IoT-Enabled Security System for Car Theft Prevention

Analysis and Design

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1. Customers/Clients

1.1. Definition

The primary customers for this IoT-enabled security system are vehicle owners seeking robust and efficient solutions for vehicle theft prevention. These customers include individuals in urban areas with higher crime rates, businesses that operate vehicle fleets, and automotive manufacturers interested in integrating advanced security features into their products. Urban residents, especially those in densely populated areas, face elevated theft rates due to limited access to secure parking facilities, which makes additional security a priority for them [1]. Businesses with vehicle fleets, such as delivery services and rental companies, require reliable anti-theft capabilities for multiple vehicles to avoid operational disruptions and financial losses [2]. Automotive manufacturers and dealerships increasingly incorporate security technology that aligns with industry standards and the latest trends, aiming to appeal to security-conscious consumers [3]. Across these customer groups, there is a shared demand for features like reliability, real-time alerts, and a user-friendly interface with minimal interference in daily vehicle operation.

1.2. Challenges

Vehicle owners face several key challenges in theft prevention that this IoT-enabled system aims to address. First, high theft rates are a persistent problem, especially in urban regions with insufficient security infrastructure. The financial impact of vehicle theft on individuals and businesses can be substantial, prompting an urgent need for reliable security solutions [4]. Cost efficiency is another critical concern;

customers expect an affordable option that does not compromise quality or reliability, making pricing a crucial factor in adoption [5]. Usability is also essential for the customer base, as complex security systems can deter users seeking simplicity and ease of use. A streamlined and user-friendly interface helps clients operate the system without frustration or needing technical expertise [6]. Finally, battery efficiency poses a significant challenge; excessive power consumption may necessitate frequent recharging for long-term GPS tracking, which is impractical for customers who lack easy access to charging points. Customers value solutions that maximize battery life to reduce maintenance and enhance convenience [7].

2. **Competitive Landscape**

In the current market for vehicle security, various systems offer distinct methods for theft prevention and vehicle tracking, each with unique advantages and limitations. Understanding the competitive landscape is essential to identify opportunities for improvement and differentiation. This analysis reviews three prominent solutions—Carlock, Ituran, and Ravelco—each addressing specific challenges in vehicle security. By examining their strengths and shortcomings, this section highlights areas where our proposed IoT-enabled vehicle security system could enhance user control, reduce costs, and offer a more robust, integrated approach to vehicle protection.

2.1. **Carlock**

How it addresses the challenges:

- Real-time GPS tracking with location updates every 30 seconds

- Instant alerts for unauthorized movement, speeding, or battery disconnection
- Remote engine immobilization via smartphone app
- Geofencing capabilities to set safe zones for the vehicle

Shortcomings:

- Requires a constant cellular connection for real-time tracking
- A monthly subscription fee may be costly for some users
- Potential for false alarms in areas with poor GPS signal
- It can be turned off if thieves locate and remove the device

Carlock offers comprehensive security features that align well with modern vehicle protection needs [8]. However, its reliance on cellular networks and the possibility of physical tampering remain significant limitations.

2.2. **Ituran**

How it addresses the challenges:

- Covert installation of tracking devices for difficult detection by thieves
- 24/7 monitoring and recovery assistance
- Integration with local law enforcement for quick response
- Utilizes both GPS and Radio Frequency technology for improved tracking

Shortcomings:

- Limited user control over the system compared to DIY solutions
- Requires professional installation, which can be inconvenient and costly

- May have coverage limitations in some geographic regions
- Lacks some advanced features like remote immobilization or real-time alerts to the owner's smartphone

Ituran's system excels in vehicle recovery due to its partnership with law enforcement and the use of multiple tracking technologies [9]. However, it offers less direct control to the vehicle owner and may not prevent the initial theft attempt.

2.3. **Ravelco**

How it addresses the challenges:

- Physically prevents the vehicle from starting without the unique plug
- No batteries or programming is required, making it difficult to bypass electronically
- One-time installation with no ongoing costs
- Visible deterrent to potential thieves

Shortcomings:

- There are no tracking capabilities if the vehicle is successfully stolen
- Lacks real-time alerts or remote monitoring features
- Requires manual activation each time the car is parked
- May not prevent theft methods that don't involve hot-wiring (e.g., key fob cloning)

The Ravelco system claims a 100% success rate in preventing hot-wiring theft attempts [10]. However, its lack of tracking and smart features limits its effectiveness against more sophisticated theft methods and doesn't provide the real-time information that modern car owners desire.

3. **Requirement Specification**

3.1. **Real-Time GPS Tracking**

The system must provide real-time GPS tracking to monitor vehicle location accurately and efficiently. This functionality is crucial for immediate vehicle recovery in the event of theft. Tracking must be continuous and responsive to prevent loss of location data.

Performance Metrics: Update location within 5-10 seconds of change, providing precision up to 5 meters.

3.2. **Motion Detection**

Motion detection is essential for identifying suspicious activity around the vehicle. The system should trigger alerts based on unauthorized motion near or within the vehicle.

Performance Metrics: Detect motion within a range of 7 meters and trigger alerts within 2 seconds of detection.

3.3. **Remote Alerts**

Upon detecting unusual activity, the system must display the vehicle's location data on a screen and trigger a red LED that flickers to indicate motion detection.

Performance Metrics: Detect motion with a range of 7 meters and trigger alerts within 3 seconds of detection.

3.4. **NEO-6M GPS Module**

The NEO-6M GPS module will serve as the core GPS component for the system, providing accurate and reliable real-time data on vehicle location. It is highly sensitive, has low power, and supports a cold start time of 27 seconds, making it well-suited for automotive use.

Specifications:

- Position accuracy: 2.5m CEP (circular error probable)
- Cold start: 27 seconds
- Power consumption: 37mA in tracking mode.

3.5. **HC-SR501 Motion Sensor**

The HC-SR501 is a passive infrared (PIR) motion sensor that will detect movement around the vehicle. It is low-cost, widely available, and easily interfaces with the system's microcontroller.

Specifications:

- Detection range: Up to 7 meters
- Delay time: Adjustable from 5 seconds to 5 minutes
- Operating voltage: 5V.

3.6. **Battery Management**

Efficient battery management ensures the system can run for extended periods without frequent recharging. The system will incorporate a low-power microcontroller and battery to support long-term GPS tracking and sensor operation.

Specifications:

- Battery capacity: 2000mAh (minimum)
- Power consumption: <50mW in idle mode, <500mW during GPS tracking.

3.7. **Safety Requirements**

The design must comply with strict power and energy limits for safety and regulation. The system cannot use, transfer, or release more than 30 watts of power, and the total energy stored must not exceed 500 millijoules (mJ). These limits help prevent overheating, electrical issues, or accidental energy discharge. Only the project system is subject to these power restrictions, and any external connections operating at higher power will require a full safety review by the teaching team. For demonstrations, no connections to external high-power systems will be allowed unless approved for safety. Components connected to a 110V AC power supply must be CSA-approved as per University of Waterloo safety rules. Lastly, no research or testing on animals or humans is allowed, as human testing requires special approval and is beyond this project's scope, so all tests must use non-living methods.

4. **Design**

4.1. **System Summary**

The IoT Vehicle Anti-Theft System is a security solution engineered to monitor a vehicle's location and detect real-time unauthorized movement. At the heart of this system is an STM32 microcontroller - the output processing unit - that coordinates data from GPS and motion sensors, both powered by a dedicated battery source. This direct battery connection to the GPS and motion modules ensures consistent, reliable operation without requiring a separate backup. A second STM32 microcontroller – the remote receiver unit – will receive and process information from the output processing unit. Each unit will be housed in a custom 3D-printed compartment specifically designed to store the modules securely.

A key system component, the GPS module continuously tracks the vehicle's position, providing real-time location data essential for monitoring and alerting. In addition, integrated motion sensors detect any unusual movements or vibrations that could indicate tampering or unauthorized access. These sensors enable the system to respond to physical disturbances, improving the vehicle's security against potential threats.

To support remote monitoring, the system is equipped with a display module that shows the vehicle's location data and a red LED that flickers when motion is detected, providing immediate visual alerts to the user. The LoRa module enables wireless communication between the two STM32 microcontrollers, transmitting location data and alerts over long distances. Designed with power efficiency and simplicity, this system leverages sleep states to deliver continuous tracking and motion detection in a compact, low-power solution adaptable to various vehicle types and scenarios.

4.2. **Component Overview and Configuration**

STM32 Nucleo Boards

The IoT Vehicle Anti-Theft System utilizes two STM32F401RE boards designated for specific functions. The first board manages the GPS module and motion sensor, providing the necessary processing power to handle sensor inputs and control the data flow. It will be referred to as the Output Processing Unit (OPU). The second board acts as a receiver for the wireless module, facilitating communication with the first board to process and display alerts. It will be referred to as the Remote Receiver Unit (RRU). The OPU will draw power from a dedicated battery, and the RRU will draw power from an outlet, ensuring the system's reliable operation.

GPS Module: NEO-6M

The NEO-6M GPS module is critical for obtaining vehicle real-time location data. It provides precise latitude and longitude coordinates that can be used to track the vehicle's movements and determine unauthorized motion. This module will connect to the OPU STM32 board via UART communication pins (TX and RX) to facilitate data transmission. Operating on a power supply ranging from 3.3V to 5V, the GPS module will also draw power from the dedicated battery connected to the system.

Motion Sensor

A motion sensor, such as a PIR sensor, will be integrated into the OPU STM32 to detect unauthorized movement. This component is essential for triggering alerts and initiating GPS tracking when suspicious activity is detected. The motion sensor will connect to a digital input pin on the OPU STM32 board and continuously draw power from the dedicated battery, ensuring it is always operational. Digital filtering techniques, such as FIR or IIR filters, will be applied to smooth the motion sensor data, helping to minimize false triggers from transient signals like wind or small animals and enhancing detection accuracy.

Display Module and LED

The display module will provide real-time visual feedback to the user, showing the vehicle's location data. It will be connected to the RRU STM32 board, which receives the location data from the first board via the LoRa module. This allows the user to monitor the vehicle's status remotely. Additionally, a red LED will begin flickering if there is unauthorized access to the vehicle.

Wireless Communication: LoraWAN Module

The HW-650 NRF905 (LoraWAN) wireless transceiver module enables wireless communication between the two STM32 boards. The first OPU STM32 board, connected to the GPS and motion sensor, will transmit data to the RRU STM32 board, receiving alerts and notifications. The NRF905 module will connect to the first board using SPI communication involving the CE, CSN, SCK, MOSI, MISO, and VSK pins. The RRU STM32 board will also incorporate an NRF905 module to receive the transmitted data from the first board. Both modules will operate at 3.3V and draw power from the dedicated battery.

Power Supply

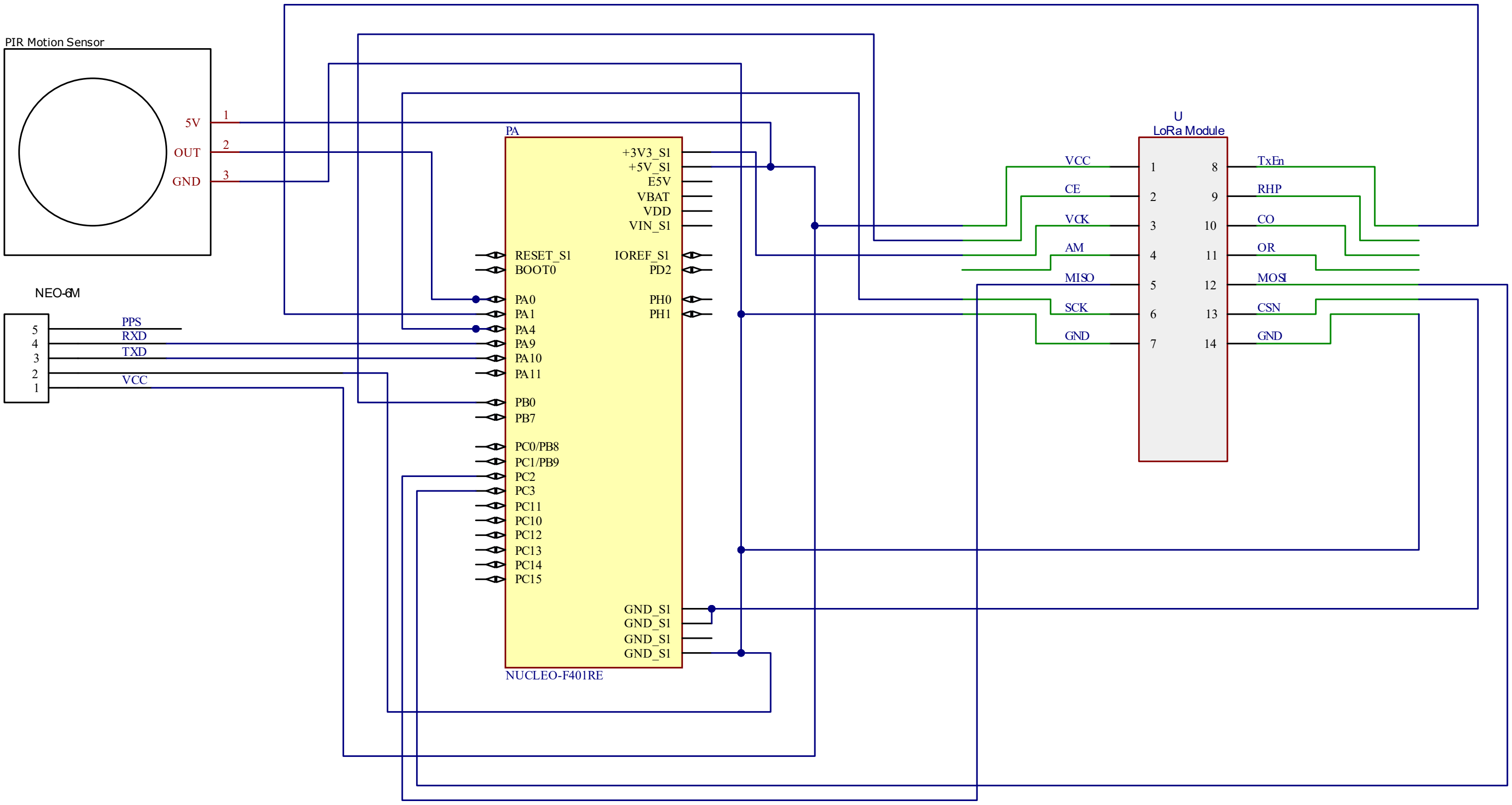
The STM32 microcontroller output processing unit will be powered by a dedicated battery that connects to all components, ensuring reliable operation of the anti-theft system without interruption. The remote receiver unit will be connected to an outlet. A rechargeable lithium-ion battery will be selected to provide sufficient energy storage for continuous operation.

Summary

In summary, this configuration details the essential components of the IoT Vehicle Anti-Theft System, with each element playing a vital role in the overall functionality. Integrating two STM32 microcontrollers, the GPS module, motion sensor, display module, and wireless transceiver creates a framework for protecting the vehicle against theft, while the continuous power supply ensures uninterrupted operation.

4.3. **Assembly and Integration Instructions**

STM32 Microcontroller Output Processing Unit

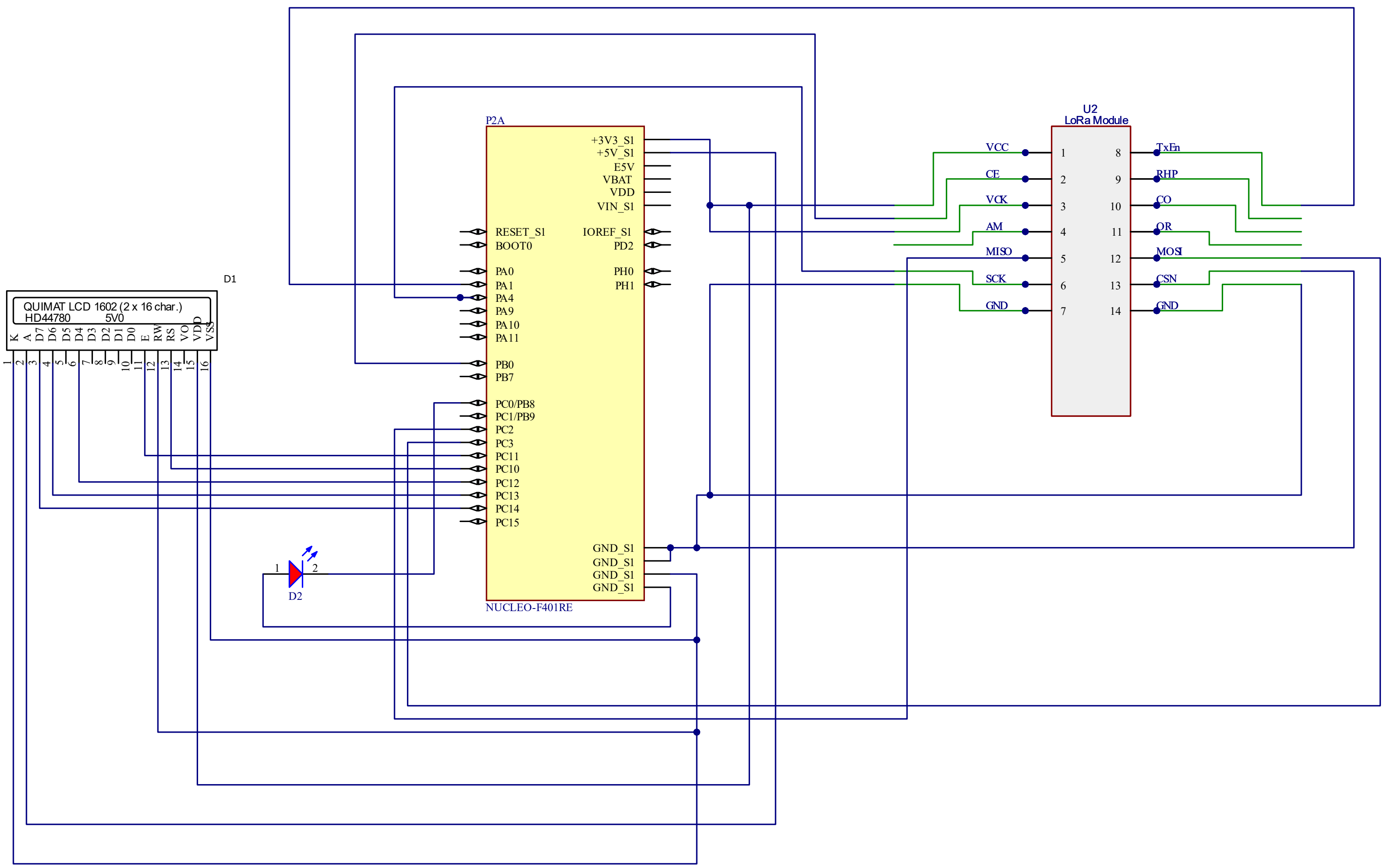


1. Prepare Components
   - Gather the STM32 microcontroller, NEO-6M GPS module, HC-SR501 motion sensor, HW-650 NRF905 transceiver, and any additional required resistors or capacitors.
   - Refer to the OPU schematic to verify each component's placement and orientation.
2. Connect the GPS Module (NEO-6M)

- Connect the NEO-6M GPS module to the STM32 microcontroller using UART pins: TX to RX and RX to TX.
- Ensure power and ground connections from the battery are secure.

3. Attach the Motion Sensor (HC-SR501)
    - Connect the HC-SR501 motion sensor to a digital input pin on the STM32, as shown in the schematic.
    - Secure power and ground connections ensure uninterrupted power for the sensor.
4. Install the NRF905 Transceiver (HW-650)
    - Follow the schematic to connect the SPI communication pins (CE, CSN, SCK, MOSI, MISO, and VSK) between the NRF905 module and the STM32.
    - Check the connections for correct orientation and secure power from the dedicated battery.
5. Power Supply Integration
    - Connect the battery source to the STM32, GPS, motion sensor, and LoRa transceiver as specified.
6. Verify Connections and Initialize
    - Double-check connections using the schematic, verifying power, data, and ground alignments.
    - Power on the OPU to verify proper functionality; confirm initialization of the GPS and motion sensors and their entry into sleep states when inactive.

Schematic 4.3.2: STM32 Microcontroller Remote Receiver Unit



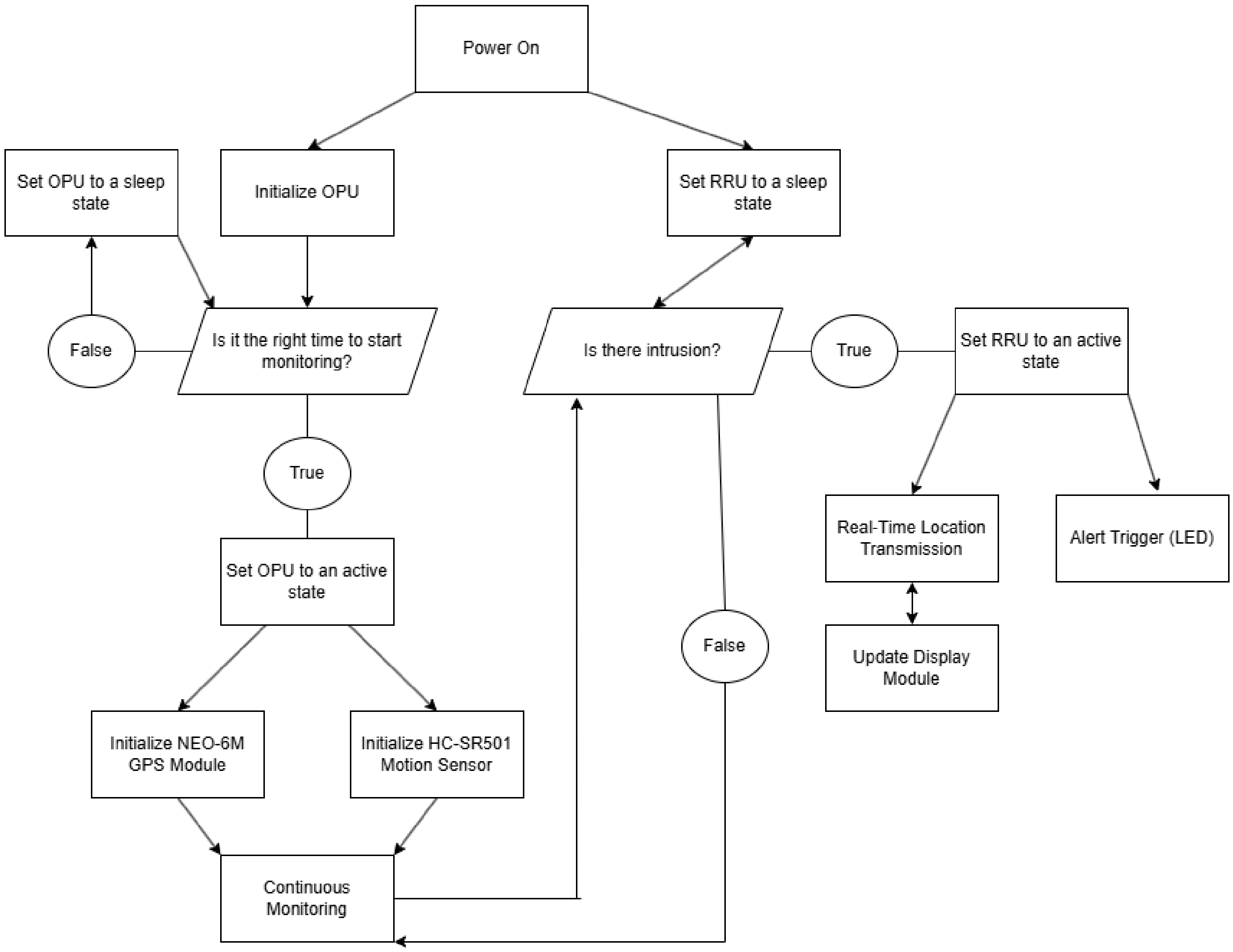
1. Prepare Components
    - Gather the second STM32 microcontroller, display module, red LED, and HW-650 NRF905 transceiver.
    - Refer to the RRU schematic to verify the placement and orientation of each component.
2. Install the NRF905 Transceiver (HW-650):

- Connect the SPI pins (CE, CSN, SCK, MOSI, MISO, and VSK) from the NRF905 module to the STM32, as shown in the schematic.
- Ensure secure connections to the RRU's power supply.

3. Connect the Display Module
    - Attach the display module to the STM32 via I2C or SPI (per the schematic), ensuring data and clock lines are correctly aligned.
    - Power the display from the RRU's power source as specified.
4. Integrate the LED Indicator
    - Connect the red LED to an appropriate output pin on the STM32 with a current-limiting resistor if needed.
    - Ensure proper alignment with power and ground as indicated in the schematic.
5. Power Supply Integration
    - Connect the RRU to a stable power source (e.g., wall adapter) and verify that all components receive sufficient power.
6. System Testing and Initialization
    - Power on the RRU and confirm proper initialization, communication with the OPU, and display functionality.
    - Check for LED activation and accurate display of GPS data as transmitted from the OPU during testing.

4.4. **Operational Workflow**

Diagram 4.4.1: Flowchart of System Operations



The operational workflow for the IoT Vehicle Anti-Theft System begins with powering both boards, which activates both the OPU and RRU in different initial states. Upon powering on, the OPU enters an initialization phase, setting up for monitoring. Here, it evaluates if it is time to begin active monitoring. If it is not time, the OPU will enter a sleep state to conserve battery power until monitoring is required. When it is time to track GPS location, the OPU transitions to an active state and begins by initializing the NEO-6M GPS module and the HC-SR501 motion sensor. These sensors will provide continuous real-time monitoring data on the vehicle's location and any movement detected near it.

In the continuous monitoring phase, the OPU remains vigilant, keeping the GPS and motion sensor operational. The OPU monitors for any signs of intrusion or suspicious movement in the vehicle's vicinity. If no unusual activity is detected, it continues in this phase without alerting the RRU. The RRU itself is initially set to a sleep state to save power. Only if the OPU detects an intrusion will it wake the RRU by transitioning it to an active state. In response to the detected intrusion, the OPU triggers an alert and begins real-time location transmission to the RRU. Upon receiving this data, the RRU updates the display module, showing the vehicle's location and visual alerts by flickering a red LED to notify the user of potential theft activity while the system remains on alert.

4.5. **Alignment with Requirement Specifications**

The IoT Vehicle Anti-Theft System has been designed to meet the functional and technical specifications outlined in the Requirement Specifications section. Each component and operational flow has been chosen to address specific performance standards and user requirements, ensuring the system functions as intended for robust vehicle security.

Real-Time Monitoring and Intrusion Detection

The system achieves continuous real-time monitoring using the NEO-6M GPS module for vehicle location tracking and the HC-SR501 motion sensor for detecting unauthorized movement. The OPU STM32 microcontroller controls these sensors and enters a low-power state when not in use, meeting the requirement for efficient monitoring.

Reliable Long-Distance Communication

The system's communication requirements are met with LoRa technology, explicitly using the HW-650 NRF905 transceiver module. LoRa enables reliable, long-range wireless communication between the OPU and the RRU to transmit GPS data and alerts over distances suited to automotive applications, even when the vehicle is out of sight.

User Notification and Alerts

The requirement for real-time notifications is supported by a display module and an LED system on the RRU, which alerts the user to potential theft activity. The red LED flickers in response to unauthorized movement, and the display module provides the vehicle's location data for the user's reference, ensuring immediate awareness and prompt response.

Power Efficiency

Power efficiency is addressed with the system's sleep modes and dedicated battery for the OPU. The duty cycling approach conserves power by only activating monitoring and communication during specific time windows when necessary, aligning with the specified battery conservation requirements while maintaining reliable performance.

Data Accuracy and Signal Processing

The system achieves accuracy requirements through GPS-based kinematic calculations, enabling precise tracking and velocity estimation. The Haversine formula calculates the distance between GPS points, while velocity and acceleration are calculated from this displacement data to detect sudden movements that may indicate theft. Additionally, signal processing filters for the motion sensor data enhance accuracy by reducing false positives, meeting the specification for reliable motion detection.

4.6. **Considerations for Alternative Designs**

Use of Accelerometer to Detect Location Changes

One alternative considered was the integration of an accelerometer to detect changes in the vehicle's location. Accelerometers can provide data on movement and acceleration, allowing the system to infer whether the car is being moved without permission. However, while accelerometers can detect motion effectively, integrating an accelerometer would not offer the precision and reliability necessary for a practical car theft prevention system, where real-time tracking is essential.

Creating a Web Server to Receive Location Data

Another alternative was the development of a web server to receive and store location data. While this could provide a user-friendly interface for tracking the vehicle in real-time, it introduces several complexities, such as the need for constant internet connectivity, increased development time, and potential security vulnerabilities associated with web applications. Furthermore, relying on external web services could lead to latency issues transmitting critical alerts. The chosen design allows direct communication between the LoRa modules to ensure reliable and timely notifications, bypassing internet dependency.

Sending SMS Messages for Alerts

The option of sending SMS messages to alert users of potential theft was also considered. While SMS notifications offer a straightforward and widely accessible communication method, they can be costly, especially for systems requiring frequent updates. Additionally, SMS delivery can be delayed due to network congestion or issues with the mobile carrier. The selected design prioritizes real-time alerts via the LoRA module with a screen displaying the information, allowing immediate notifications without incurring ongoing costs associated with SMS services.

Conclusion

After evaluating these alternatives, the decision to utilize the GPS module, LoRa communication, and display module for real-time tracking and alerting was made based on their advantages in accuracy, reliability, and cost-effectiveness. GPS provides precise location data and a way to determine motion, while LoRa offers long-range communication for this application.

This reasoning is supported by various studies demonstrating the effectiveness of GPS and LoRa technologies in similar applications, as noted in [11], [12], [13], and [14], which highlight the strengths of LoRa and GPS in IoT projects.

5. **Technical Analysis**

5.1. **Kinematics and GPS Calculation**

To accurately track the position and movement of a vehicle, this system employs GPS data combined with principles of kinematics to estimate real-time velocity, displacement, and acceleration. By converting GPS coordinates into a local Cartesian system, we can apply kinematic equations to detect and analyze changes in the car's position and velocity, ensuring reliable tracking for theft prevention.

Principle of Displacement Calculation using Haversine Formula

The Haversine formula calculates the great-circle distance between two points based on latitude and longitude, which allows us to determine the displacement between consecutive GPS readings. Given two sets of GPS coordinates $(\mathrm{lat}_1, \mathrm{lon}_1)$ and $(\mathrm{lat}_2, \mathrm{lon}_2)$ the displacement d is computed by:

$$d = 2R \times \sin^{-1} \sqrt{\sin^2 \frac{\Delta lat}{2} + \cos lat_1 \times \cos lat_2 \times \sin^2 \frac{\Delta lon}{2}}$$

Where:

- R represents the Earth's radius (approximately 6,371 km)
- $\Delta\mathrm{lat} = \mathrm{lat}_2 - \mathrm{lat}_1$
- $\Delta\mathrm{lon} = \mathrm{lon}_2 - \mathrm{lon}_1$

This formula effectively translates GPS data into actionable displacement measurements, which are then used to calculate other motion parameters [15]

Application of Average Velocity Calculation

Using the calculated displacement, we can determine the average velocity (v) of the vehicle over a specific time interval Δt with:

$$v = \frac{d}{\Delta t}$$

Where d is the distance between GPS points from the Haversine formula, this estimates the car's speed, which can be monitored for abrupt changes that may indicate theft or unauthorized movement. This velocity measure also forms the basis for subsequent acceleration calculations.

Acceleration Calculation for Theft Detection

Acceleration (a) is derived from the change in velocity over time, calculated as:

$$a = \frac{v_2 - v_1}{\Delta t}$$

Where v_1 and v_2 represent velocities at two consecutive time intervals, the system can detect sudden increases in acceleration, potentially identifying abrupt starts or stops often indicative of suspicious activity or unauthorized use.

5.2. **Signal Processing**

Signal processing is essential for accurately interpreting sensor data from the GPS module and the HC-SR501 motion sensor. The system will use filtering techniques to minimize noise and enhance the reliability of sensor readings. Digital filters will smooth motion sensor data, helping to reduce false triggers from transient signals such as wind or small animals. Data processing will be managed by the STM32 microcontrollers, allowing the system to differentiate between legitimate threats and non-threatening events, thereby ensuring precise alerts in accordance with the functional requirement for motion detection accuracy.

5.3. **Duty Cycling: Analytics**

Analyzing the median time at which vehicle thefts occur and applying outlier detection methods helps establish an optimal time range for triggering alarms or SMS notifications. We can develop an effective alert system by identifying this central value, which indicates that 50% of thefts occur before and 50% after this point. Additionally, incorporating duty cycling into the alarm system allows us to activate notifications only during the identified high-risk periods, thereby reducing unnecessary alerts during times of lower theft activity. This combined statistical and energy-efficient approach enhances alarm accuracy while conserving power, ensuring that the system remains responsive to the most likely times for theft activity.

6. **Implementation Costs and Manufacturing**

6.1. **Bill of Materials**

Component	Part Number	Quantity	Manufacturer	Location	Total Cost
STM32 Nucleo Board	STM32F401RE	2	STMicroelectronics	Switzerland	$40.62

NEO-6M GPS Module	NEO-6M	1	Bonasi	Switzerland	$3.58
PIR Motion Sensor	HC-SR501	1	ElectroPeak	China	$0.91
LoRa Module	HW-650 NRF905	2	HiLink	China	$4.79
1 MicroUSB Battery Holder & 4 Double A Batteries	1.5V AA	4	SMARTOOOLS	USA	$6.00
3D printing Plastic	TPU filament for 3D Printing	1	EasyThreed	USA	$8.99
Bread Board	LS-00019	1	OSEPP Electronics	Canada	$8.94
LCD Display	HD44780	1	diymore	South Korea	$2.82
Total					$76.65

6.2. **Installation Manual**

Environmental Requirements

Ensure the OPU is placed in a secure location within the vehicle, free from excessive heat or moisture, which could affect the thermal detector.

Required Tools and Components

- OPU: 3 high-quality AA batteries
- RRU: Standard power outlet

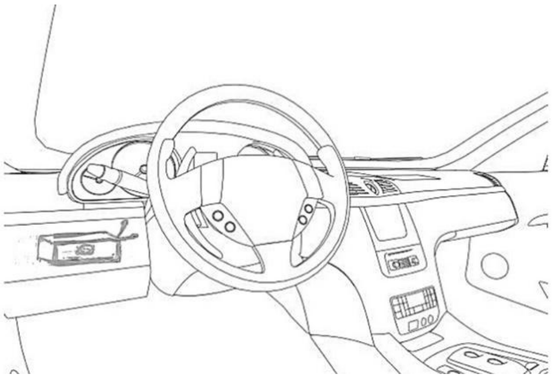
OPU Installation

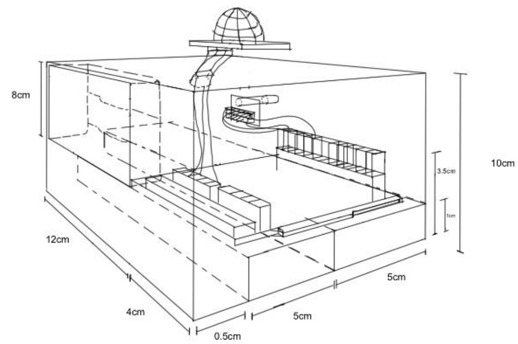
Battery Setup:

1. Open the battery compartment.
2. Insert 3 AA batteries, ensuring correct polarity. Close the compartment securely.

Placement in Vehicle:

1. Install the OPU in a concealed area, such as under the dashboard.
2. Ensure the GPS module has a clear line of sight to the sky for accurate tracking.

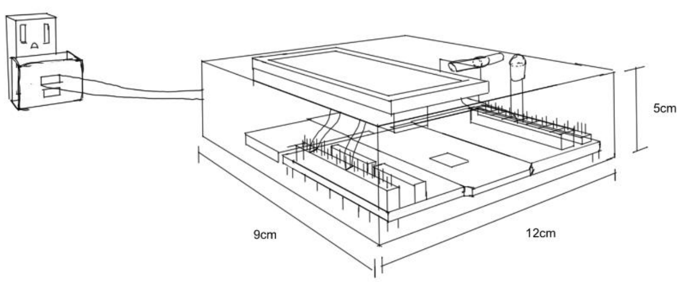




RRU Installation

Power Connection:

1. Plug the provided cable into the RRU and then into an available power outlet.
2. Ensure the RRU is positioned where the display is visible to the user.



6.3. **User Guide**

System Activation

OPU Activation:

1. Insert batteries to power on the OPU.
2. Ensure the thermal detector and GPS module are operational (indicators should signal readiness).

RRU Activation:

1. Connect the RRU to power. The display will show the monitoring status.

System Operation

Detection Mode:

- The OPU continuously monitors for unauthorized thermal signatures. If detected, it sends an alert with GPS coordinates to the RRU.

Tracking Display:

- The RRU updates the vehicle's location every 5 seconds if the vehicle is in motion.

See Diagram 4.4.1. for more technical information on system operation.

Monitoring and Alerts

- When the RRU receives a signal, it will display the current coordinates of the vehicle, updating 5-10 seconds if the vehicle is in motion.
- Shows car coordinates on-screen when motion or unauthorized access is detected, and a red LED will flash.

7. **Energy Analysis**

7.1. **Established Power Standards**

This design references relevant standards from the Institute of Electrical and Electronics Engineers (IEEE) to ensure compliance with established power limits. Specifically, IEEE P2413 [16] emphasizes the importance of energy efficiency in designing Internet of Things (IoT) systems by promoting standardized practices that optimize power consumption and enhance device interoperability. This standard provides crucial guidelines for energy efficiency, especially for battery-operated devices, which are vital for the optimal operation of the NEO-6M GPS module and the HC-SR501 motion sensor integrated into this anti-theft system.

Furthermore, the design adheres to the safety and regulatory compliance requirements outlined in the project specifications. This ensures that the system does not store or otherwise contain more than 500 millijoules (mJ) of energy at any time. Additionally, it guarantees that power consumption, including consumption during peak operation of the GPS module (37 mA) and motion sensor (5V), does not exceed 30 watts (W).

7.2. **Justification of Reference Standards**

The selected reference standard is appropriate for this design due to its focus on low-power devices, which aligns with the energy efficiency requirements of the project.

Additionally, the project specifications emphasize that the system must not store or otherwise contain more than 500 mJ of energy at any given time. The battery management strategy includes a dedicated 200 mAh rechargeable lithium-ion battery, ensuring that the combined power consumption of all components, including the GPS module and motion sensor, stays below the maximum allowable limits. This careful design approach enables real-time GPS tracking and motion detection without exceeding the power constraints, providing a reliable and practical vehicle anti-theft solution while adhering to safety and regulatory compliance standards.

7.3. **Evaluation of Energy Storage Potential**

Identification of Energy Storage Potential

The design does not include significant energy storage components, such as capacitors, that could retain energy exceeding the threshold of 500 mJ. Although the OPU STM32 microcontroller operates directly from a dedicated battery, it is classified as a power supply and, therefore, is not considered part of the system's energy storage assessment.

Assessment of Total Energy Capacity

The STM32F401RE microcontroller operates with a supply voltage range of 1.7 V to 3.6 V and includes various power consumption profiles to optimize energy efficiency. In Run mode, it consumes 146 μA per MHz of operation, while Stop mode (with Flash in Stop) has a typical consumption of 42 μA, rising to a maximum of 65 μA. In Deep Power Down mode, power consumption can drop as low as 10 μA, while Standby mode consumes only 2.4 μA without the real-time clock (RTC). To ensure the system does not exceed 500mJ and 30W, it is crucial to calculate the active time in Run mode and the durations spent in Stop, Deep Power Down, and Standby modes, considering the corresponding current draws and the operating voltage.

Additionally, the relevant specifications are as follows for the NEO-6M GPS module and the HC-SR501 motion sensor:

NEO-6M GPS Module:

- Power Consumption: 37 mA in tracking mode
- Operating Voltage: 5 V

HC-SR501 Motion Sensor:

- Operating Voltage: 5 V
- Power Consumption: <50 mW

By assessing the power consumption of the OPU STM32 Microcontroller during its run mode:

$$I_{Run} = 146\mu\text{A/MHz}$$

$$P_{Run} = I_{Run} \times V = 7.008mA \times 3.3V \approx 23.05mW$$

Assessing the power consumption of the OPU STM32 Microcontroller components:

$$P_{GPS} = 37mA \times 5V \ = 0.185W = 185mW$$

$$P_{Sensor} = 50mW \ (Assumed\ upper\ limit)$$

The total power consumption of the OPU STM32 Microcontroller during operation is:

$$P_{Total} = P_{GPS} + P_{Sensor} + P_{Run} = 185mW\ + 50mW + 23.05mW = 258.05mW$$

As a baseline, the energy consumption after one second is:

$$E_{1s} = P_{Total} \times t = (258.05mW)(1s) = 258\text{µJ}$$

To find energy storage at any given time, since the system does not use capacitors that store energy beyond operational consumption, the energy "stored" within components like the STM32 microcontroller while active can be considered negligible. Thus, when assessing the potential energy stored, we find that:

$$\mathrm{E_{Stored}}\ at\ any\ point\ in\ time\ \leq\ 258\text{µJ}$$

Similarly, for the RRU STM32 Microcontroller, since it does not use capacitors that store energy beyond operational consumption, and it will be connected to an outlet, $\mathrm{E_{Stored}} = 0$.

7.4. **Verification of Energy Limit Adherence**

The analysis confirms that the design adheres to the established energy limits by ensuring that the total energy consumption during operation, including the active and idle states of the components, remains well within the 500 mJ and 30W threshold. The power calculations indicate that the combined energy usage of the NEO-6M GPS module, HC-SR501 motion sensor, and the OPU STM32 microcontroller is consistently below the specified limits, thus preventing the system from exceeding the allowable energy storage. Moreover, implementing power management strategies, such as duty cycling and utilizing low-power modes, further compliance with IEEE 2413, ensuring that the vehicle anti-theft system operates with effective power management.

8. **Risk Analysis**

8.1. **Negative Consequences from Intended Use**

The primary risk associated with intended use is potential privacy infringement. Continuous GPS tracking could expose location data to unauthorized access if the system is compromised.

8.2. **Negative Consequences from Incorrect Use**

Improper installation or configuration may result in false alarms, causing unnecessary stress to the user and potentially misallocating law enforcement resources.

8.3. **Negative Consequences from Misuse**

Misuse of the system, such as unauthorized tracking of individuals, could result in severe privacy violations and legal consequences. If the system is hacked or repurposed, it could enable malicious tracking or assist in theft by providing real-time location data to unauthorized users.

8.4. **Potential Malfunctions**

Several potential malfunctions may affect system performance:

- GPS module failure: This could lead to inaccurate or missing location data.

- Motion sensor malfunction: False positives or negatives may trigger unnecessary alerts or fail to detect theft.
- LoRa communication issues: Transmission failures may result in data loss.
- Battery failure: Power loss in the GPS module would turn off tracking capabilities.

8.5. **Consequences of Failure Mechanisms**

- GPS module failure may result in incorrect location reporting, complicating recovery efforts during theft.
- Motion sensor malfunction could lead to undetected theft attempts or frequent false alarms, potentially undermining system reliability and user trust.
- LoRa communication failure: Might delay or prevent alerts, reducing the system's effectiveness in theft prevention.
- Battery failure: This would turn off GPS tracking, eliminating a core function of the security system.

These potential risks and failure mechanisms underscore the importance of a robust design, comprehensive testing, and straightforward user guidelines to ensure the safe and effective operation of the system.

9. **Testing and Validation**

Several tests will be conducted to evaluate and demonstrate the capabilities of our car surveillance system.

9.1. **Real-Time GPS Tracking Test**

Test Setup Real-Time GPS Tracking	Environmental Parameters	Test inputs	Quantifiable standard	Pass/Fail Criteria
GPS module connected to STM board, STM board/module to be moved by an individual 30 meters from a starting position in an arbitrary direction. Calibration of the GPS module is to be measured against a calibrated GPS that this same individual carries, and the GPS module should update the location within 5-10 seconds from the beginning of this person's movement (which can be recorded via a stopwatch).	1. Too many trees and buildings can obstruct GPS's detection of satellites. 2. There shouldn't be interference from other radio frequencies. 3. Extreme temperatures can affect the components inside the GPS.	Position accuracy: a measurement of how accurate the coordinate readings of the GPS are, and includes checking if there is a "zero error" wherein the GPS seems to change position even when the person carrying it is not moving. Update Rate: How long does it take to get new readings?	Position accuracy: accurate up to 5m Update rate: Every 5 – 10 seconds	It fails the test if the position is accurate to anything more than 5m. If it takes 10 seconds to refresh, it fails the test.

9.2. **Motion Detection Test**

Test Setup Motion Detection	Environmental Parameters	Test inputs	Quantifiable standard	Pass/Fail Criteria
Moving a large object at 1 meter increments from 1-7 meters in front of the motion detector.	1. Lighting conditions (especially when the lighting changes drastically) 2. If there is fog or if something is blocking the sensor	Motion Detection: if the module returns whether or not there is motion.	Motion detection occurs at any point within 7m of the motion sensor.	The motion doesn't detect an object's movement within 7m, which means this test has failed.

	3. If there are extreme temperatures since infrared sensors can be affected by high temperatures			

9.3. **NEO-6M GPS Module Test**

Test Setup NEO-6M GPS module	Environmental Parameters	Test inputs	Quantifiable standard	Pass/Fail Criteria
A test similar to the test for requirement #1 will be conducted, but an ammeter will also be used to measure the current passing through the module's pins.	1. Little electromagnetic interference. 2. Avoiding extreme temperatures	Position accuracy: If the module returns the position of the GPS accurately. Cold start time: Starting the module should not take an absurdly long period. Power consumption: The less energy is consumed, the better.	Position accuracy: accurate to 2.5 m Cold Start: 27 seconds Power consumption: 37mA	If the position is not precise within the 2.5-meter range, it fails. This test fails if it takes over 27 seconds to start the module. If more than 37mA of current passes through the module, it fails.

9.4. **HC-SR501 Module Test**

Test Setup HC-SR501	Environmental Parameters	Test inputs	Quantifiable standard	Pass/Fail Criteria
An object is moved in front of the motion sensor at incremental ranges to test whether or not this component meets the design requirements.	1. Lighting conditions. 2. Whether or not there is snow/fog or even a small animal that can trigger the motion sensor.	Detects motion: A motion is detected if an object moves within a certain distance from the sensor. Delay time adjustable: The delay time	The sensor detects motion up to 7m. The delay time is adjustable between 5 to 5min. A potential difference no greater than 5	Detection is less than or equal to 7 meters passes the test. The delay time, being adjustable, passes the test. A potential difference of less

		between taking readings is adjustable. Voltage: no more than a certain amount of potential difference.	volts should act on the sensor.	than 5 volts passes the test.

9.5. **Battery Management Test**

Test Setup Battery Management	Environmental Parameters	Test inputs	Quantifiable standard	Pass/Fail Criteria
The voltage can be calculated using a voltmeter, and an ammeter current can be calculated. Using a stopwatch, time can be recorded, and so the capacity of the cell can be calculated via $E_{Cell} = V * I * T$	1. Cold conditions can reduce battery capacity. 2. Hotter conditions can cause a quicker discharge of batteries, so extreme temperatures should be avoided.	Capacity: How much energy is stored in the battery? Power consumption: How much power (how many watts) does the battery consume?	Capacity should be 2000mAh Power consumption should be less than 50 mW in idle mode and less than 500 mW when not in idle mode.	If the capacity is greater or less than 2000 mAh, then this test fails. The test fails if the power consumed is greater than 50 mW for idle mode and greater than 500 when not in idle mode.

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