

Design and Experimental Evaluation of an Arduino-Based Photovoltaic Irrigation System for Efficient Water Management

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ABSTRACT

This study presents the design, simulation, and experimental implementation of a smart photovoltaic-powered irrigation system based on Arduino control and soil moisture sensing. The proposed system aims to improve water and energy efficiency in small-scale agricultural applications by enabling automatic irrigation without the use of batteries. The system was first modeled and simulated using ISIS Proteus software to validate the electrical architecture and control logic. An Arduino microcontroller was programmed to process real-time soil moisture data acquired from a humidity sensor and to control a DC water pump through a relay module. Irrigation is automatically activated when the measured soil moisture falls below a predefined threshold and stopped after a programmed watering duration. Following the simulation phase, a laboratory-scale prototype was constructed using photovoltaic panels, a DC-DC voltage regulator, a surface water pump, and an Arduino Mega 2560 board. Experimental results demonstrate the reliability of the control strategy and confirm the feasibility of combining photovoltaic energy with low-cost embedded electronics for autonomous irrigation. The proposed system represents an energy-efficient and sustainable solution suitable for remote or off-grid agricultural environments.

Keywords: soil moisture monitoring; renewable energy systems; automated control; DC pumping systems; sustainable agriculture; embedded electronics.

1. Introduction

The increasing demand for water and energy in agricultural activities has intensified interest in sustainable and autonomous irrigation solutions. In many rural and remote areas, limited access to electrical grids makes conventional water pumping systems costly and unreliable. Photovoltaic energy represents a suitable

alternative for irrigation applications due to its wide availability, low operating costs, and environmental benefits, particularly in regions with high solar potential [1,2,3]. Photovoltaic water pumping systems have been widely studied and implemented as efficient solutions for agricultural water supply, offering reduced maintenance requirements and improved system reliability compared to conventional systems [4,5].

Recent advances in embedded electronics and control technologies have enabled the development of intelligent irrigation systems capable of optimizing water use. Automatic irrigation based on soil moisture measurement allows water to be supplied only when required, thereby reducing water losses and improving irrigation efficiency [6,7]. Microcontroller-based platforms, such as Arduino, provide flexible and low-cost solutions for implementing such control strategies and for interfacing sensors, actuators, and power electronic components in renewable energy applications [8,9].

The aim of this research is to design, simulate, and experimentally implement a smart photovoltaic-powered irrigation system capable of autonomous operation without the use of batteries. The proposed system integrates a photovoltaic power supply, soil moisture sensing, and microcontroller-based control to automate irrigation processes. System simulation is carried out using ISIS Proteus software to validate the electrical architecture and control logic [10,11], followed by the realization of a laboratory-scale prototype to demonstrate the feasibility and practical applicability of the proposed approach.

2. Experimental

2.1. Materials

All materials and components used in this study were commercially available and employed without further modification. The photovoltaic power supply consisted of four photovoltaic panels rated at 5 W and 18 V and one photovoltaic panel rated at 10 W and 21 V, all connected in parallel to increase the output current. A 6 V DC surface water pump was used for irrigation purposes. Soil moisture and ambient humidity were monitored using a DHT11 digital humidity sensor. Control and data processing were performed using an Arduino Mega 2560 microcontroller board (figure 1).

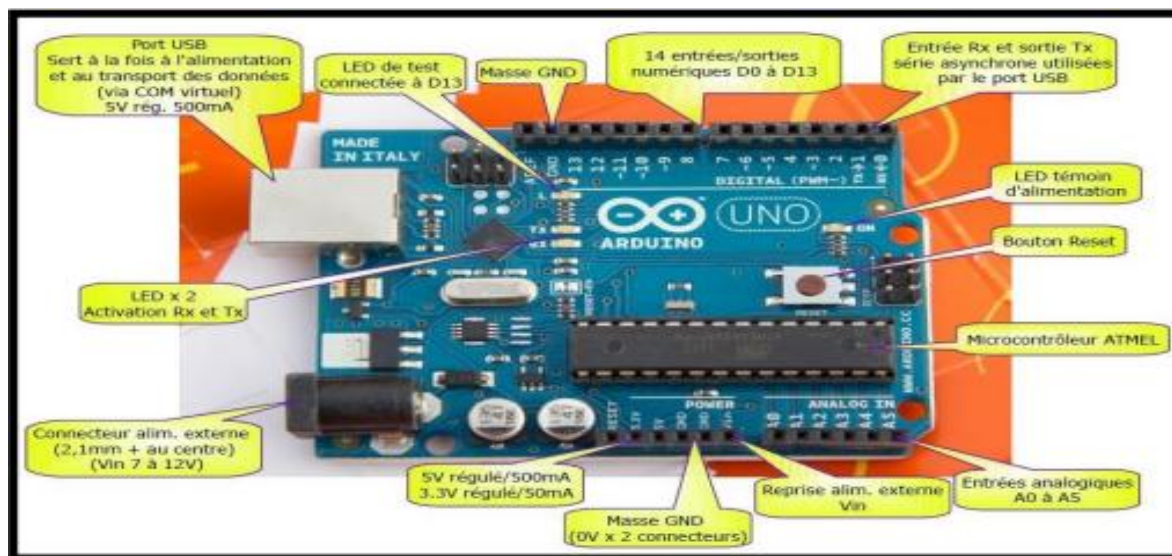


Figure 1. Description of 1Arduino board

A 5 V single-channel electromechanical relay module was employed to switch the pump operation based on control signals from the microcontroller. Voltage regulation between the photovoltaic panels and the electronic components was achieved using an LM2596 adjustable DC–DC step-down voltage regulator. Additional materials included plastic water pipes with a total length of approximately 2.15 m, a 4 L water reservoir, electrical wiring, and connectors. All components were selected to ensure compatibility with low-voltage photovoltaic systems and embedded electronic control figure 2 show the electrical diagram.

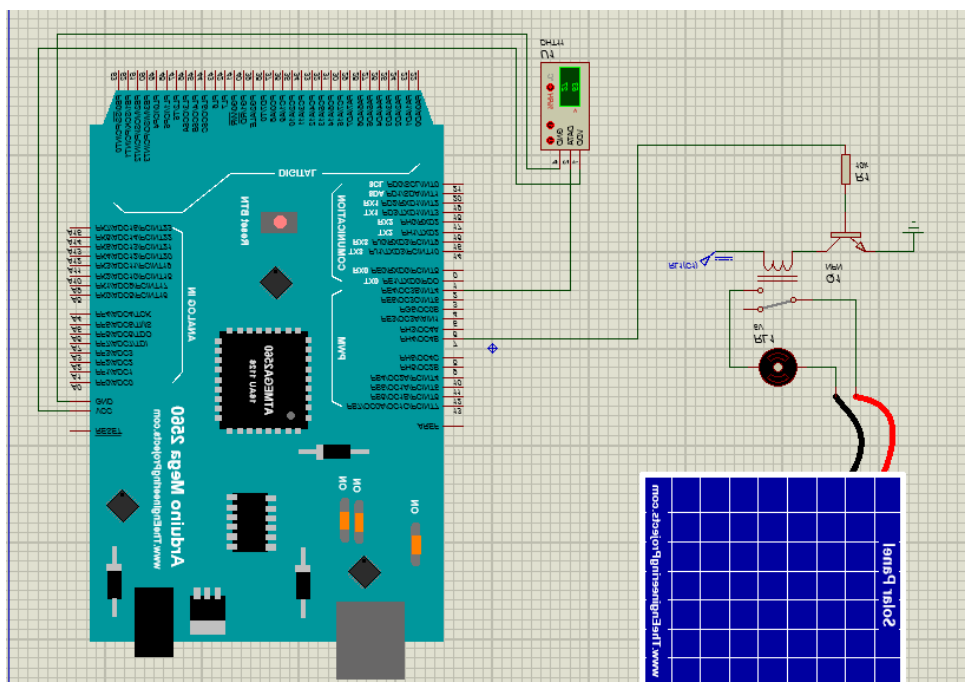


Figure 22 Electrical diagram

2.2. Simulation Tools and Software

The electrical architecture and control strategy of the proposed irrigation system were simulated using ISIS Proteus software. This software was selected due to its ability to simulate complete electronic systems, including microcontrollers and peripheral components. The Arduino control code was developed and compiled using the Arduino Integrated Development Environment (IDE), then imported into the Proteus environment for simulation and validation of system behavior prior to physical implementation.

2.3. Experimental Setup and Procedure

The experimental setup consisted of a laboratory-scale prototype representing a small irrigated area of approximately 0.35 m². The photovoltaic panels supplied electrical power directly to the system without the use of batteries. The output voltage of the panels was regulated to 6 V using the LM2596 DC–DC converter to ensure safe operation of the pump and the Arduino board figure 3.



Figure 33 Overview of the project

The DHT11 sensor continuously measured soil moisture and transmitted the data to the Arduino microcontroller. When the measured moisture level dropped below a predefined threshold, the microcontroller activated the relay to start the water pump. Irrigation was stopped automatically after a programmed watering duration. The experimental procedure was repeated under identical conditions to verify the reliability and reproducibility of the control strategy.

3. Results And Discussion

The simulation figure 4 and experimental implementation of the proposed photovoltaic irrigation system confirmed the feasibility of combining renewable energy supply with automated control for small-scale agricultural applications. Simulation results obtained using ISIS Proteus demonstrated the correct operation of the electrical architecture and control logic prior to physical realization. The interaction between the Arduino microcontroller figure 5, the soil moisture sensor figure 6, and the relay module figure 7 ensured reliable activation and deactivation of the water pump based on predefined moisture conditions.

```
#include <Adafruit_Sensor.h> // DHT22
#include <DHT.h> // DHT11
#define DHTPIN 2
#define DHTTYPE DHT11 // DHT 11
// #define DHTTYPE DHT22 // DHT 22 (AM2302)
// #define DHTTYPE DHT21 // DHT 21 (AM2301)
DHT dht = DHT(DHTPIN, DHTTYPE); // normal 16mhz Arduino:

void setup() {
  Serial.begin(9600);
  pinMode(7,OUTPUT);
  dht.begin();
}
void loop() {
  delay(500);
  float h = dht.readHumidity();
  float t = dht.readTemperature();
  float f = dht.readTemperature(true);
  if (isnan(h) || isnan(t) || isnan(f)) {
    Serial.println("Failed to read from DHT sensor!");
    return;
  }
  float hif = dht.computeHeatIndex(f, h);
  float hic = dht.computeHeatIndex(t, h, false);
  Serial.print("Humidity: ");
  Serial.print(h);
  Serial.print(" % ");
  Serial.print(" Temperature: ");
  Serial.print(t);
  Serial.println("C | ");
  if ((h<=45)) {
    Serial.println(" TROP SEC - ACTIVATION ARROSAGE ");
    for(int arrosage = 1 ; arrosage <= 2 ; arrosage = arrosage+1) // cycle maxi de 2 tests + arrosage
    {
      if ((h<=45)){
        digitalWrite(7,HIGH);
        delay(10000);
        digitalWrite(7,LOW);
        delay(4000);
      }
    }
  }
  else {
    Serial.println(" FIN CYCLE ARROSAGE ");
  }
}
```

Figure 4. 4code

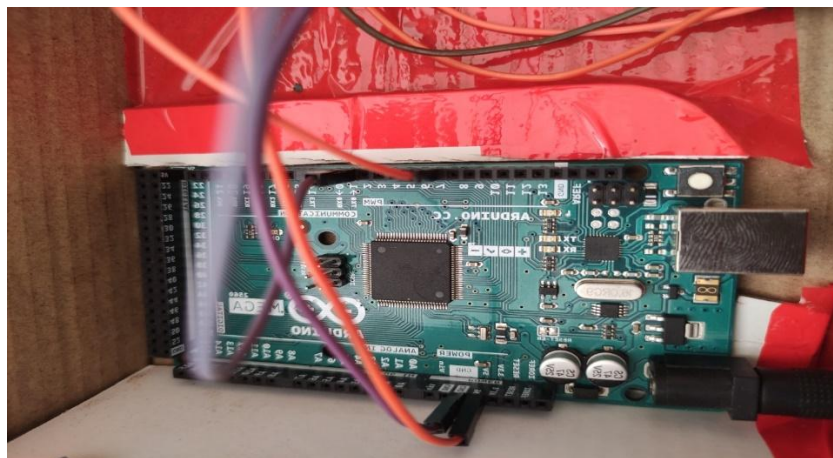


Figure 5. The Arduino MEGA 2560



Figure 6. The relay

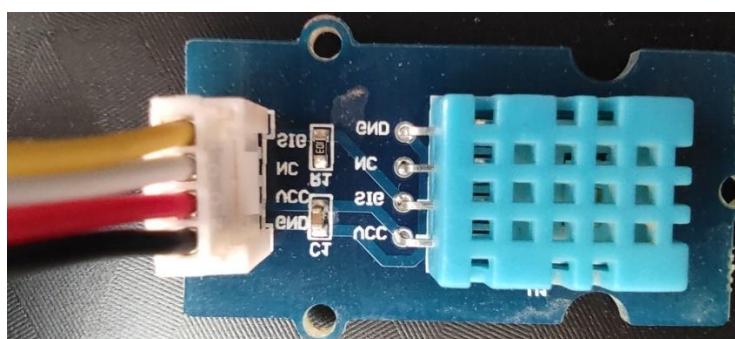


Figure 7. DHT11 moisture captor

The simulation phase allowed verification of voltage levels, signal stability, and timing behavior of the control system, reducing the risk of malfunction during implementation. The use of a soil moisture threshold enabled automatic irrigation to be triggered only when required, which represents an effective approach for minimizing unnecessary water consumption. The absence of energy storage elements simplified the system architecture and reduced maintenance requirements.

Experimental results obtained from the laboratory-scale prototype validated the simulation outcomes. The photovoltaic panels provided sufficient power to operate the system under standard conditions, and the DC–DC voltage regulator ensured stable operation of both the pump and the electronic components. The irrigation process was successfully automated, with water delivery initiated when soil moisture dropped below the set threshold and stopped after the programmed irrigation duration.

The agreement between simulation and experimental results highlights the reliability of the proposed design. The system demonstrates potential for application in off-grid or remote agricultural environments where conventional energy sources are limited.

4. Conclusion

The inclusion of a Conclusion section, which briefly summarizes the principal conclusions, is highly recommended.

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