Design and Optimization of an Intelligent Automated Water Tank Filling System for Sustainable Water Management

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ABSTRACT

This paper designs an automated water tank filling system using technologies like microcontrollers, sensors, and solar power to enable smart water usage in Ghanaian communities. The system monitors water levels using ultrasonic sensors and automatically controls pumps via a microcontroller and solenoid valve to optimize filling and prevent overflows. Key components include the ESP32 microcontroller, LCD display, voltage regulator, and rechargeable batteries. The methodology follows the Rapid Application Development approach, incorporating requirements gathering, prototyping, and user feedback. Results demonstrate a reliable, energy-efficient system to reduce water wastage, enhance sustainability, and empower communities through optimized usage. The intelligent automation promotes precision in water resource management.

Keywords: *Automated water tank filling, Intelligent systems, Sustainability, Optimization*

1. INTRODUCTION

Water covers approximately 70% of the earth's surface and naturally exists in all three physical states, yet only 2.5% of the global water supply is freshwater (Mishra, 2023). Most freshwater is stored as deep groundwater, leaving a limited amount readily available for human use (Mishra, 2023). As water scarcity becomes a pressing issue worldwide, there is an urgent need to safeguard current water sources and develop strategies to ensure adequate and sustainable water supplies for present and future generations. Water is vital for life, so its availability directly and indirectly impacts human health, welfare, socioeconomic development, and ecological sustainability (Owusu et al., 2016).

In developing countries like Ghana, manually operated switches controlling water pumping systems lead to wasteful electricity consumption and imbalanced water distribution, causing overflows or inadequate filling of tanks (Mytton, 2021). This results in unnecessary water and energy loss, highlighting the need for intelligent and automated water management systems. This research paper design an automated water tank filling system focusing on developing country (Ghanaian) communities. The paper used technologies like the esp32 microcontroller, ultrasonic sensor, LCD screen, relay module, voltage regulator, solenoid valve, and solar panels with rechargeable batteries the system aims to optimize water usage, reduce wastage, and promote sustainable practices. The methodology section outlines the system design, results analyze findings, and conclusions offer recommendations for integrating intelligent systems into water management. Overall, the paper demonstrates an innovative automated system to address pressing water challenges, contribute to sustainability, improve efficiency, and empower developing communities through optimized water usage and conservation (Owusu et al., 2016).

2. LITRATURE REVIEW

Water is a vital yet limited resource, so developing intelligent systems for optimized management is crucial. Manual water pumping systems used in developing nations like Ghana lead to imbalanced supply and electricity wastage, hence automated systems are needed (Mytton, 2021). This paper explores designing an automated water tank filling system using technologies like microcontrollers, sensors, solar panels, and batteries to enable smart water usage in Ghanaian communities (Owusu et al., 2016).

Prior studies have explored various systems. Barbade et al. (2021) developed a system using level sensors and circuits to automatically activate pumps based on thresholds. However, limitations like sensor inaccuracy, power dependency, and maintenance needs were noted. Patil and Singh (2014) used individual pumps and contact sensors for level-based control, but could not provide precise readings. Baballe et al. (2022) reviewed systems using float switches and controllers for automatic pump control to prevent wastage. But risks like sensor damage from water flow necessitated safety measures. Ahmed et al. (2018) used float switches and a microcontroller, but faced limitations regarding sensor accuracy. Hazbi and Ma (2023) designed a system using NodeMCU and IoT for remote monitoring and automated filling, but noted dependency and maintenance challenges.

Several studies utilized IoT for smart management. Singh et al. (2019) developed a comprehensive urban system using sensors, analytics, and real-time monitoring to optimize supply and reduce losses. But sensor and data issues were noted. Lee et al. (2020) proposed wireless sensor networks for automated tank filling and remote monitoring, though calibration and power challenges existed. Jain et al. (2019) used IoT sensors, data transmission, and apps for monitoring, but highlighted sensor and connectivity limitations. Olatunji et al. (2020) automated agricultural systems using sensors, microcontrollers, and actuators, while recognizing power and robustness needs.

Multiple studies highlighted benefits but also challenges of systems. Gupta et al. (2019) proposed urban IoT systems for monitoring and optimization, but noted sensor and cybersecurity issues. Li et al. (2017) reviewed wireless networks for water quality monitoring, though sensor and power concerns existed. Rahman et al. (2020) found smart metering reduced wastage and improved billing, but privacy and costs were concerns. Al-Nahar et al. (2021) explored IoT benefits like leak detection, but raised sensor and security challenges. Mishra et al. (2020) showed agricultural promise but highlighted awareness and technical barriers. Kumar et al. (2019) provided an IoT overview, acknowledging security and scalability challenges. Alaraje et al. (2020) presented an IoT design for quality monitoring, while noting sensor and calibration issues.

Additional relevant studies include: Kumar et al. (2021) proposing IoT-based systems, but noting communication and security needs; Sharma et al. (2016) exploring wireless networks for quality monitoring, though citing accuracy and efficiency requirements; Kumar and Khare (2020) investigating smart systems but highlighting sensor and data concerns; Sharma and Singh (2019) examining urban IoT benefits but acknowledging infrastructure challenges.

Previous research demonstrates the potential of automated and IoT-based systems for optimized water management through remote monitoring, data analytics, and automatic control (Owusu et al., 2016; Lee et al., 2020). However, ongoing challenges related to aspects like sensor reliability, maintenance, costs, connectivity, and cybersecurity must be addressed, especially in developing world contexts (Baballe et al., 2022; Kumar & Khare, 2020; Owusu et al., 2016). This highlights the need for continued innovation to create robust, efficient, and intelligent water management systems.

2.2 THEORETICAL FRAMEWORK

The theoretical framework for this research revolves around control theory, which is a suitable theory for this research as it provides a systematic approach to designing and optimizing intelligent automated water tank filling systems. Control theory focuses on developing algorithms and strategies to control and regulate systems to achieve desired behaviors. In this context, the theory can be used to design algorithms that continuously monitor water levels, water consumption patterns, and environmental factors to optimize water usage.(Zhang & Zhou, 2022) Employing control theory principles, the system can adjust the water flow rates, optimize the filling schedules, and maintain water levels within an optimal range, thereby ensuring efficient water usage and sustainable water management.

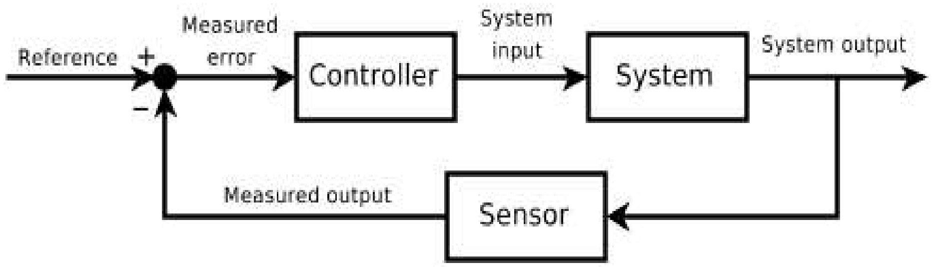

Fig. 1: Control theory
Source: (Zhang & Zhou, 2022)

2.2.1. DEFINITION OF CONSTRUCTS

The study leveraged control theory to guide the system design, incorporating key stages like sensors for data acquisition, a controller for processing inputs, reference algorithms for decision-making, actuators to execute actions, continuous feedback, and optimization. Specifically, the Ultrasonic sensor measures water levels, the ESP32 microcontroller analyzes the data, the control system determines appropriate actions based on water level thresholds, the solenoid valve is triggered to fill the tank accordingly, the LCD displays the status, feedback loops enable adjustments, and algorithms optimize the filling process for efficiency and sustainability. This sensor-controller-actuator feedback control loop with real-time monitoring and optimization enables precise, automated management of water tank filling aligned with the project's sustainable water usage goals.

3 RESEARCH METHODOLOGY

The study used qualitative methods along with the RAD approach. RAD is a structured and iterative software development process that emphasizes user involvement, prototyping, and rapid feedback.(Daraghmi & Daraghmi, 2022). In the context of this study, RAD was applied to efficiently design, develop, and optimize the intelligent automated water tank filling system. The methodology involves the following stages: Requirements Gathering, User Design, Construction and Cutover. At the User Requirements Gathering stage of this study, the researchers purposely selected 20 participants to include in the study. Interviews were conducted with the 20 participants using an interview guide to collect data for the study, observed the existing water management systems, and a comprehensive review of relevant documents. This was to identify specific requirements of the users and desired system functionality for the study.

4. RESULTS

4.1 RAPID APPLICATION DEVELOPMENT MODEL

This project adopted the Rapid Application Development (RAD) methodology, software development approach that emphasizes rapid prototyping and minimal pre-planning. This methodology allows for quicker development and facilitates easier adaptation to changing requirements. The RAD model comprises four key stages: Requirements Planning, User Design, Construction, and Cutover. These stages are essential for effectively designing and optimizing the intelligent water tank filling system to meet the objectives of sustainable water management.

Figure 1: Rapid Application Development Model

Source: (Hamzah et al., 20 19)

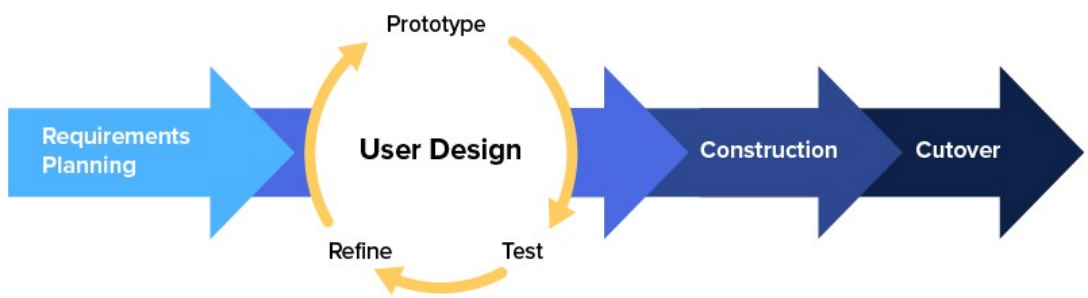

Figure 2. Phases in the Rapid Application Development (RAD) Model

4.2 REQUIREMENTS PLANNING

The study gathered essential requirements for developing an intelligent automated water tank filling system by interviewing diverse participants, including university students, households, landlords, tenants, engineers and plumbers. Interviews focused on experiences with water tanks, management practices, and desired features for optimization. The majority (90%) of participants used water tanks, with 80% having dealt with overflows and 60% facing high electricity consumption. Most (90%) had experience with automated tanks. Additionally, over a year of observations by researchers revealed challenges with manual filling including imbalanced demand and supply, causing overflows or inadequate filling. Key benefits of the proposed system highlighted were optimized usage, reduced wastage, enhanced sustainability, and improved management through preventing overflows and regulating levels. Concerns were raised about initial costs, technology dependency, and user-friendly designs. Current manual methods of gauging water levels were deemed unreliable, often leading to shortages. Larger tanks enabled longer supply, while smaller ones required more frequent refills. Accurate, real-time data was considered essential for planning and conservation. Recommendations included regular maintenance, durable sensors, and mobile app integration for remote monitoring and notifications. Generally, participants welcomed an intelligent system but stressed the importance of affordability, reliability, and intuitive design.

4.3 USER DESIGN

At the user design stage, developers created sketches and visual representations by using Unified Modeling Languages (UMLs) like Block Diagram (BD), and Data Flow Diagrams (DFD). An again moved on to develop a quick prototype of the system, for respondents from the study to engaged, test the and provide invaluable feedback. This iterative process facilitated the refinement of the design, ensuring that the system is intuitive, user-friendly, and well-suited to enhance sustainable water management. The focus extended to creating an interface and interactions that prioritize safety and efficiency in water resource utilization.

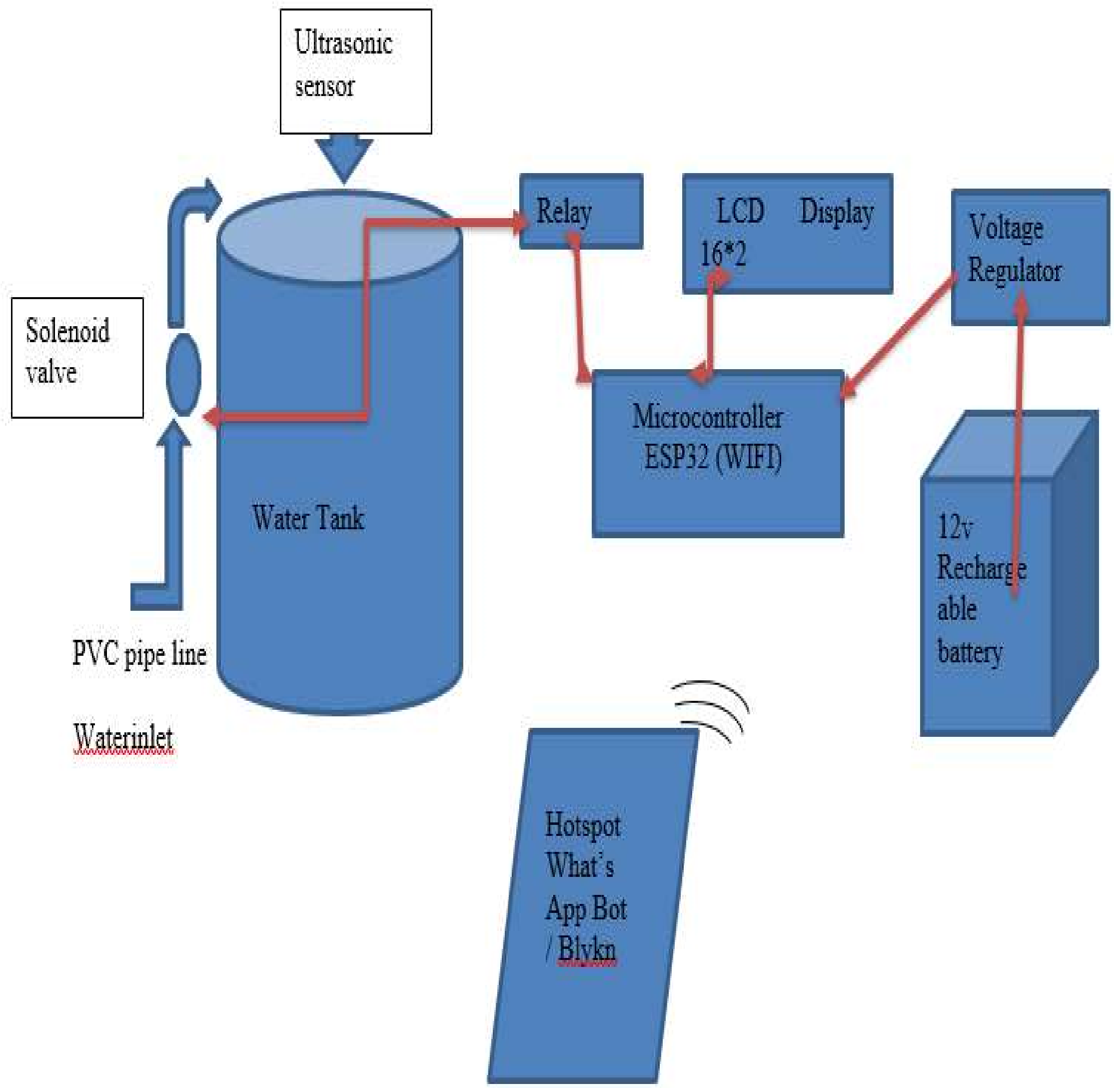

Figure 2: Block Diagram of the System

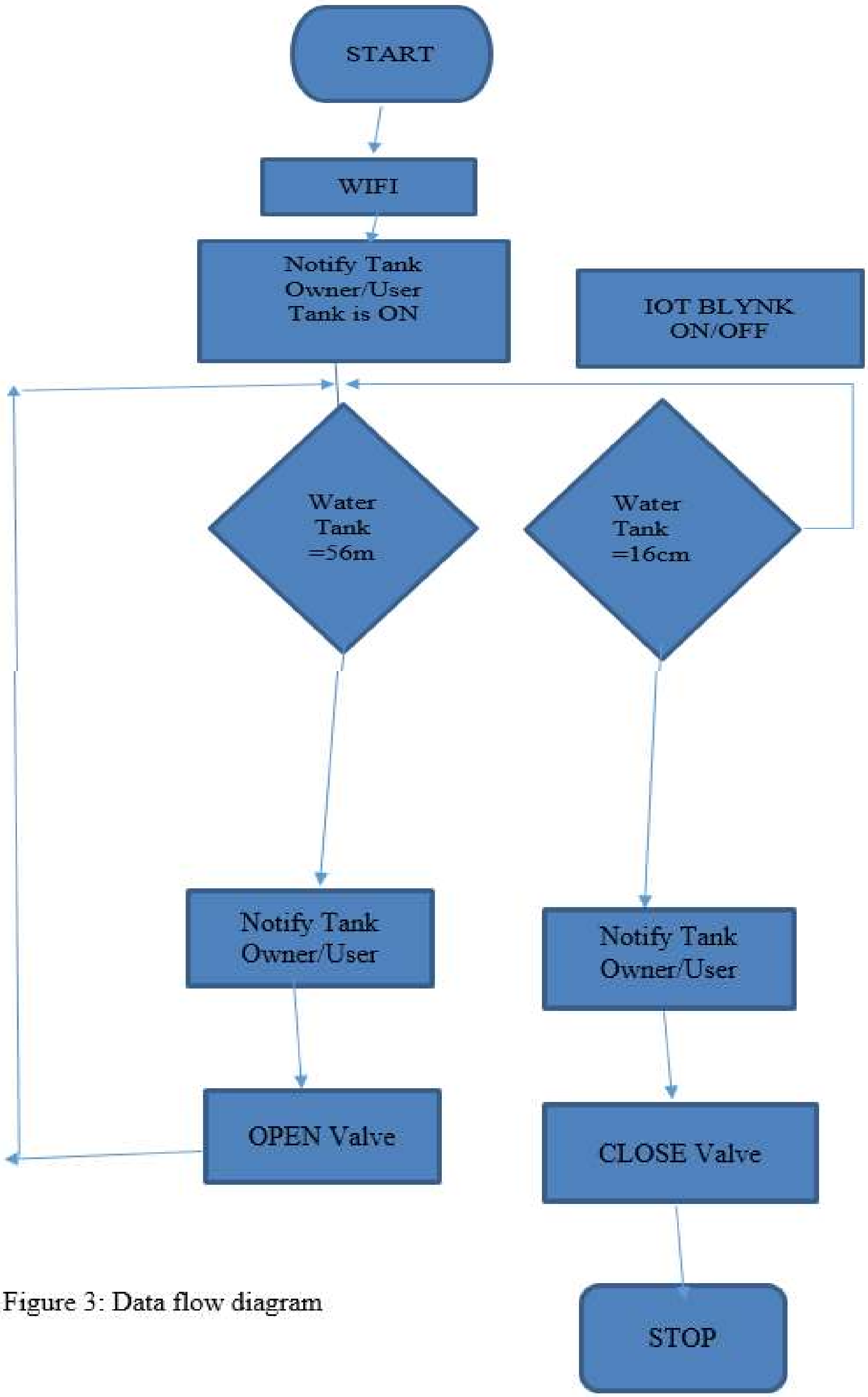

Figure 3: Data flow diagram

4.4 CONSTRUCTION

The construction phase involved collaborative planning, component selection, prototyping, iterative testing, and user-centric validation to build the system (Hehn & Mendez 2022, Avital et al. 2023). A parallel implementation approach allowed the manual and automated systems to co-exist during deployment, enabling a smooth transition (Human, 2023). The harmonization of hardware and software aimed to achieve sustainable water management through cutting-edge integration.

4.5 CUTOVER

The Cutover phase involved thorough pre-deployment testing and optimization of the system's hardware and software. Selected real-world locations like households and universities were identified for installation by technicians, along with user training for operation and troubleshooting. Continuous monitoring enabled data gathering on performance and usage patterns for issue identification and resolution. User feedback throughout this transition from development to full implementation allowed fine-tuning of parameters and interfaces for optimal functionality and user satisfaction (Human, 2023). Successful system deployment and integration contributed to sustainable water management goals.

5 CONCLUSION

In conclusion, this paper presents the design of an automated water tank filling system using advanced technologies to promote optimized and sustainable water management. The system efficiently monitors levels and controls pumping via a microcontroller and valve to prevent wasteful overflows. Components like sensors, solar panels, batteries, and displays enable intelligent automation for precision filling. The methodology incorporated user-centric design and real-world testing to maximize practicality. Overall, the innovative system provides a reliable, energy-efficient solution to improve water conservation, reduce losses, and empower communities through technology integration. The research contributes a valuable framework for leveraging automation and the Internet of Things to tackle pressing water resource challenges.

5.1 RECOMMENDATIONS

This paper exemplifies a meticulous, user-cantered approach to developing an intelligent automated water tank filling system with immense potential for sustainable impact. The thoughtful integration of advanced technologies like microcontrollers, sensors, and solar power demonstrates an innovative solution to pressing water management challenges. The real-world simulations and continuous optimization based on end-user feedback showcase the system's adaptability and practicality for widespread adoption. Given the tangible innovation, solid methodology, and revolutionary capacity to optimize water usage through precision automation, this work represents a profoundly valuable contribution worthy of strong recommendation for implementation and future research

5.2 SUGGESTIONS FOR FUTURE STUDIES

While this intelligent system presents an innovative solution for optimizing water tank filling, additional enhancements could further improve efficiency and sustainability. Future studies can explore integrating smart water quality monitoring using sensors to detect contaminants. Incorporating AI and machine learning algorithms may enable automatic anomaly and leak detection for preventative maintenance. Expanding the system to manage multiple tanks simultaneously could aid larger scale implementations. Assessing environmental and economic impacts would also quantify sustainability benefits. Overall, augmenting the system's capabilities through new technologies, expanded scope, and impact evaluations represents promising directions for advancing intelligent water management.

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