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knowledgment

In the name of Allah, the Most Gracious, the Most Merciful.
All praise and thanks are due to Allah alone, who granted us the strength, patience, and clarity to complete this work. By His mercy, the difficult became easy, and through His guidance, the path became clear.
Praise be to Allah, who taught by the pen, who bestowed upon us the blessing of knowledge, and who made every step in this academic journey possible.
May peace and blessings be upon our beloved Prophet Muhammad, the noblest of creation, and upon his family and companions.
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Dedication

To the endless source of tenderness,

To the woman who carried the burdens of the days with patience and stayed up countless nights so that we could reach our dreams,

To my beloved mother,

I dedicate this work to you as a token of love and gratitude—for your great spirit that instilled strength in us, and for your heart that was always our refuge in times of hardship. You have always been my first supporter and the inspiration that kept me going when I felt weary. Every achievement is a reflection of your sacrifices.

To those who have departed but left a lasting mark on my heart…

To the soul of my dear father, who taught me the true meaning of patience and determination,

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And to my dear colleagues, my companions on this journey,

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Abstract

This work is a master's project that aims to develop an intelligent monitoring and control system for agricultural environments using Programmable Logic Controllers (PLCs) and custom-designed sensors, along with an Arduino board. We identified several shortcomings in traditional irrigation monitoring methods, which led us to choose this specific project. Among the observed issues were the lack of accuracy in tracking water quantities, the difficulty of monitoring large-scale agricultural areas, and delayed responses to faults or leaks, resulting in water waste, increased labor, and reduced system efficiency.

Our project aims to improve the efficiency of irrigation systems by leveraging automation and smart technologies to enable precise tracking and immediate response to abnormal conditions. This approach reduces reliance on manual intervention, minimizes waste, optimizes the use of water resources, and provides farmers with a reliable method for remotely monitoring their irrigation systems. Real-time monitoring is a core feature of the system.

The project is divided into two main parts: hardware and software. On the hardware side, we designed and assembled three smart sensors: a flow sensor and a water level sensor, both connected to a PLC, and a position sensor for a pivot irrigation system, connected to an Arduino board. Each sensor was individually tested to verify accuracy and ensure proper operation. The sensors were also linked to a Human-Machine Interface (HMI) for real-time data visualization. On the software side, we programmed the PLC using Ladder Logic to control pumps and valves based on sensor inputs. Additionally, the Arduino was programmed to process magnetic signals and provide real-time information on the number of pivot rotations, direction, and current position.

Finally, the complete system was tested in a real agricultural environment and yielded accurate and effective results. The interface displayed real-time data for flow rate, water level, and system position, allowing for timely remote control decisions. These results align with the project's objectives of supporting smart agriculture and achieving efficient resource management.

Keywords: smart agriculture, smart sensors, Programmable Logic Controllers (PLC), Arduino, irrigation systems, real-time monitoring.

Résumé

Ce travail est un projet de master visant à développer un système intelligent de surveillance et de contrôle dans les environnements agricoles, en utilisant des Automates Programmables Industriels (API) et des capteurs conçus sur mesure, ainsi qu'une carte Arduino. Nous avons identifié plusieurs lacunes dans les méthodes traditionnelles de surveillance de l'irrigation, ce qui nous a conduits à choisir ce projet. Parmi les problèmes observés figurent le manque de précision dans le suivi des quantités d'eau, la difficulté à surveiller de grandes surfaces agricoles, ainsi que le retard de réaction face aux pannes ou aux fuites, entraînant un gaspillage d'eau, une augmentation de la charge de travail et une baisse de l'efficacité du système.

Notre projet vise à améliorer l'efficacité des systèmes d'irrigation grâce à l'exploitation des technologies d'automatisation et des capteurs intelligents, permettant un suivi précis et une réaction immédiate en cas de conditions anormales. Cette approche réduit la dépendance à l'intervention humaine, minimise les pertes, optimise l'utilisation des ressources en eau et offre aux agriculteurs un moyen fiable de surveiller leurs systèmes à distance. La surveillance en temps réel constitue une caractéristique essentielle du système.

Le projet se divise en deux parties principales : le matériel et le logiciel. Du côté matériel, nous avons conçu et assemblé trois capteurs intelligents : un capteur de débit et un capteur de niveau d'eau, tous deux connectés à un API, ainsi qu'un capteur de position pour un système d'irrigation pivot, relié à une carte Arduino. Chaque capteur a été testé individuellement pour garantir la précision des mesures et le bon fonctionnement. Les capteurs ont été connectés à une Interface Homme-Machine (IHM) pour l'affichage des données en temps réel. Du côté logiciel, nous avons programmé l'API en langage Ladder Logic pour commander les pompes et les vannes en fonction des signaux des capteurs. L'Arduino a également été programmé pour traiter les signaux magnétiques et fournir des informations sur le nombre de rotations du pivot, sa direction et sa position actuelle.

Enfin, le système complet a été testé dans un environnement agricole réel, donnant des résultats précis et efficaces. L'interface a affiché en temps réel les données relatives au débit, au niveau d'eau et à la position du système, permettant ainsi une prise de décision à distance rapide. Ces résultats sont en adéquation avec les objectifs du projet, à savoir promouvoir l'agriculture intelligente et assurer une gestion efficace des ressources.

Mots-clés : agriculture intelligente, capteurs intelligents, automates programmables industriels (API), Arduino, systèmes d'irrigation, surveillance en temps réel

ملخص:

هذا العمل هو مشروع ماستر يهدف إلى تطوير نظام مراقبة وتحكم ذكي في البيئات الزراعية باستخدام المتحكمات المنطقية المبرمجة (PLC) وحساسات مخصصة، بالإضافة إلى استخدام لوحة Arduino. وقد لاحظنا عدة أوجه قصور في طرق المراقبة التقليدية لأنظمة الري، مما دفعنا إلى اختيار هذا المشروع بالتحديد. ومن بين المشكلات التي تم تحديدها غياب الدقة في تتبع كميات المياه، وصعوبة مراقبة المواقع الواسعة، وتأخر الاستجابة للأعطال أو التسربات، مما يؤدي إلى هدر المياه والجهد وتراجع كفاءة النظام.

يهدف مشروعنا إلى تحسين كفاءة أنظمة الري من خلال الاستفادة من تقنيات التحكم الآلي والأنظمة الذكية لتمكين التتبع الدقيق والتفاعل الفوري مع الحالات غير الطبيعية. تقلل هذه التقنية من الاعتماد على التدخل البشري، وتسمح بتقليل الهدر وتحقيق استغلال أمثل للموارد المائية، وتوفر للمزارعين وسيلة موثوقة لمراقبة أنظمة الري عن بُعد. وتعد القدرة على المراقبة في الوقت الفعلي سمة أساسية للنظام.

ينقسم مشروعنا إلى قسمين رئيسيين: الأجهزة والبرمجيات. في مرحلة الأجهزة، قمنا بتصميم وتصنيع ثلاث حساسات ذكية: حساس التدفق، وحساس مستوى الماء، وهما مرتبطان بوحدة تحكم مبرمجة (PLC)، بالإضافة إلى حساس الموضع لنظام الري المحوري، المرتبط بلوحة Arduino. تم اختبار كل حساس على حدة، وتأكدنا من دقة القياسات وسلامة التوصيلات. كما تم ربط الحساسات بوحدة عرض (HMI) لعرض البيانات بشكل فوري. بالانتقال إلى الجانب البرمجي، قمنا ببرمجة وحدة PLC باستخدام Ladder Logic للتحكم في المضخات والصمامات حسب المدخلات، كما تم برمجة Arduino لاستقبال إشارات مغناطيسية وتحويلها إلى معلومات عن عدد دورات نظام الري واتجاهه وموقعه الحالي.

وأخيرًا، قمنا باختبار النظام بأكمله في بيئة زراعية حقيقية، وحصلنا على نتائج دقيقة وفعالة. حيث عرضت لنا الواجهة قيمًا لحظية لتدفق المياه والمستوى والموقع، مما سمح لنا باتخاذ قرارات تحكم فورية عن بُعد. وتتوافق هذه النتائج مع أهداف مشروعنا في دعم الزراعة الذكية وتحقيق إدارة فعالة للموارد.

الكلمات المفتاحية: الزراعة الذكية، الحساسات الذكية، المتحكمات المنطقية المبرمجة (PLC)، الأردوينو (Arduino)، أنظمة الري، المراقبة في الوقت الحقيقي.

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Notation

- V_1: is the voltage across both ends of the resistor R1.
- V_2: It is a voltage across both ends of the resistor R2.
- *I:* is the current passing through the circuit.
- R_1: is the value of the first resistance.
- R_2: is the value of the second resistance.
- *Vs*: is the input voltage.
- V_{c1}: is the voltage across both ends of the capacitor C1
- V_{c2}: is the voltage across both ends of the capacitor C2
- *I*: is the current passing through the circuit
- C_1: is the first capacitor value
- C_2: is the value of the second capacitor
- *Vs*: is the input voltage
- V_{out} :is the voltage in the secondary coil.
- N: is the number of turns in the secondary coil.
- Φ: is the magnetic flux.
- I_p is the primary current,
- I_s is the secondary current,
- N_p, N_s are the turns in the primary and secondary coils respectively.
- Q: is the flow rate
- A: is the area of the pipe
- V: is the water velocity
- f : Pulse frequency (pulses/second)
- k : Calibration factor (pulses per liter)
- f_e: electric force
- f_m: magnetic force
- V_d:Drift speed charge carriers (m/s)
- *B:* Magnetic field strength (Tesla)
- E_H: Hall field strength
- q: the charge carrier of the current

- n_q: Charge density
- *A*: Cross-sectional area of the slice
- *t*: Slice thickness
- *d:* Slide show
- I: current
- V_H: voltage hall
- V = Voltage produced across membrane due to ion exchange (volts)
- R = Universal gas constant (8.315 J/mol·K)
- T = Absolute temperature (Kelvin)
- n = Number of electrons transferred per ion exchanged (unitless)
- F = Faraday constant, in coulombs per mole (96485 C/mol e^-)
- C1 = Concentration of ion in measured solution (moles per liter of solution, M)
- C2 = Concentration of ion in reference solution (moles per liter of solution, M)
- **D** = the distance from the sensor to the object (in meters or centimeters)
- **V** = speed of sound in air (approximately **343 m/s** at 25°C)
- **t** = total time between the emitted pulse and the received echo (in seconds)
- C: Capacitance, measured in Farads (F), representing the ability to store electric charge.
- Q: Electric charge in Coulombs (C).
- V: Voltage or potential difference between the plates, in Volts (V).
- E: Electric field strength between the plates, measured in Volts per meter (V/m)
- ε: Absolute permittivity of the material, in Farads per meter (F/m).
- A: Area of each electrode plate, in square meters (m^2).
- d: Distance between the two plates or electrodes, in meters (m).
- C**:** Capacitance, measured in Farads (F)
- εo:dielectric permittivity of free space (or dielectric constant)
- εr: relative permittivity of dielectric medium
- A: Area of each of the conducting object
- d: distance between two conducting objects.
- θ: is the volumetric water content.
- V: is the voltage output.
- a and b: are experimentally derived coefficients.
- ε_b = bulk dielectric constant of the soil
- c = speed of light in a vacuum $(3 \times 10^8\ m/s)$
- t = travel time of the electromagnetic pulse

- L = length of the probe embedded in the soil

General Introduction

General Introduction

In recent years, the agricultural sector has witnessed a radical transformation thanks to the rapid advancement of technology, particularly in the fields of monitoring and control. Sensors have become one of the most critical tools driving this change, playing a vital role in the development of smart farming systems by collecting data, analyzing it, and enabling precise automated decision-making. From this perspective, this dissertation addresses the development of an integrated system for monitoring and control in agricultural environments using Programmable Logic Controllers (PLCs) and custom-designed smart sensors aimed at improving the performance of modern irrigation systems [1][2].

This dissertation consists of three main chapters, summarized as follows:

The first chapter addresses the fundamental concepts related to agricultural sensors, including their definition, role, and technological evolution over time. It also presents an overview of existing sensor-based monitoring systems and identifies the key components in farms that require automation, such as irrigation, soil quality, and climate. The chapter highlights the importance of sensors in smart farming and their benefits in terms of efficiency, resource optimization, and sustainability, while also discussing the current limitations and challenges of sensor technologies.

The second chapter focuses on the importance of PLCs (Programmable Logic Controllers) in smart agriculture and their integration with various sensors to automate farming processes. It includes a study of Ladder Logic programming with illustrative examples, as well as the role of Human-Machine Interfaces (HMI) and SCADA systems in real-time monitoring and large-scale management. The chapter also covers the integration of analog and digital sensors with PLCs for diverse agricultural applications [3][4].

The third chapter presents the practical aspect of the project, involving the design and development of smart sensors tailored specifically for modern agricultural needs. These include:

Flow-Based Water Sensor: Operates on the principle of detecting water passage to send control signals, helping to accurately track irrigation.

Water Level Sensor: Monitors the water levels in tanks in real-time and triggers automatic responses when necessary.

Position Sensor for Pivot Irrigation System: One of the key innovations in this project, this sensor monitors the number of rotations performed by the pivot system, the direction of rotation, and its current position (east, west, etc.). It uses magnets and switches arranged in a specific design, connected to an Arduino programmed to detect each position. The data is transmitted to an HMI or server-based application that displays percentage positions and rotation count in real time.

The chapter also discusses hardware-software integration, technical challenges, testing methodology, and performance evaluation, in addition to communication protocols such as Modbus and IoT integration with real-world applications.

Through this research, we have completed both the theoretical and practical aspects of our study, successfully designing a set of smart sensors dedicated to agricultural applications. These sensors enable precise and efficient monitoring of irrigation and water systems, representing a significant step toward more sustainable and automated farming practices. They also lay the groundwork for the broader adoption of control and monitoring technologies in the agricultural sector.

Chapter I : State of the Art on Agricultural Sensors

I.1 Introduction

This chapter provides an overview of the current state of sensor technologies used in agriculture, with a particular focus on their role in enabling precision farming. The integration of sensor-based systems has significantly transformed traditional agricultural practices by allowing real-time, accurate, and automated monitoring of environmental and crop conditions [1][8]. These sensors are essential components of smart farming systems, where data-driven approaches are used to optimize water use, monitor soil health, control greenhouse environments, and enhance overall productivity [5][6].

In this chapter, we discuss the evolution of sensor technologies and their application in key farm components such as irrigation systems, soil quality monitoring, and climate control [1][2][4]. The chapter also outlines the different types of data collected through these systems and explains how this data contributes to more sustainable and efficient agricultural practices [5][7].

Recent studies have shown that the focus in agricultural research is shifting not only toward the deployment of these technologies but also toward addressing challenges such as sensor calibration, data accuracy, interoperability between systems, and scalability in large-scale farms [6]. The purpose of this chapter is to present the foundational concepts necessary to understand the integration of sensor technologies in smart farming, setting the stage for the more technical discussions that follow in later chapters.

Figure I.1: Smart Farming Application in Use for Crop Monitoring

I.2 Main Components in a Farm

Modern agriculture relies increasingly on sensing and automation technologies to optimize productivity and resource efficiency. Figure I.2 provides a visual overview of the essential components and technologies commonly used in smart farming systems.

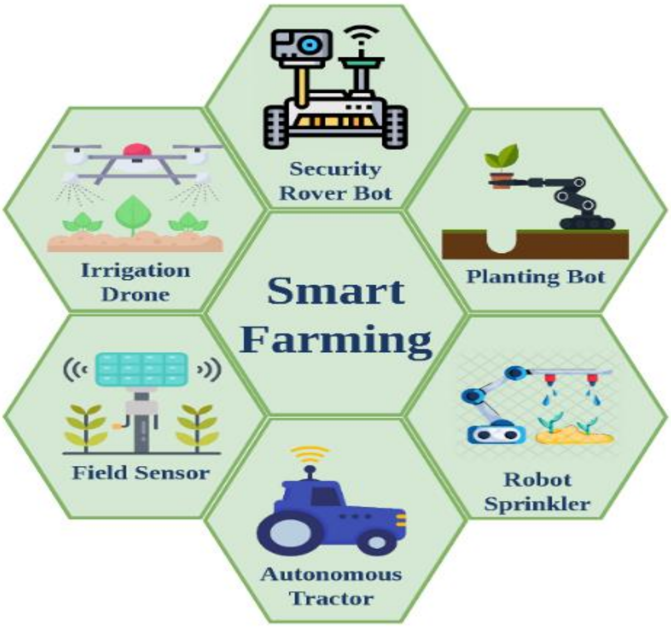


Figure I.2 Smart Farming Technologies Overview

The key components of a farm that require continuous monitoring and automation include:

I.2.1 Soil Conditions

Monitoring soil moisture, temperature, pH, and nutrient levels is critical for crop health. Capacitive soil moisture sensors [21] provide accurate, real-time data to manage irrigation schedules and avoid over- or under-watering. Additionally, pH and EC (electrical conductivity) sensors help assess soil fertility [17][18].

I.2.2 Irrigation Systems

Precision irrigation systems rely on data from soil sensors and weather forecasts to automate water delivery. Integration with **flow meters**, **valves**, and **water level sensors** [22][24] allows real-time control and optimization, reducing water waste and improving crop yield [3][30].

I.2.3 Climate and Environmental Monitoring

Environmental factors such as **temperature**, **humidity**, **light intensity**, and **wind speed** impact plant growth and must be monitored using sensors like DHT22 and light sensors [17][30]. These parameters are essential for greenhouse automation and open-field decision-making.

I.2.4 Crop Health and Pest Management

Vision-based systems and IoT-enabled sensors are used to detect plant diseases, pest infestations, and nutrient deficiencies. This enables targeted application of pesticides or fertilizers, reducing costs and environmental impact [1][3].

I.2.5 Water Resources

Monitoring **water levels in tanks or canals** using **ultrasonic sensors** [10][11][19] helps ensure efficient water distribution. Automated refill and cutoff mechanisms can be implemented to maintain optimal levels and prevent spillage.

Table I.1 summarizes the key data types collected from different farm components, along with the associated sensors and their intended agricultural applications

Farm Component	Type of Data Collected	Sensor Type / Technology	Purpose / Application
Irrigation System	Soil moisture, water level, water flow rate	Soil Moisture Sensor, Ultrasonic Level Sensor, Flow Meter	Automate irrigation, prevent over/under watering, optimize water usage
Soil Monitoring	Soil moisture, pH, temperature	Soil Moisture Sensor, pH Sensor, Temperature Sensor	Evaluate soil health and nutrient availability
Climate Monitoring	Air temperature, humidity, rainfall, sunlight intensity	DHT22, Rain Sensor, Light Sensor (LDR/BH1750)	Control greenhouse climate, detect weather changes
Crop Health Monitoring	Leaf chlorophyll level, stress index, growth anomalies	NDVI Cameras, Multispectral Sensors, Image Processing Units	Early disease detection, monitor plant health and performance
Water Quality Control	pH level, TDS, turbidity	pH Sensor, TDS Sensor, Turbidity Sensor	Ensure safe and efficient irrigation, monitor water pollution

I.3 Electrical Sensors

This category includes sensors used to measure electrical quantities such as voltage and current. These sensors are essential in monitoring and controlling power systems, detecting faults, and ensuring energy efficiency in various electrical applications.

I.3.1 Voltage sensor

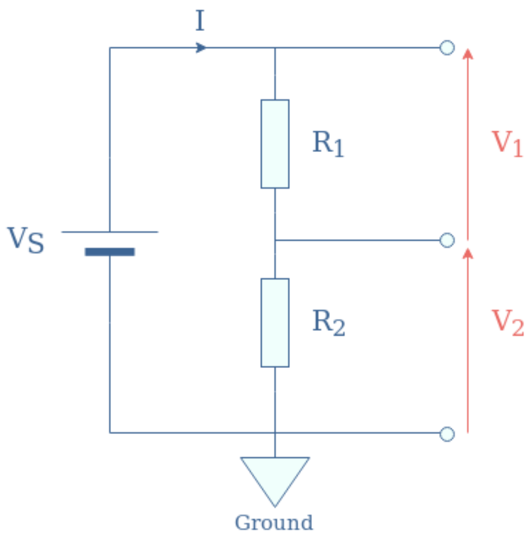
Voltage sensors are essential components in electropump systems, where they monitor voltage levels to ensure safe and efficient operation. These sensors detect the electrical potential difference between two points and convert it into a readable signal either analog or digital. In smart systems, they play a crucial role in fault detection, power regulation, and system diagnostics.

There are different types of voltage sensors depending on the sensing mechanism and application requirements. The most common types include capacitive and resistive voltage sensors.

Among the most commonly used voltage sensing techniques are the following:

a) Resistive Voltage Divider:

A resistive voltage divider is a fundamental electrical circuit used to obtain a portion of an input voltage. It consists of two resistors, R_1 and R_2, connected in series across a voltage source Vs. The principle of operation is based on Ohm's Law and Kirchhoff's Voltage Law, where the voltage drop across each resistor is directly proportional to its resistance value, since the same current flows through both resistors[26].



FigureI.3. Illustration of a resistive voltage divide

Let:

- V_1 be the voltage across R_1
- V_2 be the voltage across R_2
- I be the current flowing through the circuit.

Using Ohm's Law:

$$V_1 = I.R_1 \quad (I.1)$$

$$V_2 = I.R_2 \quad (I.2)$$

And from Kirchhoff's Voltage Law:

$$Vs = V_2 + V_1 = I.R_1 + I.R_2 \quad (I.3)$$

Solving for current:

$$I = \frac{Vs}{R_1 + R_2} \quad (I.4)$$

Substituting this back to find the voltages across each resistor:

$$V_1 = \frac{Vs.R_1}{R_1 + R_2} \quad (I.5)$$

$$V_2 = \frac{Vs.R_2}{R_1 + R_2} \quad (I.6)$$

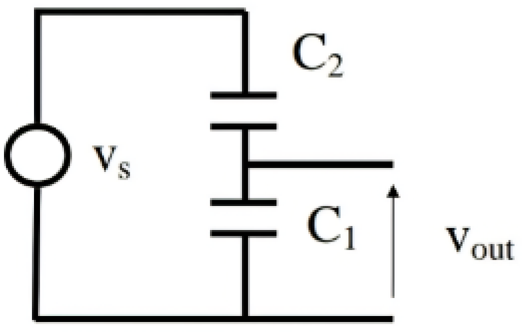
These expressions show how the total voltage Vs is divided between the two resistors in proportion to their resistance values. This configuration is widely used in signal conditioning, sensor interfacing, and voltage level adjustments in electronic circuits[26].

where:

- V_1: is the voltage across both ends of the resistor R1.
- V_2: It is a voltage across both ends of the resistor R2.
- *I:* is the current passing through the circuit.
- R_1: is the value of the first resistance.
- R_2: is the value of the second resistance.
- Vs: is the input voltage.

b) Capacitive Divider Voltage:

A capacitive voltage divider functions on the same principle as a resistive divider; however, it uses capacitors instead of resistors to divide the input voltage[25].



FigureI.4. Typical capacitor voltage sensor

$$V_{c1} = \frac{Vs.\,Ceq}{C_1} \quad (I.7)$$

$$V_{c2} = \frac{Vs.\,Ceq}{C_2} \quad (I.8)$$

$$Ceq = \frac{C_1.\,C_2}{C_1 + C_2} \quad (I.9)$$

$$V_{c1} = \frac{Vs\,.\,C_2}{C_1 + C_2} \quad (I.10)$$

$$V_{c2} = \frac{Vs\,.\,C_1}{C_1 + C_2} \quad (I.11)$$

where :

- V_{c1}: is the voltage across both ends of the capacitor C1
- V_{c2}: is the voltage across both ends of the capacitor C2
- I: is the current passing through the circuit
- C_1: is the first capacitor value
- C_2: is the value of the second capacitor
- Vs: is the input voltage

I.3.2 Current sensor

A current sensor is a device used to detect and measure the electric current flowing through a wire or circuit. Among the various types of current sensors, the **transformer-type sensor** is one of the most commonly used.

It is considered a reliable and accurate solution for measuring electric current, especially in AC systems. Therefore, we will highlight this type in the following section:

I.3.2.1 Current Transformer Sensor (CT Sensor)

Current Transformers (CTs) are widely used sensors for measuring alternating current (AC) in power systems. Their primary function is to produce a reduced current in the secondary winding proportional to the current flowing in the primary conductor, which allows for safe and isolated current measurement[27][28].

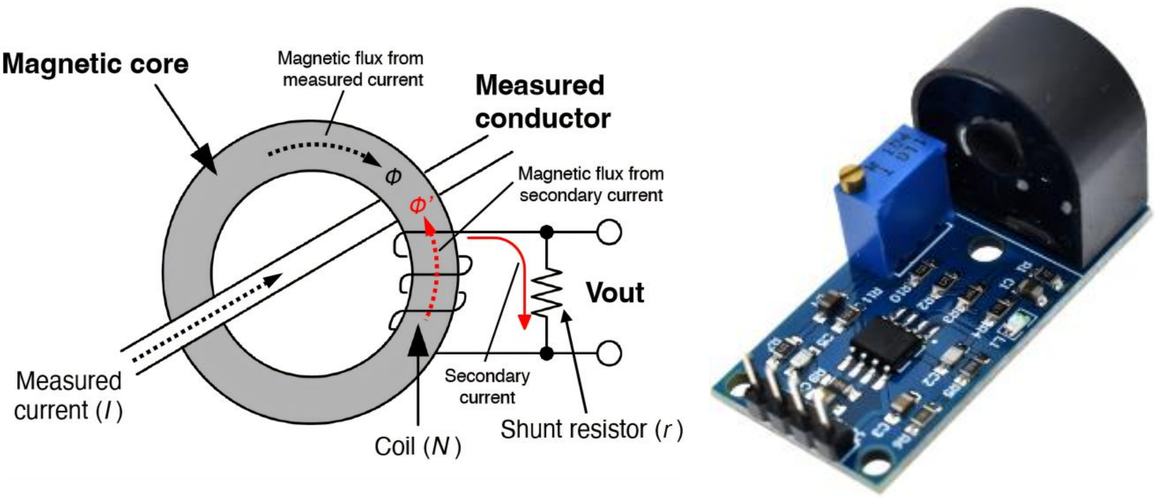


Figure I.5: Current transformers.

The working principle is based on Faraday's Law of Electromagnetic Induction, which states that a time-varying current in the primary conductor induces a voltage in the secondary winding:

$$V_{out} = N\frac{d\Phi}{dt} \tag{I.12}$$

Where:

- V_{out} :is the voltage in the secondary coil.
- N: is the number of turns in the secondary coil.
- Φ: is the magnetic flux.

For sinusoidal steady-state AC, the current relationship is given by the turns ratio:

$$\frac{I_s}{I_p} = \frac{N_p}{N_s} \tag{I.13}$$

Where:

- I_p is the primary current,
- I_s is the secondary current,
- N_p, N_s are the turns in the primary and secondary coils respectively.

CT sensors are non-intrusive, meaning they can measure current without interrupting the circuit, making them ideal for use in energy monitoring**,** protection systems, and industrial control[29].

I.4 Hydraulic Sensor

Hydraulic Sensors are devices used to monitor the behavior of fluids, especially water, as they move. These sensors play a crucial role in applications where precise control of water flow is required. One of the most common sensors in this category is the **Water Flow Sensor**, which accurately measures the rate at which water passes through a system.

I.4.1 Flow Sensors (Water Flow Rate Sensors)

Water flow sensors are widely used in smart agriculture and industrial systems to monitor the rate of liquid flow through pipelines. One of the most effective and low-cost types is the Hall-effect-based flow sensor. It operates by converting the mechanical motion of water into electrical signals using electromagnetic principles.

The sensor consists of a small turbine (impeller) fitted with a permanent magnet. As water flows through the pipe, it spins the impeller. Each time the magnet passes by a stationary Hall Effect sensor, it generates a digital pulse. These pulses are counted over time to determine the flow rate[21][22].

The flow rate can be calculated using two approaches:

- **Geometrical Equation (Volumetric Flow)**

$$Q = A \times V \tag{I.14}$$

where :

- Q: is the flow rate
- A: is the area of the pipe
- V: is the water velocity

- **Pulse Frequency Method (Hall Sensor)**

$$Q = \frac{f}{k} \tag{I.15}$$

Where:

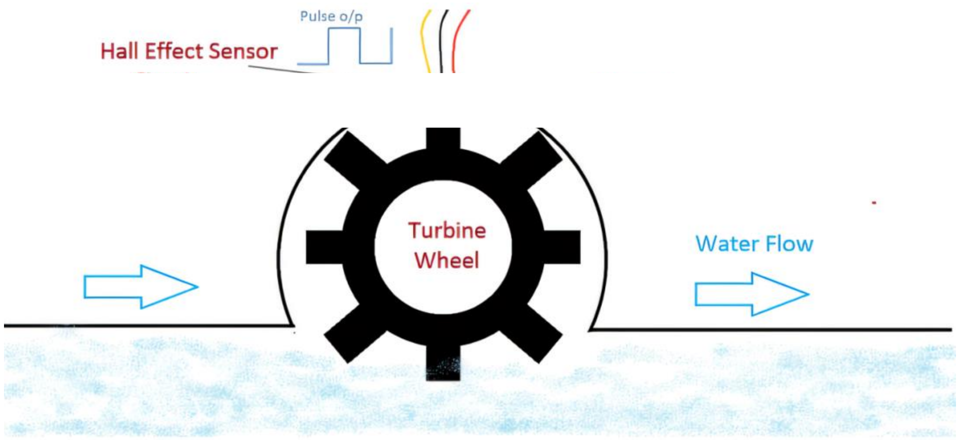
- f : Pulse frequency (pulses/second)
- k : Calibration factor (pulses per liter)

✓ Working Principle Using the Hall Effect

One widely adopted method for measuring water flow—especially in Arduino-based projects involves the Hall Effect. This technique is used in many commercial water flow sensors designed for simplicity and cost-effectiveness.

These sensors typically contain a rotor (fan blade) that spins as water flows through it. The rotor shaft is connected to a magnet, which rotates along with it. A Hall Effect sensor is placed nearby to detect changes in the magnetic field caused by the rotating magnet. Each rotation generates an electrical pulse.

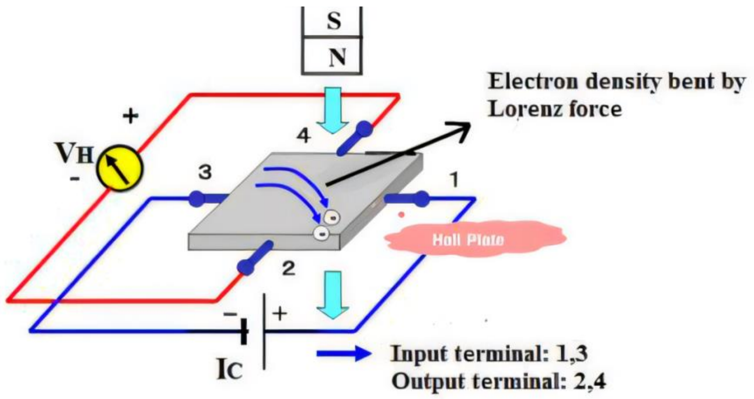
For example, a common flow sensor outputs approximately 4.5 pulses per liter of water. By counting these pulses over time, the microcontroller can compute both the flow rate (e.g., liters/hour) and the total water volume. As shown in (FigureI.7), the diagram illustrates the internal working of a Hall Effect-based water flow sensor, including the rotor, magnet, and sensor[21].



FigureI.6. Working Principle of water flow sensor

- **The Hall Effect**

The Hall Effect occurs when a current-carrying conductor is placed in a perpendicular magnetic field. The magnetic field exerts a Lorentz force on the moving charge carriers (electrons or holes), pushing them to one side of the conductor. This leads to the buildup of an electric field, called the Hall field.



FigureI.7. Behaviour of hall element in presence of magnetic field[22]

At equilibrium, the electric force f_e balances the magnetic force f_m, leading to the relation:

$$f_e = f_m \tag{I.16}$$

$$q.E_H = V_d.q.B \tag{I.17}$$

Become

$$E_H = V_d . B \tag{I.18}$$

Where

f_e: electric force

f_m: magnetic force

V_d:Drift speed charge carriers (m/s)

B: Magnetic field strength (Tesla)

E_H: Hall field strength

q: the charge carrier of the current

Since electric current **I** is defined by

$$I = n_q . A . V_d \tag{I.19}$$

where

n_q: Charge density

A: Cross-sectional area of the slice

$A = t . d$

t: Slice thickness

d: Slide show

I: current

Become:

$$V_d = \frac{I}{n_q . A} \tag{I.20}$$

We substitute it into E_H we find

$$E_H = \frac{I}{n_q . A} . B \tag{I.21}$$

And also equal

$$E_H = \frac{V_h}{d} \tag{I.22}$$

Where:

V_H: voltage hall

equal relations(I.13) and (I.14)

$$\frac{V_h}{d} = \frac{I}{n_q . A} . B \tag{I.23}$$

Since:

$A = t . d$ (with t being the thickness and d the width of the strip)

Substituting into the Hall voltage equation:

$$V_H = \frac{I}{n_q . t} . B \qquad \text{(I.24)}$$

We define the Hall coefficient R_H as: $R_H = \frac{1}{n_q}$

Hence, the final form of the Hall voltage becomes:

$$V_H = \frac{B . I}{n_q . A} \qquad \text{(I.25)}$$

This equation shows that Hall voltage is directly proportional to the current and the magnetic field and inversely proportional to the thickness of the conductor. It forms the basis for current and flow measurement in Hall effect sensors used in water flow systems.

I.5 Environmental sensors

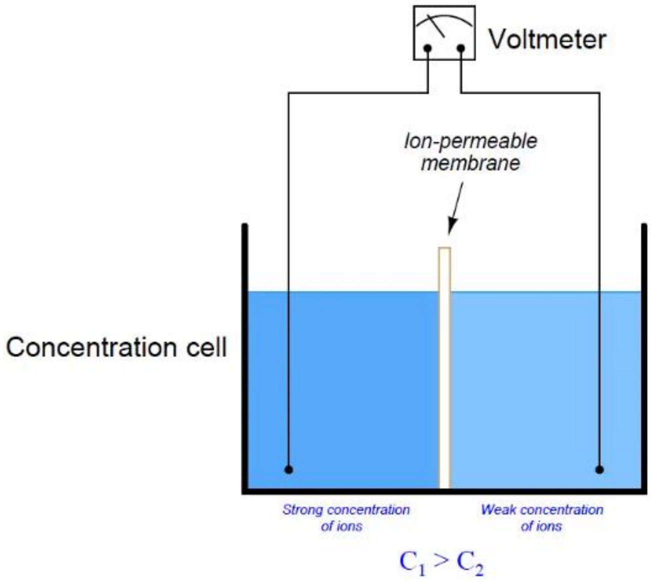
Those sensors are used to monitor environmental conditions that affect agriculture, water management, and ecosystem health. These sensors contribute to the sustainable use of resources, improve the efficiency of irrigation systems, and support more effective decision-making in agriculture and environmental monitoring.

Among these sensors, we mention the following:

I.5.1 Potentiometric pH Measurement

Measuring pH is incredibly important in many applications, especially for **water quality monitoring** and environmental systems. While traditional methods, like using color-change indicators, are fine for manual lab tests, they're not practical for continuous monitoring. That's why **potentiometric pH sensors** are widely used; they offer accuracy and real-time readings.

These sensors work based on **electrochemical principles**. They use pH-sensitive electrodes that generate an electrical voltage which changes depending on the hydrogen ion concentration in the solution. This voltage follows the **Nernst equation** , which explains the relationship between the electrical potential across a selective membrane and the difference in ion concentrations between two solutions. For example, Figure I.8 illustrates this concept using a concentration cell, where different ion concentrations in two compartments create a voltage across a selective membrane. This fundamental principle makes potentiometric pH sensors ideal for reliable and continuous pH measurement in various aquatic environments.



FigureI.8. Principle of pH Measurement Using a Potentiometric Electrode

Nernst equation:

$$V = \frac{RT}{nF} \ln \frac{C_1}{C_2} \tag{I.26}$$

Where:

- V = Voltage produced across membrane due to ion exchange (volts)
- R = Universal gas constant (8.315 J/mol·K)
- T = Absolute temperature (Kelvin)
- n = Number of electrons transferred per ion exchanged (unitless)
- F = Faraday constant, in coulombs per mole (96485 C/mol e^-)
- C1 = Concentration of ion in measured solution (moles per liter of solution, M)
- C2 = Concentration of ion in reference solution (moles per liter of solution, M)

I.5.2 Water Level Measurement Using Ultrasonic Sensors

Ultrasonic sensors are effectively used for monitoring water levels in tanks, reservoirs, and open channels [19]. Water surfaces reflect sound waves similarly to solid objects [15]. When the sound wave strikes the water surface, it reflects back as an echo, which is then detected by the sensor. The time elapsed between the transmitted and received signals is used to calculate the water level height [15], as shown in **Figure 1**.

In practical systems, this time is converted into a percentage, representing the fill level of a tank or container. This method is particularly beneficial for smart irrigation systems, water treatment plants, and industrial automation [19].

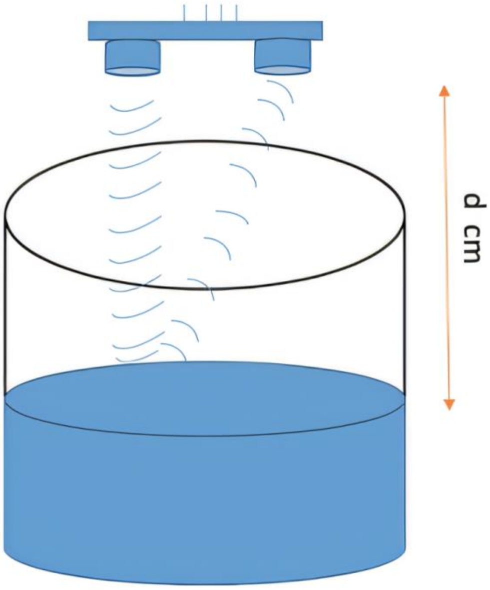


Figure I.9.ultrasonic sensor measuring water level in a tank

It is important to note that the sound wave travels twice (to the water and back), so the measured distance is half of the total time. This relationship is based on the velocity formula:

$$Distance = \frac{Vt}{2} \tag{I.26}$$

Where:

- **Distance** = the distance from the sensor to the object (in meters or centimeters)
- **V** = speed of sound in air (approximately **343 m/s** at 25°C)
- **t** = total time between the emitted pulse and the received echo (in seconds)

This **non-contact method** is suitable for situations where physical sensors shouldn't touch the fluid [15]. It has been validated in multiple studies as a reliable approach for real-time water monitoring [19]

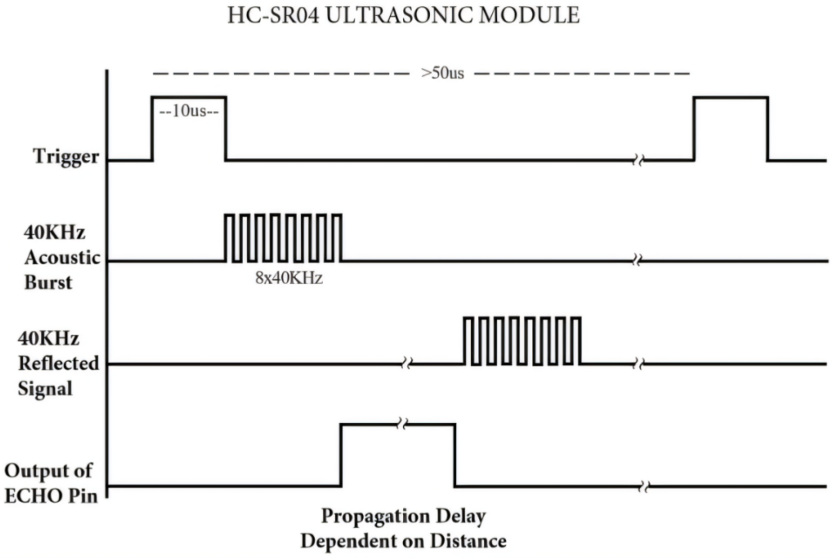


Figure I.10: Representation of trigger signal, acoustic bursts, reflected signal and output of echo pin.

In proposed systems, the **"Trig"** (trigger) and **"Echo"** components are integrated with a microcontroller that precisely measures the round-trip time and translates it into a water level reading. This makes ultrasonic sensors highly practical for automated systems due to their simplicity, reliability, and accuracy [20]. Unlike optical sensors, ultrasonic sensors are unaffected by color, transparency, or ambient light, which makes them suitable for challenging environments [15]. Their application has proven effective in both agriculture and robotics [20].

I.5.3 Soil Moisture Sensors

Soil moisture sensors are essential tools in agriculture and environmental monitoring. They help determine the water content of soil, which is critical for irrigation control, crop health, and efficient water resource management. There are several types of soil moisture sensors, but two of the most commonly used types are Capacitive Sensors and Time Domain Reflectometry (TDR) Sensors.

a) Capacitive Soil Moisture Sensors

Capacitive soil moisture sensors operate based on the principle of capacitance, which is influenced by the dielectric properties of the medium between two conductive electrodes. In this case, soil acts as the dielectric material, and its water content strongly affects its relative permittivity [13].

Capacitance is defined as the ratio of the charge stored Q to the voltage V applied between two conductors:

$$C = \frac{Q}{V} \tag{I.27}$$

Where:

- C: Capacitance, measured in Farads (F), representing the ability to store electric charge.
- Q: Electric charge in Coulombs (C).
- V: Voltage or potential difference between the plates, in Volts (V).

In a parallel-plate capacitor, the electric field E between the plates is given by:

$$E = \frac{Q}{A\varepsilon} \tag{I.28}$$

Where:

- E: Electric field strength between the plates, measured in Volts per meter (V/m)
- ε: Absolute permittivity of the material, in Farads per meter (F/m).
- A: Area of each electrode plate, in square meters (m²).

And the voltage across the plates is The capacitance C is given by:

$$V = E.d = \frac{Qd}{A\varepsilon} \tag{I.29}$$

Where:

- d: Distance between the two plates or electrodes, in meters (m).

Substituting into the original definition:

$$C = \frac{Q}{V} = \frac{Q}{\left(\frac{Qd}{A\varepsilon}\right)} = \frac{A}{d}\varepsilon \tag{I.30}$$

Where:

- $\varepsilon = \varepsilon_0 \varepsilon r$

- ε_0: Permittivity of free space (vacuum), approximately 8.854×10^{-12} F/m8.854
- ε_r : Relative permittivity (dimensionless), which depends on the dielectric (e.g., soil moisture).

Using the relationship $\varepsilon=\varepsilon_0\varepsilon r$, we get the final form:

$$C = \varepsilon_0\ \varepsilon_r\ \frac{A}{d} \tag{I.31}$$

Where:

- C**:** Capacitance, measured in Farads (F)
- εo:dielectric permittivity of free space (or dielectric constant)
- εr: relative permittivity of dielectric medium
- A: Area of each of the conducting object
- d: distance between two conducting objects.

This shows that capacitance depends linearly on the relative permittivity ε_r, which increases with soil moisture content.

- **Influence of Soil Moisture**

Since water has a much higher dielectric constant (~80) than dry soil (~2–5), small changes in moisture content significantly alter εr\varepsilon_rεr, and thus the measured capacitance [13].

When voltage is applied, the electrodes accumulate opposite charges, forming an electric field. The fringing field lines interact with the soil medium. As the water content increases, the dielectric constant increases, which results in a measurable increase in capacitance [21].

Capacitive sensors come in different designs such as rod-type, flat-type, and cylindrical configurations. These differ in measurement depth, installation convenience, and operating frequency range, typically between 50–150 MHz [23].

To convert the raw output of the capacitive soil moisture sensor"typically voltage or frequency" into volumetric water content θ, an empirical calibration process is necessary. A commonly used form of the calibration equation [21]is:

$$\theta = a\left(\frac{1}{V}\right) + b \tag{I.32}$$

Where:

- θ: is the volumetric water content.
- V: is the voltage output.

- a and b: are experimentally derived coefficients.

Capacitive soil moisture sensors are practical and cost-effective tools for monitoring soil moisture. However, site-specific calibration is essential due to variability in soil composition, texture, and environmental conditions [13][21][23].

b) Time Domain Reflectometry (TDR) Sensors

TDR sensors measure soil moisture by sending a short electromagnetic pulse through a probe inserted into the soil and analyzing the time it takes for the signal to reflect back. The travel time of the pulse is affected by the **bulk dielectric constant** of the soil, which is directly related to its water content.

The dielectric constant is calculated using:

$$\varepsilon_b = \left(\frac{c}{v}\right)^2 = \left(\frac{ct}{2L}\right)^2 \qquad (I.33)$$

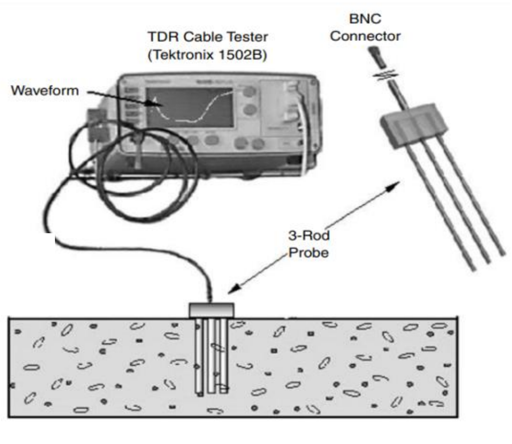
Where:

ε_b = bulk dielectric constant of the soil

c = speed of light in a vacuum $(3 \times 10^8\ m/s)$

t = travel time of the electromagnetic pulse

L = length of the probe embedded in the soil



FigureI.11. Illustration of a TDR sensor with three-rod probe and signal reflection path in soil

Water has a high dielectric constant (~81 at 20°C), compared to other soil components, so its presence greatly influences the signal speed. Once the dielectric constant is known, it can be converted into volumetric water content using calibration models [24].

Both capacitive and TDR sensors are widely applied in precision agriculture**,** greenhouse monitoring, and hydrological studies. Capacitive sensors are affordable and ideal for real-time applications, while TDR offers higher precision, especially in research and scientific studies.

I.6 Importance of Sensors in Agriculture

The integration of sensor technologies has significantly revolutionized traditional farming by transforming it into a smart, data-driven, and highly efficient system. Sensors play a crucial role in modern agriculture by enabling precise monitoring and control over various environmental and operational parameters, such as soil moisture, temperature, humidity, and crop health. This real-time data allows farmers to apply the right amount of water, fertilizers, and pesticides exactly when and where needed, enhancing productivity while minimizing waste [3].

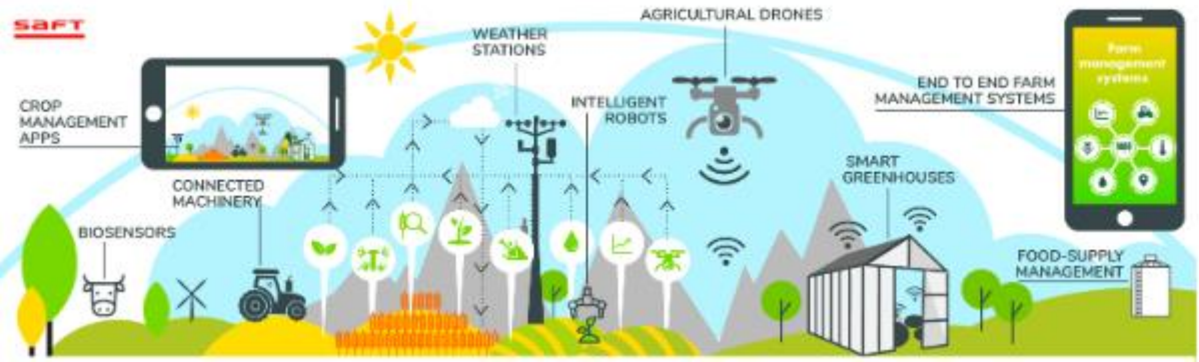


Figure I.12 Agritech – Making farming smarter and more environmentally sustainable through sensor integration.

Through precision agriculture, sensors contribute to a more strategic use of resources. They support informed decision-making by offering accurate insights into field conditions, helping farmers increase yields, reduce costs, and improve land management [6]. The automation enabled by these sensors not only streamlines critical operations like irrigation and fertilization but also reduces the need for manual labor, thus improving operational efficiency [2].

Moreover, the adoption of sensor-based systems supports environmental sustainability by ensuring controlled application of agrochemicals, reducing runoff, conserving water, and decreasing greenhouse gas emissions. This makes agriculture not only more productive but also more environmentally friendly [10].

Despite these advantages, the implementation of sensor technologies in agriculture comes with several challenges. The high initial cost of devices and systems can be a barrier, especially for smallholder farmers [1]. In addition, the massive amount of data generated by sensors requires robust infrastructure for data storage, analysis, and management [5].

Furthermore, sensors exposed to outdoor conditions are susceptible to weather-related damage and may require regular calibration and maintenance to maintain accuracy [7]. Compatibility issues between different sensor brands and systems also pose integration challenges [9].

Nonetheless, overcoming these limitations is essential for the broader adoption of smart farming technologies. As research continues and technology becomes more affordable and reliable, sensor systems are expected to become a cornerstone in the advancement of sustainable and intelligent agriculture [4].

I.7 Conclusion

The advancement of sensor technologies has played a transformative role in shaping the landscape of modern agriculture. This chapter has provided a comprehensive overview of various sensor types and how they contribute to smart farming practices. By enabling real-time data collection and analysis, these technologies have improved the precision, efficiency, and sustainability of agricultural operations.

We explored the integration of sensors into key components of farming systems, such as irrigation control, soil monitoring, environmental sensing, and electrical energy management. Furthermore, we examined the working principles behind these sensors and their respective contributions to optimizing resource use, enhancing productivity, and reducing environmental impact.

As we conclude this chapter, we now turn our attention to the role of monitoring and sensors in PLC-based systems. The upcoming chapter will explore how Programmable Logic Controllers (PLCs) integrate with agricultural sensors to enable automated control, real-time monitoring, and enhanced decision-making in smart farming environments.

Chapter II: Monitoring and Sensors in PLC-Based Systems

II.1 Introduction

In the context of smart agriculture, continuous monitoring and automated control are essential for enhancing productivity, optimizing resource usage, and minimizing human intervention. This chapter explores the integration of monitoring systems and sensors within PLC-based control architectures, a critical component in the development of intelligent agricultural systems[35][32].

Sensor monitoring refers to the systematic collection of real-time data from various agricultural parameters, including environmental conditions (temperature, humidity, rainfall), soil characteristics (moisture, pH, nutrient levels), and water quality (pH, EC, level). These sensors provide the essential inputs that drive decision-making processes, whether performed manually by operators or autonomously by control systems.

At the heart of such systems lies the Programmable Logic Controller (PLC), which serves as the central processing unit for automation. PLCs are widely adopted in agricultural automation due to their robustness, flexibility, and ability to execute real-time control logic [34][33]. They interface directly with a broad array of sensors through analog [47][48] and digital I/O modules], and support industrial communication protocols like RS485 and Modbus RTU, enabling seamless integration with weather stations and other monitoring equipment **Figure II.1** illustrates the fundamental components of a typical PLC system.

By examining the principles and implementation of sensor monitoring within PLC-based systems, this chapter lays the foundation for understanding how smart farming technologies operate and evolve, ultimately contributing to more sustainable and efficient agricultural practices.

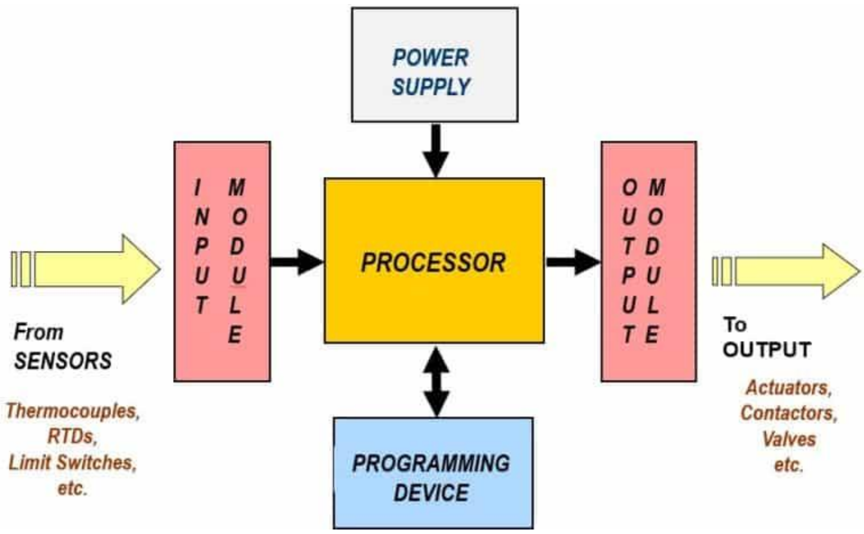


Figure II.1 Architecture of Programmable Logic Controller (PLC)

II.2 The Main Programming Languages Used in PLC Systems

Programmable Logic Controllers (PLCs) are essential components in industrial automation. Historically, providers of PLCs often offered their own, specific programming platforms. However, over the last decade, many major European, Asian, and American PLC providers have begun offering new platforms based on the IEC 61131-3 standard. This standard aims to standardise controller programming, covering elements such as data types, programming languages, functions, and basic function blocks. It also introduces the concept of Programmable Organization Units (POUs)-such as programs, functions, and function blocks-to support reusable and transferrable code across various hardware platforms[40].

The IEC 61131-3 standard defines five programming languages as shown in Figure II.2 , specifying their syntax, semantics, and practical use cases. These languages are: LD (Ladder Diagram) [33], IL (Instruction List), FBD (Function Block Diagram), ST (Structured Text), and SFC (Sequential Function Chart) [37][46].

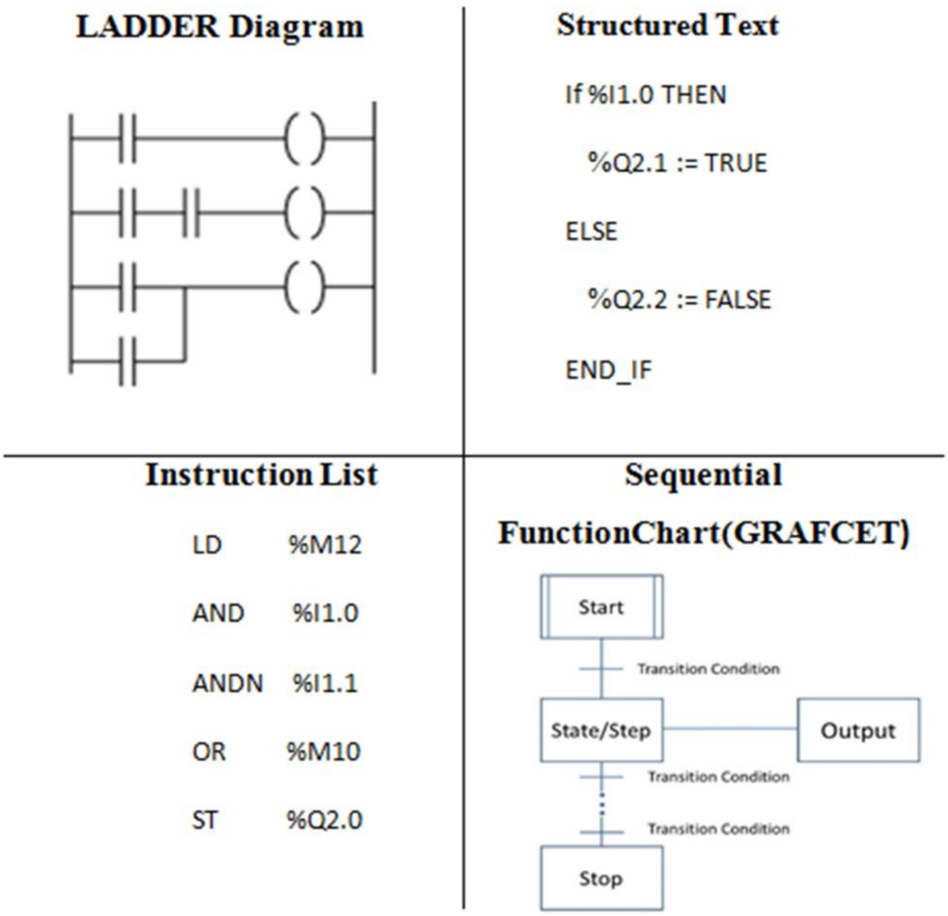


Figure II.2 PLC Programming languages(IEC 61131-3)

II.2.1 LADDER LOGIC

Ladder Diagram (LD) is a visual programming language commonly used in industrial control systems. Its structure mimics traditional relay-based electrical schematics, making it accessible for technicians familiar with wiring diagrams. LD is especially suitable for representing simple digital logic and boolean operations in a clear, left-to-right flow[33].

Ladder Logic is widely adopted in both legacy and modern automation systems. It is especially useful in applications involving digital inputs/outputs and simple control logic. However, LD has limitations when it comes to implementing complex algorithms, as it lacks features such as routines, functions, and encapsulation. This can lead to longer, harder-to-maintain programs in complex systems.

II.2.1.1 Basic Elements: Contacts and Coils in Ladder Logic

Ladder Diagram uses standardized graphical symbols to represent logical conditions and actions. Among the most fundamental elements are **contacts** and **coils**, which simulate the behavior of physical relays and switches.

a. Normally Open Contact (NO)

This type of contact represents control logic inputs, such as switches, sensors, output contacts, or internal control flags. During execution, the referenced input is evaluated for a **TRUE** (logical 1) condition. If the condition is met, the contact closes, allowing logic to flow from left to right. If the condition is **FALSE** (logical 0), the contact remains open and blocks logic flow.

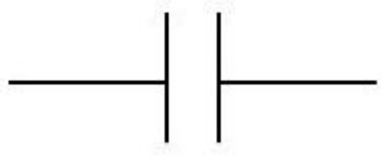


Figure II.3 Normally Open Contact diagram

b. Normally Closed Contact (NC)

Normally Closed Contacts are used to detect a **FALSE** (logic 0) condition. If the input is OFF, the contact closes and allows logic to pass. If the input is ON (logic 1), the contact opens and prevents logic from continuing.

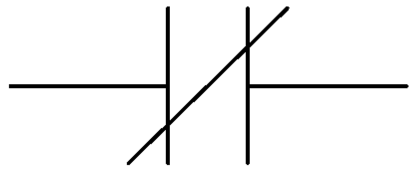


Figure II.4 Normally Closed Contact diagram

c. Normally Open Coil

This element represents a discrete output in the control system. When evaluated, if the logic path to the left of the coil is **TRUE**, the referenced output is energized (logic 1). If the logic condition is **FALSE**, the output remains de-energized.

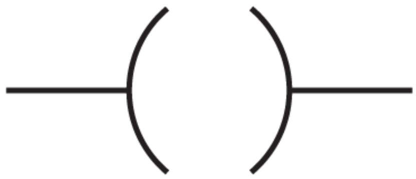


Figure II.5 Normally Open Coil diagram

d. Normally Closed Coil

A Normally Closed Coil behaves inversely. If the logic condition is **0**, the output is turned ON. If the logic is **1**, the output is turned OFF.

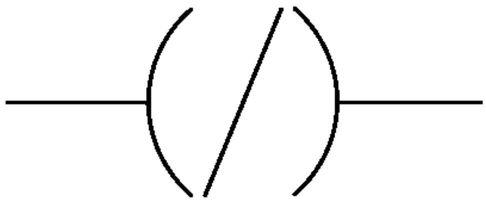


Figure II.6 Normally Closed Coil diagram

II.2.1.2 Boolean Logic in LD: AND and OR Gates

- **AND Gate Logic:**

  To represent an AND condition, two or more contacts are placed in series within a rung. For the output (such as a coil) to be activated, all series-connected contacts must be TRUE.

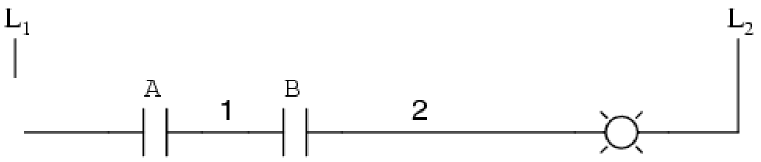


Figure II.7 Simplified AND gate

- **OR Gate Logic:**

  An OR condition is created by placing contacts in parallel. If any of the parallel contacts is TRUE, logic flows to the output. The output is only FALSE if all inputs are FALSE

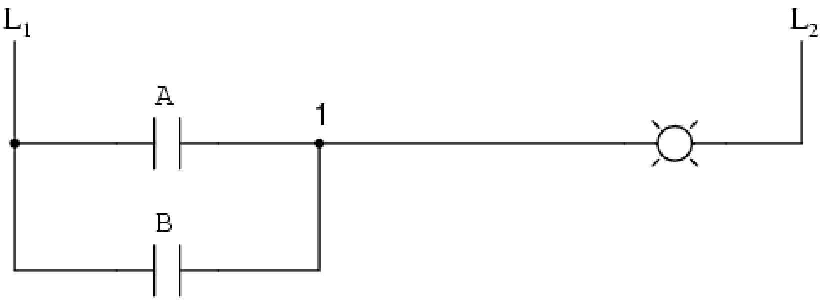


Figure II.8 Simplified OR gate

II.2.2 Function Block Diagram (FBD)

Function Block Diagram (FBD) is a graphical language that uses interlinked function blocks to represent logic and mathematical operations. It is ideal for applications that require repetitive or structured control, particularly in processes dealing with analog signals and numerical data. FBD promotes modularity and clarity in design[40].

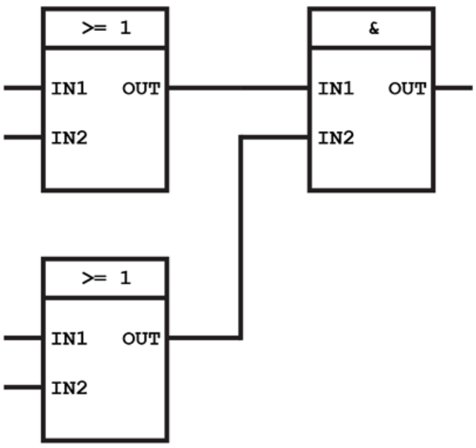


Figure II.9 Basic Function Block Diagram

II.2.2.1 FBD Components and Structure

FBD consists of basic blocks used to create logical or arithmetic relationships between input variables (on the left) and output variables (on the right). These blocks may include:

- Basic logic operations (e.g., AND, OR, ADD, SUB)

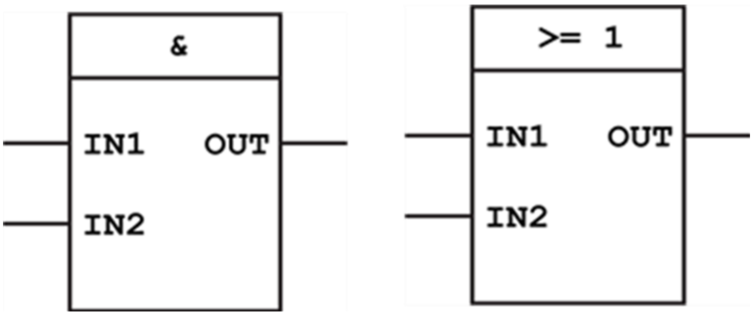


Figure II.10 Example of basic logic blocks (AND / OR)

This image shows how the logical operations AND and OR are represented in FBD.

- Comparison functions (e.g., Less Than LT, Greater Than GT, Equal EQ, Not Equal NE)
- Mathematical functions (e.g., SIN, ABS)
- Standard or user-defined function blocks

These blocks are reusable units that may perform a subroutine, a function, or a complete function block. FBD function blocks encapsulate data and methods in a way similar to object-oriented programming (OOP), although they do not support inheritance or polymorphism.

II.2.3 Sequential Function Chart (SFC)

Sequential Function Chart (SFC) is a graphical language tailored for programming processes that follow a specific sequence of operations. It breaks down control logic into steps and transitions, making it highly effective in systems that require step-by-step execution such as batch processing and machine cycles[37].

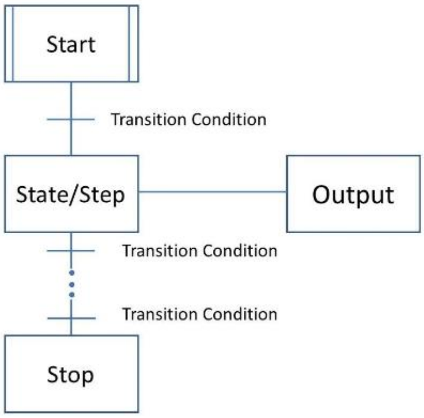


Figure II.11 SFC diagram

II.2.3.1 Components and Structure of SFC

SFC programs are composed of three primary elements: Steps**,** Actions**, and** Transitions**.**

- **Steps**: Each **step** represents a specific state in the process. It can be either active or inactive. Steps are displayed in sequential order and have associated actions. Only certain steps are active in each cycle, and each step has a unique number[46].

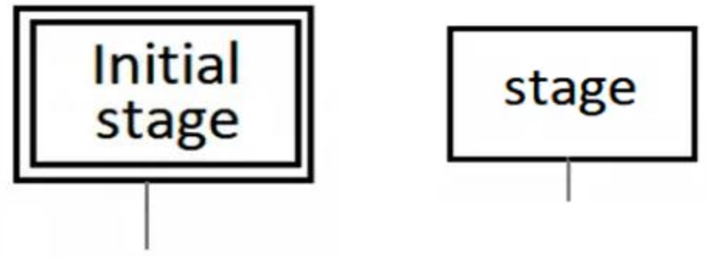


Figure II.12 step(stage) in Sequential Function Chart

- **Transitions:** a transition acts as a connection between two steps, shown as a horizontal line crossing a vertical line. It contains the logical condition that allows the transfer from one step to another. Transitions are linked to a condition, which can be a logical function of inputs and internal system variables [46].

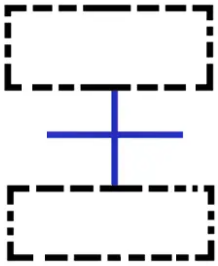


Figure II.13 transition in Sequential Function Chart

- **Actions:** actions are associated with the steps and are represented by a rectangular side box indicating the type of action to be performed. A step can have one or more actions linked to it, and these actions are only active when the step is active. The process is broken down into steps, which are activated sequentially[46].

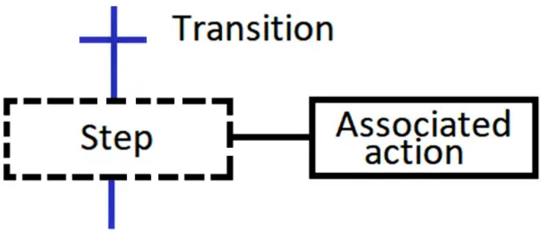


Figure II.14 action in Sequential Function Chart

Sequential Function Chart (SFC) is a powerful and highly structured graphical language tailored for sequential operations in PLC systems. While it excels in clarity, organization, and user accessibility, it may not be suitable for all applications—particularly those requiring fast execution or advanced computational capabilities. Nonetheless, it remains a popular and valuable tool in the field of industrial automation.

II.2.4 Structured Text (ST)

Structured Text (ST) is a high-level textual language used for complex control algorithms and data-intensive applications. Inspired by conventional programming languages like Pascal and C, ST is preferred when developing functions that involve calculations, conditional logic, and structured programming[40].

a. Structure and Syntax

Structured Text follows a well-defined syntactic framework with similarities to general-purpose programming languages. Its key structural features include:

- Loop constructs like **FOR, WHILE-DO**, and **REPEAT-UNTIL**, enabling iterative processes.
- Conditional statements such as **IF-THEN-ELSE** and **CASE**, allowing branching logic.
- Semicolon-terminated lines, maintaining clear separation of statements.
- Support for variable assignments, function and function block calls, mathematical and logical expressions, and operator selection.
- Algorithmic execution through a sequence of operators that calculate and assign values, control execution flow, and manage transitions within Program Organisation Units (POUs).
- Instructions can be organized across multiple lines or condensed into single-line statements, offering flexibility in programming style.

Example: Conditional Statements (IF-THEN-ELSE)

Let's say we want to turn on a motor if the temperature exceeds 50 degrees Celsius; otherwise, it should be turned off. This can be represented in **ST** as follows:

```
IF Temperature > 50.0 THEN

   Motor_ON := TRUE;

ELSE

   Motor_ON := FALSE;

END_IF;
```

- Temperature is a variable representing the temperature reading.
- Motor_ON is a boolean variable that controls the motor's state (TRUE for ON, FALSE for OFF).
- The IF-THEN-ELSE structure is used to make a decision based on the Temperature value.

II.3 HMI (Human-Machine Interface) and SCADA

In the context of modern automation systems, effective control of processes is not the only crucial aspect; it extends to the ability to monitor and adjust them with ease. This is where the vital role of Human-Machine Interfaces (HMIs) and Supervisory Control and Data Acquisition (SCADA) systems emerges. These technologies serve as a bridge connecting Programmable Logic Controllers (PLCs) and complex industrial processes on one hand, with human operators on the other. This integration provides real-time insights and centralized control capabilities, enhancing operational efficiency and decision-making in applications such as smart agriculture and diverse industrial environments[31], as typically configured in Figure II.15.

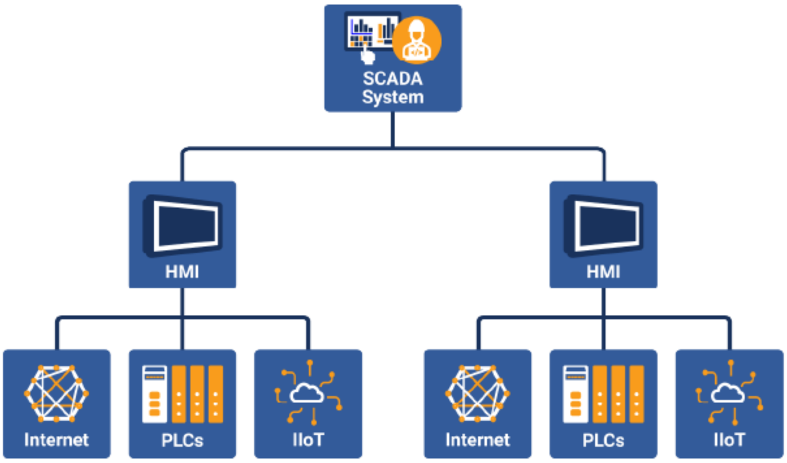


Figure II.15 Traditional HMI Configuration within a SCADA System

II.3.1 Human-Machine Interface (HMI) in Industrial Automation

The Human-Machine Interface (HMI) refers to the platform or software that facilitates interaction between humans and machines in industrial and automation systems. It plays a critical role in supervisory control and data acquisition (SCADA) systems and in PLC-based automation environments.

HMIs provide visual representations of industrial processes, display real-time data, allow manual input for control, and log alarms and historical trends. Their core objective is to simplify the interaction between operators and complex automated processes. Through graphical user interfaces (GUIs), HMIs convert raw data into intuitive visuals such as graphs, status indicators, alarms, and dashboards, enabling informed decision-making.

Modern HMIs are deployed across a wide range of industries, including manufacturing, energy, transportation, and water treatment. They range from simple touch panels with basic control features to advanced multi-screen systems with data analytics, user access management, and remote connectivity [43].

II.3.2 HMI in PLC-Based Systems

In PLC-based control systems, the HMI acts as a critical communication bridge between the operator and the PLC. While the PLC handles control logic and interacts directly with field devices such as sensors, actuators, motors, and valves, the HMI visualizes system status and receives operator commands to pass to the PLC.

II.3.2.1 Key HMI functions in a PLC environment include

- **System Monitoring:** Displaying sensor data, machine status, and alarms in real-time.
- **Manual Control:** Allowing operators to start/stop processes and adjust parameters.
- **Data Logging:** Recording historical operational data for analysis.
- **Alarm Management:** Notifying users of system faults or abnormal events.
- **User Access Control:** Regulating access levels and securing sensitive operations.

II.3.2.2 Case Study: HMI Design for a Motor Control System

A practical implementation of an HMI in a PLC-based system is presented by Xiaoming Cui et al. [42], who developed a motor speed control system using variable-frequency drives (VFDs) and HMI.

Their system utilized the MCGS embedded configuration software and was structured into six distinct functional pages:

- Main Interface
- Control Panel
- Operation Monitoring
- Parameter Settings
- User Management
- Event History

This structured design ensures that users can easily navigate through various system functionalities.

Figure II.16 illustrates the overall interface structure of the HMI, showing how different functional screensare organized to support logical process control and user interaction. This hierarchical layout improves usability by allowing operators to access specific system are<

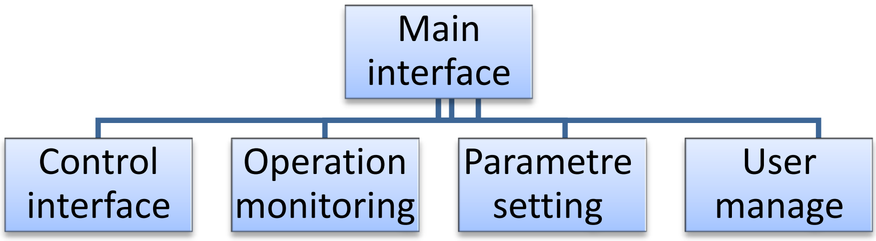


Figure II.16 HMI Interface Design Structure showing organized navigation layout

Figure II.17 presents the control interface screen of the HMI. It provides real-time visualization of key parameters for multiple motors (M1, M2, M3) and variable frequency drives (VFD1, VFD2), including operational status and control states. This screen enables operators to monitor and manage the motor control system with high precision and responsiveness [42].

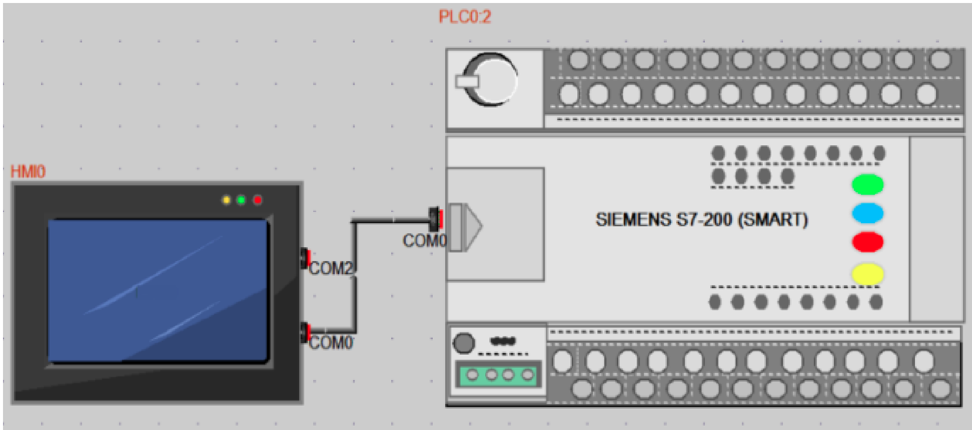


Figure II.17 HMI Control Interface for Motor and Drive Monitoring

This example demonstrates how a well-designed HMI can significantly enhance the flexibility, usability, and automation efficiency of a PLC-based industrial control system.

This structured layout improves usability and system navigation.

II.3.3 Supervisory Control And Data Acquisition*(SCADA)*:

Supervisory Control and Data Acquisition (SCADA) refers to a category of software and hardware systems designed to monitor and control industrial processes and infrastructure across wide geographical areas. A SCADA system enables centralized supervision and real-time control of field devices such as sensors, actuators, and controllers deployed in various sectors including industry, utilities, and agriculture [44].

At its core, SCADA provides a comprehensive framework for collecting data from remote locations, transmitting it to a central control unit, analyzing it, and enabling both automated and manual responses based on the system's status. It combines real-time data acquisition, process visualization, event logging, alarm management, and supervisory-level decision-making within an integrated environment[45].

Unlike traditional local control systems, SCADA operates at a higher level, focusing on the centralized monitoring and coordination of distributed systems. It is widely used in applications such as power grid control, water and wastewater management, oil and gas pipelines, transportation systems, and precision agriculture [38] [45].

II.3.4 Integration of SCADA with PLC Systems

In modern automation environments, Programmable Logic Controllers (PLCs) and SCADA systems are often deployed together to achieve comprehensive and efficient control architectures. While PLCs operate as real-time controllers executing logic at the field level, SCADA systems serve as the supervisory layer that oversees, visualizes, and coordinates the entire process [38].

The typical workflow involves PLCs collecting data from sensors and executing local control strategies, then transmitting this data to the SCADA system, which logs, analyzes, and displays the information for operators. SCADA systems can also send high-level control commands back to the PLCs when needed [31].

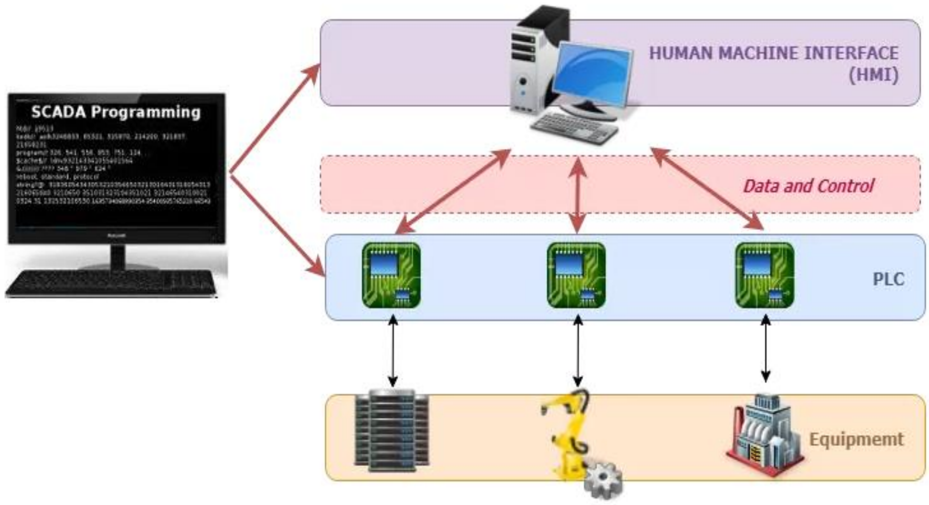


Figure II.18 SCADA Diagram Example System with Main Components

This integration offers several key benefits:

- **Centralized Monitoring:** SCADA provides a unified view of multiple PLCs across a plant or distributed sites.
- **Data Logging and Visualization:** Real-time and historical data from PLCs is stored and visualized through the HMI layer of SCADA.
- **Remote Control:** Operators can send setpoints or control commands to PLCs via the SCADA interface.
- **Alarm and Event Management:** SCADA systems manage alarms generated by PLCs and ensure timely operator intervention.
- **Scalability:** SCADA can integrate with dozens or hundreds of PLCs across a large-scale infrastructure.

This layered control structure where PLCs handle local automation and SCADA handles supervisory control results in a powerful, flexible, and scalable automation solution for industrial and infrastructure systems [38] [31].

II.3.5 Common Application Areas of SCADA

SCADA is implemented across diverse domains beyond traditional industrial use. Its flexibility, scalability, and remote access capabilities make it essential in many sectors:

- **Industrial Automation:** Monitoring and controlling assembly lines, robotics, and chemical processing plants.
- **Energy and Utilities:** Managing power generation (conventional and renewable), electricity grids, substations, and load balancing [38].
- **Water and Wastewater Management:** Controlling pumping stations, reservoirs, and treatment plants for safe and efficient water supply.
- **Oil and Gas Pipelines:** Supervising flow rates, pressure, leakage detection, and emergency response.
- **Agriculture:** Automating irrigation systems, soil moisture monitoring, and greenhouse climate control for efficient crop management [32].
- **Smart Buildings and Facilities:** Monitoring HVAC systems, lighting, fire safety, and energy usage in commercial buildings.
- **Transportation and Traffic Control:** Managing railway networks, highway traffic lights, and tunnel safety systems.

The figure below (II.19) provides a visual representation of these common application areas where SCADA systems are widely utilized.

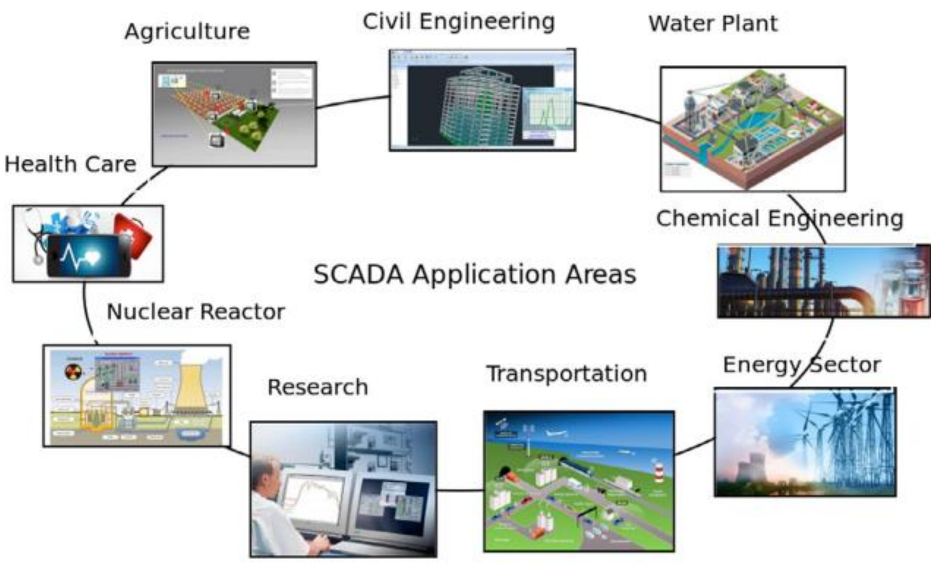


Figure II.19 SCADA Application Areas in Industrial and Infrastructure Sectors [45]

SCADA systems serve as the "nervous system" of modern infrastructure, enabling remote diagnostics, predictive maintenance, and operational efficiency through real-time insights and automated decision-making [45][32].

II.3.6 Case Study: Tank Level Automation Using PLC, SCADA, and HMI

This study aims to demonstrate how to automate liquid-level measurement in a tank using a Programmable Logic Controller (PLC) and provide real-time user interface monitoring through a SCADA and HMI system. Through this application, we seek to achieve automatic control of valve opening and closing based on changing tank levels, prevent overflow or dry-run situations, and improve the accuracy and efficiency of pumping operations, while illustrating the ability to continuously monitor the tank's operational status via HMI screens and analyze the collected data in SCADA [38] as shown in Figure II.20.

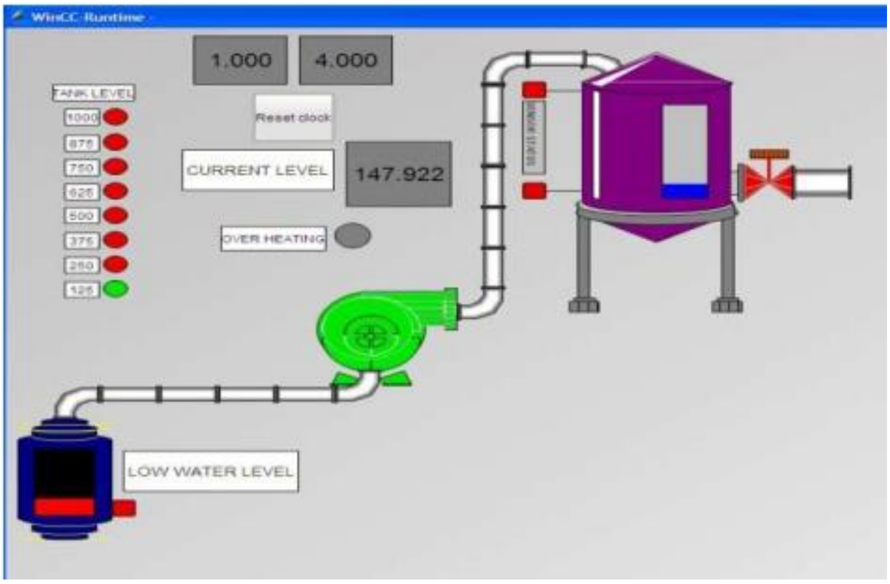


Figure II.20 SCADA Interface for the Tank Level Control

II.3.7 System Component Description

The system is organized into four primary modules:

1. Level Sensor
2. PLC (Programmable Logic Controller)
3. Relay and Motor
4. HMI (Human-Machine Interface)

The level sensor continuously measures the current liquid level in the tank and sends this information to the PLC. Based on the sensor input, the PLC determines whether to switch the motor (via the relay) ON or OFF. The overall system status is communicated to a computer through MPI (Multi-Point Interface), allowing the user to monitor and control operations remotely via the HMI.

II.4 Analog and Digital Sensor of PLC

Sensors "both analog and digital" are fundamental and indispensable components of modern agriculture, especially in the context of automation and Supervisory Control and Data Acquisition (SCADA) systems. These sensors function as the primary interface between the physical environment and digital control systems, enabling situational awareness by continuously collecting real-time data on key environmental and crop-related parameters. This sensor-derived data constitutes the foundation for efficient monitoring, autonomous control, and informed, data-driven decision-making processes.

II.4.1 Analog Signals and Sensors with PLCs

Analog sensors produce a continuous output signal (voltage or current) that's directly proportional to the physical quantity being measured, such as temperature, pressure, liquid level, or flow rate [48]. These differ from digital sensors, which simply provide an "on/off" signal.

Although PLCs operate with binary (0 and 1) values, they can translate analog electrical signals into binary numbers [47]. For this purpose, Analog Input Modules are used within the PLC. These modules contain Analog-to-Digital Converters (ADCs) that transform the continuous analog signal from the sensor into a digital value the PLC can process [47].

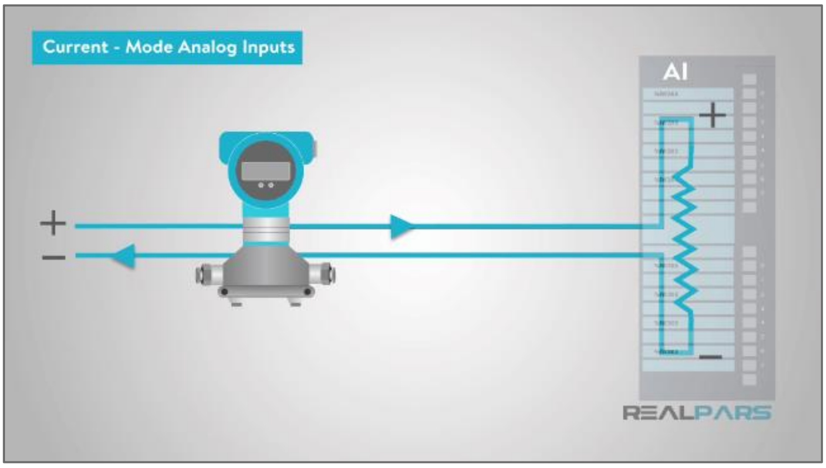


Figure II.21 Analog Sensor (Current Signal) Connection to a PLC Analog Input Module

This figure illustrates how an analog sensor (current signal) is connected to an Analog Input (AI) module in a Programmable Logic Controller.

II.4.2 Common Analog Input Signal Types (0-10V and 4-20mA)

There are two primary types of analog input signals commonly used by sensors and PLC modules [47]:

- **Voltage Signal:**
  - **0-10 VDC (0-10 Volts Direct Current)**: This common analog control signal is frequently used in the HVAC sector for controlling damper and valve actuators, Variable Frequency Drive (VFD) control, and various sensors [47].

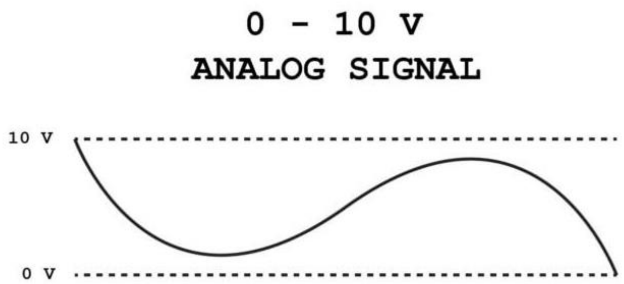


Figure II.22 Analog signal (0 – 10)

- **Current Signal:**
  - **4-20 mA (4-20 Milliamperes)**: This signal is typically used in the process automation industry to send signals from field instruments and sensors to a controller. It offers greater immunity to interference compared to voltage-based signals [47]. The 4-20mA signal is also part of the IEC 61131 standard for analog signals in PLCs [48].

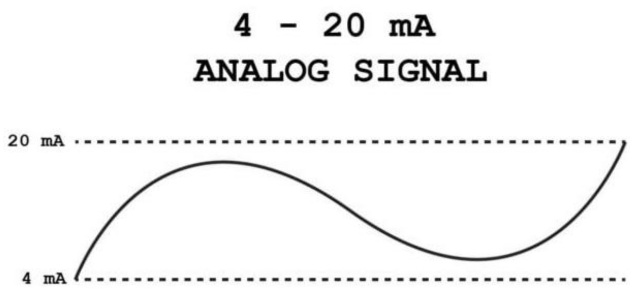


Figure II.23 Analog signal (0 – 10)

Within the PLC, analog signals are represented using binary numbers, and the resolution of the analog signal conversion depends on the number of bits used in the conversion process [48].

II.4.3 Digital Sensors and Signals

Digital sensors, also known as binary sensors, are devices that output either an **"ON"** or **"OFF"** signal, logically represented as 1 or 0 respectively [50]. These sensors are among the most common in PLC systems [52].

II.4.3.1 How Digital Sensors Work with PLCs:

Digital sensors are connected to **Digital Input Modules** in the PLC [53]. Each digital input on the PLC reads the "ON" or "OFF" state from the connected sensor, and the PLC processes this binary signal to make decisions within the control program [50]. It is important to understand the wiring types of digital sensors, such as PNP (Sourcing) and NPN (Sinking), to ensure correct connection to the PLC input modules [51][53].

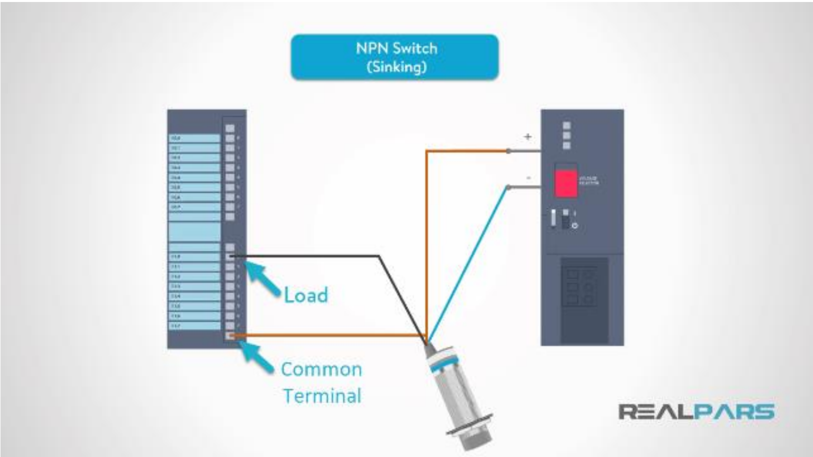


Figure II.24 Digital Sensor (NPN Switch) Connection to a PLC Module

This figure illustrates how an NPN type digital sensor is connected to an input on a Programmable Logic Controller module.

II.4.4 Comparison Between Analog and Digital Sensors

a) Signal Type

- Analog Sensors: Produce a continuous electrical signal (voltage 0-10V or current 4-20mA) that varies proportionally with the measured physical parameter.
- Digital Sensors: Output discrete digital signals (ON/OFF state or 0/1values) or communicate through digital protocols (e.g., I2C, 1-Wire).

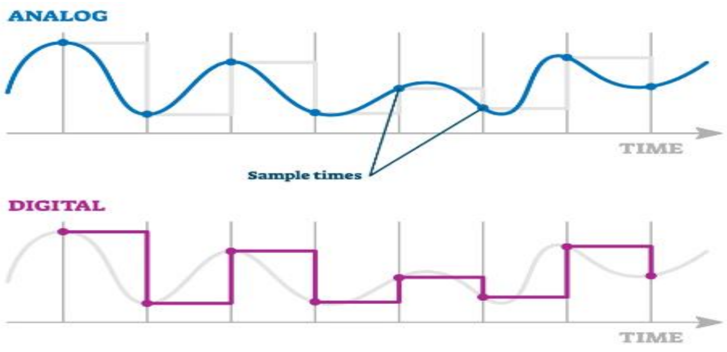


Figure II.25 Analog vs digital signals

b) Data Processing

❖ **Analog Sensors:**
  - Require signal conditioning (e.g., voltage scaling, amplification).
  - Need Analog-to-Digital Converters (ADC) for use with microcontrollers or PLCs.

❖ **Digital Sensors:**
  - Provide output directly in digital format.
  - Can be directly connected to controllers without requiring ADCs.

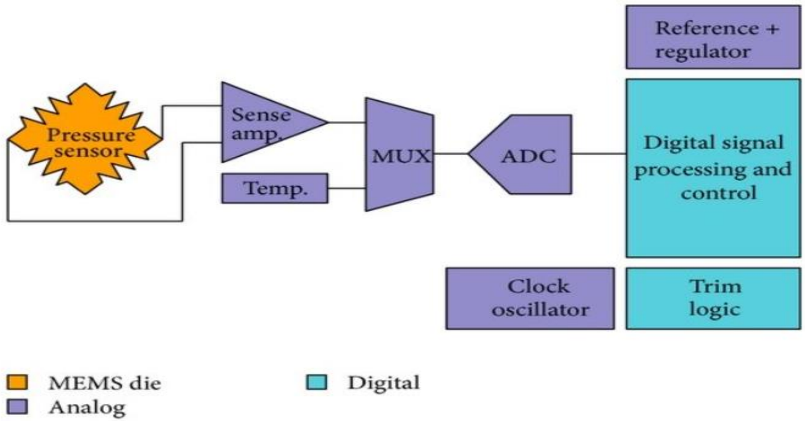


Figure II.26 Example of a sensor circuit, with highlighted analog and digital blocks, eventually sharing the same chip and power supplies.

II.4.4.1 Applications and Examples

The table below presents examples of PLC-compatible sensors commonly used in smart agriculture. It distinguishes between analog and digital types based on their signal output. Analog sensors typically use 0–10V or 4–20mA signals, while digital sensors provide simple ON/OFF signals. Each sensor is matched with a practical application to show how it contributes to automation and monitoring in agricultural systems.

Sensor Type	Example	Signal Type	Application
Analog	PT100 RTD (with transmitter)	4–20 mA	Precise soil temperature monitoring
Analog	Capacitive Soil Moisture Sensor (analog)	0–10 V	Automated irrigation systems
Digital	IFM O6H-FPKG/0.3M	ON/OFF	Object detection in greenhouse automation
Digital	SICK WTB4-3P2431	ON/OFF	Crop position sensing on conveyor systems
Analog	Druck PMP 140	4–20 mA	Monitoring water pressure in irrigation pipelines
Analog	Vegabar 38	0–10 V	Monitoring liquid fertilizer levels

Table II.1: PLC Sensors and Applications.

II.5 Conclusion

The systematic integration of monitoring and sensor technologies within PLC-based control architectures has proven to be a cornerstone for advancing smart agriculture. This chapter has thoroughly explored how these crucial components work in concert to enhance productivity, optimize resource utilization, and significantly reduce the need for manual intervention in modern farming practices.

We delved into the fundamental aspects of sensor monitoring, emphasizing the collection of real-time data across various agricultural parameters—from environmental conditions and soil characteristics to water quality. Furthermore, we examined the pivotal role of Programmable Logic Controllers (PLCs) as the central processing units in these automated systems, highlighting their robustness, flexibility, and their seamless interface with diverse sensor types through analog and digital I/O modules, alongside industrial communication protocols. The chapter also detailed the key programming languages (LD, IL, FBD, ST, SFC) that empower PLCs to execute sophisticated control logic.

As we draw this chapter to a close, having established the foundational understanding of monitoring and sensors within PLC-based systems, our focus now shifts towards more specialized advancements. The upcoming **Chapter III: Innovative Sensors for Smart Agriculture** will further delve into the development, implementation, testing, and integration of novel sensor technologies specifically designed to push the boundaries of precision and efficiency in agricultural environments.

Chapter III:

Implementation of Innovative Sensors for Smart Agriculture

III.1 Introduction

In the face of increasing demands for food production and growing concerns over water scarcity, the agricultural sector must adopt smart, automated technologies to ensure sustainability and efficiency. Smart agriculture-driven by sensor integration, automation systems, and real-time data monitoring-offers innovative solutions to these challenges. Central to this transformation is the implementation of intelligent sensors capable of tracking key environmental and operational parameters, such as water levels, flow rates, and equipment positioning [54][55].

This chapter focuses on the design and implementation of a sensor-based system to support efficient water management and precision irrigation in agricultural settings. Specifically, we present the development and integration of two primary sensors: a water level sensor for monitoring storage tanks and a flow switch sensor for detecting water movement through pipelines. The water level sensors are vital for ensuring accurate monitoring of water resources, avoiding shortages or waste, while flow sensors ensure the efficient distribution of water throughout irrigation systems [56][60]. Additionally, we address the importance of pivot position monitoring, a critical aspect of controlling irrigation systems to ensure uniform water distribution across cultivated land and optimize the number of turns and overall system coverage [61][62].

The system's hardware development involves the selection of electronic components, PCB (Printed Circuit Board) design, and sensor assembly. Once built, the system is integrated with Siemens S7-1200 PLCs, enabling real-time control and automation. The use of PLC systems provides flexibility in programming and allows the continuous monitoring of water levels and flow, improving the precision of irrigation management [63][64]. A SCADA (Supervisory Control and Data Acquisition) interface, including HMI (Human-Machine Interface), is used to monitor the performance and effectiveness of the sensors, providing a user-friendly visualization and control environment [65][66].

Moreover, the pivot position system used to monitor the orientation, movement, and number of rotations of irrigation pivots is developed using Arduino-based technology, offering a cost-effective and flexible platform for sensor deployment and testing. Accurate pivot control is vital in modern irrigation systems to prevent overwatering or under-irrigation and to optimize water usage based on field geometry and crop needs [67] [68].

The chapter details each stage of the system’s development, from component selection and circuit design to integration, testing, and validation. These efforts aim to demonstrate how sensor based smart systems can significantly enhance agricultural practices by reducing water waste, increasing automation, and improving data-driven decision-making. By combining PLCs, SCADA systems, and microcontroller platforms like Arduino, the proposed system exemplifies a hybrid approach to smart agriculture implementation, offering a comprehensive solution to modern farming challenges [59] [69].

III.2 Proposed Sensors

To enable efficient monitoring and control in smart agricultural systems, three types of sensors are proposed in this work: a Level Water Sensor, a Flow Switch Sensor, and a Pivot Irrigation Position Sensor. Each sensor plays a crucial role in managing water resources and ensuring optimal performance of the irrigation infrastructure. The sensors are designed to be integrated with control systems such as PLCs and microcontrollers, allowing real-time monitoring, automation, and enhanced decision-making. The following subsections detail the operating principles and technical design of each sensor.

III.2.1 Level Water Sensor

The Level Water Sensor is essential for monitoring the water level in storage tanks or reservoirs. Accurate level detection allows for efficient water resource management, preventing overflow or dry-run conditions in irrigation systems.

The proposed design operates based on an electromechanical principle involving a relay module and a transistor switching circuit. The core of the sensor includes a set of electrodes or float mechanisms that detect the water level. When water makes contact with the electrode or float reaches a certain height, a signal is triggered.

This innovation contributes to simplifying the process of monitoring water levels within tanks through an electronic design free from mechanical components. This approach ensures higher reliability and fewer failures during operation. Unlike traditional sensors that rely on float mechanisms or fixed-level digital signals, this sensor provides continuous and gradual level measurement, offering greater precision and flexibility.

Short-Term Benefits:

- Enhances the accuracy and efficiency of monitoring systems.
- Supports applications in smart irrigation, the food industry, and pumping stations.

- Reduces installation costs and system complexity.

Long-Term Potential:

- Enables integration with Internet of Things (IoT) technologies for fully connected water management systems.
- Paves the way for more advanced smart solutions in the field of water resource management.

List of Components as shown in Figure III.1:

1. Voltage divider resistors
2. Transistors
3. Base resistors for transistors
4. Power supply
5. PLC system
6. Water tank
7. Water contact point at the second level

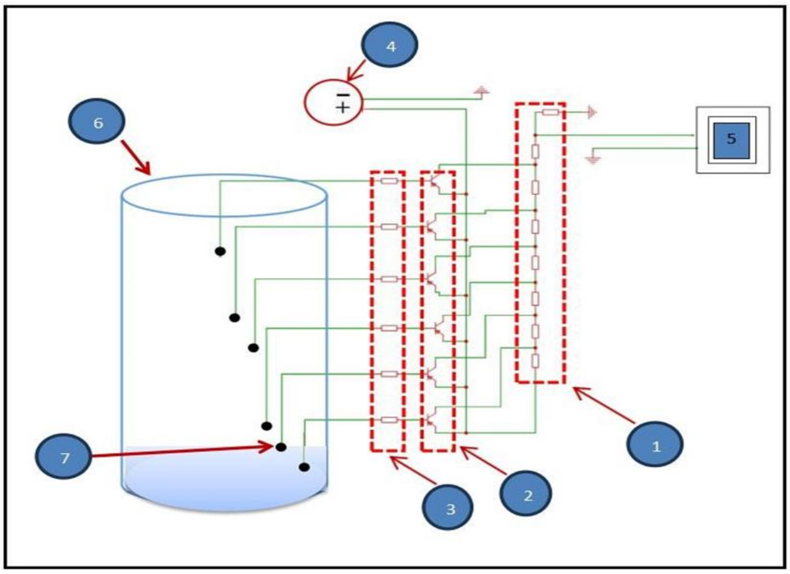


Figure III.1: Illustrative Diagram of Sensor Operation

III.2.2 Flow Switch Sensor

This section presents the design of a cost-effective and reliable electronic sensor intended for detecting water flow in agricultural and industrial systems. The sensor operates based on a straightforward principle: it measures the electrical resistance between two conductive needles inserted into the pipe. The presence of water changes the resistance, triggering a digital signal that can be directly transmitted to control systems such as a Programmable Logic Controller (PLC). This eliminates the need for complex mechanical components or expensive electronic circuits.

The proposed design ensures a fully electronic system devoid of moving parts, significantly reducing the risk of mechanical failure and improving operational reliability. Its compact architecture allows for quick response to variations in water flow, making it particularly suitable for environments that require low-cost, easy to install, and high-performance monitoring solutions.

This flow switch sensor serves as an intelligent, non-intrusive solution for detecting water presence without disrupting the flow or relying on internal mechanical parts. Its simplicity and efficiency make it ideal for integration into smart agricultural or industrial automation systems.

The operating principle of the device is illustrated in **Figure III.1**, which highlights the main components of the circuit:

1. Resistors
2. Transistor
3. Voltage Regulator
4. LED Indicator
5. Connection Terminals
6. Printed Circuit Board (PCB)
7. Water Sensing Needles
8. Protection Diode
9. Relay

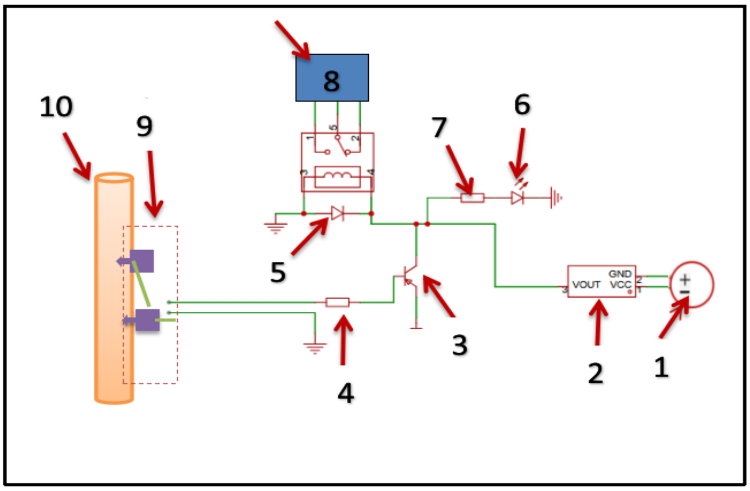


Figure III.2: Schematic Diagram of the Device Operation

III.2.3 Pivot Irrigation Position Sensor

The Pivot Irrigation Position Sensor is designed to track the rotational position of a center pivot irrigation system, which is critical for managing coverage, timing, and efficiency of irrigation cycles.

This sensor relies on a magnetic switching mechanism. The system consists of:

- Ten small permanent magnets fixed along the rotating structure
- Magnetic reed switches (or Hall sensors) placed at fixed positions
- Each full rotation of the pivot causes the magnets to pass by the fixed switches
- The switches toggle ON/OFF depending on the magnetic field's presence

This toggling generates pulses corresponding to the pivot’s movement. The number and timing of these pulses allow calculation of:

- Total number of turns completed by the pivot
- Current angular position
- Speed of rotation

The graphical representation includes the circular layout of magnets, placement of switches, and signal wiring to an Arduino microcontroller, which processes the pulse data [12].

This information can be displayed or relayed to an HMI or SCADA system for real-time visualization and control [65][73].

III.3 Implementation of Sensors

This section presents the practical realization and integration of the three proposed sensors into smart monitoring systems. Each sensor is designed and developed using a tailored set of electronic and electromechanical components to fulfill its specific function: water level measurement, flow detection, and pivot position sensing for irrigation systems. The designs emphasize simplicity, robustness, and full compatibility with automated control systems, particularly Programmable Logic Controllers (PLCs).

Each sensor system includes a combination of key components such as PNP transistors, resistors, diodes, LED indicators, voltage regulators, relay modules, magnetic switches (reed switches), and permanent magnets. The use of magnetic sensors enhances detection reliability, especially in harsh or wet environments where non-contact measurement is preferred. The integration of voltage divider circuits, header connectors, and protective elements ensures stable signal transmission to the PLC.

All circuits are assembled on printed circuit boards (PCBs) that organize and secure the components while maintaining electrical safety and facilitating maintenance. The inclusion of relays allows for reliable switching between states based on sensor activation. Furthermore, visual feedback is provided via LEDs to indicate sensor status during operation.

The comprehensive list of components used in the construction of these sensors is detailed in the following table:

Hardware	Description	Quantity
PCB Board	Provides a platform for mounting and connecting all components	3
PNP Transistors	Used to detect activation based on water contact or signal logic	4 per sensor
Resistors	Limit current and enable voltage division	Various
Diodes	Protect transistors from reverse voltage	As required
LEDs	Indicate sensor status (e.g., water detected, flow present, pivot aligned)	3–6
Voltage Regulator	Steps down and stabilizes voltage (e.g., 24V to 12V)	1 per sensor
Relay Module	Acts as an electromechanical switch triggered by sensor outputs	1–2 per sensor
Header Connectors	Facilitate wiring and connection between sensors and PLC	As required
Magnetic Switch (Reed)	Detects magnetic field presence (used in flow and pivot sensors)	1–2
Permanent Magnet	Triggers reed switch when aligned	1–2
Wires and Probes	Serve as detection elements for water level in tanks	4 per tank

Table III.1: List of Selected Components for All Sensors

These components collectively form the functional base of the three sensor systems, which are essential for the reliable automation of water management and irrigation processes.

III.3.1 Level Water Sensor

The water level sensor is an integrated electronic system designed to monitor the water level in tanks with high accuracy and reliability. It consists of several coordinated electronic components that work together to detect water levels and transmit corresponding electrical signals to a controller, such as a PLC, for further processing.

Main Components:

- **4 PNP Transistors**: Each transistor is activated when water contacts its respective probe level.
- **Resistors**: Used for current limiting and to form a voltage divider circuit for analog signal generation.
- **Voltage Divider Circuit**: Converts the 24V supply into an analog voltage signal (0V–10V), depending on how many transistors are activated.
- **Header Connectors**: Facilitate connections between the probes, the sensor, and the PLC system.
- **Printed Circuit Board (PCB)**: Organizes and holds all electronic components securely in place.

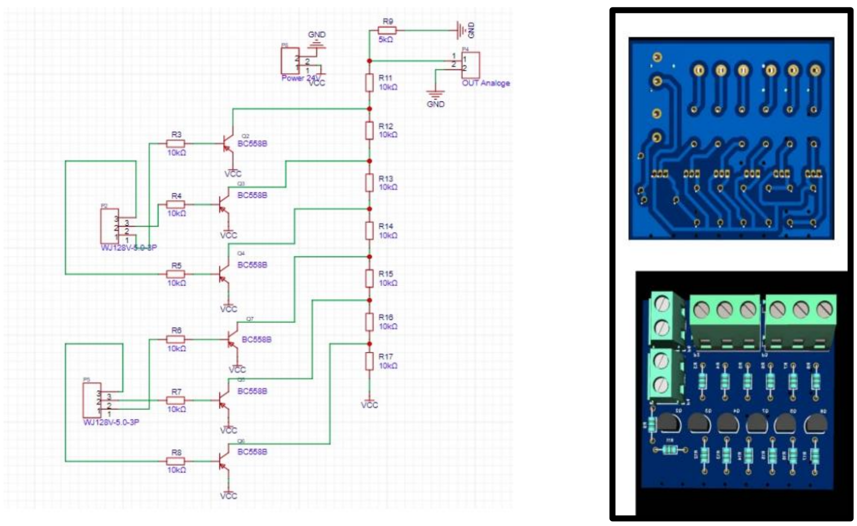


Figure III.3: PCB Layout and Schematic Diagram of the Level-Based Water Sensor

The sensor operates by placing four conductive probes at different heights inside the tank. When the water reaches a given level, it makes contact with the corresponding probe, which allows a small current to activate a PNP transistor. This triggers the transistor to pass a signal through a voltage divider, generating an analog voltage proportional to the number of activated probes.

As water levels increase, additional transistors are triggered, raising the analog output voltage sent to the PLC. This allows continuous and gradual monitoring of the water level rather than binary (on/off) detection.

Water level sensors are essential components in industrial and agricultural automation systems that utilize PLCs. In smart agriculture, these sensors optimize irrigation by accurately monitoring tank or pipe levels, thereby improving water use efficiency, minimizing waste, and Enhancing crop productivity. Integrated with PLCs, they provide real-time data to regulate irrigation processes effectively [60][61].

In industrial applications, such sensors enable automated control of processes, such as activating pumps or valves based on liquid levels [65].
For instance, when a tank reaches a set level, the sensor sends a signal to the PLC to engage or disengage a pump, improving energy efficiency and reducing downtime [65].
These systems are also commonly used in water treatment plants and pumping stations to ensure consistent water flow and supply [73].

Furthermore, water level sensors play a key role in safety and alarm systems by detecting leaks or potential flooding [72].

They are also integral to urban water management systems, where they help monitor and regulate water distribution in reservoirs and supply networks, thereby enhancing resource allocation and service continuity [73]

III.3.2 Flow switch sensor

The sensor we designed consists of an integrated set of electronic components that work together to detect the presence of water flow inside a pipe between two points, then generate an electrical signal that is processed using a controller such as a PLC.

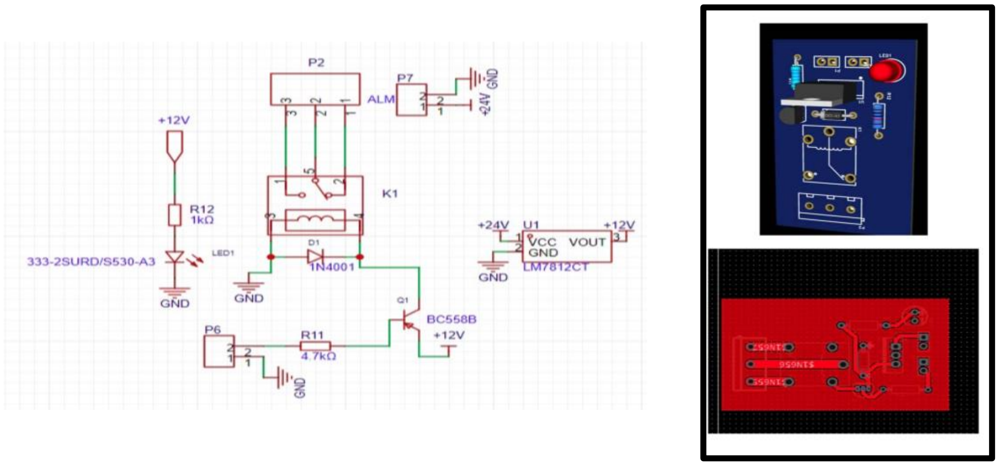


Figure III.4: PCB Layout and Schematic Diagram of the Flow Switch Water Sensor

Elements:

- **12V Relay:** Acts as an electric switch that changes its state upon detecting water flow.
- **PNP Transistor:** Responsible for activating the relay when it senses the electric current generated by water passing between the two probes.
- **Voltage Regulator:** Used to convert the voltage from 24V to 12V to ensure the relay operates within its required voltage range.
- **Protection Diode:** Protects the transistor and relay from potential reverse currents when the circuit switches off.
- **Resistors:** Used to limit the current and protect the other electronic components.
- **LED:** Lights up when water flows, providing a clear visual indication.

. The working principle of the sensor:

The water flow sensor is an innovative electronic device designed to detect the movement of water inside pipes in a simple and reliable manner. The sensor operates by inserting two conductive probes into the pipe, utilizing the natural electrical conductivity of water to detect its presence, providing a low-cost and highly reliable solution compared to traditional mechanical systems. In the absence of water, the electrical circuit between the two probes remains open, preventing the relay from being activated. When water flows, the electrical resistance between the probes decreases, allowing a small current to pass, which activates a PNP transistor. The transistor, in turn, operates a 12V relay, switching it from the Normally Open (NO) state to the Normally Closed (NC) state. This system integrates seamlessly with a control unit such as a PLC, incorporating protection elements like a voltage regulator, diodes, and resistors to ensure stable and reliable operation.

III.3.3 Position Pivot Irrigation Sensor

This section illustrates the implementation of the pivot irrigation position sensor. The accompanying image shows a real-world setup where 10 magnets are evenly distributed on the rotating part of the irrigation system. A magnetic switch (reed switch) is installed on the fixed section.

As the rotating assembly turns, each magnet passes by the fixed magnetic switch, causing it to toggle ON and OFF in succession. This pulse generation accurately records the rotational movement of the pivot, enabling precise monitoring of its position and the number of completed rotations.

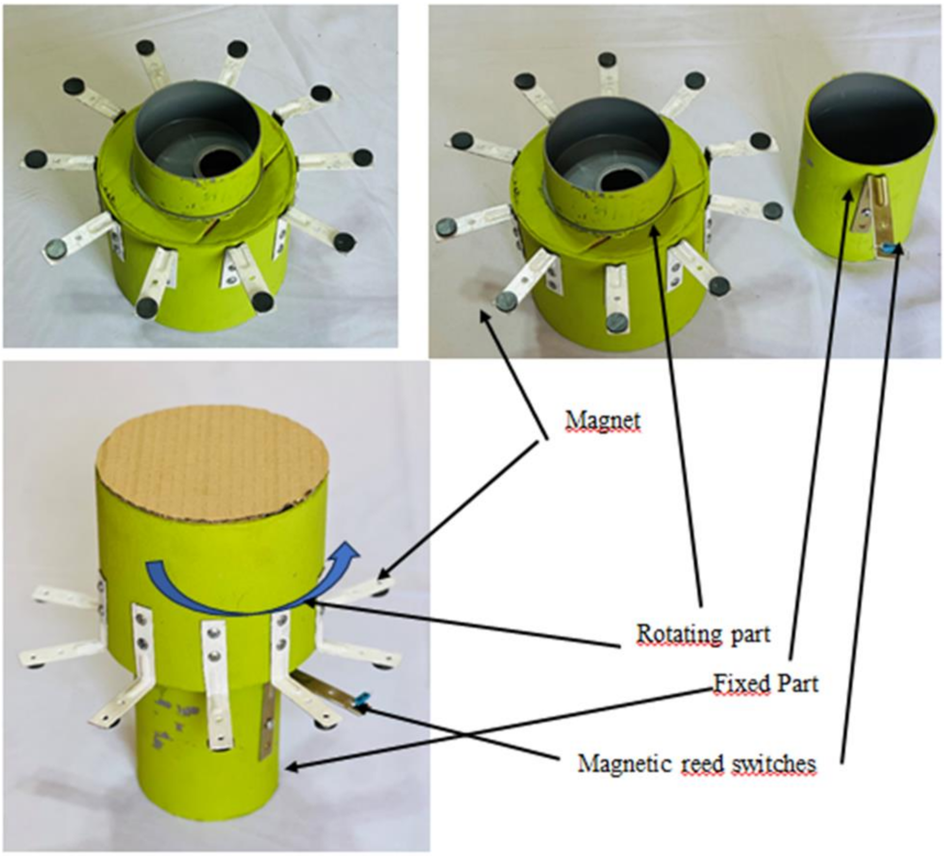


Figure III.5: Real-World Implementation of the Pivot Irrigation Position Sensor with Magnets and Magnetic Switch

III.4 PCB Design and Manufacturing Steps:

The manufacturing of a Printed Circuit Board (PCB) involves a series of precise technical steps to ensure the production of a high-performance and reliable board. This section outlines the main stages of the PCB fabrication process, starting from design to final assembly.

Before initiating the manufacturing process, the circuit is designed using **Altium Designer** in its 3D environment. This allows the creation of an accurate layout, reflecting real-world dimensions and component placements.

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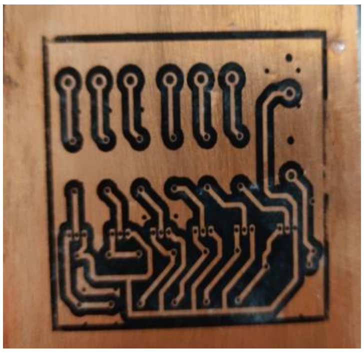
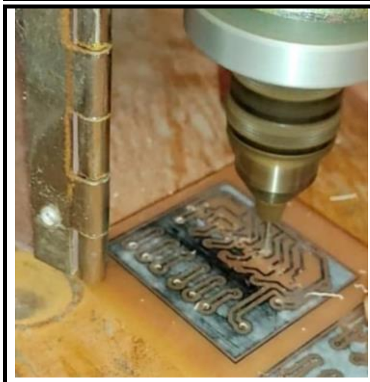
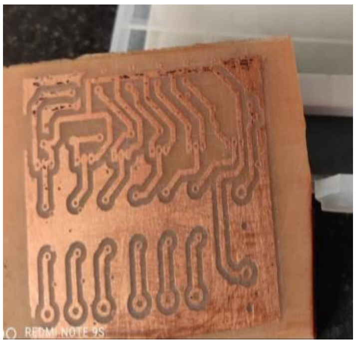
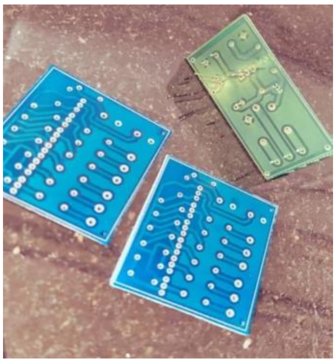
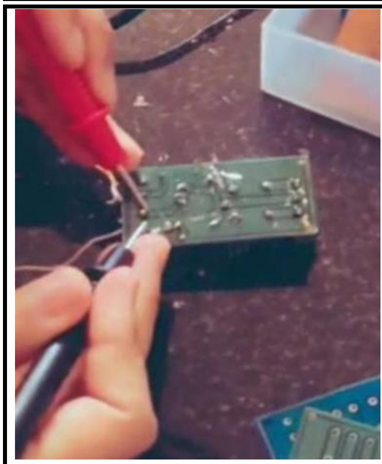
Table III.2: Summary of PCB Manufacturing and Assembly Steps

Steps	Image	Step Description	Step Name
1		We start by transferring the circuit design onto a copper board using UV exposure and then immerse the board in an etching solution to remove the unwanted copper, leaving only the circuit traces.	(Etching)
2		After etching, we use a CNC machine to drill precise holes at the component mounting points to allow for easy placement of through-hole components.	(Drilling)
3		The PCB is cleaned to remove any remaining photoresist or etching residue, ensuring a smooth and conductive surface for further processing.	(Cleaning)

4		A solder mask layer is applied to insulate and protect the copper traces, revealing only the pads where components will be soldered.	(Solder Mask Application)
5		We manually solder the electronic components onto the PCB using a soldering iron, carefully placing and connecting each element to the correct pad.	(Soldering)
6		Finally, all components are fixed on the PCB, and the board is tested to ensure proper functionality and correct signal flow.	(Component Assembly Complete)

This systematic process ensures that the final PCB is robust, functionally accurate, and suitable for integration into larger smart monitoring systems.

III.5 Integration of Sensors in Automation Systems

This section presents the integration of the developed sensors into automated monitoring and control systems [73].

The water level and flow switch sensors are incorporated into a Programmable Logic Controller (PLC)-based system using Siemens S7-1200, supported by an HMI/SCADA interface for real-time visualization and control [63][65].

Meanwhile, the Pivot Irrigation Position Sensor is implemented with an Arduino board and monitored through a graphical user interface via serial communication [65].
Th.e following subsections detail each integration process

III.5.1 Integration of Water Level Sensor and Flow Switch Sensor with Siemens S7-1200 and SCADA

This subsection outlines the configuration and programming of a Siemens S7-1200 Programmable Logic Controller (PLC) using the TIA Portal for the integration of a water level sensor and a flow switch sensor into an industrial control system [63][65].
The complete setup is connected to a SCADA system for monitoring and control purposes [63][73].

The experimental test bench comprises an S7-1200 PLC, a 24V power supply, relays, a water tank equipped with a water level sensor, and a pipeline with a flow switch sensor [63][65].

The PLC receives digital and analog signals from the sensors and responds by actuating a pump and an electrovalve to control water flow [65].
The SCADA interface, developed using TIA Portal, enables real-time visualization, control, and alarm management, ensuring efficient and automated water management [63][73].

The integration allows for:

- Real-time monitoring of the water level in the tank.
- Detection of water flow within the pipeline.
- Interactive control and visualization via the SCADA HMI.

- Reliable sensor-based automation for irrigation or fluid management systems.

The following figures illustrate the key components of the setup and implementation steps:

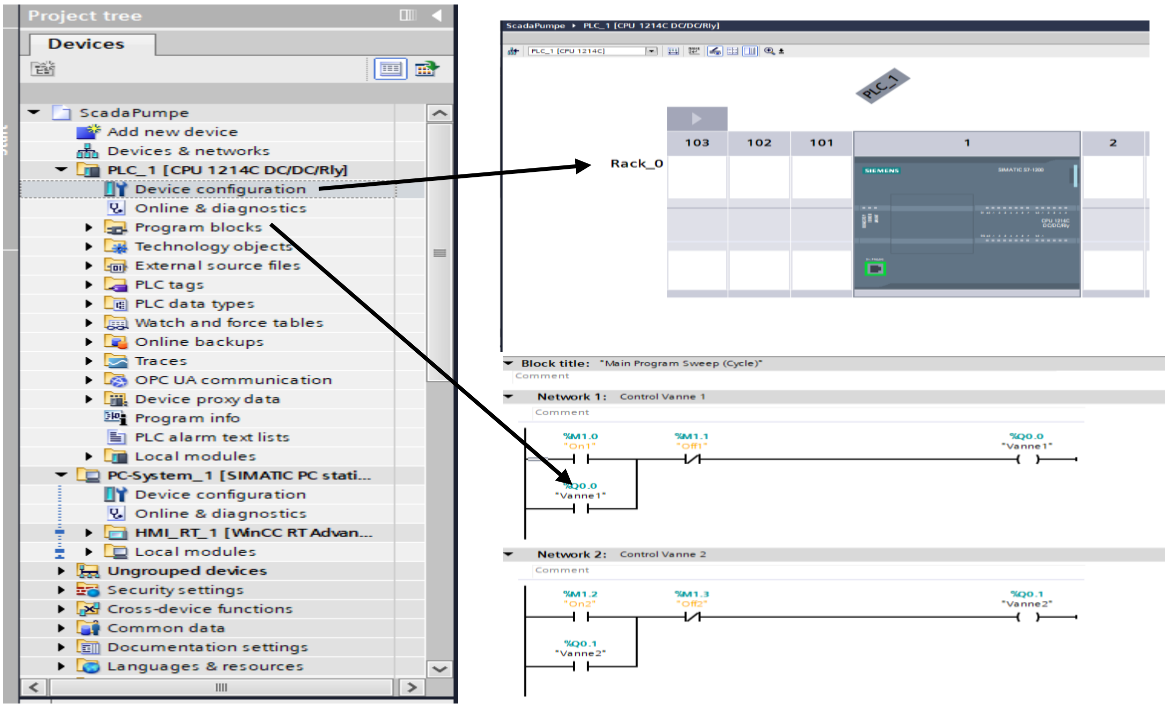


Figure III.6: TIA Portal Device Configuration for the S7-1200 PLC

This figure shows the selection and configuration of the S7-1200 PLC model in the TIA Portal, including Ethernet settings for network communication and the preparation of programming blocks for sensor integration and process control.

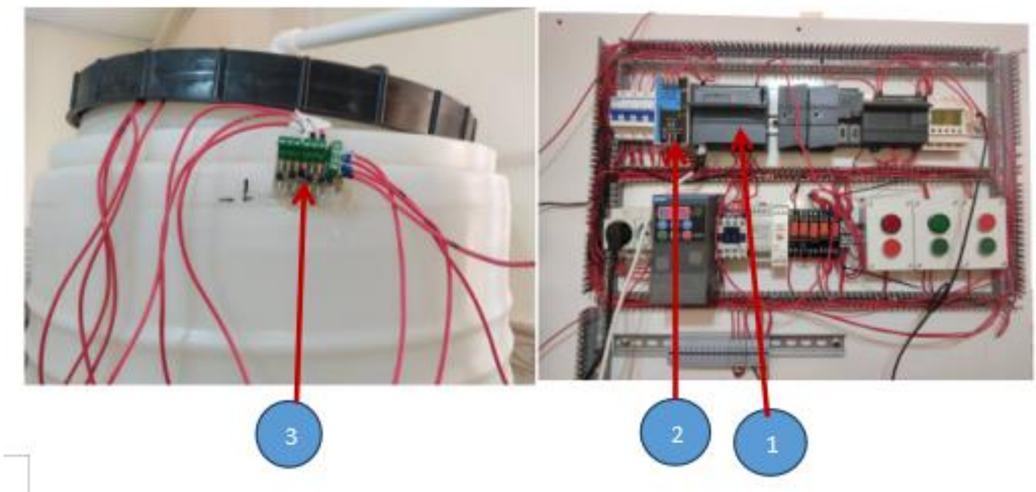


Figure III.7: Implementation of the Water Level Sensor in the PLC-Based Test Bench

The test bench includes:

1. The Siemens S7-1200 PLC (as labeled in Figure III.6).
2. A 24V DC power supply and relays for actuation.
3. A water tank with an integrated water level sensor for monitoring liquid levels.

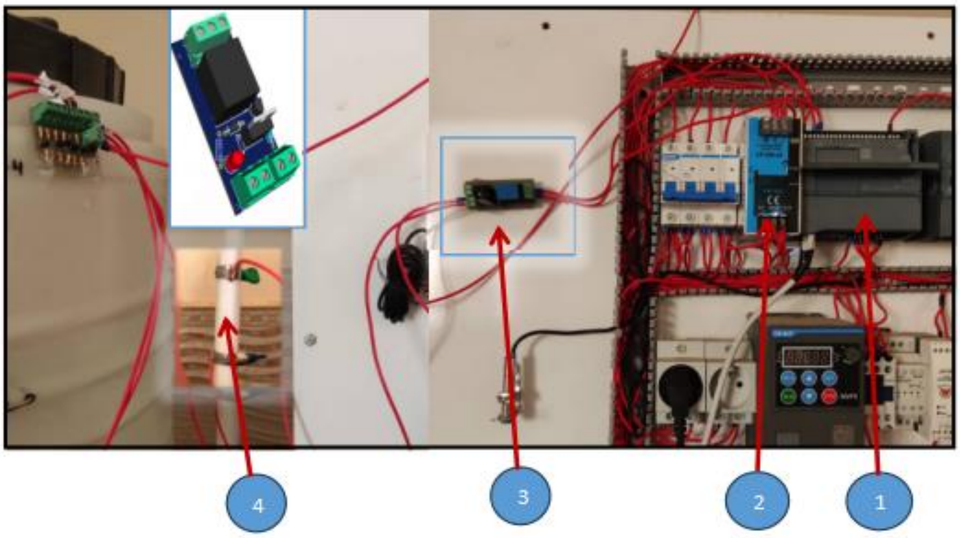


Figure III.8: Implementation of the Flow Switch Sensor in the PLC-Based Test Bench

This setup includes:

1. The Siemens S7-1200 PLC (as previously shown).
2. A 24V DC power supply and relays.
3. A flow switch sensor installed in the pipeline.
4. Connection pins for detecting the presence and circulation of water through the pipeline.

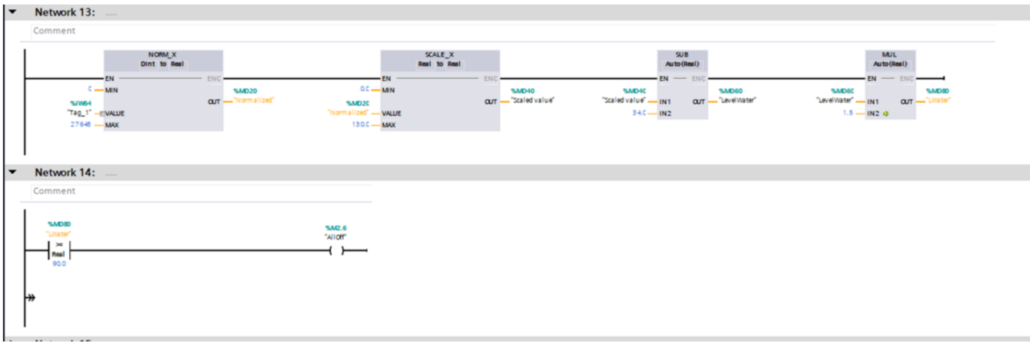


Figure III.9: Ladder Logic for Analog Signal Acquisition in the S7-1200 PLC

This ladder diagram illustrates how the analog voltage from the water level sensor is read through input address IW64, converted to a memory double word MD20, and scaled using the SCALE_X function to convert the data into a floating-point value MD80, suitable for display and processing in the HMI.

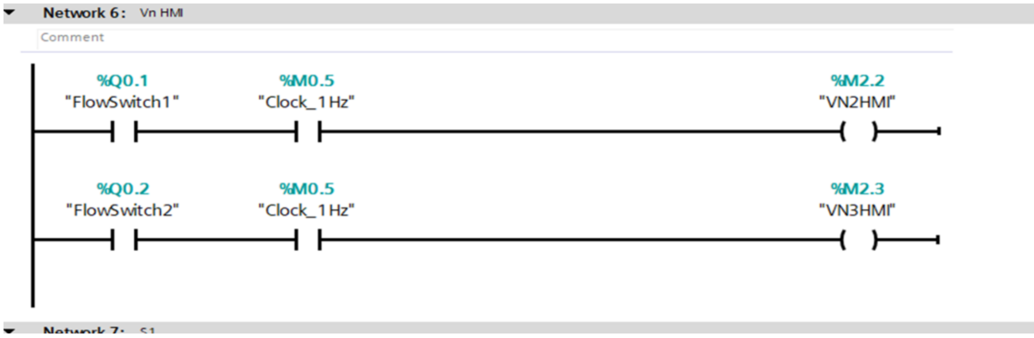


Figure III.10: Ladder Logic for Flow Switch Sensor Integration with the S7-1200 PLC

The flow switch sensors are connected to digital inputs I0.1 and I0.2. A 1 Hz clock pulse is used to trigger animations on the SCADA HMI, simulating real-time ON/OFF switching with a 1-second interval to enhance visualization of water flow detection.

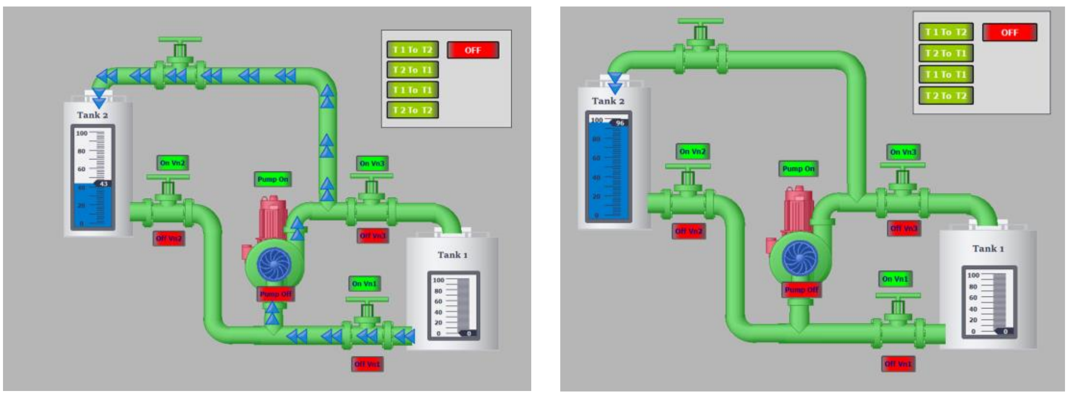


Figure III.11: SCADA HMI Visualization of Sensor Data in the Proposed System

This figure presents the graphical interface in the SCADA system, displaying real-time results from the water level and flow switch sensors. The interface includes visual indicators such as blue arrows to represent water flow, dynamic water level bars, and interactive components for system control and status monitoring.

III.5.2 Integration of Pivot Irrigation Position Sensor Using Arduino and Graphical Interface

This section presents the development and integration of a standalone monitoring system for pivot irrigation, based entirely on an **Arduino microcontroller** and a **web-based graphical interface**. Unlike the previous systems, this solution operates independently, without the use of any **PLC** or **SCADA platform**, making it particularly suitable for **low-infrastructure** or **remote agricultural environments**.

The system relies on **magnetic reed switches** installed along the rotating structure of the pivot irrigation system. **Magnets** mounted on the pivot arm trigger the reed switches as the arm rotates, generating **digital pulses** corresponding to specific angular positions or sections of the pivot. These pulses are detected and counted by the Arduino, which interprets them to determine the real-time position of the pivot.

The Arduino is connected to a PC via **USB serial communication**. A **graphical user interface (GUI)**, developed using **HTML, CSS, and JavaScript**, receives the serial data and visualizes the current status of the system. This web-based interface provides:

- **Live tracking** of the pivot's rotational position,
- **Visual indicators** of which section is active,
- **Position history**, showing movement over time,
- The potential to include **alerts** or **status changes** in response to specific events.

This flexible, low-cost architecture enables real-time monitoring without the need for industrial automation hardware. Additionally, the use of web technologies allows the interface to run on any device with a compatible browser, supporting cross-platform access and ease of deployment.

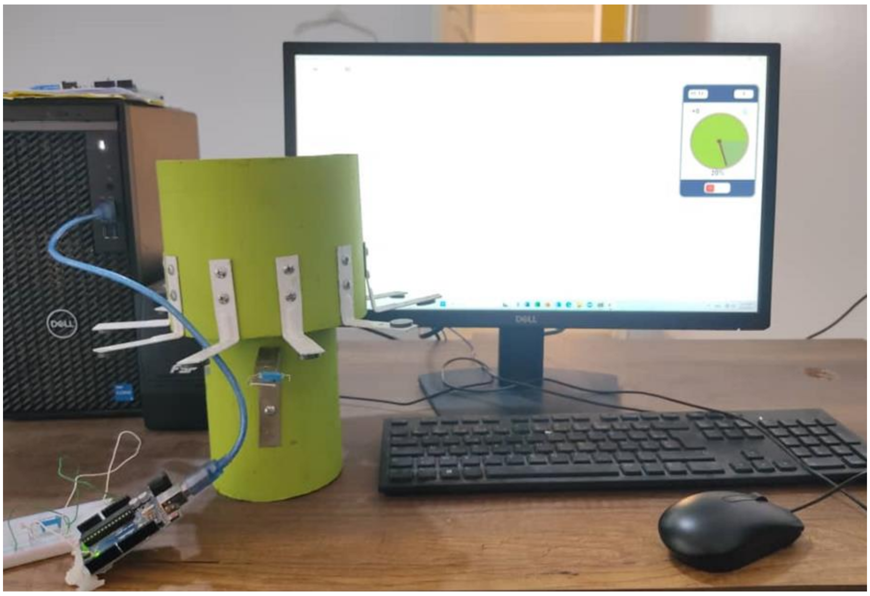


Figure III.12: Hardware Implementation of the Pivot Irrigation Position Sensor Using Arduino

This figure displays the complete hardware setup, including the Arduino board, reed switch sensors, magnets on the pivot arm, and USB connection to the PC. It also highlights the sensor alignment and wiring necessary for accurate pulse detection.

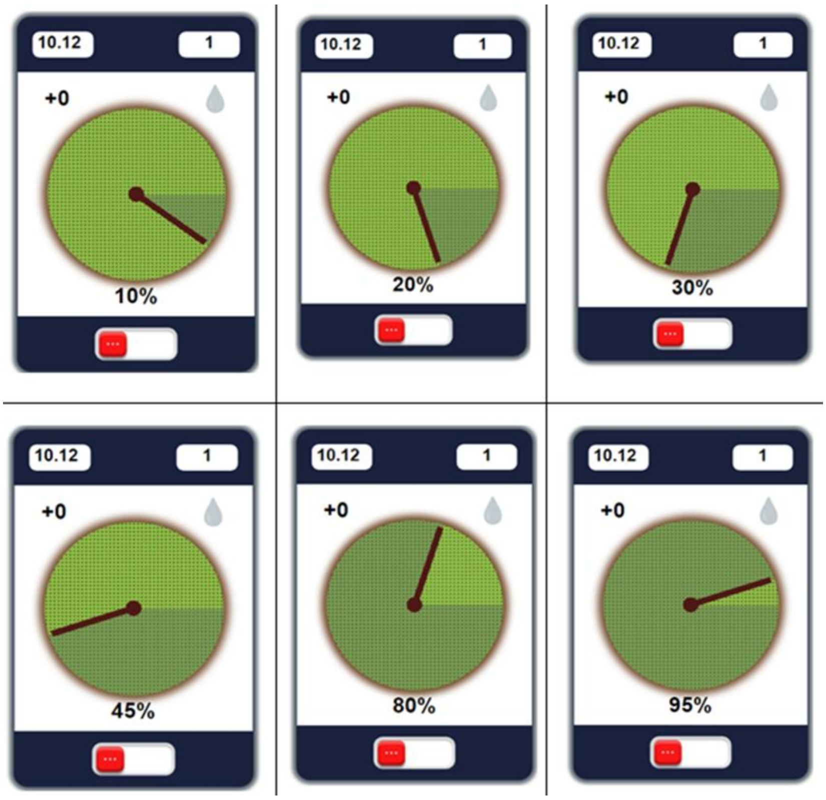


Figure III.13: Real-Time Display of Pivot Positions in the HTML-Based Interface

This figure shows the HTML-based graphical user interface used to visualize the pivot's position. It includes live updates based on the pulses received from the Arduino, with clear visual indicators representing different angular positions of the pivot system.

III.6 Conclusion

The development of the proposed sensor systems marks a significant step toward achieving cost-effective, reliable, and adaptable smart agricultural infrastructure. Through the design and implementation of three key sensor types Level Water Sensor, Flow Switch Sensor, and Pivot Irrigation Position Sensor this work demonstrates the feasibility of deploying efficient, low-complexity monitoring solutions tailored to water management challenges.

Each sensor was developed using fundamental electronic components such as transistors, relays, voltage regulators, and reed switches, assembled on compact printed circuit boards (PCBs). These systems were carefully engineered to function independently of complex control units like PLCs or SCADA systems, while remaining compatible for future integration. The use of passive and active electronic components ensures minimal maintenance, high durability in agricultural environments, and accurate real-time data acquisition.

The Level Water Sensor offers a granular, analog-level detection approach, optimizing tank management and preventing overflow or dry run conditions. The Flow Switch Sensor employs water conductivity to deliver an intuitive, mechanical free solution for detecting water presence, thereby reducing failure rates and installation costs. The Pivot Irrigation Position Sensor, based on magnetic field detection, ensures precise control over irrigation patterns and operational coverage.

Collectively, these innovations address the critical needs of modern agriculture by promoting resource efficiency, system reliability, and scalability. This foundational work paves the way for future integration with IoT and automation platforms, enabling advanced functionalities such as remote monitoring, data logging, and intelligent decision making essential components of next-generation precision agriculture.

General conclusion

General conclusion

In this project, we designed and developed a smart system for monitoring, controlling, and protecting electromechanical systems in agricultural applications, relying on advanced sensor technologies and the Internet of Things (IoT). To achieve these objectives, we went through several stages that included studying agricultural systems, designing sensors, programming, and integrating them into smart systems.

Initially, we focused on monitoring water tanks using a water level sensor, which allows automatic control of tank filling to prevent overflow or dryness. We then added a water flow sensor that detects the passage of water through the pipes, thereby enhancing precise monitoring of irrigation distribution systems.

Subsequently, we introduced an innovative sensor for detecting the position of the pivot irrigation system. This sensor determines the number of rotations the system performs and its direction of movement, in addition to identifying its current geographical position (east, west, etc.). The sensor was designed using a switch influenced by a series of magnets fixed on the rotating part of the system, while the switch is fixed to the stationary part. This system is programmed using an Arduino microcontroller, and the data is transmitted to a smart application through a cloud server, where the information is displayed in real time and interactively.

The system was tested in a real-world environment to simulate agricultural usage conditions and yielded accurate and efficient results. Despite the challenges and difficulties we encountered-such as the failure of certain electronic components-we managed to overcome them by improving the circuits and enhancing the overall device design.

This project represents a first step toward generalizing the use of smart technologies in agriculture. In the future, we aim to add new features such as monitoring motor temperature, tracking operating time, and implementing smart alerts and notifications, with the goal of increasing agricultural productivity and optimizing resource usage.

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