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DEVELOPMENT OF A UNIVERSAL ENERGY-EFFICIENT AUTOMATED METER READING SYSTEM USING ESP32-CAM

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Abstract. The article discusses the design and development of a universal automated meter reading system capable of handling multiple resource types, including water, gas, and electricity. The developed system addresses common challenges associated with manual meter reading, such as accessibility, inconsistent data recording, and human error. The primary innovation presented is integrating the ESP32-CAM module to automate image capturing and data transmission to utility services through a user-friendly mobile application. Special emphasis is placed on optimizing energy efficiency to ensure extended device autonomy. The proposed system includes a robust algorithm for image preprocessing, meter reading validation, and secure wireless communication. Rigorous testing across Android and iOS platforms demonstrated the application's usability, functionality, and consistent performance. Optimization efforts significantly improved device battery life from approximately 50 days to four months. Future improvements are suggested, including developing a custom hardware board to reach the industry-standard operational duration of one year.
Keywords: *automated meter reading, ESP32-CAM, IoT, energy efficiency, mobile application, neural network, utility management*

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1. Introduction

Today, more than ever before, society strives to make life easier and automate all possible processes. Moreover, process automation is gaining momentum, which has caused the appearance of new devices with a relatively large number of advantages, such as high autonomy of work, accuracy, speed of work, and others [1–3].

One of these devices is devices or smart meters that automatically read indicators and transmit them to utility services without human intervention. These devices and smart meters help people. They have quite a lot of advantages. But its main problem is the price. This field is growing quickly, so we chose it to develop our device that would help people read meters and transmit them to utilities [4–5]. Also, a rather significant drawback of the devices currently offered on the market was that the device could transmit only one type of energy, i.e., water, gas, or electricity. That's why we made our solution universal. And can interact with any counter. This feature is our main advantage after the price.

2. Problem statement

Today, numerous solutions allow customers to monitor data on resource consumption, such as gas, water, and electricity. However, there are a lot of old meters that will enable only manual data entry. One of the main issues is the difficulty of consistently recording meter readings. Many people forget to take these readings regularly [6–7]. As a result, the process is often delayed or neglected, leading to accumulated debt or billing discrepancies. Another significant issue is the accessibility of meters. Many meters are located in inconvenient or remote places, which makes accessing them challenging. Even if the customer manages to get readings, the issue of submitting data to a service provider remains [8]. Human error can also play a role because individuals might mistakenly enter incorrect values and, as a result, get inaccurate calculations and potentially higher bills [9–10]. The primary feature of the system described in this work is its ability to automate the entire process of collecting meter readings. This system eliminates the need for consumers to record data manually. It captures readings at regular intervals, reducing the situation when customers forget to get readings.

Purpose: to develop a universal hardware-software solution for automated meter reading and data visualization, ensuring reliability, convenience, and prolonged device operation.

Object: automated meter reading systems for utilities (water, gas, electricity).

Subject: methods and technologies for automatically capturing, processing, and transmitting meter data.

Methods and tools: the system integrates hardware and software methodologies, utilizing the ESP32-CAM microcontroller, deep-sleep power optimization techniques, image preprocessing algorithms, neural network-based optical character recognition (OCR), and secure wireless communication via Wi-Fi and Bluetooth. Kotlin Multiplatform was employed to create a unified, cross-platform mobile application with rigorous functional, usability, and performance testing.

This work aims to create a hardware device that will take photos of your meter and a software application to interpret data taken from photos to charts. Another essential requirement is the device's lifetime because it must be on a high level for comfortable usage. Its battery should last a long time to keep the device running smoothly and reduce the need for frequent upkeep, giving users a worry-free experience. The final application should deliver a complete and automated data collection and monitoring solution. This system will allow users to quickly see their consumption without repeating the task of manual data submission, ensuring accuracy and timely updates to billing information and eliminating the risk of billing discrepancies.

3. Algorithm for taking data from counter

The algorithm for reading and processing data from counters integrates both hardware and software functionalities to ensure seamless operation:

1. Activation: The device activates once a month, following a predefined schedule.
2. Image Capture: The ESP32-CAM module captures an image of the meter display. The

device ensures proper alignment and clarity using auto-focus or fixed-focus settings optimized during setup.

3. Preprocessing: The captured image undergoes preprocessing via the onboard processor, including contrast enhancement, noise reduction, and cropping to focus on the meter's reading area.

4. Data Validation: Recognized values are checked against expected ranges or historical data to identify anomalies such as sudden spikes in usage.

5. Transmission: Processed data is transmitted securely to the mobile application via Wi-Fi or Bluetooth, ensuring real-time updates for the users.

6. Standby Mode: Once the reading is complete, the device reverts to low-power standby mode to conserve energy until the subsequent scheduled activation

4. Development and testing of mobile application and user interface

Development of a mobile application and user interface for automated meter reading systems. The proposed mobile application is a critical interface between end-users and a universal automated meter-reading device, emphasizing usability and intuitive operation. The application's architecture focuses on secure user authentication and efficient device management, facilitating rapid setup and seamless control.

User Authentication and Account Security.

To ensure both security and a personalized user experience, the application integrates a robust user registration and authentication system. New users create an account by providing essential details, such as a valid email and a password, enabling the secure association of user data and device configurations with individual accounts. Upon returning, users log in to access their personalized dashboard, manage devices, and monitor meter readings, maintaining a secure and streamlined experience.

Device Integration and Connectivity.

The application simplifies the onboarding of new devices. Users can add devices through an intuitive “Add Device” function, with connectivity options including Bluetooth and Wi-Fi. Guided instructions assist users in pairing devices, establishing a connection efficiently, and enabling immediate monitoring. This user-centric process minimizes technical complexity, ensuring accessible setup and reliable connectivity.

Device Management Interface.

Following successful device pairing, the application presents users with a management interface for real-time control. This interface includes options for basic settings adjustments and initiating meter readings, emphasizing clarity and ease of use. Users can activate, deactivate, and check device status and initiate updates, supporting continuous monitoring with minimal user effort.

This optimized design prioritizes accessibility and efficiency, allowing users to concentrate on managing utility consumption with minimal setup and operational demands.

Application testing. To ensure the reliability and robustness of the mobile application, a comprehensive testing strategy was implemented, encompassing functional, usability, and performance evaluations across Android and iOS platforms. Initial functional testing validated core features, including user registration, device connectivity, and data retrieval accuracy, ensuring each function met specified requirements.

Usability testing was conducted with a focus group of target users to assess the interface's intuitiveness and streamline workflows, particularly in device pairing and meter-reading functions. To evaluate the app’s responsiveness and stability, performance testing examined its behavior under various conditions, including network strengths and data loads. Cross-platform testing on Android and iOS devices also ensured uniform functionality and interface behavior, leveraging Kotlin.

Multiplatform’s capabilities for consistent operation across platforms. This rigorous testing process reinforced the application's reliability and capacity to deliver a seamless, user-centered experience aligned with the demands of an automated utility management environment.

Why did we choose the ESP-32 cam itself for our device? For the development of our device, we considered several microcontroller options that meet the key requirements: camera support and energy efficiency. The leading candidate was the ESP32 board, but we also compared it with other popular solutions: Raspberry Pi Zero W, Arduino MKR1000, and STM32F746G Discovery.

Table 1. Comparison of output data properties of expert systems and neural networks

Characteristics	ESP32	Raspberry Pi Zero W	STM32F746G Discovery
Camera	Built-in support	Additional module	Possible with an adapter
Energy efficiency	High, up to 1.67 mAh	Medium (up to 100 mAh)	HLow (up to 200 mAh)
Price	low	medium	High
Processor	Dual-core, 240 MHz	Single core, 1 GHz	Single-core, 216 MHz
Memory	520 KB of RAM	512 MB of RAM	320 KB of RAM

Review of Boards.

1. ESP32. The ESP32 is a microcontroller with a dual-core processor (240 MHz), built-in Wi-Fi and Bluetooth modules, and support for external cameras via the ESP32-CAM module. The ESP32 has become a popular choice for IoT projects thanks to its high energy efficiency and affordability.

Advantages: built-in camera support; deep sleep modes that significantly reduce power consumption (down to 1.67 mAh in our test); low cost; support for various peripheral devices;
Disadvantages: limited RAM (520 KB); specialized module (ESP32-CAM) is required for camera operation.

Suitability: Ideal for budget-constrained projects requiring autonomy and camera functionality.

2. Raspberry Pi Zero W. The Raspberry Pi Zero W is a compact single-board computer with a 1 GHz processor and built-in Wi-Fi and Bluetooth modules. It is well-suited for projects requiring greater computational power and flexibility.

Advantages: supports camera connection via the dedicated Raspberry Pi Camera module; significant memory capacity (512 MB RAM); large user community and extensive software availability; Disadvantages: high power consumption even in idle mode (up to 100 mAh); requires an additional module for camera operation, increasing costs; relatively higher cost compared to ESP324.

Suitability: best suited for projects where performance and the need for a Linux environment are critical, but energy efficiency is not a priority.

3. STM32F746G Discovery is a powerful board based on the STM32 microcontroller with a 216 MHz processor, used in projects with high computational requirements. The board supports camera connections via adapters.

Advantages: powerful processor; large RAM capacity (320 KB RAM); ability to connect cameras through external adapters.

Disadvantages: low energy efficiency (power consumption up to 200 mAh); very high cost; complexity in use due to a multi-component design.

Suitability: Suitable for high-tech projects where computational power is critical but autonomy is not.

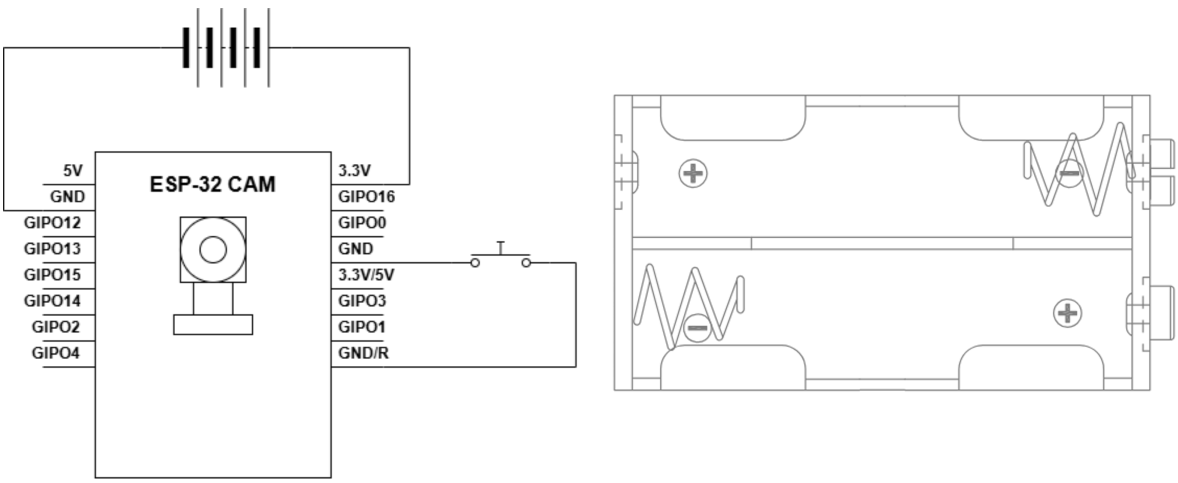
By choosing the ESP32, we achieved the optimal balance between functionality, energy efficiency, and cost. Its support for cameras and low power consumption enables the creation of autonomous devices that can operate for extended periods without battery replacement. Additionally, the built-in Wi-Fi and Bluetooth modules provide seamless integration into IoT infrastructure, while its affordable price makes this board the perfect choice for budget-friendly projects.

5. Analysis and Optimization of Device Operational Duration

A key aspect of our device is its extended operating time, which is crucial for such solutions. We approached this issue with utmost seriousness.

First, we analyzed our competitors to determine how long similar devices could function without battery replacement. The analysis revealed that, on average, competitor devices can operate for a year. Using this information, we initiated tests to evaluate the operational duration of our device under various modes using our firmware.

Initially, we tested the device with non-optimized firmware, configured to operate in a deep sleep mode and activate once a month to read meter indicators and transmit them to utility services. For power, we chose two batteries with a capacity of 2500 mAh each. This option was selected due to the convenience of replacing batteries when necessary (Fig. 1).



a) board | b) battery holder

а) плата | б) плейсхолдер для батареї

Fig. 1 - The device resources

Testing revealed that this setup, combined with the standard plug-in for our ESP32-CAM board, was suboptimal. The batteries were discharged by 60%(1) after one month. Calculations indicated that our board consumed 4.16 mAh in this mode, resulting in an operational duration of only 50 days:

Calculation: 60% = 3000 mAh; 3000 / 30 ≈ 100 mA/day; 100 / (24) = 4.16 mAh

To determine how many days the device can operate at full charge (100%). 1. Total battery capacity: 100% = 5000 (two batteries, each with 2500 mAh). 2. Daily consumption is based on the calculations: 100 mAh/day. 3. Operational duration on a full charge: 5000 mAh / 100 mAh / day = 50 days; (5000 mAh) / (100 mAh) = 50 days.

Conclusion: The device can operate for 50 days on a full charge.

This performance was unsatisfactory and not competitive in the market. Faced with this result, we decided to make significant changes. Several options were considered, including optimizing the firmware or increasing the batteries to four. However, adding more batteries was not appealing due to the increased cost and the inconvenience of replacing four batteries every few months. Ultimately, we opted to focus on firmware optimization.

After optimizing the firmware, we repeated the tests with the same two 2500 mAh batteries. After one month, we were pleasantly surprised by the results: the batteries were discharged by only 24%. This meant our device could now operate for approximately four months. Calculations confirmed that the board’s consumption had decreased from 4.16 mAh to 1.67 mAh.

Calculation:

Step 1: Battery usage after one month. Total battery capacity: 5000 mAh (two batteries of 2500 mAh. Discharge after one month: 24%. Consumed capacity in one month = 5000 mAh × 0.24 = = 1200 mAh.

Step 2: Daily consumption. Number of days in one month: 30 days. Daily consumption = 1200 mAh / 30 days = 40 mAh/day. Hourly Consumption: 40 mAh / day / 24 hours ≈ 1.67 mAh/hour.

Step 3: Operational duration for 100% charge. Total capacity: 5000 mAh. Daily consumption: 40 mAh. Operational duration = 5000 mAh / 40 mAh/day = 125 days.

Step 4: Verify consumption rate decrease. Previously, consumption was 4.16 mAh/hour, now 1.67 mAh/hour. The device can operate at full charge for approximately 125 days (about 4 months). This improvement was a significant step forward, and we decided to retain the optimized firmware due to its enhanced energy efficiency.

However, despite these advancements, we have not yet achieved the one-year operational benchmark set by our competitors. To reach this goal, further improvements are necessary. Our plans include developing a custom board tailored to our device’s needs rather than relying on the standard ESP32-CAM board. This step is expected to significantly enhance the device’s energy efficiency, as competitors typically use custom-designed boards for their solutions.

6. Conclusions

This study presented a novel automated meter reading solution designed to overcome traditional challenges faced in manual data collection. Initial analysis identified critical issues, including inconsistent manual readings, difficulty accessing meters, human error in data transcription, and the limited universality of existing devices. The proposed universal solution, built around the ESP32-CAM microcontroller, effectively addressed these limitations by enabling the automated collection and wireless transmission of readings for gas, water, and electricity meters through a user-friendly mobile application.

One of the critical aspects of the proposed device was ensuring energy efficiency. Initial tests with standard firmware configurations revealed suboptimal battery performance, lasting approximately 50 days on a single charge. Recognizing this issue, significant firmware optimizations were implemented, resulting in a dramatic improvement in energy efficiency. Subsequent testing demonstrated that the optimized system significantly reduced power consumption from 4.16 mAh/hour to 1.67 mAh/hour, extending the operational duration to approximately four months on two 2500 mAh batteries.

Despite these substantial improvements, the achieved battery life still fell short of the one-year benchmark set by market competitors. As a result, the research identified the need for further enhancements through custom hardware development. Developing a custom circuit board optimized for system needs was identified as a crucial move to boost lifespan and energy efficiency for better market performance.

The developed mobile application provided secure, intuitive device management, data visualization, and user authentication, leveraging Kotlin Multiplatform to ensure consistent performance across Android and iOS devices. Comprehensive usability and performance tests validated the application's ease of use, responsiveness, and reliability, confirming its suitability for widespread adoption.

In conclusion, this project significantly contributes to modernizing utility management systems by automating meter readings, enhancing accuracy, reducing human error, and improving consumer convenience. Although there remains room for improvement in hardware optimization, the developed solution successfully meets core objectives, establishing a solid foundation for future development and scalability within automated utility management technologies.

Conflicts of Interest: the authors declare no conflict of interest.

References

1. Das, M., Kaur, A., Sadiq, S., Ekka, G.S., Ghosh, T.K. (2024). Hybrid home automation system using IoT. *In Advances in Networks, Intelligence and Computing*, pp.198-209. CRC Press ISBN 9781003430421
2. Zubkov, O.V., Yakovenko, O.C., Starokozev, C.V., Skorbatuk, M.V. (2024). Development and research of an algorithm for automated recognition of gas meter readings. *Radiotekhnika*, (219) , 46-52 [in Ukrainian] DOI: https://doi.org/10.30837/rt.2024.4.219.05
3. Labunsky, V., Zaschepkina, N., Labunskaya, A. (2023). Improving the method of water meter calibration. Measuring and computing devices in technological processes, (2), 67-71. [in Ukrainian]. DOI: https://doi.org/10.31891/2219-9365-2023-74-22
4. AlRuwais, S., AlQahtani, R., AlHajri, N., AlHashim, B., Bashar, A., & AlZubaidi, L. (2021). S-LIGHT: Smart LED Lamppost using PWM-based Adaptive Light Controller. *In 2021 10th IEEE International Conference on Communication Systems and Network Technologies (CSNT)* (pp. 325-331). IEEE. DOI: https://doi.org/10.1109/CSNT51715.2021.9509652
5. Navarrete-Sanchez, M. A., Olivera-Reyna, R., Olivera-Reyna, R., Perez-Chimal, R. J., & Munoz-Minjares, J. U. (2025). IoT-Based Classroom Temperature Monitoring and Missing Data Prediction Using Raspberry Pi and ESP32. *Journal of Robotics and Control (JRC)*, 6(1), 234-245 DOI: https://doi.org/10.18196/jrc.v6i1.24345
6. Abadade, Y., Temouden, A., Bamoumen, H., Benamar, N., Chtouki, Y., & Hafid, A. S. (2023). A comprehensive survey on tinyml. IEEE Access, 11, 96892-96922. DOI: https://doi.org/10.1109/ACCESS.2023.3294111
7. Kaur, A., Jadli, A., Sadhu, A., Goyal, S., & Mehra, A. (2021). Cloud based surveillance using ESP32 CAM. In 2021 international conference on intelligent technology, system and service for internet of everything (ITSS-IoE) (pp. 1-5). IEEE. DOI: https://doi.org/10.1109/ITSS-IoE53029.2021.9615334
8. Kumar, S., Sharma, K., Raj, G., Datta, D., Ghosh, A. (2022). Arduino and ESP32-CAM-Based Automatic Touchless Attendance System. In: Sikdar, B., Prasad Maity, S., Samanta, J., Roy, A. (eds) *Proceedings of the 3rd International Conference on Communication, Devices and Computing. ICCDC 2021. Lecture Notes in Electrical Engineering, vol 851.* Springer, Singapore. DOI https://doi.org/10.1007/978-981-16-9154-6_14
9. R. R. PBV, V. Sonaleo Mandapati, S. L. Pilli, P. Lahari Manojna, T. H. Chandana and V. Hemalatha, "Home Security with IOT and ESP32 Cam - AI Thinker Module," 2024 *International Conference on Cognitive Robotics and Intelligent Systems (ICC - ROBINS)*, Coimbatore, India, 2024, pp. 710-714, DOI: https://doi.org/10.1109/ICC-ROBINS60238.2024.10533960

РОЗРОБКА УНІВЕРСАЛЬНОЇ ЕНЕРГОЕФЕКТИВНОЇ АВТОМАТИЗОВАНОЇ СИСТЕМИ ЗНЯТТЯ ПОКАЗАНЬ ЛІЧИЛЬНИКІВ З ВИКОРИСТАННЯМ ESP32-CAM

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Анотація: У цій статті обговорюється проектування та розробка універсальної автоматизованої системи зняття показань лічильників, здатної працювати з різними типами ресурсів, включаючи воду, газ та електроенергію. Розроблена система вирішує загальні проблеми, пов'язані з ручним зняттям показань лічильників, такі як доступність, непослідовність запису даних та людські помилки. Основною інновацією є інтеграція модуля ESP32-CAM для автоматизації захоплення зображень та передачі даних до комунальних служб через зручний мобільний додаток. Особливий акцент зроблено на оптимізації енергоефективності для забезпечення тривалої автономності пристрою. Запропонована система включає надійний алгоритм попередньої обробки зображень, перевірку показань лічильників та безпечний бездротовий зв'язок. Ретельне тестування на платформах Android та iOS продемонструвало зручність, функціональність та стабільну роботу програми. Зусилля з оптимізації значно збільшили час роботи пристрою від батареї з приблизно 50 днів до чотирьох місяців. Пропонується подальше вдосконалення, зокрема розробка спеціальної апаратної плати для досягнення стандартної тривалості роботи в один рік.

Ключові слова: *автоматизоване зчитування лічильників, ESP32-CAM, IoT, мобільний додаток, енергоефективність, нейронна мережа, управління комунальними послугами*

Конфлікт інтересів

Автори повідомляють про відсутність конфлікту інтересів.