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Obstacle Detection & ABS Implementation Using FPGA

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Abstract

This thesis explores the implementation of an Anti-lock Braking System (ABS) combined with obstacle detection using Field-Programmable Gate Arrays (FPGAs). The primary objective is to enhance vehicle safety by integrating real-time braking control with object detection capabilities in a single system. ABS prevents wheel lockup during emergency braking, ensuring optimal traction and steering control. Simultaneously, the obstacle detection module identifies potential hazards, triggering the braking system to avoid collisions.

The system is designed using digital hardware principles and implemented on an FPGA platform to leverage its high-speed processing and reconfigurability. The obstacle detection system employs sensor data processing to identify objects and calculate their relative distance and velocity, ensuring accurate and timely responses.

Key components include a hardware description language (HDL), implementation of the control algorithms, integration of sensor interfaces, and rigorous simulation and verification to ensure reliability. The design is validated through real-time testing scenarios, demonstrating its ability to respond to dynamic environments effectively. This work highlights the potential of FPGA-based systems in automotive safety applications, providing a foundation for future advancements in intelligent transportation technologies.

Acknowledgement

First and foremost, we would like to express my sincere gratitude to **Dr. Heba Draz**, my project supervisor, for their invaluable guidance, support, and encouragement throughout this journey. Their expertise and constructive feedback have been instrumental in shaping this work and overcoming challenges along the way.

A special thanks to **Cairo university** and the faculty members of the **Computer and Communications department** for providing the necessary resources and a conducive environment for completing this project.

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Introduction

Automotive safety is an ever-evolving field, driven by the need to reduce accidents. The primary objective of this project is to prevent wheel lockup during emergency braking situations while simultaneously detecting and responding to obstacles in the vehicle's path. ABS ensures optimal traction and steering control, particularly during sudden stops, by preventing the wheels from locking. At the same time, the obstacle detection system identifies potential hazards in the surrounding environment and provides timely inputs to the braking system to avoid collisions. Together, these functionalities contribute to safer and more reliable vehicle operation.

This project leverages the power of Field-Programmable Gate Arrays (FPGAs) to implement the system. FPGAs are known for their high-speed processing capabilities and reconfigurability, making them ideal for real-time applications like automotive safety. By utilizing digital hardware design principles, our system processes sensor data in real-time to calculate critical parameters such as the distance and velocity of detected obstacles. These calculations enable the system to respond swiftly and accurately, ensuring that the vehicle adapts to its environment effectively.

The development process involves several key stages, including the design and implementation of control algorithms, integration of sensor interfaces, and rigorous testing to ensure system reliability. Hardware description languages (HDLs) are used to create the digital circuits that form the backbone of the system. Extensive simulation and verification are performed to validate the design under various scenarios, ensuring its robustness and efficiency in real-world applications.

In conclusion, our project serves as a testament to the transformative power of digital hardware design in addressing real-world challenges. By combining innovative technologies and a commitment to safety, this work provides a strong foundation for the continued evolution of automotive safety systems.

Motivation

Automotive safety continues to be one of the most critical challenges faced by societies worldwide, largely due to the alarming rates of traffic accidents and the resulting fatalities. Despite significant advancements in vehicle technology, the increasing density of road networks and unpredictable driving environments necessitate more innovative and reliable safety measures. Ensuring the protection of drivers, passengers, and pedestrians requires the adoption of cutting-edge technologies capable of minimizing human error and mitigating the consequences of unforeseen circumstances.

Advanced safety systems have evolved from being optional features to essential components in modern vehicles. They play a pivotal role in reducing risks on the road and improving overall driving experiences. Among these systems, the integration of technologies such as Anti-lock Braking Systems (ABS) and Obstacle Detection stands out as a transformative approach to enhancing vehicle safety. Together, these systems address two fundamental aspects of accident prevention: the ability to maintain control during emergency braking and the capacity to detect and respond to potential hazards in the vehicle's surroundings.

The adoption of Field-Programmable Gate Arrays (FPGAs) for implementing these systems further strengthens their effectiveness. FPGAs offer unparalleled advantages, including high-speed data processing and the ability to reconfigure hardware designs to adapt to evolving requirements. This makes them an ideal platform for addressing the complexities of real-time safety challenges in automotive applications. The capacity to process large volumes of sensor data instantaneously and dynamically adjust system responses ensures that vehicles can adapt to rapidly changing environments, whether in urban traffic, highways, or adverse weather conditions.

Justification

The decision to focus on ABS and Obstacle Detection is justified by the growing demand for integrated safety solutions in the automotive industry. These systems complement each other, creating a comprehensive solution for accident prevention. Specifically:

- **Hands-on Experience with Cutting-Edge Technology:** Working with FPGAs allows us to gain real-world experience with advanced hardware systems that are increasingly used in industries like automotive and aerospace. This practical exposure is invaluable for our future careers.

- **Portfolio Enhancement:** Successfully completing this project will greatly enhance our portfolios. It's an impressive, real-world project that we can showcase to potential employers, proving that we have both the technical know-how and the problem-solving skills needed in the industry.

- **Affordable and Practical Learning:** Our project uses low-cost components, such as ultrasonic sensors and a single FPGA platform, making it affordable while still teaching us the principles of high-performance system design. We're learning how to achieve more with less, an essential skill in engineering.

- **Building a Safer Future:** We're contributing to the development of safety-enhancing technologies in vehicles, which are key to the future of autonomous driving. Our project could be a stepping stone toward innovations that make driving safer for everyone.

- **Pioneering Automotive Innovation:** This project gives us the opportunity to contribute to the development of advanced vehicle systems. As electric and autonomous vehicles continue to evolve, having experience in FPGA-based control systems positions us as innovators capable of advancing technologies like obstacle avoidance, adaptive cruise control, and more.

- **Alignment with Industry Trends:** Companies like Valu and Siemens are pioneers in digital electronics, especially in automotive and smart systems. Our project on FPGA-based obstacle avoidance and ABS aligns perfectly with their focus areas, making us well-prepared for roles within these companies.

- **Boom in Automotive Sales:** With global automobile sales steadily increasing, especially in the electric and autonomous vehicle sectors, companies are prioritizing innovations that enhance vehicle safety and performance. Our project aligns with this demand, giving us practical knowledge in technologies that these companies are focusing on. Recent research done by Siemens digital industries softwares done on the 12th of January 2021 shows how automotive trends are changing the ways we move from point A to B.

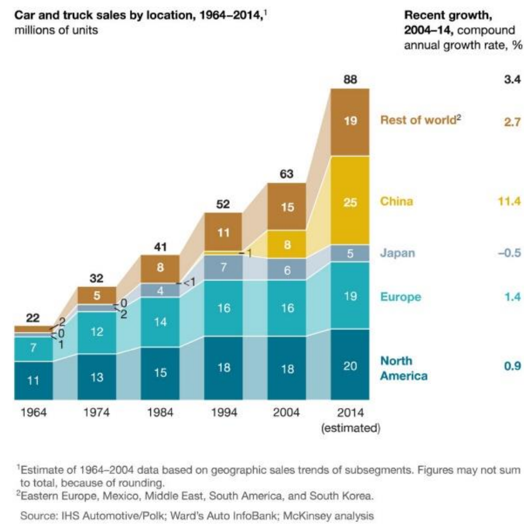


Figure 1

- **R&D in Digital Electronics:** The growing complexity of automotive systems is driving demand for engineers skilled in R&D related to digital electronics. By working on an FPGA project, we are gaining the critical skills needed to design, optimize, and implement digital systems, which are essential for future industry development.

- **Talent Pipeline for Digital Electronics:** The increasing demand for engineers skilled in FPGA, embedded systems, and automotive technologies is creating a talent gap in the industry. Our project allows us to develop the exact skills companies are looking for, ensuring we are ready to meet this demand.

- **Passion for Automotive Innovation:** We chose this project because we are passionate about contributing to the innovations that are transforming the automotive industry. With collision avoidance sensors being one of the highest-demand technologies in the automotive market, we specifically focused our project on real-time systems that enhance vehicle safety. By working on these critical safety systems, we are positioning ourselves to contribute to the technologies that will define the future of transportation.

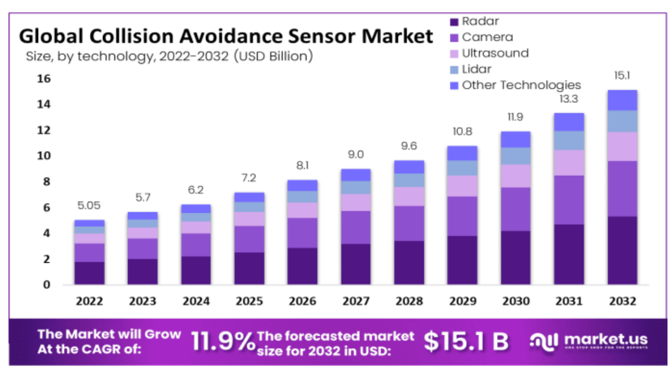


Figure 9

Problem Definition

With the rapid growth of automotive technologies, ensuring road safety has become a critical concern. Accidents often occur due to delayed human reaction times or failure to recognize potential hazards in time. This calls for intelligent systems capable of autonomously assessing the environment and acting swiftly to prevent collisions.

The challenge lies in designing a reliable braking system that can accurately detect objects in the vehicle's path and make real-time decisions based on the speed and proximity of the object. The system must integrate hardware sensors, efficient signal processing, and a robust control mechanism to ensure timely and effective braking actions.

The project aims to address these challenges by developing an object detection and braking system in SystemVerilog. The system will utilize an ultrasonic sensor to measure the distance between the car and any object, process this information alongside the vehicle's speed, and determine whether braking is necessary to avoid a collision. The solution must meet real-time performance constraints and demonstrate safety, reliability, and efficiency.

Project Outcomes

i. Object Detection System:
   - Development of an efficient object detection module using an ultrasonic sensor to measure the distance between the vehicle and obstacles accurately.
   - Real-time processing of sensor data to assess proximity and identify potential collision risks.

ii. Speed-Based Decision Making:
   - Integration of speed input with the object detection module to dynamically evaluate braking requirements based on real-time driving conditions.
   - Logical decision-making system that prioritizes safety without unnecessary braking.

iii. Automated Braking Mechanism:
   - Implementation of a braking control module in SystemVerilog that triggers the brakes autonomously when an obstacle is detected within a critical range.
   - Ensures rapid response times to prevent collisions.

iv. System Reliability and Validation:
   - Validation of the braking system under various test scenarios, ensuring consistent performance across different speeds and distances.
   - Demonstration of the system's ability to handle edge cases, such as sudden appearances of objects or varying object sizes.

v. Hardware-Software Integration:
   - Successful implementation of the project in hardware simulation environments or prototype setups to demonstrate feasibility.
   - Optimization of resource usage in the SystemVerilog design to meet performance constraints.

vi. CAN Communication Protocol Implementation:
   - Use of the Controller Area Network (CAN) protocol to enable reliable and efficient communication between the object detection module and the braking system module.
   - Ensures low-latency data transfer and robust synchronization between components for accurate decision-making.

Progress Report

Object Detection Module

We have successfully designed and implemented the Object Detection Module, which has been subdivided into two functional sub-modules: OD_Distance and OD_Time.

- OD_Distance Sub-Module:
    - This module processes the input distance data and evaluates whether the distance between the vehicle and the detected object is safe.
    - The system transitions between states (IDLE, FAR_OBSTACLE, and NEAR_COLLISION) based on the distance value and handles timeout errors from the ultrasonic sensor.
    - We have tested this module using multiple test cases in Questasim to validate its functionality and re-ran the design on Vivado to verify the elaborated implementation and its hardware compatibility.

- OD_Time Sub-Module:
    - This module calculates the time required for the vehicle to reach an object based on the speed and evaluates whether an object poses a collision risk within the calculated time.
    - Like the distance sub-module, it also transitions through states (IDLE, FAR_OBSTACLE, and NEAR_COLLISION) based on time values and sensor timeout errors.
    - We followed the same rigorous testing and validation approach using Questasim and Vivado to ensure its reliability and correctness.

Testing and Validation:

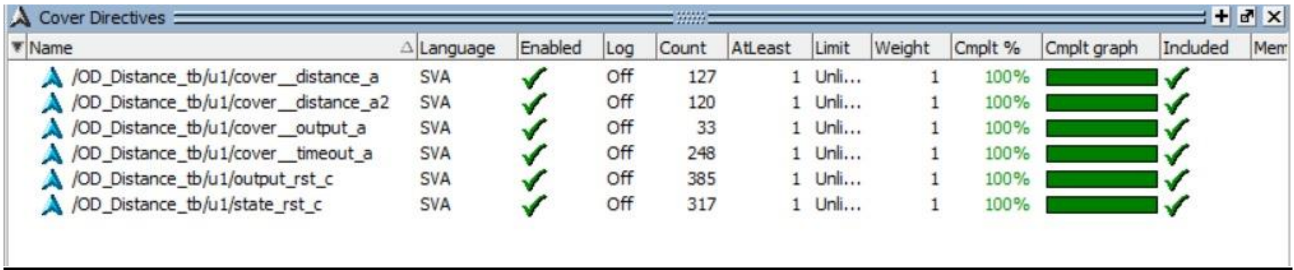
- Both sub-modules were extensively tested with diverse scenarios to cover edge cases and confirm their functionality.
- Assertions and coverage properties were integrated to verify the system's state transitions and output logic under various conditions.
- Running the modules on Vivado allowed us to confirm the synthesizability and correctness of the implementation.

Summary of Achievements

- Designed and implemented the Object Detection Module, including OD_Distance and OD_Time, with fully verified functionality.
- Established a robust foundation for the braking system and communication protocols through modular design and extensive testing.
- Progressed through simulation and validation stages using industry-standard tools like Questasim and Vivado.

Simulation Results

OD_distance module



Cover Directives

Name	Language	Enabled	Log	Count	AtLeast	Limit	Weight	Cmplt %	Cmplt graph	Included	Mem
/OD_Distance_tb/u1/cover__distance_a	SVA	✓	Off	127	1	Unli...	1	100%		✓	
/OD_Distance_tb/u1/cover__distance_a2	SVA	✓	Off	120	1	Unli...	1	100%		✓	
/OD_Distance_tb/u1/cover__output_a	SVA	✓	Off	33	1	Unli...	1	100%		✓	
/OD_Distance_tb/u1/cover__timeout_a	SVA	✓	Off	248	1	Unli...	1	100%		✓	
/OD_Distance_tb/u1/output_rst_c	SVA	✓	Off	385	1	Unli...	1	100%		✓	
/OD_Distance_tb/u1/state_rst_c	SVA	✓	Off	317	1	Unli...	1	100%		✓	

Figure 3

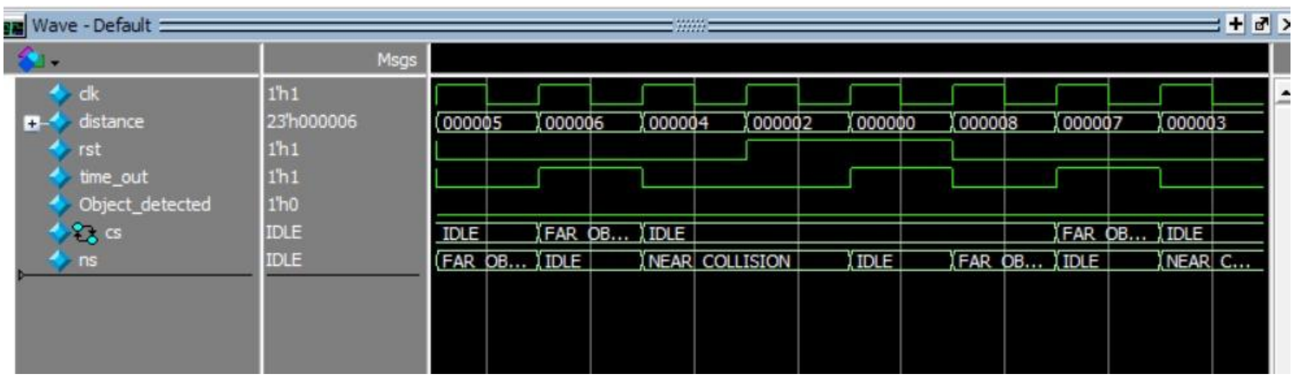


Figure 4

OD_time module

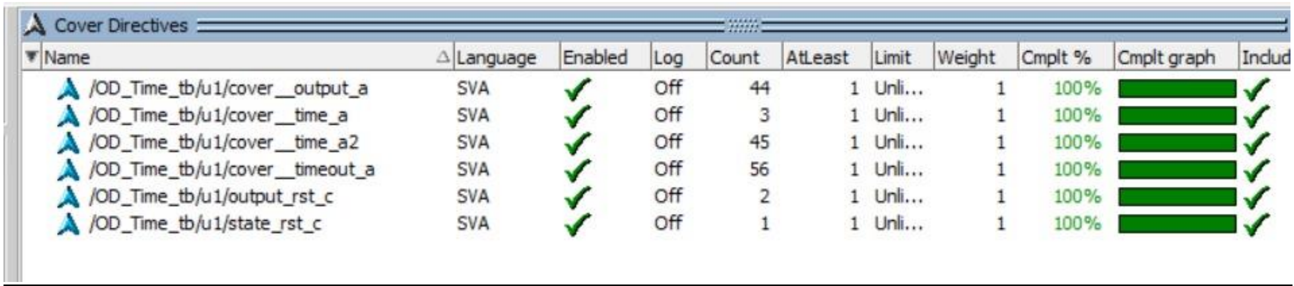


Figure 5

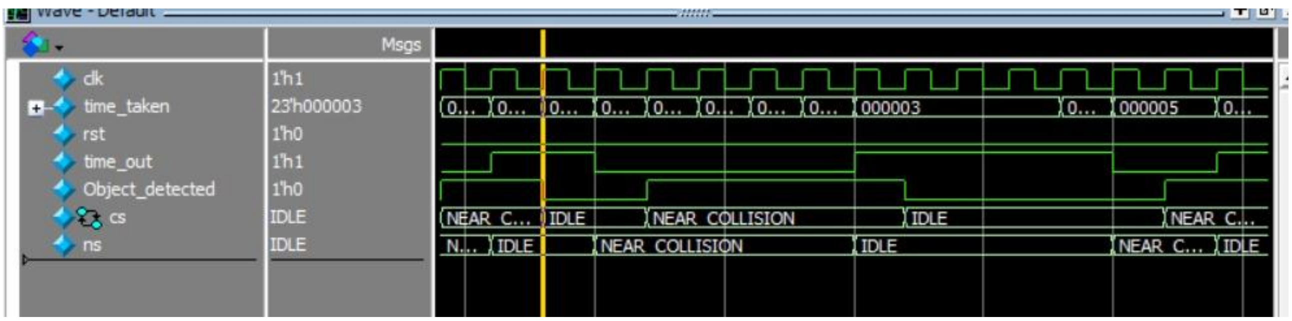


Figure 6

FSM diagram

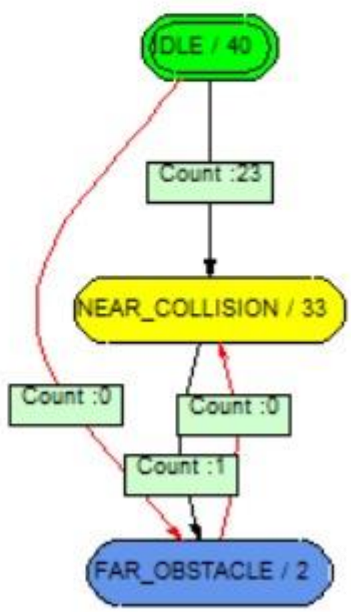


Figure 7

OD_distance on Vivado

- Implementation

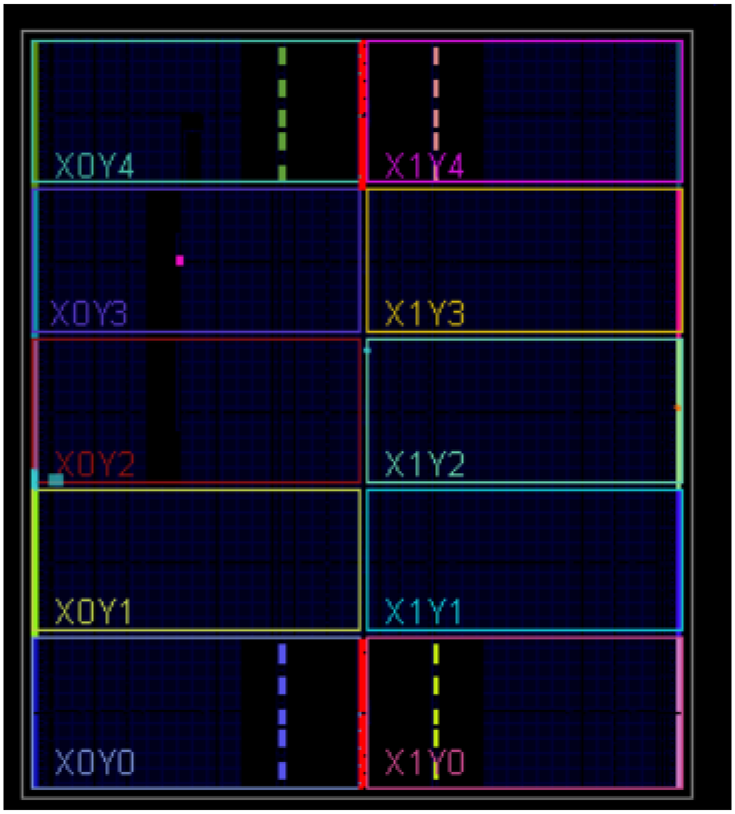


Figure 8

- Report utilization

Name	Slice LUTs (134600)	Slice Registers (269200)	Bonded IOB (500)	BUFGCTRL (32)
N OD_distance	3	2	7	1

Figure 9

Plan for Remaining Work

The next steps of the project are planned over the course of the next semester to ensure steady progress toward a fully functional system. The tasks have been divided into three phases, with clear objectives and deliverables for each phase.

- Phase 1: Braking System Module Development
  - Objectives:
    - Design and implement the braking system logic based on inputs from the object detection module.
    - Ensure the braking system operates with both distance-based and time-based collision detection data.

- Phase 2: CAN Communication Protocol Implementation
  - Objectives:
    - Develop a reliable communication interface using the CAN protocol to connect the object detection module with the braking system.

- Phase 3: System Integration and Comprehensive Testing
  - Objectives:
    - Integrate all modules (object detection, braking system, and CAN communication) into a cohesive system.
    - Perform end-to-end testing and optimization to meet performance, safety, and reliability goals.

Conclusion

The integration of ABS and Obstacle Detection into a single system marks a pivotal advancement in automotive safety. This project not only demonstrates the feasibility of combining these technologies but also highlights the potential of FPGA-based solutions in addressing real-time, safety-critical applications.

Through rigorous design and testing, the system ensures reliable performance under various driving conditions, contributing to enhanced vehicle control and accident prevention. This work underscores the importance of innovation and adaptability in automotive safety, paving the way for further exploration in intelligent transportation systems.

In essence, this project serves as a testament to the transformative power of technology in creating safer roads and smarter vehicles, offering a robust platform for future advancements in the field.

الملخص

تهدف هذه الرسالة إلى استكشاف تطبيق نظام الفرامل المانعة للانغلاق (ABS) مع نظام كشف العوائق باستخدام المنصات القابلة للبرمجة (FPGAs). الهدف الأساسي هو تحسين سلامة المركبات من خلال دمج التحكم في الفرامل في الوقت الفعلي مع قدرات كشف العوائق في نظام واحد. يعمل نظام ABS على وقف العجلات، مما يضمن الثبات والسيطرة على التوجيه، بينما يكشف نظام التعرف على العوائق المخاطر المحتملة ويقوم بتنشيط الفرامل لتجنب التصادم.

تم تصميم النظام باستخدام مبادئ الأجهزة الرقمية وتنفيذه على منصة FPGA للاستفادة من سرعة المعالجة العالية وقابليتها لإعادة البرمجة. يعتمد نظام كشف العوائق على معالجة بيانات الحساسات لتحديد الأجسام وحساب المسافة والسرعة النسبية بدقة، مما يضمن استجابة فعالة وفي الوقت المناسب.

تتضمن المكونات الرئيسية استخدام لغة لوصف الأجهزة (HDL)، وتنفيذ خوارزميات التحكم، ودمج واجهات الحساسات، مع محاكاة واختبارات دقيقة لضمان الاعتمادية. تم التحقق من التصميم من خلال سيناريوهات اختبار في الوقت الفعلي، مما يبرز قدرته على التفاعل مع البيئات المتغيرة بفعالية. تسلط هذه الدراسة الضوء على إمكانيات الأنظمة القائمة على FPGA في تطبيقات سلامة المركبات، وتوفر أساسًا لتطوير تقنيات النقل الذكية مستقبلاً.

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