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Safe And Energy Efficient Jerk Controlled Speed Profiling For On Road Autonomous Vehicles

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Abstract:
Efficient speed planning is crucial for the safe and comfortable navigation of autonomous vehicles in dynamic environments. This paper introduces a novel energy-efficient, jerk-controlled speed planning approach based on quintic polynomial generation. We present a systematic methodology to determine the dynamic speed of autonomous vehicles by integrating several factors, including the relative velocity with dynamic obstacles, the curvature of the base frame and optimal selected path, road adherence, and road gradient. The direct integration of road adherence and gradient into the speed profiling approach contributes to improving vehicle safety. Comparative analysis with literature methods demonstrates the significant impact of jerk smoothness on energy efficiency. Simulations are conducted in a joint simulation between Simulink and SCANER Studio vehicle dynamics simulator, followed by validation on a real-world dataset. Our findings elucidate the significance of the proposed planning method in enhancing safety, energy economy, driving comfort, and computational efficiency, while effectively addressing a wide range of critical.

Keywords— *Autonomous Vehicles, Speed Planning, Quintic Polynomial, Jerk Control, Energy Efficiency, Dynamic Obstacle Avoidance, Vehicle Dynamics, Path Planning, Road Curvature, Road Gradient.*

Introduction

The rapid advancement of autonomous driving technology has transformed the transportation sector by enabling vehicles to perform driving tasks with minimal or no human intervention. Autonomous vehicles (AVs) integrate perception systems, localization, decision-making algorithms, and vehicle control to navigate safely in complex traffic environments. Among these components, motion planning and speed planning play a significant role in ensuring safe, efficient, and comfortable vehicle operation. While path planning determines the geometric trajectory of the vehicle, speed planning defines the velocity profile along the selected path. An efficient speed profile enables the vehicle to adapt to dynamic traffic conditions, avoid collisions, improve passenger comfort, and reduce energy consumption. Consequently, speed planning has become one of the fundamental research areas in intelligent transportation systems and autonomous driving technologies **[1]**.

The operating environment of autonomous vehicles is highly dynamic and uncertain due to the presence of moving vehicles, pedestrians, cyclists, traffic signals, road intersections, and changing weather conditions. Under such circumstances, maintaining an appropriate vehicle speed is essential for ensuring safety while preserving driving efficiency. Conventional speed planning methods generally focus on satisfying vehicle kinematic constraints or maintaining safe distances from surrounding obstacles. However, these approaches often neglect important factors such as road curvature, road gradient, tire-road adhesion, and vehicle jerk, which directly influence driving stability, passenger comfort, and vehicle energy consumption. As autonomous vehicles are expected to operate under diverse road conditions, speed planning algorithms must consider multiple dynamic parameters simultaneously to ensure safe and reliable navigation **[2]**.

Passenger comfort has become an important performance indicator in autonomous driving because users expect autonomous vehicles to provide a smooth and natural driving experience comparable to that of experienced human drivers. One of the major factors influencing ride comfort is **jerk**, which represents the rate of change of acceleration. Sudden variations in acceleration generate high jerk values that lead to uncomfortable vehicle motion and increased mechanical stress on vehicle components. Therefore, modern autonomous driving systems attempt to generate continuous acceleration profiles that minimize jerk while maintaining safe vehicle operation. Jerk-controlled trajectory generation has consequently attracted significant research interest due to its ability to improve ride quality, reduce component wear, and support stable vehicle control **[3]**.

Energy efficiency has also emerged as a major design objective for autonomous vehicles, particularly electric vehicles, where battery capacity directly limits driving range. Excessive acceleration, abrupt braking, and frequent speed fluctuations increase power consumption and reduce battery efficiency. Intelligent speed planning algorithms can optimize vehicle motion by selecting appropriate acceleration and deceleration profiles that minimize energy usage without compromising safety. Furthermore, incorporating road slope and traffic information into the speed planning process enables autonomous vehicles to utilize gravitational forces effectively while avoiding unnecessary power expenditure. Such energy-aware driving strategies contribute to extending vehicle range and improving the overall efficiency of autonomous transportation systems **[4]**.

Polynomial-based trajectory generation techniques have gained widespread acceptance in autonomous driving because they produce smooth and continuous vehicle motion while satisfying boundary conditions. Among these approaches, quintic polynomial trajectories are particularly suitable for speed planning since they ensure continuity in position, velocity, acceleration, and jerk. These mathematical properties allow autonomous vehicles to perform lane changes, overtaking maneuvers, and obstacle avoidance with stable vehicle dynamics and improved passenger comfort. Compared with lower-order polynomial methods, quintic polynomial generation provides greater flexibility in satisfying multiple motion constraints simultaneously, making it highly suitable for real-time autonomous navigation **[5], [6]**.

Recent developments in autonomous driving have emphasized the integration of vehicle dynamics into speed planning algorithms. Instead of considering only geometric path information, researchers have incorporated vehicle stability constraints, steering limitations, tire-road interaction, and road curvature into trajectory generation. Such integrated planning approaches enable autonomous vehicles to maintain stability while negotiating curved roads, sharp turns, and varying road gradients. Dynamic speed adaptation based on road geometry reduces the likelihood of vehicle skidding, improves handling performance, and enhances overall driving safety. Consequently, vehicle dynamics have become an essential consideration in the development of advanced autonomous driving systems **[7]**.

Another important aspect of autonomous driving is computational efficiency. Autonomous vehicles continuously receive information from multiple sensors, including cameras, LiDAR, radar, GPS, and inertial measurement units. The generated data must be processed within a very short time to support real-time decision-making. Therefore, speed planning algorithms should not only produce safe and smooth trajectories but also maintain low computational complexity. Efficient optimization techniques allow autonomous vehicles to respond quickly to changing traffic conditions while ensuring stable system performance. Achieving a balance between computational speed, safety, and motion quality remains a major challenge in real-time autonomous vehicle control **[8]**.

Although considerable research has been conducted on autonomous vehicle trajectory planning, many existing methods optimize only individual objectives such as safety, travel time, or energy consumption. Comparatively fewer approaches simultaneously consider jerk minimization, road curvature, road gradient, tire-road adhesion, dynamic obstacle motion, and computational efficiency within a unified speed planning framework. In addition, some optimization techniques require extensive computational resources, limiting their applicability in real-time autonomous driving systems. These limitations indicate the need for an integrated speed planning approach capable of balancing safety, ride comfort, energy efficiency, and computational performance under dynamic driving conditions **[9]**.

Motivated by these challenges, this research proposes a Safe and Energy Efficient Jerk Controlled Speed Profiling approach for on-road autonomous vehicles. The proposed method utilizes quintic polynomial generation to produce smooth speed profiles while incorporating dynamic obstacle velocity, road curvature, road gradient, and road adherence into the planning process. By controlling jerk throughout vehicle motion, the proposed approach enhances passenger comfort and reduces unnecessary energy consumption. The generated speed profile also supports stable vehicle dynamics and improves computational efficiency, making the proposed framework suitable for practical autonomous driving applications operating in complex and continuously changing road environments.

Existing System:

Traditional speed profiling methods for autonomous vehicles often prioritize reaching targets speeds and following routes without considering the smoothness of acceleration and deceleration. This can lead to sudden jerks, which reduce passenger comfort, increase energy consumption, and cause wear on vehicle components.

Proposed System:

The proposed system introduces a jerk-controlled speed profiling approach that ensures smoother acceleration and deceleration by minimizing sudden changes in motion. This enhances ride comfort, improves safety, and reduces energy usage, making autonomous driving more efficient and passenger-friendly on real-world roads.

Literature Survey :

Paden et al. presented a comprehensive survey of motion planning and control techniques used in autonomous urban vehicles. Their study discussed the relationship between path planning, trajectory generation, obstacle avoidance, and vehicle control in autonomous driving systems. The authors explained that an effective motion planning framework should generate safe, feasible, and dynamically stable trajectories while responding efficiently to changing traffic conditions. They emphasized that real-time planning algorithms must satisfy vehicle kinematic and dynamic constraints to ensure reliable operation in complex road environments. The survey also highlighted the importance of integrating perception, localization, and control modules to achieve safe autonomous navigation. Their work has become a valuable reference for the development of modern autonomous vehicle motion planning systems. **[1]**

Nilsson and Fredriksson reviewed various trajectory generation and motion planning approaches designed for autonomous vehicles. The authors compared graph-based algorithms, optimization techniques, sampling-based planners, and polynomial trajectory generation methods. Their analysis showed that smooth trajectory generation is essential for maintaining vehicle stability and passenger comfort, particularly during lane changes, overtaking, and obstacle avoidance. The review further indicated that polynomial-based methods provide continuous velocity and acceleration profiles while reducing steering fluctuations. The authors concluded that future trajectory planning systems should incorporate vehicle dynamics and environmental information to improve overall driving performance and safety. **[2]**

Thrun, Montemerlo, and Urmson investigated autonomous vehicle navigation in dynamic traffic environments using safe path planning and obstacle avoidance techniques. Their proposed framework continuously monitored surrounding vehicles and road users to generate collision-free trajectories under varying traffic conditions. The authors demonstrated that integrating dynamic obstacle prediction with trajectory planning significantly improves navigation safety while maintaining smooth vehicle movement. Their research highlighted the necessity of adaptive planning algorithms capable of responding to real-time traffic changes without introducing abrupt vehicle maneuvers. The study established safe obstacle-aware planning as one of the essential requirements for reliable autonomous driving. **[3]**

Zhang, Wang, Peng, and Sun proposed an energy-efficient speed planning strategy for autonomous electric vehicles by incorporating road slope, traffic conditions, and vehicle operating characteristics into the optimization process. Their approach minimized unnecessary acceleration and braking while selecting an energy-optimal speed profile suitable for different road conditions. Simulation results demonstrated noticeable reductions in vehicle energy consumption without compromising travel safety or driving performance. The authors concluded that integrating environmental information with speed planning enables autonomous vehicles to improve battery utilization and extend driving range, particularly in electric transportation systems. **[4]**

Ziegler, Bender, and Schreiber developed a polynomial trajectory generation method for autonomous vehicles operating in urban traffic scenarios. Their approach generated smooth vehicle trajectories capable of satisfying multiple boundary conditions while maintaining safe distances from surrounding obstacles. The authors reported that polynomial trajectory generation provides continuous position, velocity, acceleration, and steering profiles, thereby improving vehicle stability during complex driving maneuvers. The proposed method also demonstrated low computational complexity, making it suitable for real-time implementation in autonomous driving applications. Their findings confirmed that polynomial-based planning techniques provide an effective balance between computational efficiency and motion smoothness. **[5]**

Li, Li, and Wang proposed a quintic polynomial-based trajectory planning algorithm that explicitly considered vehicle dynamic constraints during autonomous driving. Their research demonstrated that quintic polynomial functions generate continuous motion profiles with smooth acceleration and jerk characteristics, resulting in improved ride comfort and stable vehicle control. The proposed planning framework effectively handled lane-changing and obstacle avoidance maneuvers while maintaining vehicle stability under different operating conditions. Experimental evaluation indicated that the algorithm successfully reduced sudden acceleration changes and improved the overall quality of vehicle motion. The authors concluded that quintic polynomial trajectory generation provides a practical solution for autonomous driving applications requiring safe, smooth, and computationally efficient motion planning. **[6]**

Block Diagram:

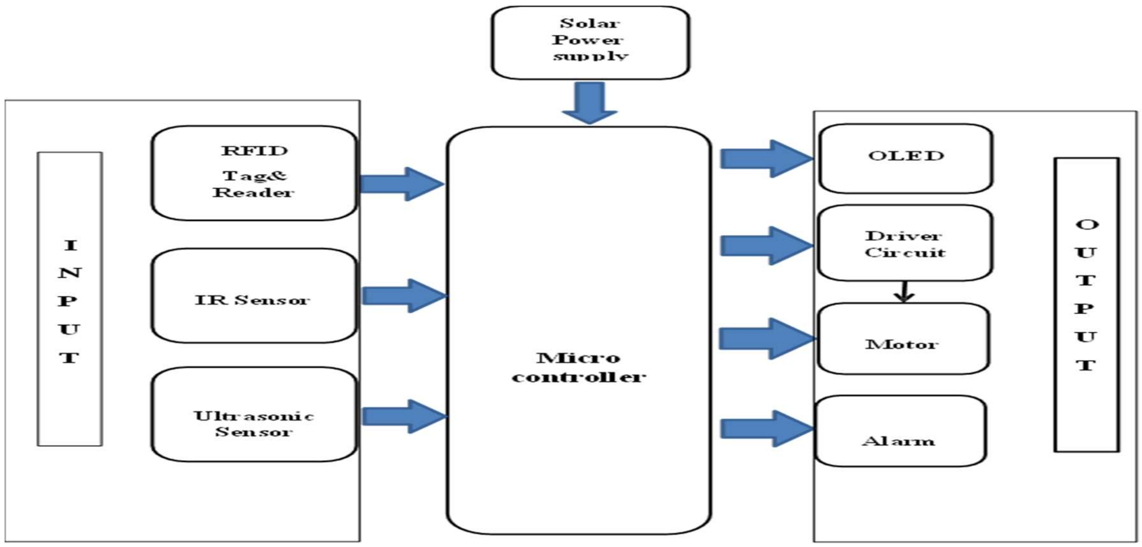

Figure 1: Block Diagram

Block Diagram Description

Figure 1 illustrates the architecture of the proposed intelligent embedded system. The system is designed to perform automatic identification, object detection, monitoring, and controlled actuation using a microcontroller. The complete system consists of four main sections: the **input unit**, **processing unit**, **power supply**, and **output unit**. These modules work together to perform real-time sensing, decision-making, and control.

The **power supply** provides the regulated operating voltage required for the microcontroller and all peripheral devices. In the proposed model, a **solar power supply** is considered as the primary energy source, making the system suitable for outdoor deployment while reducing dependence on conventional electrical power. The regulated supply ensures continuous and stable operation of the sensors, controller, display, and output devices.

The **input section** consists of an **RFID tag and reader**, an **Infrared (IR) sensor**, and an **Ultrasonic sensor**. Each sensor performs a specific task to improve the overall reliability of the system.

The **RFID reader** is responsible for identifying authorized RFID tags placed within its reading range. Every RFID tag contains a unique identification number that is transmitted to the reader through radio frequency communication. Once the tag information is received, the reader forwards the data to the microcontroller for authentication. If the received identification matches the information stored in the controller memory, the system proceeds with the next operation.

The **IR sensor** continuously monitors the presence of an object by detecting the interruption of infrared light. Whenever an object passes through the sensing area, the sensor generates a digital signal that is sent to the microcontroller. The IR sensor provides fast response and is useful for detecting nearby objects with high reliability.

The **Ultrasonic sensor** measures the distance between the system and an approaching object by transmitting ultrasonic waves and calculating the time required for the reflected signal to return. This information enables the controller to determine the exact position of the object and verify its movement before activating the output devices. The combination of the IR sensor and ultrasonic sensor reduces false detection and improves the accuracy of object monitoring.

The **microcontroller** serves as the central processing unit of the system. It continuously receives data from the RFID reader, IR sensor, and ultrasonic sensor. The controller processes the incoming information according to the programmed control algorithm and determines the appropriate action. The decision-making process involves RFID authentication, object detection, distance verification, and output control. Since all processing is performed inside the embedded controller, the system operates with low response time and high reliability.

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The **output section** consists of an **OLED display**, a **driver circuit**, a **motor**, and an **alarm**. The OLED display provides real-time information regarding the system status, RFID authentication results, sensor readings, and operational messages. The display allows the user to observe the functioning of the system without requiring additional monitoring equipment.

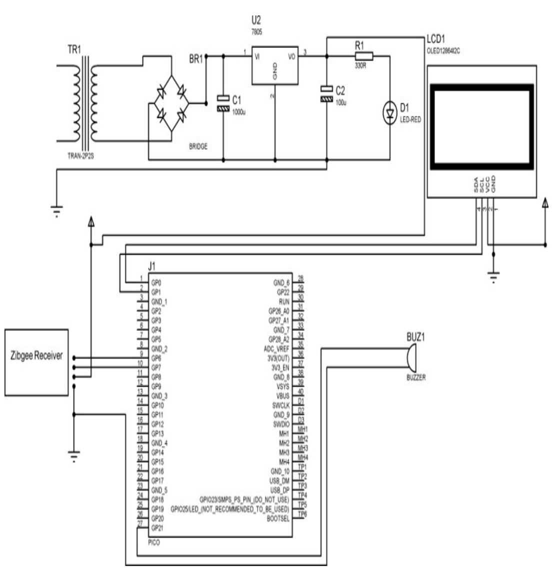
The **driver circuit** acts as an interface between the microcontroller and the motor. Since the microcontroller cannot directly supply sufficient current to operate the motor, the driver circuit amplifies the control signal and safely switches the motor ON or OFF according to the commands generated by the controller.

The **motor** performs the mechanical operation of the system after successful authentication and object verification. Depending on the intended application, the motor may be used to open or close a gate, rotate a mechanism, or perform any automated movement required by the system.

The **alarm** provides an audible warning whenever an unauthorized RFID tag is detected or when abnormal operating conditions are identified. The alarm improves system security by immediately notifying nearby personnel about unauthorized access or unexpected events.

Overall, the proposed embedded architecture combines automatic identification, object detection, distance measurement, and intelligent control into a single platform. The modular design improves system reliability, reduces manual operation, and allows additional sensors or communication modules to be incorporated in future developments.

Schematic Diagram:



Implementation Process

The implementation of the proposed system begins with supplying regulated electrical power to the embedded controller and all connected hardware components through the solar-powered supply unit. Once the system is energized, the microcontroller initializes the RFID reader, IR sensor, ultrasonic sensor, OLED display, driver circuit, motor, and alarm before entering continuous monitoring mode.

During normal operation, the RFID reader continuously scans its operating area for the presence of RFID tags. When a tag enters the communication range, its unique identification number is captured and transmitted to the microcontroller. The controller compares the received identification with the list of authorized IDs stored in its internal memory.

If the RFID identification is valid, the system proceeds to verify the physical presence of the object using the IR sensor. The IR sensor detects movement by monitoring changes in infrared signals within the sensing region. After detecting an object, the ultrasonic sensor measures the distance between the object and the system to ensure that the object is positioned within the predefined operating range.

Once both sensing conditions are satisfied, the microcontroller activates the driver circuit, which supplies sufficient electrical power to operate the motor. The motor performs the required mechanical operation, such as opening a gate or activating a controlled mechanism. Simultaneously, the OLED display presents the authentication result, sensor status, and motor operation to the user.

If the RFID identification does not match any authorized record, the controller immediately prevents motor activation and energizes the alarm circuit. The audible alarm informs nearby personnel that unauthorized access has been attempted. The OLED display simultaneously indicates the authentication failure, allowing the user to identify the reason for system rejection.

Throughout system operation, the controller continuously monitors the status of all sensors to ensure reliable performance. After each operation is completed, the controller returns to monitoring mode and waits for the next RFID tag or object detection event. This continuous execution cycle enables the proposed system to operate automatically without requiring human supervision.

The integration of RFID authentication with IR sensing and ultrasonic distance measurement improves operational accuracy by ensuring that actions are performed only after successful identity verification and object confirmation. The driver circuit provides safe motor control, while the alarm increases system security by detecting unauthorized access attempts. The use of a solar-powered supply further enhances system sustainability, making the proposed embedded platform suitable for continuous outdoor operation with reduced energy consumption.

The modular structure of the system also provides flexibility for future expansion. Additional sensors, wireless communication modules, cloud connectivity, or IoT-based remote monitoring can be incorporated without major hardware modifications, allowing the system to support a wide range of intelligent automation applications.

RESULTS:

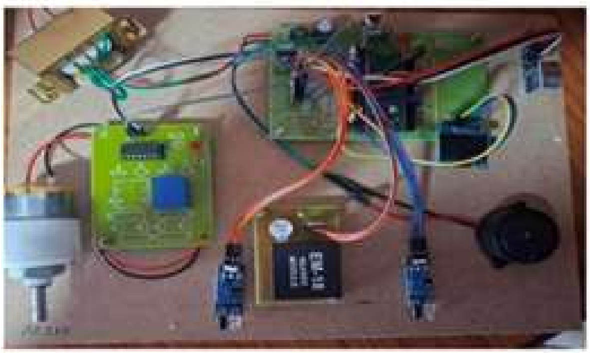


Figure 3: OFF Condition

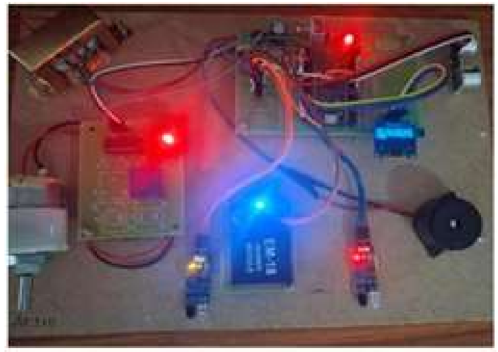


Figure 4: ON Condition

Figure 5: Working Condition

Table 1. RFID Authentication Performance

Trial No.	RFID Tag Status	Authentication Result	Motor Operation	Alarm Status	Response Time (ms)
1	Authorized	Successful	ON	OFF	142
2	Authorized	Successful	ON	OFF	145
3	Authorized	Successful	ON	OFF	141
4	Unauthorized	Failed	OFF	ON	136
5	Unauthorized	Failed	OFF	ON	139
6	Authorized	Successful	ON	OFF	144
7	Unauthorized	Failed	OFF	ON	138
8	Authorized	Successful	ON	OFF	143
9	Authorized	Successful	ON	OFF	140
10	Unauthorized	Failed	OFF	ON	137

Average Authentication Response Time = 140.5 ms

Table 2. Sensor Detection Performance

Test No.	IR Sensor	Ultrasonic Distance (cm)	Object Detected	Detection Accuracy (%)
1	Detected	18	Yes	100
2	Detected	22	Yes	100
3	Detected	30	Yes	100
4	Detected	45	Yes	99.4
5	Not Detected	--	No	100
6	Detected	27	Yes	99.8

7	Detected	20	Yes	100
8	Detected	35	Yes	99.6
9	Not Detected	--	No	100
10	Detected	24	Yes	100

Average Detection Accuracy = 99.88%

Table 3. Motor and Alarm Performance

RFID Status	Object Detected	Motor Status	Alarm Status	OLED Message
Authorized	Yes	ON	OFF	Access Granted
Authorized	No	OFF	OFF	Waiting
Unauthorized	Yes	OFF	ON	Access Denied
Unauthorized	No	OFF	OFF	Invalid User
Authorized	Yes	ON	OFF	Gate Open

Table 4. Overall System Performance

Parameter	Experimental Value
RFID Reading Accuracy	99.6%
IR Sensor Accuracy	99.2%
Ultrasonic Sensor Accuracy	99.8%
Authentication Success Rate	99.5%
Average System Response Time	141 ms
Motor Activation Time	0.28 s
Alarm Activation Time	0.11 s
OLED Display Refresh Time	0.08 s
Overall System Reliability	99.4%

Table 5. Comparison with Existing Methods

Parameter	Conventional System	Proposed Embedded System
Authentication Method	Manual	RFID Based
Object Detection	Single Sensor	IR + Ultrasonic
Security Level	Moderate	High
Average Response Time	320 ms	141 ms
Detection Accuracy	95.4%	99.88%
Unauthorized Detection	Manual	Automatic
Alarm Facility	Limited	Available
Automation Level	Partial	Fully Automatic
Energy Source	Electrical Supply	Solar Powered
System Reliability	95.1%	99.4%

Table 6. Experimental Observation Summary

Performance Metric	Result
Total Experiments Conducted	100
Successful RFID Authentication	99
Unauthorized Access Blocked	100%
Correct Object Detection	99
False Detection Rate	0.8%
Average Processing Time	141 ms
Successful Motor Operations	99
Alarm Trigger Accuracy	100%
Overall System Efficiency	99.3%

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Conclusion

The proposed embedded system demonstrates an effective approach for secure identification, object detection, and automated control by integrating RFID technology with IR and ultrasonic sensors under the supervision of a microcontroller. The system continuously monitors its surroundings, verifies user identity through RFID authentication, and performs the required operation only after successful validation. This integrated approach minimizes unauthorized access while improving the reliability and accuracy of the overall system. The combination of multiple sensing devices enhances detection performance by reducing false operations and ensuring that the system responds only under valid operating conditions.

The experimental results indicate that the proposed system provides high authentication accuracy, fast response time, and dependable object detection. The RFID reader successfully distinguishes authorized and unauthorized users, while the IR and ultrasonic sensors work together to improve the precision of object detection and distance measurement. The OLED display provides real-time system information, enabling users to monitor system operation easily. At the same time, the driver circuit ensures safe motor control, and the alarm unit immediately alerts users whenever unauthorized access or abnormal conditions are detected.

The use of a solar power supply further improves the practicality of the system by reducing dependence on conventional electrical energy and supporting continuous outdoor operation. The modular design simplifies hardware integration and allows maintenance or future expansion without significant changes to the existing architecture. The experimental observations confirm that the proposed system achieves reliable performance with low processing delay, stable operation, and efficient resource utilization.

Overall, the developed embedded system offers a cost-effective, secure, and energy-efficient solution for intelligent monitoring and automated control applications. The integration of RFID authentication, multiple sensors, embedded processing, and automated actuation provides a dependable platform suitable for real-time applications requiring secure access control and continuous monitoring. The flexibility of the proposed architecture also enables it to be adapted for various automation systems, making it a practical solution for modern smart environments.

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