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# Smart Sunroof Control System:

## Enhancing Automotive Vehicle Safety and Efficiency with BLDC Motor Technology

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## ABSTRACT

This study investigates the enhanced application of BLDC motors in automotive sunroof control systems. Motor selection, control strategies, sensor integration, and their impacts on system performance and user satisfaction are all included in the study. This study aims to demonstrate the improved performance of BLDC-powered sunroofs over traditional systems in terms of speed, accuracy, dependability, and energy efficiency through analysis and case studies. In order to increase system resilience and durability, the study also addresses problems with noise, vibration, and thermal management. Additionally, the research explores the use of sophisticated control algorithms to refine motor performance and adapt to varying environmental conditions, ensuring a seamless operation of the sunroof. By offering insights into the design and optimization of BLDC-driven sunroof control systems, the findings advance automotive technology and open the door to improved vehicle comfort, safety, and energy economy.

## INTRODUCTION

Sunroof systems are essential parts of contemporary cars that improve the driving experience for passengers by letting in more natural light and air. However, for them to function properly, a complex control system is required to guarantee accurate, seamless, and dependable performance. Traditional sunroof control systems usually use brushed DC motors, which are simple but have inherent drawbacks like lower efficiency from frictional losses, higher maintenance costs from brush wear, and a shorter lifespan, making them less appropriate for modern automotive applications. The adoption of BLDC motors addresses these shortcomings, offering a superior alternative characterized by enhanced efficiency, improved reliability, and precise control capabilities, thereby contributing to a more refined and seamless sunroof operation. This research article gives a complete study of a BLDC motor-driven sunroof control system.

The research includes motor selection, developing control algorithms, integrating sensors, and optimizing the system, all aimed at improving sunroof performance in speed, accuracy, smoothness, and energy efficiency. Additionally, the study explores advanced features like anti-pinch systems, obstruction detection, and adaptive control strategies, which focus on improving safety and enhancing user experience. This research illustrates the potential of microcontroller-based motor control in automotive applications, providing a safe and scalable solution for automated sunroofs. Furthermore, the study investigates the incorporation of communication protocols like LIN to support smooth connectivity with the vehicle's main control unit, allowing for enhanced features such as remote management and diagnostic oversight (Angleviel et al., 2006). The study also examines the application of optimized Pulse Width Modulation control to minimize power usage, thereby enhancing the system's cost-effectiveness and reliability.

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## LITERATURE REVIEW

1. (Deepak et al., 2022):This review provides a comprehensive overview of BLDC motors, focusing on their state-of-the-art control techniques and diverse applications. It serves as a valuable resource for researchers and engineers working with BLDC motors in various fields, including automotive engineering.

2. (Kumar et al., 2018) also provides a review of speed control methods for BLDC motors. These reviews are valuable for understanding the fundamental principles and advanced strategies in BLDC motor control.

3. (Real et al., 2010) points out BLDC motors inherently require rotor position information for proper current commutation in the stator windings. Traditionally, this information is obtained using sensors such as Hall-effect sensors. However, the use of sensors can decrease the reliability and increase the cost and complexity of the system. This is where sensorless control techniques come into play.

4. (Wang, 2012) focuses on the design and implementation of a BLDC motor drive and control system. The paper details the design of the IR2130 drive circuit, H-bridge drive circuit, and speed detection circuit. It also incorporates a PID algorithm to improve motor performance.

5. (Emadi, 2010) likely provides a broad and deep coverage of automotive power electronics and motor drives, including the fundamentals, components, and applications of BLDC motors also can serve as a comprehensive reference for understanding the principles, technologies, and design considerations related to BLDC motor drives in automotive applications, including sunroof control systems.

   (Kim et al., 2016) discusses a data-driven thermal protection algorithm for preventing overheating of the sunroof motor. The development of a data-driven thermal protection algorithm is motivated by the need to ensure the longevity and reliability of the motor, as excessive heat can degrade performance and lead to premature failure.

6. Explores PWM characteristics for accurate motor control, emphasizing the limitations that need to be overcome in converting digital signals into analog voltages for coil excitation (Mihai & Nicolae, 2013).

7. Presents a systematic comparison of sensorless techniques, evaluating their performance, cost, and complexity to guide the selection of appropriate strategies for varied BLDC motor applications (Real et al., 2010).

8. Highlights the use of flux-weakening methods to broaden the speed range of PMBL motors, improving power density and efficiency, which can be particularly relevant for automotive applications requiring flexible motor performance (Shen et al., 2017).

9. Discusses various advanced control methods like fuzzy logic, predictive control, and sliding mode control in BLDC motors, emphasizing their potential to enhance efficiency and reduce torque ripples (Ara□jo & Freitas, 2000).

10. Shows the development of a fuzzy self-tuning PI controller of HEV DC/DC converter, that is compared to PI control and it has been verified that the fuzzy PI controller has better control effect (Zhang & Kang, 2013).

11. Presents a PWM technique aimed at reducing losses in low-power BLDC motor drives, which may be adapted or used as a basis for similar power-saving techniques in automotive BLDC motor applications (Salah et al., 2011).

## SYSTEM ARCHITECTURE AND BLOCK DIAGRAM

The BLDC motor-driven sunroof control system architecture comprises several key components that work in synergy to achieve precise, efficient, and safe operation.

A brushless DC motor serves as the primary actuator, offering superior efficiency, durability, and control compared to traditional brushed DC motors, providing the necessary mechanical force to open and close the sunroof .

A high-performance microcontroller acts as the central processing unit, executing control algorithms, processing sensor data, and managing communication with other vehicle systems, selected for its processing power, memory capacity, and peripheral interfaces .

An electronic motor driver regulates the power supplied to the BLDC motor, controlling its speed and direction based on signals from the microcontroller, ensuring efficient and reliable motor operation.

A rotary encoder or Hall-effect sensor provides feedback on the sunroof's position, enabling precise control and accurate positioning, sending real-time data to the microcontroller for closed-loop control.

A current sensor monitors the motor's current draw, enabling the detection of obstructions or abnormal operating conditions, allowing the microcontroller to implement anti-pinch functionality and prevent motor damage.

The system is designed in compliance with ASIL B standards, ensuring functional safety in case of system faults .

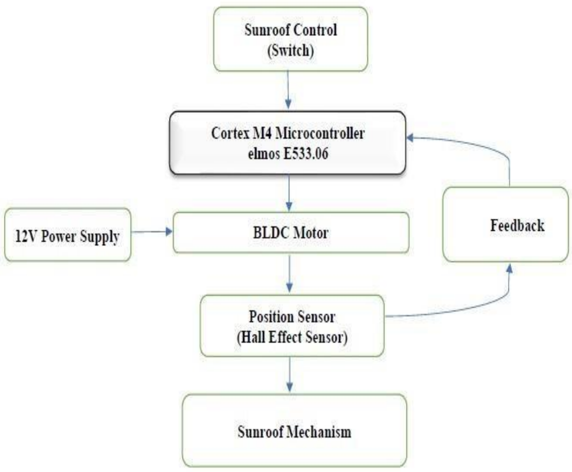


**Fig. 1: Block diagram of sunroof control system**

**The system operates as follows**:

The sunroof control system's operation is facilitated by a harmonious integration of electronic and mechanical components: A stable 12V DC supply from the vehicle's electrical system powers the system, activating the BLDC motor, sensors, and E533.06 microcontroller.

1. **User Input and Microcontroller Activation:**

   Upon activation, the microcontroller monitors the hall-effect sensors and responds to user-initiated commands. When the user engages the sunroof control switch, a signal is transmitted to the Cortex M4 Microcontroller, prompting the initiation of the sunroof's opening or closing sequence . The microcontroller interprets the user inputs and determines the necessary actions, subsequently sending instructions to the BLDC motor controller.

2. **BLDC Motor Control:**

   The BLDC motor controller adjusts the voltage and current supplied to the motor, enabling precise control over the sunroof's movement by achieving the desired speed and torque.

   The LIN communication protocol facilitates data exchange between the sunroof control system and the vehicle's other electronic systems, enabling features such as remote operation, automatic closing in rain, and diagnostic monitoring.

   Hall-effect sensors continuously monitor the motor's position and speed, providing real-time feedback to the microcontroller. To ensure seamless and safe operation, the control algorithm employs closed-loop feedback, while the anti-pinch detection system continuously monitors the motor's torque and current.

3. **Communication and Integration**

   The system adheres to ASIL B safety criteria, ensuring its ability to respond safely and reliably in the event of a system failure, thereby safeguarding the sunroof's

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operation across various environmental conditions.

- **Smooth Sunroof Operation:**

The incorporation of the ELMOS E533.06 microcontroller enhances precision in motor control, leading to smooth sunroof movement and improved energy efficiency.

The integration of a 32-bit ARM Cortex-M microcontroller facilitates precise management of safety mechanisms, processing of user inputs, and efficient motor control. Feedback data from Hall-effect sensors integrated within the BLDC motor provides the microcontroller with real-time insights into the motor's position and speed. The Power MOSFET regulates the power supplied to the BLDC motor, facilitating precise speed and torque control to manage the sunroof's movement effectively. This helps automakers fulfill stringent energy efficiency rules and enhances vehicle performance. LIN communication is essential for integrating the sunroof system with onboard automotive electronics, enabling smooth operation with other systems such as lighting and locking .

**Safety and Anti-Pinch Mechanism:**

The torque and current of the motor are continuously monitored by an anti-pinch detecting system. In order to prevent harm or damage, the control system instantly stops the sunroof's movement when there is a sudden increase in current, which suggests a possible obstruction. The system complies with ASIL B safety standards, guaranteeing dependable and secure reactions in the event of a system failure. The Cortex M4 microprocessor's real-time obstacle detection enables an anti-pinch mechanism that guarantees prompt and reliable reactions, improving safety.

## SIMULATION AND TESTING

Intensive simulations and hardware testing were carried out under a range of operating scenarios in order to verify the suggested sunroof control system's functionality and dependability. Prior to hardware implementation, MATLAB/Simulink simulations were used to describe the behavior of the BLDC motor, control algorithms, and anti-pinch mechanism. This allowed for parameter optimization and system verification.

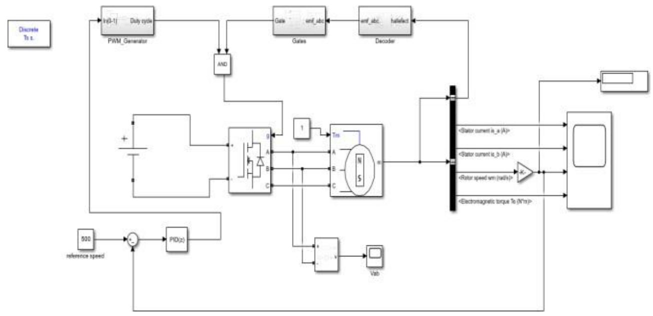

**Fig. 2: Matlab Simulation**

Pulse-width modulation signals generated by the PWM Generator control the BLDC motor. Gates regulate how the motor driving circuit switches. The control signals are converted by a decoder to guarantee accurate motor operation. The flawless operation of the sunroof is made possible by feedback sensors that track its location and speed. When the desired and actual sunroof positions disagree, the feedback loop dynamically modifies the PWM impulses.

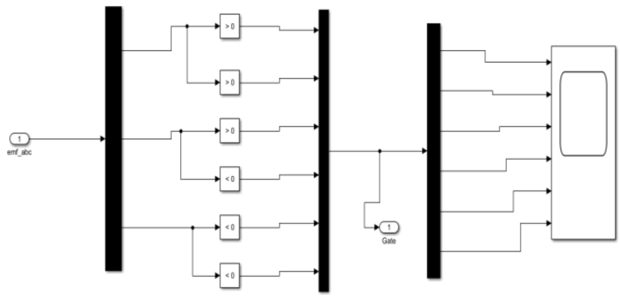

**Fig. 2(a): Gates**

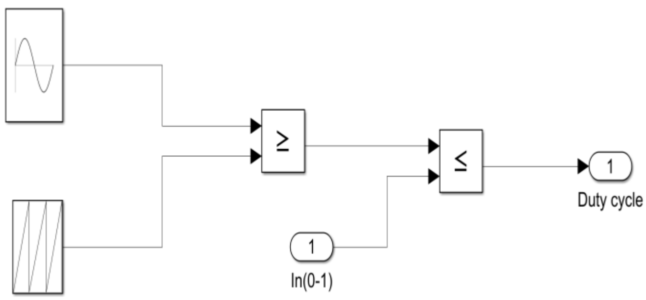


**Fig.2(b): PWM Generator**

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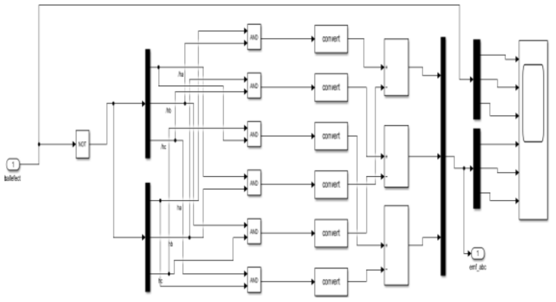

Fig. 2(c): Decoder

Hardware-in-the-loop testing was also used to test how the system responded to real-world situations and replicate the vehicle environment. The outcomes of the simulation show how well the control algorithms work to provide accurate sunroof alignment, seamless operation, and dependable anti-pinch functioning. The system's compliance with industry safety standards was further confirmed by a detailed evaluation of its capacity to identify blockages, avoid pinching, and ensure safe operation.
The system was exposed to a range of external factors during hardware testing, including as vibration, temperature changes, and electromagnetic interference, in order to evaluate its resilience and dependability. Through an evaluation of its speed, torque, and economy, the BLDC motor's suitability for sunroof applications was confirmed.

Laboratory automobiles were also used to test the electric sunroof pinch detection system, and the findings demonstrated exceptional performance under various circumstances.
To make sure the anti-pinch mechanism was effective in preventing injuries, measurements were made of its sensitivity and speed of response. The smooth integration of the LIN communication interface with the electronic systems of the car was tested. Using the LIN communication protocol, the system easily connected with the car's electronics and reacted swiftly to user directions. A comparison to current sunroof control techniques shows how much better the suggested approach is in terms of efficiency, safety, and user experience.

## DESIGN AND IMPLEMENTATION

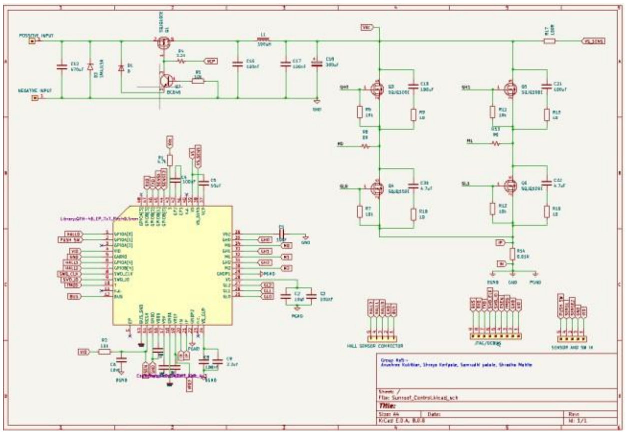

Fig. 3 : Circuit Schematic Of Sunroof Control System

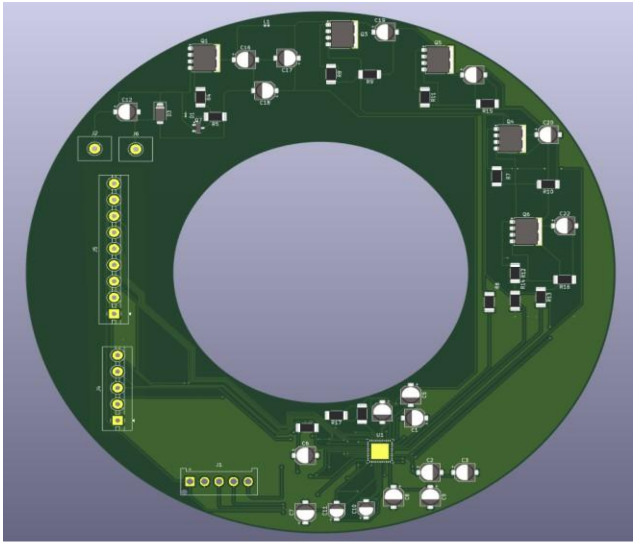

Fig.4 : 3D PCB Layout of the Sunroof Control System

The circuit operates on +12V, a common voltage for automotive applications. Capacitors are used to filter and stabilize the power supply. A flyback diode, D3, protects against voltage spikes.

The Elmos E553.06 IC serves as the central controller for the BLDC motor, with multiple GPIO and control pins connected to external components, including Hall sensor inputs that provide rotor position feedback.

To power the Blocking & Digital MOSFETs, which require a higher voltage than the main supply, a charge pump circuit is used. This charge pump generates the necessary extra voltage, limiting current and helping to stabilize its operation. The RG resistor limits current and also aids in stabilizing the charge pump operation. A BC107 transistor acts as a switch to control the charging of the charge pump capacitor. Diode D3 ensures the charge pump voltage flows in the correct direction and prevents voltage drop during switching.

An inductor, L1, and capacitors help with noise filtering and voltage stabilization. A Pi circuit, consisting of two capacitors and one inductor, is used for power supply filtering to smooth the voltage.

An H-bridge configuration of MOSFETs, Q2, Q7, Q8, and Q9, is used to drive the motor. The high-side MOSFETs are connected to Vdd, while the low-side MOSFETs are connected to GND, allowing controlled current flow through the motor.

A Current Sensing Resistor measures the motor current for feedback control. Pull-down resistors ensure the MOSFETs turn off properly, and RC circuits provide noise filtering.

The M0 and M1 drive signals control the MOSFET switching. The IP and IN signals are common shunt resistors that measure the shunt current, with the low-side shunt resistor measuring the current at the low-side return path of the motor. PGND handles large current, mainly for the MOSFET motor drive, while DGND is used for low-power digital components.

Finally, SW-CLK and SWD-IO are used for debugging and programming the microcontroller.

## RESULTS AND DISCUSSION

The sunroof control system that uses a BLDC motor represents a significant improvement over traditional brushed DC motor setups. It includes features that improve energy efficiency, operational accuracy, and overall dependability. The greater efficiency of the BLDC motor leads to a decrease in overall energy use, which aligns with the automotive sector's increasing focus on sustainability. The lack of mechanical commutators in BLDC motors not only reduces noise but also enhances efficiency and minimizes energy losses. The implementation of the LIN communication protocol within the system guarantees smooth integration with other electronic systems in the vehicle, improving overall functionality and user experience. This integration allows for features such as automatically closing the sunroof during bad weather and remote operation through a smartphone application. The sunroof's motion may be precisely controlled thanks to the integration of Hall-effect sensors and advanced control algorithms, which produces trustworthy and seamless functioning. By tracking data from various sensors, the control system continuously adjusts to shifting operating conditions, guaranteeing optimal performance and reliability. Anti-pinch detection and ASIL B compliance are two of the system's essential safety elements for averting mishaps and ensuring the wellbeing of passengers. The system is safer because of the Cortex M4 microprocessor's capacity to identify obstacles and react quickly, which lowers the possibility of damage or injury. As shown in adaptive headlamp systems, the microcontroller's use of fuzzy logic in conjunction with parts like gears and a ten-turn potentiometer may produce steady and seamless operation. Additionally, testing has shown that the precision and reaction time of the sunroof mechanism remain consistent under a range of climatic circumstances, highlighting the system's resilience and dependability. It may be deployed in a variety of settings because its performance is constant in both hot and cold conditions. This assures that the sunroof will function effectively in any weather.

## CONCLUSION

When compared to traditional competitors, the BLDC motor-driven sunroof control system offers significant improvements in terms of user experience, safety, and efficiency. It satisfies the need for more sophisticated, dependable, and energy-efficient electronic control systems in the automobile sector. The system is a useful addition to contemporary cars because of its advanced features, which include accurate motor control, smooth vehicle electronics integration, and improved safety measures. Future studies might concentrate on using machine learning algorithms to increase the system's intelligence, which could allow for predictive control and customization of sunroof functioning. Using microprocessors to control motors and sensors, solar tracking systems maximize power generation from solar irradiance by reorienting a solar array to face the sun continuously. Furthermore, improvements in sensor technology and control algorithms could make the system even more flexible in response to shifting environmental circumstances, guaranteeing top performance and security. The importance of sunroof controls in improving vehicle safety and user experience is highlighted by the car industry's ongoing transition to smarter and more effective electronic control systems. Without a doubt, the knowledge gained from this study will help progress automotive technology even further, opening the door for creative and advanced vehicle control systems.

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