measurement systems are considered acceptable when they have a dispersion error of less than 10%. Based on this information, samples of the proposed system were collected to evaluate its reliability and acceptance. Three composite samples of twelve points at known distances were collected and after collecting the data, the calculations of mean and standard deviation of the system were employed. In each sample, it was defined that the reservoir started with a water depth that was 0.22 m away from the sensor. With the operation of the pump, the depth increased the distance from the sensors and these values were measured with the aid of a metal limnimeter scale.

The data obtained by the system and manually were compared through standard regression analysis with the Correlation Coefficient (r) and Determination (r^2), where:

$$r = \frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}} \quad (1)$$

where, n is the number of observations, P_i refers to the values of the distance variable obtained in the ultrasonic sensor database, $\bar{P}$ is the average of the values of the distance variable obtained in the ultrasonic sensor database, O_i to the observed data through the distance obtained with a tape measure and $\bar{O}$ is the average of the observed data through the distance obtained with a scale.

3. Results and Discussion

3.1 System assembly

The system has great simplicity in design, assembly, and management, in addition to the benefits provided by the intelligent meter, such as the possibility of remotely observing the water volume of the reservoir, with the possibility of issuing alerts for low water levels, turning off the pumping system in critical conditions, and future expansions of data processing just by modifying the programming. The diagram of the system can be observed in Fig. 3. The proposed system is economical, saves energy, and assists in the water's environmental cycle. The system used a microcontroller, Arduino (ESP32), to semi-automate the water pumping process in a reservoir, with the ability to detect the low water level in the reservoir, and thus turn off the pump, display the status on a set of indicator LEDs, and only allow reactivation again with the presence of a person to press the reset button for the protection of the pumping unit.

The assembled circuit is shown in Fig. 4, the main components are the ESP32, the "brain" of the prototype, and the Ultrasonic Sensor, in addition to the LEDs, re-sponsible for assisting in the on-site visualization of the water level obtained by the sensor and processed by the ESP32.

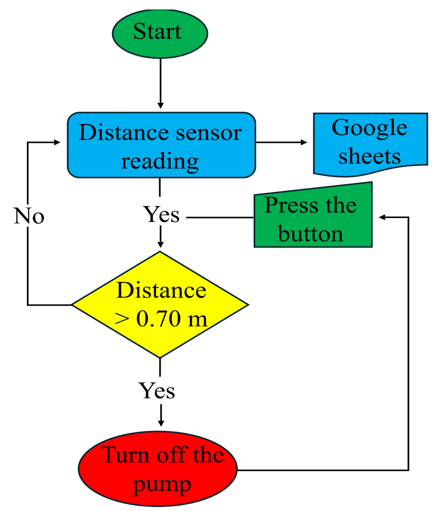

Figure 3. Diagram of the Proposed System.
Source: The Authors.

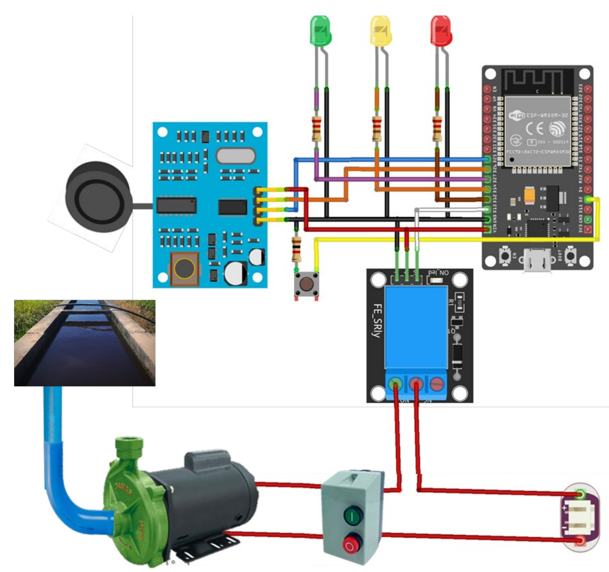

Figure 4. Diagram of component connections.
Source: The Authors.

The Trig pin (receives an electrical pulse and sends a sound pulse) of the JSN-SR04T sensor is connected to the D0 digital port of the ESP32, the Echo pin (re-ceives the return of the sound pulse and sends the data with the time the pulse took to return to the sensor) is connected to the D2 digital port, the sensor is also connected to the 5-volt power supply of the board and to the GND (ground) pin. If the level inside the reservoir is low, a beep sound is generated, and when the level is low, the pump will automatically turn off, protecting the motor against dry operation. However, this system notifies the responsible person by means of a beep sound when the water level is at a critical point. This alert can only be heard when the alerted person is near the tank, and in addition, the user can view the current water status on their smartphone or laptop. Similar projects have observed that the prototypes taught farmers basic computer skills and the wonders of modern ICT applications [23].

3.2 Transmission to the internet via Google Sheets

In order to monitor the data obtained through the JSN-SR04T sensor, so that a precise analysis of the water depth in the reservoir can be obtained, Google Sheets software/application was used, which is an online spreadsheet similar to Excel. The transmission to the spreadsheet occurs through the internet connection. The sending of this data occurs through the URL of the website located in the address bar at the top of the web between slashes, but it must have the interaction of a platform called: Apps Script (script platform that uses JavaScript-based programming language). It can be accessed at: Extensions and then Apps Script. With the interrelationships of the two applications, it will be possible to connect to the Arduino IDE software (development software written in C++ and C, used to perform uploads or loading on boards that are compatible with Arduino) by connecting to the ESP32.

3.3 Calibration of the ultrasonic sensor

The result of the system tests in the reservoir is represented in Fig. 5. The cali-bration data were obtained by the system sequentially from the initial water level of the reservoir, 0.22 m, and the electric pump operated until the programmed 0.55 m. After a comparison between the system's measurements and the results of manual measurement, it was found that the precision of the measurement system is quite good, presenting a slight overestimation in the measurement value by the system, which may even be associated with the variation of the water surface. Similar results to those ob-tained in this system, also using sensors based on the physical principle of ultrasound, were found by [24], where they suggest that the combination of Arduino and ultrason-ic sensors is a technically and economically viable way to accurately measure water levels in channels for distances greater than 20 cm, both for permanent and transient flows, including conditions where turbulence is high. This was supported by the fact that there was little change in the errors in the statistical comparison of measurements between the different regimes.

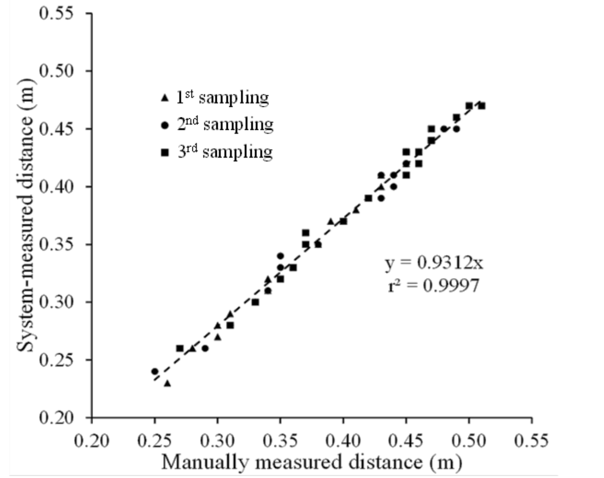

Figure 5. Correlation between manually measured and system-measured distance data.
Source: The Authors.

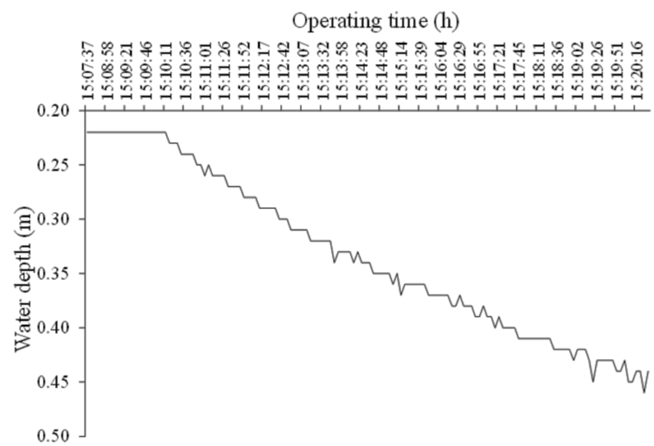

Figure 6. Water depth monitored by the system over the operating time.
Source: The Authors.

In addition to the validation between the collection methodology through the sensor and the standard collection (limnimeter scale), it is possible to observe the his-tory of the reservoir emptying over the operation of the pump (without water replen-ishment) (Fig. 6). The test results suggested that the difference in value between manual measurement and using the system was less than 5 mm, a result also found by [25]. This is in accordance with the resolution of the JSN-SRT04 sensor contained in the sensor datasheet, which is also 5 mm.

3.4 Control system

The control system developed in this work was the single-phase system and is presented with the control diagram (Fig. 7). It is composed of a contactor, a thermal relay, a bipolar circuit breaker, a simple control relay (a relay that represents the actu-ation by the ESP32) and two buttons, one normally closed and the other normally open. The power circuit is represented by an indirect start of a single-phase pump with the actuation command through the normally closed relay of the ESP32, and the shutdown can be performed by receiving the inverse command from the ESP32. The direct actua-tion system can be resumed if maintenance is required on the ESP32 platform. In addi-tion to the example developed in this work, a single-phase system with a 1 hp pump, the control command can be easily adjusted for a three-phase system, which will have the components illustrated as two-phase replaced by three-phase and minor changes to the control diagram (Fig. 8). This three-phase case is the most commonly used system in agricultural systems, as three-phase electrical energy is the most economical source of energy for irrigation, with lower daily energy costs, maintenance, equipment and controls [26].

After the development of the control system, which has the ability to deactivate the electric pump when the water level is in a critical state, an advance can be noted compared to the study by [27], who developed and tested a low-cost real-time water level monitoring prototype. The system used low-cost equipment and open-source software with the aim of monitoring water levels and alerting. After testing the prototype, it became possible to monitor the water status in a tank, alert users and view past data in real-time, but the existence of a control system that turns off the pump was not observed.

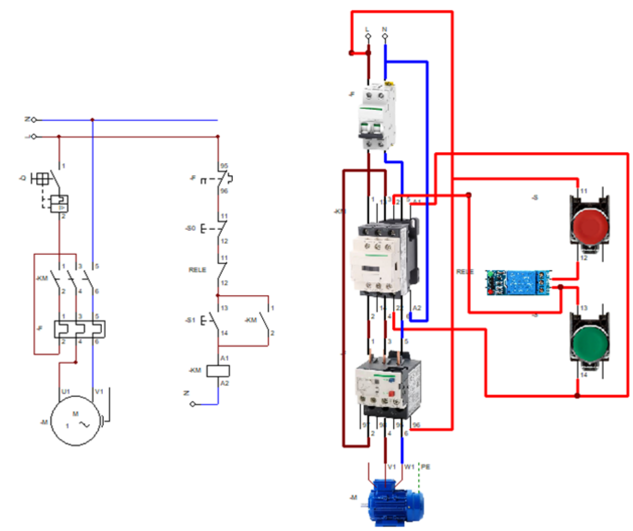

Figure 7. Diagram of the control system for the single-phase system.
Source: The Authors.

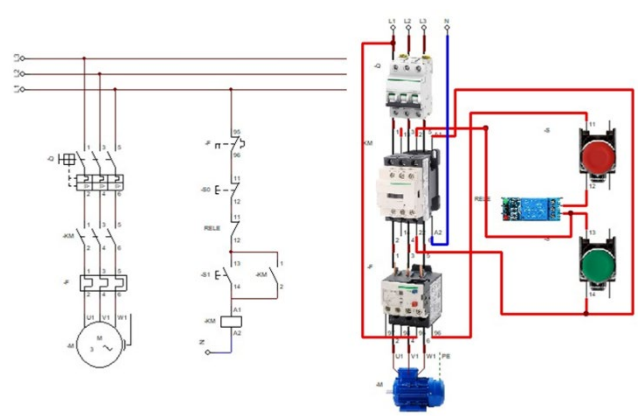

Figure 8. Diagram of the control system for the three-phase system.
Source: The Authors.

Furthermore, for some time now, Programmable Logic Controllers (PLCs) have been available on the market, which can be applied in automation systems in pump station control systems using contactor switches and thermal relays. However, [28], reports that there are difficulties in the construction and assembly process of an equipment that would simulate the PLC input points, difficulty in the PLC selection process that would be most suitable for the project and in the parameterization, which required constant consultation with the manufacturer's support.

When comparing PLCs with Arduino applications, [29] developed a comparative study of PLCs, Raspibarry and Arduino, in which he observed that the Arduino platforms used were highly versatile, allowing the addition of several other modules and sensors to improve the projects. An example of this is the relay connected to one of the Arduino ports, this suggestion makes the project even more efficient because it connects it to the machine's emergency switch or button, causing it to turn off immediately when the absence of a certain condition is detected.

In the context of selecting Arduino platforms for automation applications, such as control command, [30] noted that Arduino has inspired creativity in digital electronics. The impact of its radical development of new ideas is driven solely by the voluntary contributions of users worldwide, as highlighted by [31].

The improvements over study [15] and [22] were properly identified and can be outlined in four main aspects. The first refers to the simplicity in the system's design, assembly, and management, which enables easy replication at low cost and facilitates maintenance. The second improvement lies in the data transmission to the internet via Google Sheets, allowing real-time remote monitoring of the reservoir's water volume—a feature not present in the previous study. The third contribution was the calibration of the ultrasonic sensor, whose tests demonstrated satisfactory accuracy, with a margin of error of less than 5 mm compared to manual measurements, ensuring system reliability. Lastly, the development of a control system capable of automatically shutting off the pump under critical conditions stands out, along with the possibility of adapting it to three-phase systems, which broadens its applicability in agricultural contexts. These enhancements make the system more efficient, safer, and technically feasible for different usage scenarios.

3.5 Main limitations and challenges for system implementation

Despite the effectiveness and low cost of the proposed system, certain limitations must be considered in its implementation. One major drawback is the dependence on proximity for alert notifications. The system emits a beep when the water level reaches a critical point, but this alert can only be heard by someone physically near the reservoir. Additionally, after the system automatically turns off the pump to prevent dry running, it requires manual intervention to press a reset button, which limits remote management and full automation of the system.

Another relevant challenge lies in the need for reliable internet connectivity. The system transmits water level data to Google Sheets via the ESP32 using Apps Script integration. However, many rural areas may suffer from unstable or unavailable Wi-Fi or cellular networks, making real-time monitoring difficult. Furthermore, setting up the data transmission requires knowledge of JavaScript, the Arduino IDE, and web application integration, which may be a barrier for users without technical expertise.

Hardware limitations should also be addressed. The JSN-SR04T ultrasonic sensor, although cost-effective, may present slight overestimations in readings due to water surface variation, turbulence, or external environmental factors. The control system, while functional, requires careful electrical installation with relays, contactors, and safety features. Although the Arduino platform provides flexibility and modularity, scaling the system for more demanding or industrial applications may require transitioning to more robust hardware like PLCs, which involves added complexity in setup and configuration.

4. Conclusions

The results from the project proposal to design an intelligent system for automat-ed management of water depth in a reservoir were satisfactory. The prototype was tested for a period of 30 days, functioning correctly continuously 24 hours a day. User intervention in water monitoring was no longer necessary, allowing farmers to forgo traditional methods of measuring water levels. Thus, the project achieved the general objective of constructing a system for automated visualization and management of the water level in a reservoir, for the control of consumption and management of the available water resource. The hardware device for reading the water volume of a reservoir was successfully developed, with an excellent correlation index between the data obtained through a scale measurements and the ultrasonic sensor data. The software, Google Sheets, for monitoring and processing the data obtained by the hardware works correctly.

The original contributions of this study lie in the development of an intelligent, low-cost, and replicable water reservoir management system designed for agricultural use. Key innovations include a simplified system architecture that facilitates ease of assembly and maintenance, the integration of real-time remote monitoring through Google Sheets—enabling data transmission via ESP32 and Apps Script—and the implementation of an automatic pump shutoff mechanism triggered under critical water level conditions. The system was further enhanced by the accurate calibration of the JSN-SR04T ultrasonic sensor, which demonstrated measurement precision with an error margin of less than 5 mm compared to manual readings. Additionally, the proposed solution includes adaptability for three-phase systems, expanding its applicability in more complex agricultural contexts. Together, these advancements contribute to improved water resource management, operational safety, and energy efficiency in irrigation systems.

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