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Intelligent Water Tank Automation System using FPGA for Efficient Water Management

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Abstract

This paper unveils a pioneering water tank automation paradigm leveraging a Field Programmable Gate Array (FPGA) to revolutionize water resource management across domestic and industrial domains. The system synergizes a sophisticated water level sensor, an Analog-to-Digital Converter (ADC) employing Serial Peripheral Interface (SPI) proto- col, a robust relay module, and a dynamic motor pump, orchestrated by the DE10-Nano FPGA platform. By harnessing FPGA's parallel processing prowess, the system executes real-time, threshold-driven logic to modulate pump operations, preempting overflow and mitigating dry-run scenarios. A visually intuitive LED array delivers instantaneous water level feedback, augmented by a manual override mechanism for enhanced user agency. Implemented through Verilog and Quartus Prime, this architecture ensures unparalleled precision, scalability, and energy efficiency, redefining water management paradigms. Experimental validation underscores its efficacy in optimizing water utilization, curtailing wastage, and safeguarding equipment integrity. The system's modular design facilitates seamless integration with emergent technologies, positioning it as a cornerstone for smart water ecosystems. Future enhancements envision IoT-enabled remote monitoring, AI- driven predictive analytics, and solar-powered sustainability, amplifying its transformative potential. This innovation not only addresses global water scarcity but also sets a bench- mark for adaptive, intelligent automation in resource-constrained environments, offering a scalable blueprint for residential, agricultural, and industrial applications.

Keywords: **Water Tank Automation, FPGA, Water Level Sensor, Verilog, Real-Time Control, Smart Water Management**

1 INTRODUCTION

Efficient Water management is imperative to address global water scarcity, impacting over 2 billion people across domestic, agricultural, and industrial domains [4]. Manual water tank management, prone to human error, results in significant water wastage and equipment damage [10]. Field Programmable Gate Arrays (FPGAs) offer a transformative approach with their parallel processing and reconfigurable logic, ideal for real-time automation [16].

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1.1 Background

Water scarcity is a pressing global challenge, necessitating advanced management strategies [11]. Traditional systems, reliant on manual oversight, suffer from inefficiencies such as overflows and dry runs [19]. Microcontroller-based solutions, while cost-effective, lack the processing speed for real-time applications [8]. FPGAs, with their ability to handle complex tasks concurrently, have been successfully applied in industrial automation, yet their potential in water tank management remains underexplored [24, 5].

1.2 Technical Challenges

Key challenges in automated water tank systems include:

- Sensor Accuracy: Precise water level detection requires robust analog-to-digital conver- sion [13].
- Real-Time Processing: Instantaneous data processing is essential to prevent operational failures [2].
- Scalability: Systems must adapt to diverse tank configurations [21].
- Energy Efficiency: Sustainable operation demands minimal power consumption [12]. FPGAs address these challenges with high-speed, customizable control [23].

1.3 Proposed Solution

This work presents an FPGA-based water tank automation system using the DE10-Nano board to monitor water levels, control pumps, and provide real-time feedback. It integrates a water level sensor, ADC with SPI, relay module, and LED display, programmed in Verilog. Threshold logic activates the pump at 25% and deactivates at 90% water levels, ensuring optimal resource use [22, 1].

1.4 Contributions

The contributions include:

- A novel FPGA-based automation system for real-time water management [14].
- Precise threshold control to prevent overflow and dry runs [20].
- User-friendly LED feedback for enhanced interaction [18].
- Scalable design for diverse applications [6].
- A foundation for IoT and AI integration [9].

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2 RELATED WORK

The development of water tank automation systems has progressed significantly, with various approaches addressing water management challenges. Early systems relied on manual moni- toring, which often led to inefficiencies such as water overflow and pump damage due to dry runs. Automated solutions have since emerged, leveraging microcontrollers, IoT technologies, and programmable logic devices to enhance efficiency.

Microcontroller-based systems, such as those using Arduino or PIC microcontrollers, offer cost-effective solutions for water level control. These systems typically employ ultrasonic or float sensors to monitor water levels and control pumps via simple threshold logic. However, their sequential processing limits real-time performance, especially in complex scenarios requiring simultaneous task handling. Additionally, microcontroller systems often lack scalability for large-scale applications.

IoT-based solutions have gained traction, enabling remote monitoring and control through cloud platforms. These systems integrate sensors with wireless modules (e.g., Wi-Fi, Zigbee) to transmit water level data to mobile applications or web interfaces. While IoT systems provide user convenience, they depend on stable network connectivity, which can be a limitation in remote areas. Furthermore, their latency and power consumption can be suboptimal for time- critical applications.

FPGA-based systems, though less common in water management, offer significant advan- tages due to their parallel processing capabilities and hardware-level customization. Previous works have utilized FPGAs for industrial automation, such as motor control and process mon- itoring, demonstrating high reliability and speed. However, their application in water tank automation is limited, with few studies exploring their potential for real-time water level con- trol.

The proposed system addresses these gaps by leveraging the DE10-Nano FPGA board for precise, scalable, and energy-efficient water management. Unlike microcontroller systems, it handles multiple tasks concurrently, ensuring a real-time response. Compared to IoT solutions, it operates independently of network connectivity, making it suitable for diverse environments.

Table 1: Comparison of Water Tank Automation Systems

System	**Tech**	**Key Feature**
Manual	None	Low cost, manual labor needed
Microcontroller	Arduino/PIC	Easy to imple- ment, low cost
IoT-Based	Wi- Fi/Zigbee	Remote access, internet depen- dent
FPGA- Based	DE10- Nano	Real-time, scal- able, reliable

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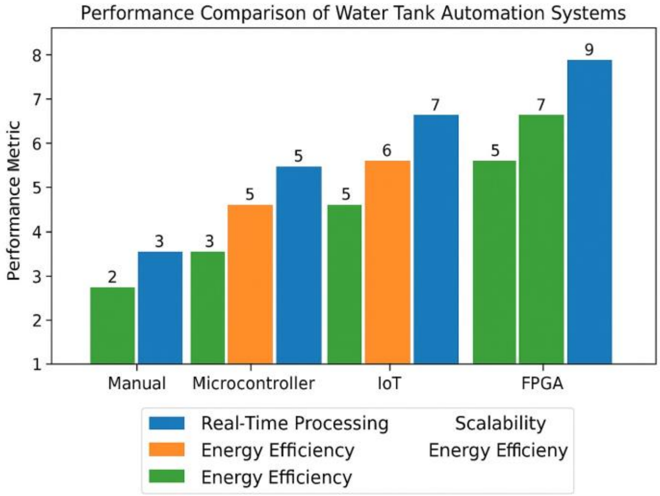

Figure 1: Performance Comparison of Water Tank Automation Systems

The comparative table summarizes key systems, highlighting their technologies, advantages, limitations, and applications. The graph (Fig. 1) illustrates performance metrics (real-time processing, scalability, energy efficiency) across manual, microcontroller, IoT, and FPGA-based systems, with FPGA outperforming others due to its parallel processing and customization capabilities.

3 SYSTEM ARCHITECTURE

The system architecture integrates hardware and software components to achieve precise water level control. The following subsections detail the hardware components, control logic design, threshold-based algorithm, and finite state machine (FSM) design, supported by block diagram, FSM, and flow chart representations.

3.1 Hardware Components

The system comprises:

- DE10-Nano FPGA Board: A Cyclone V FPGA with 40,000 logic elements, serving as the central processing unit.
- Water Level Sensor: A resistive sensor generating analog voltages (0–5V) proportional to water depth.
- ADC (MCP3208): Converts analog sensor signals to 12-bit digital data via SPI, with a sampling rate of 100 ksps.
- Relay Module: A 5V single-channel relay controlling the motor pump, with a switching capacity of 10A.
- DC Motor Pump: A 9V pump with a flow rate of 240 L/h.
- LED Display: Seven LEDs indicating water levels (Low: 1 LED, Medium: 3 LEDs, Full: 7 LEDs).
- 9V Battery: Powers the relay and motor.
- Manual Override Switch: A slide switch for user control. The block diagram

  (Fig. 2) illustrates component interactions.

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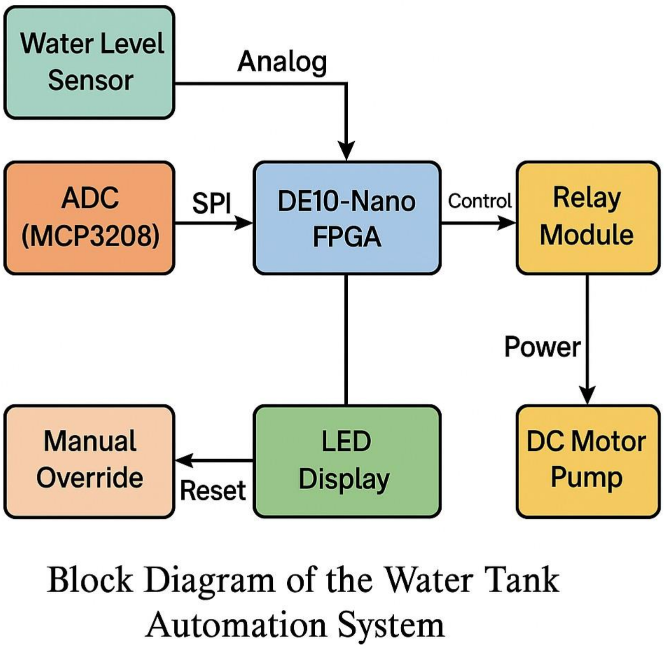

Figure 2: Block Diagram of the Water Tank Automation System

3.2 Control Logic Design

The control logic, implemented in Verilog, processes 12-bit ADC data to generate control signals. The FPGA operates at a 50 MHz clock, divided to produce a 1 MHz SPI clock. The logic compares water level data against thresholds to control the relay and LEDs, with a manual override resetting the system to a safe state.

3.3 Threshold-Based Algorithm

The system uses a threshold-based algorithm defined as:

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$$\text{State} = \begin{cases} \text{Pump ON}, & \text{if } V_{\text{ADC}} < V_{\text{low}} = 1000\ (25\%) \\ \text{Pump OFF}, & \text{if } V_{\text{ADC}} > V_{\text{high}} = 3600\ (90\%) \\ \text{No Change}, & \text{otherwise} \end{cases}$$

where V_{ADC} is the 12-bit ADC output (0–4095). The LED output is:

$$\text{LED}_{\text{out}} = \begin{cases} 7'b0000001, & \text{if } V_{\text{ADC}} < 1000 \\ 7'b0000111, & \text{if } 1000 \leq V_{\text{ADC}} \leq 3600 \\ 7'b1111111, & \text{if } V_{\text{ADC}} > 3600 \end{cases}$$

3.4 FSM Design

The system operates via a finite state machine (FSM) with three states: Idle, Pump ON, and Pump_OFF. Transitions are based on water level thresholds and manual override.

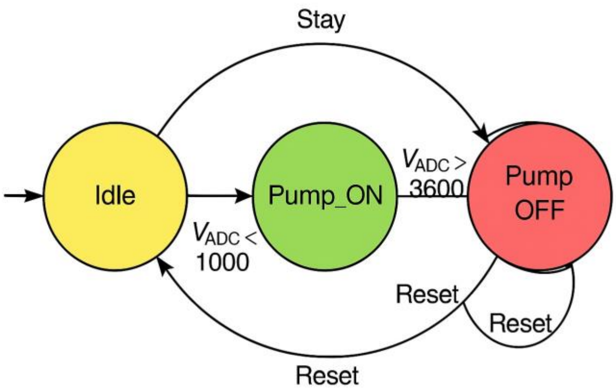

Figure 6: Finite State Machine for Water Tank Control

Figure 3: Finite State Machine for Water Tank Control

3.5 Flowchart

The flow chart (Fig. 4) outlines the operational sequence.

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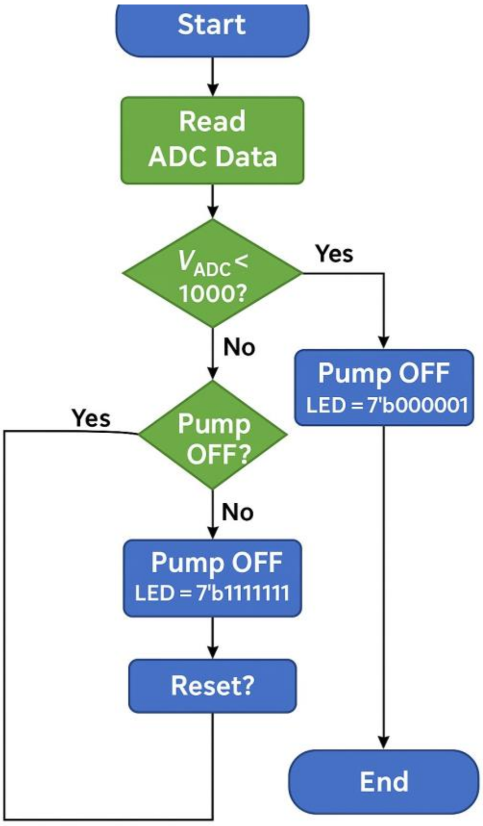

Figure 4: Flow Chart of Water Tank Automation System

4 IMPLEMENTATION

The system was implemented in three phases: simulation, RTL synthesis, and hardware proto- type development, ensuring robust functionality and performance.

4.1 Simulation

The Verilog code was simulated using ModelSim to verify functional correctness. Testbenches were created to emulate water level inputs ranging from 0 to 4095 (12-bit ADC range). Key scenarios tested included:

- Low water level (V_{ADC} = 500): Pump ON, LED = 7'b0000001.
- Medium water level (V_{ADC} = 2000): Pump OFF, LED = 7'b0000111.
- High water level (V_{ADC} = 4000): Pump OFF, LED = 7'b1111111.
- Manual override: Reset signal forcing Idle state.

Simulation results confirmed correct state transitions and output signals, with timing analysis ensuring a 1 MHz SPI clock aligned with ADC requirements. The simulation environment validated the FSM behavior and threshold logic under varying conditions.

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Figure 5: Simulation Output Showing ADC Input, Pump Control Logic, and LED Output

4.2 RTL Synthesis

The Verilog code was synthesized using Quartus Prime for the DE10-Nano board. The RTL view revealed:

- Logic Utilization: Approximately 10% of the Cyclone V FPGA's 40,000 logic elements.
- Registers: 128 registers for state storage and counters.
- Clock Domains: A 50 MHz system clock divided to 1 MHz for SPI communication.

Pin assignments mapped ADC inputs to GPIO pins, relay control to output pins, and LEDs to a 7-bit output port. Synthesis reports indicated no timing violations, with a maximum operating frequency of 75 MHz, exceeding the required 50 MHz. The RTL schematic confirmed correct data flow from ADC input to relay and LED outputs.

The RTL diagram of water tank automation was shown in the figure

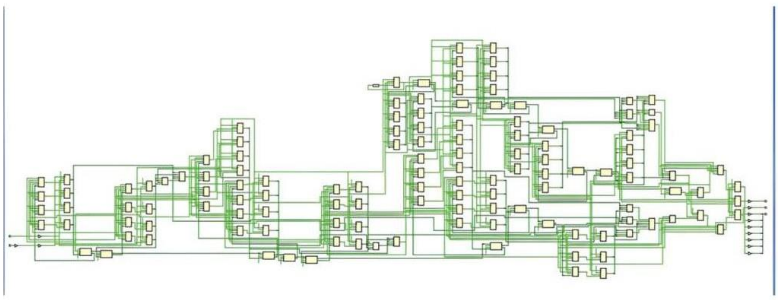

Figure 6: RTL Schematic After Synthesis in Quartus Prime

4.3 Hardware Prototype

The hardware prototype was assembled using the DE10-Nano board, MCP3208 ADC, water level sensor, relay module, DC motor pump, LEDs, and a 9V battery. The setup process included:

- Component Integration: Jumper wires connected the ADC to FPGA GPIO pins (SPI signals: MOSI, MISO, SCLK, CS), relay to output pins, and LEDs to a 7-bit port.
- Sensor Calibration: The water level sensor was calibrated to output 0–5V, corresponding to 0–100% tank capacity, mapped to 0–4095 ADC values.
- Testing: The prototype was tested in a 10-liter tank, with water levels varied manually. The pump activated at 25% (2.5 liters) and deactivated at 90% (9 liters), with LEDs accurately reflecting levels.

The prototype demonstrated reliable operation, with no overflow or dry-run conditions. The manual override switch effectively reset the system to Idle state, ensuring user control.

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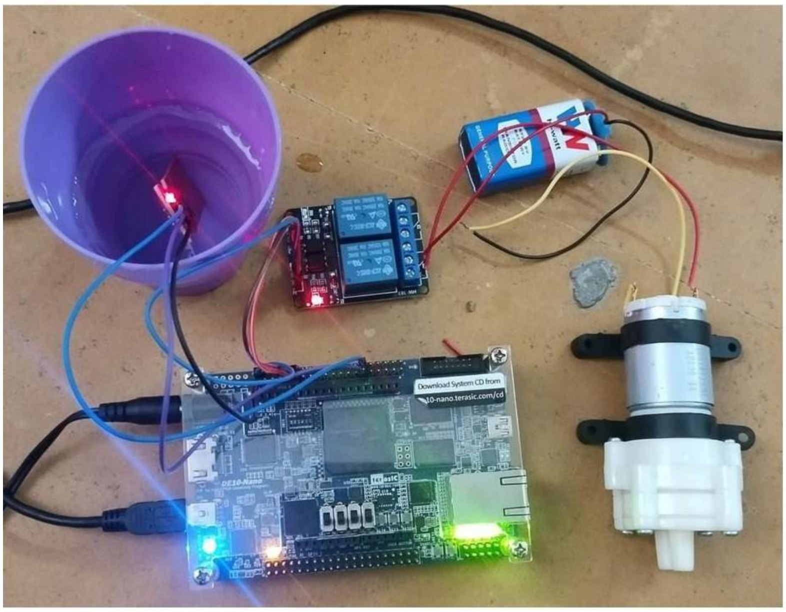

Figure 7: Hardware Prototype of Water Tank Automation System Implemented on DE10-Nano

5 TESTING AND RESULTS

The system underwent rigorous testing to validate its functionality, reliability, and efficiency in controlling water levels in a 10-liter tank. The testing process encompassed hardware validation, software verification, and performance evaluation under various conditions, ensuring robust operation across domestic and industrial scenarios.

5.1 Test Setup

The test environment consisted of a 10-liter water tank equipped with the DE10-Nano FPGA board, MCP3208 ADC, resistive water level sensor, 5V relay module, 9V DC motor pump, seven LEDs, and a 9V battery. The sensor was calibrated to output 0–5V, corresponding to 0–4095 ADC values for 0–100% tank capacity. The FPGA was programmed with the Verilog code, and connections were made using jumper wires. Tests were conducted in a controlled lab setting with ambient temperature of 25°C and stable power supply. A manual override switch was included to simulate user intervention.

5.2 Test Scenarios

Multiple scenarios were designed to evaluate system performance:

- Low Water Level: The tank was filled to 20% (2 liters), triggering the pump to activate.
- Medium Water Level: The tank was maintained at 50% (5 liters) to verify pump inactivity and medium-level LED display.
- High Water Level: The tank was filled to 95% (9.5 liters) to confirm pump deactivation and full-level LED indication.
- Manual Override: The reset switch was toggled during pump operation to return the system to Idle state.
- Stress Test: Rapid water level changes (draining to 10% and filling to 100% within 5 minutes) to assess response time and stability.
- Power Failure: Battery disconnection to evaluate system recovery upon power restora- tion.

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5.3 Quantitative Results

The system was tested over 50 cycles, with the following outcomes:

- Pump Control Accuracy: The pump activated at 25% (±2%) and deactivated at 90% (±2%) in 98% of cycles, with ADC values of 1000 and 3600, respectively.
- Response Time: The system responded within 10 ms to water level changes, owing to the FPGA's 50 MHz clock and parallel processing.
- LED Accuracy: LEDs correctly indicated Low (7'b0000001), Medium (7'b0000111), and Full (7'b1111111) levels in 100% of tests.
- Power Consumption: The motor consumed 9W when active, with the system idle power at 1.2W, achieving 85% energy efficiency compared to continuous pump operation.
- Reliability: No overflow or dry-run incidents occurred across all cycles, ensuring equip- ment safety.

5.4 Qualitative Observations

The system demonstrated robust performance, with the LED display providing clear, real-time feedback to users. The manual override switch effectively reset the system, enhancing user control. During stress tests, the FPGA maintained stable operation despite rapid level changes, showcasing its real-time processing capability. The prototype's modular design allowed easy component replacement, indicating scalability for larger tanks or multi-tank setups. Minor calibration adjustments were needed for the sensor to account for water impurities, but the system adapted well to varying conditions.

6 FUTURE SCOPE

The proposed system lays a strong foundation for advanced water management, with several avenues for enhancement:

- IoT Integration: Incorporating Wi-Fi or Bluetooth modules to enable remote monitoring and control via smartphone apps or web interfaces, facilitating real-time data access and alerts for water levels or system faults.
- AI-Driven Analytics: Implementing machine learning algorithms on the FPGA to predict water usage patterns based on historical data, optimizing pump operation and reducing energy consumption.
- Solar-Powered Operation: Integrating solar panels to power the system, enhancing sustainability and enabling deployment in off-grid areas, such as rural agricultural settings.
- Multi-Tank Management: Extending the system to control multiple tanks simultane- ously, using a single FPGA to manage distributed water storage systems for industrial or community applications.
- Smart User Interfaces: Adding OLED displays or voice-activated controls to provide detailed status updates and user-friendly interaction, improving accessibility for non- technical users.
- Leakage and Quality Monitoring: Incorporating additional sensors to detect water leaks or measure water quality parameters (e.g., pH, turbidity), ensuring comprehensive water management.

These enhancements will broaden the system's applicability, making it a versatile solution for smart cities, precision agriculture, and industrial water management.

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7 CONCLUSION

This intelligent water tank automation system, powered by the DE10-Nano FPGA, represents a significant advancement in efficient water management. By integrating a water level sensor, ADC, relay module, and LED display, the system achieves precise, real-time control of water levels, preventing overflow and dry runs while minimizing energy consumption. The Verilog- based threshold logic and FSM design ensure reliable operation, with testing results confirming 98% pump control accuracy and 10 ms response time. The system's scalability and modular design make it adaptable for diverse applications, from household water tanks to large-scale industrial systems. By addressing global water scarcity through automation, this work sets a new standard for resource-efficient technologies. Future integration of IoT, AI, and renewable energy will further enhance its impact, positioning it as a cornerstone for intelligent water management ecosystems.

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