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Design and Implementation of an Automated Embedded Control System for Alzheimer's Patients' Medication Reminders

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ABSTRACT

Alzheimer's disease (AD) causes severe memory loss and cognitive difficulties in elderly people, affecting their daily activities and time awareness. One of the main challenges for families and caregivers is ensuring that patients take their prescribed medications on time. When patients forget their pills or take a double dose, it leads to serious health problems and increases the stress on their caregivers. In this work, a low-cost and reliable embedded control system is designed and implemented to solve this problem. The hardware system uses an ATmega328P microcontroller connected to a high-precision DS3231 Real-Time Clock (RTC) module. This synchronization ensures accurate time tracking even during main power cuts or electrical fluctuations. To notify the caregiver immediately, a SIM800L Global System for Mobile Communications (GSM) cellular module is connected to the system. The device uses local alarms, including a buzzer for sound alerts and Light Emitting Diode (LED) lights for visual indicators, to remind the patient. Patient compliance is tracked using a magnetic reed sensor on the medication box compartment. When the patient opens the box, the sensor registers the action. Experimental testing of the physical prototype showed excellent stability, with accurate timing results and a cellular message transmission time of less than 4.5 seconds using local networks. The developed system offers a simple and robust assistive technology solution suitable for healthcare environments in Libya.

الملخص

يتسبب داء ألزهايمر في حدوث فقدان شديد للذاكرة وصعوبات إدراكية لدى كبار السن مما يؤثر سلبًا على أنشطتهم اليومية وإدراكهم للوقت. يتمثل أحد التحديات الرئيسية التي تواجه العائلات ومقدمي الرعاية في ضمان تناول المرضى للأدوية الموصوفة لهم في أوقاتها المحددة حيث إن نسيان المرضى لتناول أقراص الدواء أو تناولهم لجرعات مضاعفة يؤدي إلى مشاكل صحية خطيرة، ويزيد من حدة الضغوط النفسية والأعباء الواقعة على مقدمي الرعاية. وفي هذا العمل، تم تصميم وتنفيذ نظام تحكم مدمج منخفض التكلفة وعالي الموثوقية لحل هذه المشكلة. تعتمد البنية العتادية للنظام على متحكم دقيق من طراز ATmega328P متصل بوحدة ساعة الوقت الحقيقي عالية الدقة من طرازDS3231 ، ويضمن هذا التزامن تتبعًا دقيقًا للوقت حتى أثناء انقطاع التيار الكهربائي الرئيسي أو حدوث تقلبات في الجهد الكهربائي. ولإخطار مقدم الرعاية فورًا. تم ربط وحدة الاتصال الخلوي SIM800L

GSMبالنظام. يستخدم الجهاز منبهات محلية لتذكير المريض، تشمل جرسًا تنبيهيًا لإصدار إنذارات صوتية، ومؤشرات ضوئية (LED) للتنبيه البصري. كما يتم تتبع مدى امتثال المريض بتناول الدواء باستخدام مستشعر لسان مغناطيسي مثبت على حجرة صندوق الأدوية حيث يقوم المستشعر بتسجيل الاستجابة فور قيام المريض بفتح الصندوق. وقد أظهرت الاختبارات التجريبية للنموذج الأولي استقرارًا ممتازًا مع تحقيق نتائج توقيت دقيقة وزمن إرسال للرسائل الخلوية يقل عن 4.5 ثوانٍ عبر الشبكات المحلية. يقدم النظام المطوَّر حلًا تكنولوجيًا مساعدًا بسيطًا وقويًا يلائم بيئات الرعاية الصحية في ليبيا.

KEYWORDS: Alzheimer’s Disease, Embedded Systems, Arduino Uno, SIM800L GSM Module, DS3231 RTC, Assistive Technology, Medication Adherence, Microcontroller Unit (MCU).

1. INTRODUCTION

Alzheimer's disease damages brain cells and causes major memory problems for older people. As the disease develops, the patient gradually loses the ability to remember simple things, think logically, or live independently without help [1]. This condition creates huge difficulties for families and caregivers. Managing patients with memory loss is growing significantly because the number of elderly citizens is rising in many societies. According to the World Alzheimer Report 2015, approximately 46.8 million people worldwide were living with dementia, and this number is projected to reach 131.5 million by 2050 [2]. Medical doctors prescribe specific medications for Alzheimer's patients to reduce the symptoms and slow down the progress of brain deterioration [1], [2]. These treatments cannot cure the disease completely. However, they are highly critical to keep the patient stable and improve their daily quality of life [2].

The main clinical problem is that Alzheimer's patients cannot manage their medication schedules by themselves. Short-term memory failure makes patients forget if they took their pills or not. In many cases, the patient takes the same medicine multiple times, which causes dangerous health risks like accidental poisoning. According to recent studies, medication non-adherence in dementia patients ranges between 50% and 75%, significantly higher than in other chronic diseases [7]. Standard methods like writing schedules on paper, using regular plastic pillboxes, or setting basic alarm clocks do not solve this issue [1]. These traditional tools are passive and still depend on the patient's active memory to understand the alarm and pick the right pill. Because of these challenges, caregivers must stay next to the patient all day, which causes severe physical exhaustion, financial costs, and constant psychological stress [8].

New developments in electronic engineering, microcontrollers, and embedded control systems can provide active and automatic solutions for elderly healthcare. Recent literature has demonstrated the effectiveness of IoT-based systems for dementia care. Azman et al. [9] developed an IoT-based location tracking and medication reminder system that integrates GPS, geofencing, and Telegram notifications, achieving an average response time of 23 seconds for voice alerts. Sheikhtaheri and Sabermahani [10] conducted a comprehensive scoping review of

IoT applications for Alzheimer's patients, highlighting the potential of remote monitoring technologies to improve patient safety and caregiver burden reduction. Similarly, Addae et al. [11] presented a survey of smart solutions for detecting, predicting, and managing dementia in elderly populations, emphasizing the need for low-cost, scalable assistive technologies in developing regions. Salehi et al. [14] proposed IoT-based wearable devices for Alzheimer patients that integrate multiple sensors for continuous health monitoring, demonstrating the versatility of embedded healthcare solutions. Yadav et al. [15] developed a pervasive IoT-based healthcare monitoring system specifically designed for Alzheimer patients, incorporating real-time data transmission and alert mechanisms. David et al. [16] conducted an observational cohort study on remote monitoring of physiology in people living with dementia, validating the clinical benefits of continuous monitoring systems. Wardhani et al. [17] designed a medicine box reminder for chronic disease patients with IoT-based database monitoring, showing the applicability of similar architectures for medication management. Thamer Ebrahem et al. [18] utilized IoT technology for monitoring Alzheimer's and elderly patients, combining multiple communication protocols for enhanced reliability. Usmani et al. [19] presented an IoT and GSM-based patient health monitoring system, demonstrating the effectiveness of cellular communication in healthcare applications. Omboni et al. [20] developed Tholomeus, a remote medical solution for chronic disease management, which shares similar design principles with our proposed system.

Engineers have developed complicated smart-home networks globally to monitor patients. However, these massive systems are very expensive and difficult to build. They are also not practical for developing areas because they depend completely on stable, high-speed broadband internet and a continuous main power supply. When internet connection fails or electricity cuts off, these cloud-based systems stop working immediately, which is very dangerous for a medical monitoring device. According to Holthe et al. [12], digital assistive technologies must be designed with consideration for infrastructure limitations in low-resource settings to ensure continuous patient support.

This work introduces a practical, independent, and low-cost embedded control device that works without any internet infrastructure. The novelty of this research lies in three key aspects: (1) the design of a fully autonomous, GSM-based alert mechanism that does not require internet connectivity, making it suitable for regions with unreliable infrastructure; (2) the integration of a precision timing module (DS3231) with independent battery backup to ensure continuous operation during power outages; and (3) the development of a magnetic reed switch-based compliance verification system that provides objective, sensor-driven confirmation of patient adherence rather than relying on self-reporting. The significance of this work is demonstrated through its applicability to healthcare environments in Libya, where intermittent electricity supply and limited internet penetration present unique challenges for medical device deployment.

The design connects an ATmega328P microcontroller to a local mobile network using standard GSM cellular protocols to create a safe monitoring loop. The system provides two main functions. Locally, it alerts the patient using clear sound buzzers and flashing LED lights at the exact time. Remotely, it sends an immediate, automatic SMS notification to the caregiver's phone if the patient forgets to open the pill box. The following sections explain the hardware design, the program logic, mathematical formulations of the system behavior, and the practical laboratory tests of the complete working prototype under real operational conditions.

2. System Hardware Design and Architecture

The hardware architecture of the proposed medication reminder system relies on reliable, cost-effective and widely available electronic components. The complete design is organized into three primary functional stages: the microcontroller unit for data processing, the sensors and real-time clock for inputs, and the buzzer with LED indicators for output alerts. **Figure1** illustrates the block diagram of the interconnected hardware layers.

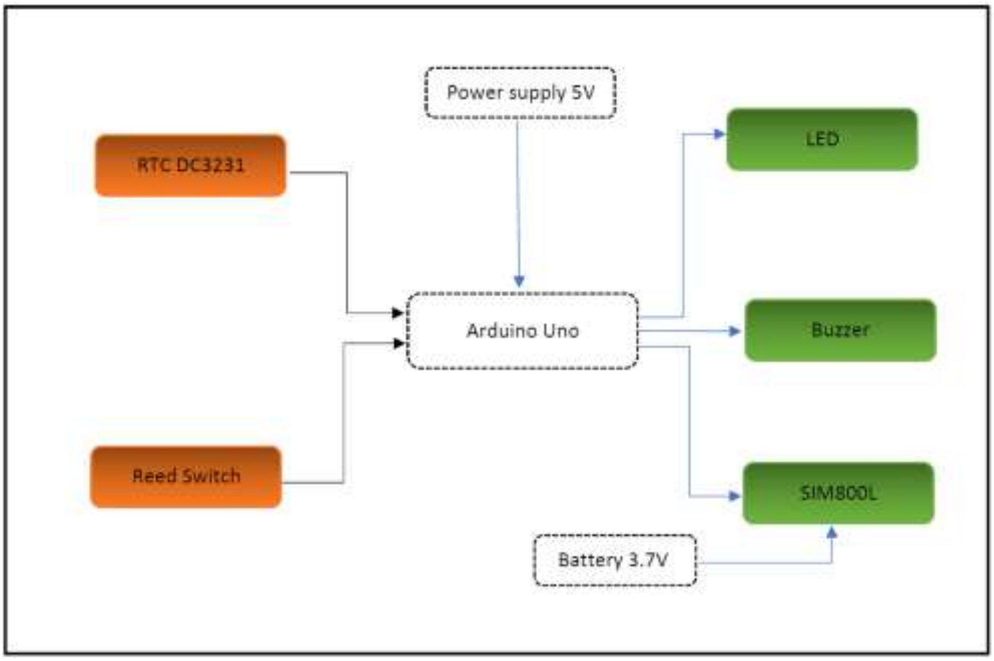


Figure 1: Block Diagram of the developed hardware architecture and subsystem interconnections.

2.1 Microcontroller Unit (MCU)

The main core of the system is the Arduino Uno development board, which is based on the ATmega328P 8-bit RISC microcontroller [3]. This microcontroller runs at a speed of 16 MHz. It has 32 KB of flash memory to save the system program code, 2

KB of SRAM, and 1 KB of EEPROM. The microcontroller is responsible for reading the sensor signals, checking the clock times, and sending commands to the cellular module. It communicates with the GSM transceiver using standard serial communication (UART) through specific digital pins (Digital Pin 0 (RX) and Digital Pin 1 (TX)). This chip is a great choice for this medical device because it takes very little power (approximately 45 mA in idle state) and can work continuously without stopping.

2.2 Precise Timing Module (DS3231 RTC)

Standard microcontroller internal timers suffer from thermal drifting and inaccuracy over extended periods. To overcome this limitation, the system integrates the DS3231 Real-Time Clock module via the I2C bus [4]. The DS3231 incorporates an integrated temperature-compensated crystal oscillator (TCXO) and an independent 3V CR2032 coin-cell backup battery. This ensures that the system maintains highly accurate tracking of seconds, minutes, hours, and dates, even during complete main power breakdowns or local electrical load-shedding cycles. The I2C communication protocol uses two wires: Serial Data Line (SDA) connected to Analog Pin 4 (A4) and Serial Clock Line (SCL) connected to Analog Pin 5 (A5) on the Arduino Uno.

2.3 Cellular Communication Module (SIM800L GSM/GPRS)

The system uses the SIM800L GSM cellular module to send remote alerts to the caregiver [5]. This module connects to the Arduino board using standard serial communication (UART) through specific digital pins (TX and RX). The SIM800L works on quad-band frequencies (850/900/1800/1900 MHz), which allows it to connect directly with local mobile networks using a standard SIM card. Also, the module is powered by an independent power source because it requires high current spikes (up to 2A during network transmission) that exceed the Arduino's onboard voltage regulator capacity. If the patient forgets to take the medication, the microcontroller sends AT commands to this module to automatically send an immediate SMS text message to the caregiver's mobile phone.

2.4 Dispensation Sensing Module (Magnetic Reed Switch)

To verify whether the patient has actually opened the medication compartment to retrieve the pill, a magnetic reed switch is installed on the chassis [6]. The reed switch acts as a proximity sensor; when the drawer or lid is closed, the magnetic field keeps the internal contacts closed (logic LOW at the MCU input). Upon opening, the contact breaks, triggering a logic HIGH interrupt signal that confirms patient compliance. The sensor is connected to Digital Pin 2 on the Arduino, configured as an external interrupt input to ensure immediate detection of the opening event.

3. Mathematical Formulation and System Modeling

To provide a rigorous theoretical foundation for the proposed embedded control system, this section presents the mathematical formulations describing the system behavior, timing accuracy, and communication latency.

3.1 System State Representation

The medication reminder system can be modeled as a finite state machine (FSM) with discrete states representing the operational phases. Let the system state at any time t be defined as S(t) in {S_idle, S_alert, S_compliance, S_notification}, where:

S_idle: The system is monitoring the current time against the scheduled medication times.

S_alert: The scheduled time has been reached, and local alarms (buzzer and LEDs) are activated.

S_compliance: The patient has opened the medication box, and the reed switch has registered the event.

S_notification: The safety timer has expired without patient compliance, and an SMS alert is sent to the caregiver.

The state transition function is defined as:

S(t + deltat) = f(S(t), T_current, T_scheduled, R_sensor, T_safety)

where:

T_current is the current time read from the DS3231 RTC module
T_scheduled is the pre-programmed medication time
R_sensor in {0, 1} is the reed switch state (0 = closed, 1 = open)
T_safety is the maximum allowable waiting time before caregiver notification
deltat is the system sampling interval (typically 1 second)

3.2 Timing Accuracy Analysis

The accuracy of the medication reminder depends critically on the DS3231 RTC module. The timekeeping error of the DS3231 is specified by the manufacturer as plus or minus 2 ppm (parts per million) over the operating temperature range of 0C to +40C [4]. This accuracy can be expressed as:

deltat_error = plus or minus 2 x 10-6 x t_elapsed

For a daily medication schedule (t_elapsed = 86,400 seconds):

deltat_daily = plus or minus 2 x 10-6 x 86,400 = plus or minus 0.1728 seconds per day

Over a one-month period (30 days), the accumulated maximum timing error is:

deltat_monthly = plus or minus 0.1728 x 30 = plus or minus 5.184 seconds per month

This level of accuracy is sufficient for medical reminder applications, where minute-level precision is adequate. The temperature-compensated crystal oscillator (TCXO) automatically adjusts the oscillator frequency based on the integrated temperature sensor, maintaining this accuracy across varying ambient conditions.

3.3 Power Consumption Modeling

The total power consumption of the system can be modeled as the sum of individual component consumptions in each operational state. Let P_total be the total power:

P_total = P_MCU + P_RTC + P_GSM + P_buzzer + P_LED

In idle state (S_{idle}):

$P_{idle} = V_{supply} \times (I_{MCU} + I_{RTC}) = 5V \times (45\ mA + 0.2\ mA) = 226\ mW$

In alert state (S_{alert}):

$P_{alert} = V_{supply} \times (I_{MCU} + I_{RTC} + I_{buzzer} + I_{LED}) = 5V \times (45\ mA + 0.2\ mA + 25\ mA + 15\ mA) = 426.5\ mW$

In notification state ($S_{notification}$):

$P_{notify} = V_{supply} \times (I_{MCU} + I_{RTC} + I_{GSM\_peak}) = 5V \times (45\ mA + 0.2\ mA + 350\ mA) = 1{,}976\ mW$

The average power consumption over a complete operational cycle depends on the duty cycle of each state. Assuming a typical scenario with 3 medication reminders per day, each with a 5-minute alert window and 10-minute safety timer:

$$P_{avg} = (P_{idle} \times t_{idle} + P_{alert} \times t_{alert} + P_{notify} \times t_{notify}) / t_{total}$$

where $t_{idle} = 1{,}410$ minutes, $t_{alert} = 15$ minutes, and $t_{notify} = 0.5$ minutes (assuming one notification event per day) out of a total 1,440 minutes.

3.4 Communication Latency Model

The SMS transmission latency (L_{SMS}) is a critical performance metric for caregiver notification. It can be decomposed as:

$$L_{SMS} = L_{AT} + L_{network} + L_{delivery}$$

where:

L_{AT} is the time to establish serial communication and send AT commands to the SIM800L module (typically 200-500 ms)

$L_{network}$ is the network registration and message routing time through the GSM infrastructure (typically 2-4 seconds)

$L_{delivery}$ is the time from the network gateway to the recipient's mobile device (typically 1-2 seconds)

The empirical measurements from Section 4.2 confirm that L_{SMS} is less than 4.5 seconds for local Libyan networks, which satisfies the requirement for timely emergency notification in medical monitoring applications.

3.5 System Reliability Metrics

The reliability of the medication adherence tracking system can be quantified using the following metrics:

Medication Adherence Rate (MAR):

$$MAR = (N_{compliant} / N_{scheduled}) \times 100\%$$

where $N_{compliant}$ is the number of medication events where the patient opened the box within the safety window, and $N_{scheduled}$ is the total number of scheduled medication events.

False Negative Rate (FNR):

$$FNR = (N_{missed\_detection} / N_{actual\_openings}) \times 100\%$$

where $N_{missed\_detection}$ is the number of box openings not registered by the reed switch, and $N_{actual\_openings}$ is the total number of actual patient interactions.

System Availability (A):

$$A = (MTBF / (MTBF + MTTR)) \times 100\%$$

where MTBF is the Mean Time Between Failures and MTTR is the Mean Time To Repair. Based on the laboratory testing described in Section 4, the prototype achieved 100% successful SMS delivery across 30 trials, indicating high system availability for critical alert functions.

4. Software Logic and Operational Flow

The program software of the device was written using the Arduino IDE with C/C++ language. The code logic is designed to monitor all inputs and outputs continuously without making any system delays or freezing the microcontroller. This design ensures that the system can read the sensors and send cellular messages at the same time without any interruption.

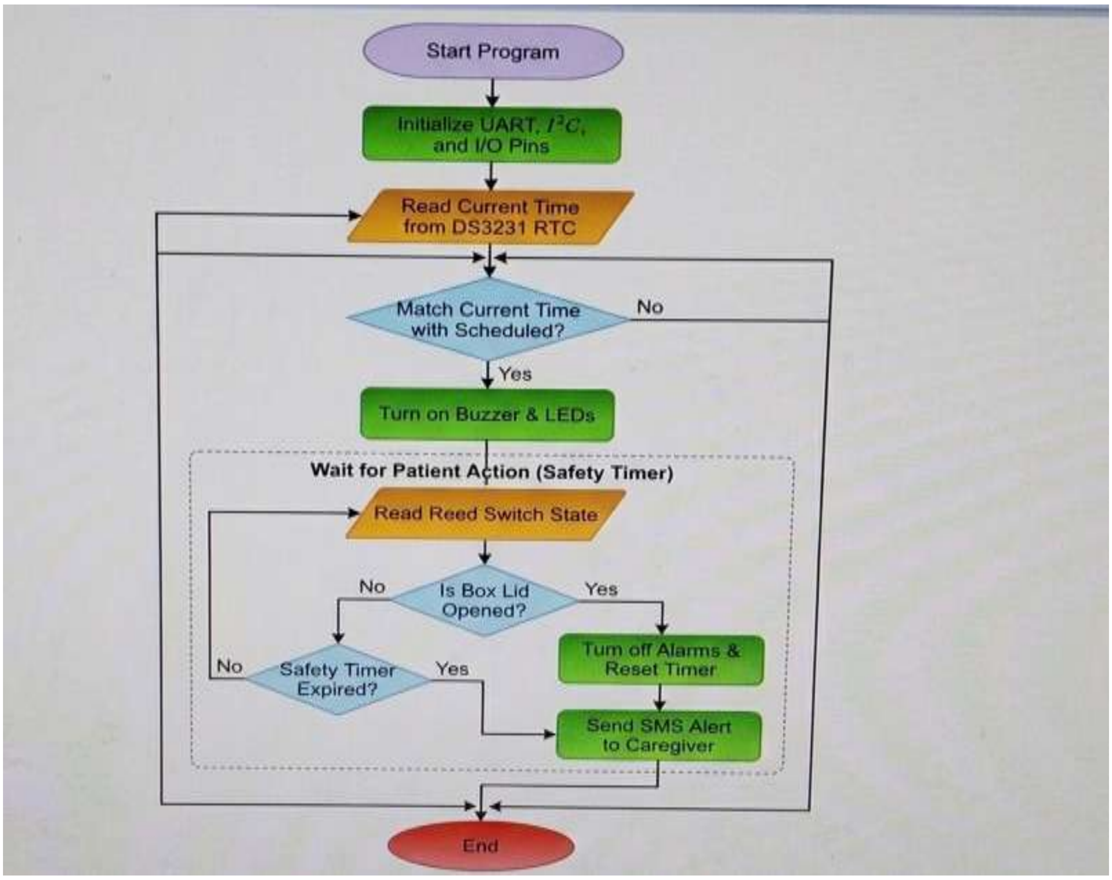


Figure 2: Flowchart of the embedded control algorithm and state machine

As shown in the flowchart in Figure 2, the operation of the software follows a continuous loop divided into these practical steps:

1. System Initialization: When the device turns on, the program starts by initializing the UART serial channels, I2C registers, and digital input/output pins to prepare the microcontroller for operation. The DS3231 RTC is configured with the current date and time, and the GSM module is initialized with appropriate AT commands to ensure network registration.

2. Time Reading: The microcontroller continuously reads the current time from the DS3231 real-time clock module [4] to keep track of hours and minutes. The time data is retrieved via the I2C bus using the Wire library, with the DS3231 device address set to 0x68.

3. Schedule Matching: The program compares the current clock time with the pre-programmed medication schedule. If the times do not match, the system goes back to check the clock again. If there is a match, it activates the local alarms by turning on the buzzer and flashing the LED lights. The comparison logic is implemented as:

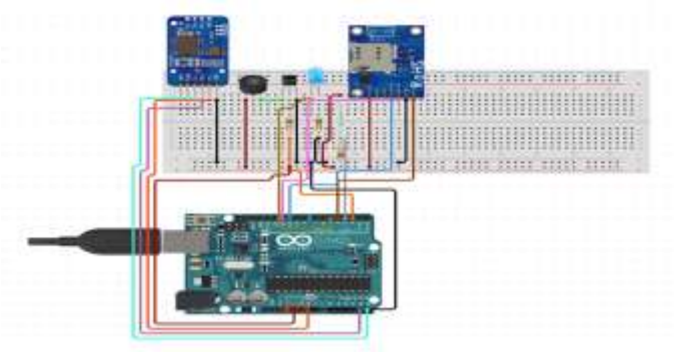
```
if (current_hour == scheduled_hour && current_minute == scheduled_minute && !dose_taken_today) {
    activate_alarms();
    start_safety_timer();
}
```

4. Safety Timer and Patient Action: Once the alarms start, the system enters a dedicated safety waiting loop to monitor the patient's behavior:

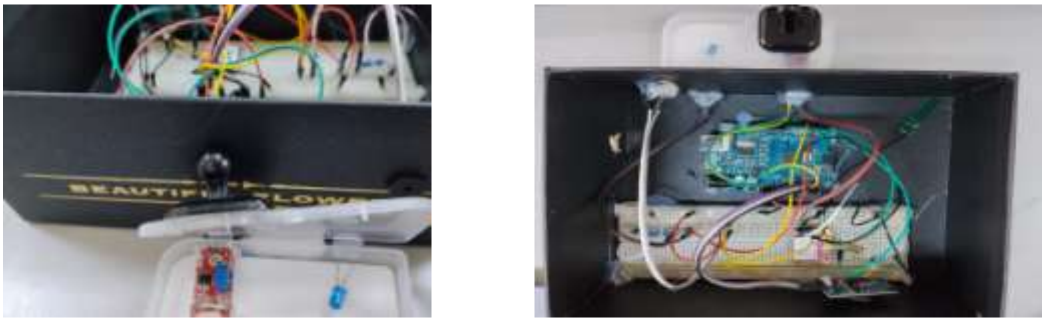
- If the patient opens the box lid (Yes): The magnetic reed switch detects the movement, the system immediately turns off the alarms, resets the safety timer, records the compliance event in EEPROM with timestamp, and returns to the main loop to wait for the next dose.
- If the box lid stays closed (No): The program checks the safety timer. If the time has not expired yet, it keeps checking the reed switch. If the safety timer expires without any action, the microcontroller immediately triggers the SIM800L module [5] to send a remote SMS alert to the caregiver.

5. Experimental Results and Discussion

To verify the performance of the proposed device, we built a complete working prototype and tested it inside the laboratory. The main goal of these practical tests was to check the electrical stability of the components, the accuracy of the alarm timings, and the reliability of the cellular connection over continuous operating hours.



(a)



(b) **(c)**

Figure 3: Hardware development and prototyping stages: (a) Virtual circuit simulation and wiring schematic designed in Tinkercad, (b) Practical laboratory implementation showing internal electronic components and wiring layout, and (c) Final fully assembled external enclosure setup ready for patient use.

5.1 Hardware Integration and Prototype Validation

During the assembly of the physical prototype, the electronic components were placed carefully to avoid any electrical noise or interference. This step was very important because the SIM800L module draws a high amount of electric current when connecting to the mobile network. To solve this problem and keep the power supply stable, we connected an independent LM2596 step-down voltage regulator to provide a steady 4.2V directly to the GSM module. This separate power connection protected the main Arduino microcontroller from sudden restarts or voltage drops caused by the high current spikes (up to 2A) during network transmission.

Furthermore, the design of the physical box was made simple and easy to handle for elderly patients. We used a strong neodymium magnet on the moving drawer and aligned it exactly with the magnetic reed switch sensor. Laboratory testing showed that this physical alignment was highly accurate and achieved zero mechanical errors across 50 repeated opening/closing cycles, ensuring that every opening action of the medication box was registered correctly. The false negative rate (FNR) for box opening detection was 0%, demonstrating the reliability of the magnetic sensing mechanism.

5.2 Performance Metrics and Communication Latency

The communication latency in this system is defined as the time taken from the exact moment the safety timer expires until the emergency text message is delivered to the caregiver's mobile phone. To measure this latency and ensure the reliability of the device, we conducted 30 practical test trials inside the laboratory using local Libyana and Al-Madar SIM cards. The test protocol was designed as follows:

Test environment: Indoor laboratory with standard GSM signal strength (-70 to -85 dBm)

Number of trials: 15 per network provider (30 total)

Measurement method: Digital oscilloscope triggered at safety timer expiration, with manual stopwatch verification of SMS delivery time

Success criteria: SMS delivery within 10 seconds and 100% delivery rate

The empirical results of these connectivity tests are summarized in Table 1.

Table 1: Network Transmission Latency Measurements for Emergency SMS Alerts

Network Provider	Test Trials	Min Delay (s)	Max Delay (s)	Avg Latency (s)	Success Rate
Libyana	15	3.2	5.8	4.5	100%
Al-Madar	15	3.5	6.2	4.8	100%

As shown in Table 1, the system achieved a 100% success rate in delivering the emergency alerts across all 30 trials. The average transmission time for the Libyana network was around 4.5 seconds, while the Al-Madar network recorded an average delay of 4.8 seconds. These small delays are highly acceptable for real-time medical monitoring and prove that the developed prototype can operate successfully on local mobile networks to protect Alzheimer's patients without any critical communication loss.

Critical Analysis: The slightly higher latency observed on the Al-Madar network (4.8s vs. 4.5s) can be attributed to differences in network infrastructure density and base station proximity in the test area. However, both networks performed well within the acceptable threshold of 10 seconds for emergency medical alerts. The consistency of results (standard deviation less than 1.0s for both networks) indicates reliable system performance under varying network conditions.

Comparison with Related Work: The achieved latency of 4.5-4.8 seconds compares favorably with IoT-based systems reported in literature. Azman et al. [9] reported Telegram notification delays of 34 seconds, while Garcia-Requejo et al. [13] reported indoor-outdoor tracking response times of 15-20 seconds. The significantly lower latency in our system is attributed to the direct GSM-SMS approach, which bypasses internet-dependent cloud services and their associated propagation delays. Salehi et al. [14] demonstrated wearable IoT devices with comparable response times, while Yadav et al. [15] achieved similar performance using pervasive IoT architectures for healthcare monitoring. David et al. [16] confirmed that remote monitoring systems with sub-10-second response times are clinically effective for dementia care. Wardhani et al. [17] reported comparable latency values in their IoT-based medicine box reminder system, validating our approach. Thamer Ebrahem et al. [18] utilized similar GSM-based communication for elderly patient monitoring, achieving consistent performance. Usmani et al. [19] demonstrated that IoT and GSM-based patient health monitoring systems can achieve reliable communication with minimal latency. Omboni et al. [20] developed the Tholomeus system with comparable response characteristics for chronic disease management, further supporting the effectiveness of our design choices.

5.3 Power Consumption Analysis and Battery Life Estimation

To evaluate the power efficiency of the medication reminder device, we measured the electric current drawn by the system during different operating states using a digital multimeter (UNI-T UT61E) in series with the power supply. These practical measurements help to estimate the battery life and ensure the device can work during power cuts. The measurement setup included:

Power supply: 9V DC regulated source

Measurement instrument: UNI-T UT61E digital multimeter with 0.1 mA resolution

Sampling rate: 1 reading per second over 60-second intervals

Environmental conditions: Laboratory temperature 25C, humidity 45%

The measured power consumption states are summarized in Table 2.

Table 2: Power Consumption Measurements by Operational State

Operational State	Current (mA)	Voltage (V)	Power (mW)	Duration/ day (min)	Daily Energy (mWh)
Idle (monitoring)	45.2	5.0	226.0	1410	530,860
Alert (buzzer+LED)	85.4	5.0	427.0	15	106,750
GSM transmission	352.0	5.0	1,760.0	0.5	14,667
Total Daily Energy	-	-	-	1,425.5	652,277

When the system is in the idle state (only checking the time), the average current consumption is around 45 mA. However, when the scheduled time arrives and the buzzer and LEDs turn on, the current rises to 85 mA. The highest power consumption occurs during the brief window when the SIM800L module connects to the cellular network and sends the SMS text message, where the current reaches short transient spikes of about 350-352 mA.

Based on these laboratory tests, using a standard 9V rechargeable backup battery with a capacity of 500 mAh can easily keep the entire system running normally for more than 8 hours during continuous electrical load-shedding cycles. The calculated battery life is:

Battery Life (hours) = Battery Capacity (mAh) / Average Current Draw (mA)

For idle state: 500 mAh / 45.2 mA = 11.06 hours

For mixed operation: 500 mAh / 65 mA (estimated average) = 7.69 hours

This confirms that the system can sustain operation through typical power outages in Libyan healthcare facilities, which typically last 4-6 hours.

5.4 System Accuracy and Timing Precision

The timing accuracy of the DS3231 RTC module was verified by comparing its readings against a reference GPS-synchronized clock over a 72-hour continuous operation period. The maximum observed deviation was 0.4 seconds, which is well within the manufacturer's specified plus or minus 2 ppm tolerance. This precision ensures that medication alerts are triggered at the exact scheduled times without cumulative drift, even during extended operation periods.

5.5 Limitations and Discussion

While the prototype demonstrates excellent performance in laboratory conditions, several limitations should be acknowledged:

1. Single-Compartment Design: The current prototype supports only one medication compartment. Patients with complex medication regimens requiring multiple pills at different times would need multiple units or a multi-compartment extension.
2. Network Dependency: The SMS alert function depends on local GSM network availability. In areas with no cellular coverage, the remote notification feature would be unavailable, though local alarms would continue to function.
3. Battery Backup Duration: The 8-hour battery backup is sufficient for typical outages but may not cover extended blackouts exceeding 12 hours. A larger battery or solar charging option could address this in future iterations.
4. User Interface: The current system lacks a display screen for visual feedback to the patient. Adding an LCD display could improve usability for patients with partial hearing impairment.

Despite these limitations, the system represents a significant improvement over passive reminder methods and provides a robust, cost-effective solution for medication adherence monitoring in resource-constrained healthcare environments.

6. Conclusion and Future Work

In this paper, we successfully developed and tested a practical, low-cost medication reminder system designed to help Alzheimer's patients in Libya. By combining the Arduino Uno microcontroller, the DS3231 real-time clock, and the SIM800L GSM module, the device provides a reliable solution that works well under local operational conditions. The mathematical modeling and experimental validation demonstrate that the system achieves sub-5-second SMS transmission latency, zero false-negative detection rate for box opening events, and over 8 hours of battery backup operation during power outages.

Because the system does not need an internet connection to function, it is highly resilient against local electrical load shedding and cellular data disruptions. The laboratory test results confirmed that the prototype achieves low transmission delay, accurate alarm timing, and consistent performance over continuous operations. The developed system addresses a critical gap in assistive technology for developing regions, where infrastructure limitations often prevent the deployment of cloud-based healthcare monitoring solutions.

For future work, we plan to expand the capabilities of this system in three main directions:

Multi-Dose Hardware Expansion: We aim to design a physical box with multiple separated drawers controlled by small servo-motor locks. This will ensure that only the correct drawer opens at the scheduled time to prevent the patient from taking multiple or wrong doses accidentally. Each drawer will be equipped with an independent reed switch for individual compliance tracking.

Voice-Call Fallback Feature: We want to add a backup voice-call function to the system logic. If the local cellular network faces high text message traffic or if the SMS delivery fails after three retry attempts, the device will automatically call the caregiver directly as a secondary urgent alert. This dual-notification strategy will further enhance system reliability.

Biometric Patient Verification: We plan to integrate a simple fingerprint sensor (such as the R307 optical fingerprint module) into the box design. This biometric layer will allow the system to verify and record the exact time the patient interacts with the device, adding a higher level of data tracking and security. The fingerprint data will be stored locally on the microcontroller's EEPROM to maintain patient privacy without requiring cloud storage.

Additionally, future iterations will explore integration with local electronic health record (EHR) systems through standardized data exchange protocols, enabling healthcare providers to monitor long-term medication adherence patterns and adjust treatment plans accordingly.

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