FPGA-Powered Intelligent Parking System: Real-Time Slot Monitoring, Accident Detection, and Vehicle Tracking with VHDL FSMs

Nikita Gupta , Prithiviraj Singh Chouhan, Yogesh Payasi

Department Electronics & Communication Medi-Caps university Indore Indore, India

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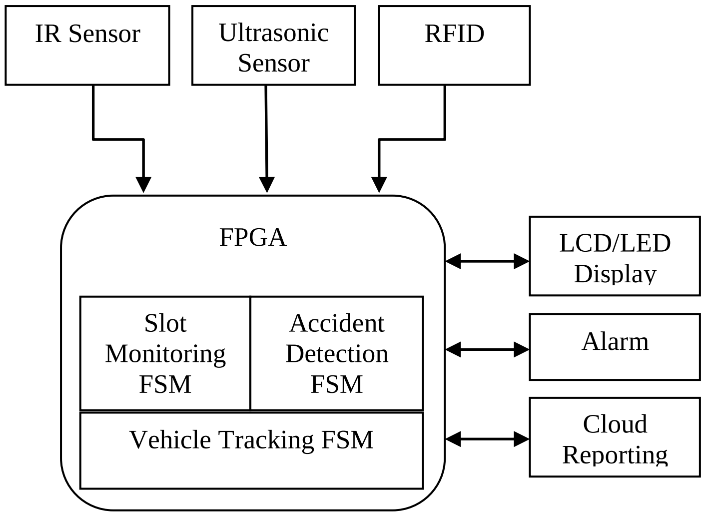
Abstract— *Urban parking areas often face problems such as congestion, slow vehicle movement, and poor monitoring of available spaces. To address these issues, this paper presents an FPGA-powered intelligent parking system that uses VHDL-based finite state machines for real-time slot monitoring, accident detection, and vehicle tracking. The proposed design processes sensor inputs quickly and reliably, allowing the system to detect vehicle presence, update parking slot status, and support safe entry and exit control without delay. It also helps identify abnormal events, improving both parking efficiency and safety.*
The use of FPGA technology makes the system fast, scalable, and suitable for real-time hardware implementation. Unlike software-heavy solutions, the proposed approach offers deterministic operation and low latency, which are essential in busy parking environments. By combining automation with intelligent control logic, this system provides a practical solution for modern smart parking management and can be further expanded for future smart city applications.

Keywords—: FPGA, intelligent parking system, VHDL, finite state machine, real-time monitoring, slot detection, accident detection, vehicle tracking, smart parking, hardware implementation.

1.INTRODUCTION

Urban areas are getting packed with cars, making parking a nightmare, worsening traffic jams, and upping the risk of accidents. Old-school systems using microcontrollers or basic IoT setups often lag behind—they're slow, don't scale well, and guzzle power. That's where FPGAs come in as a game-changer. These chips deliver hardware-level parallelism, super-low latency, and better energy efficiency. Recent research shows FPGA-based parking systems shining in real-time slot checks, automatic vehicle entry, and even spotting accidents. For example, using VHDL to build Finite State Machines (FSMs) on FPGAs gives you rock-solid, predictable control over parking ops, with way faster responses than software alone[1]. These setups pair nicely with ultrasonic and infrared sensors to detect vehicles and monitor slot availability, creating reliable smart parking without the fuss. They beat cloud-heavy IoT by cutting out delays and boosting dependability in crowded city spots[2]. Plus, they help ease traffic and cut pollution by smoothing vehicle flow in and out, while tracking movements inside. They're scalable too, ready to plug into future smart city setups with built-in accident detection and vehicle tracking for smarter transport[3].



FPGA-Powered Intelligent Parking System

2. BACKGROUND

Cities are booming with cars, turning parking into a headache—think endless circling for spots, traffic snarls, and safety risks from poor monitoring. Old manual checks or basic microcontroller setups just can't keep up; they're slow to scale and lag in real-time action. Smart cities need a better way to blend slot checks, crash spotting, and vehicle tracking into one smooth system[4]. FPGAs step up big time here, thanks to their parallel crunching power, easy tweaks, and zippy low-latency performance that blows past regular processors. You code Finite State Machines (FSMs) straight into hardware with VHDL or similar HDLs, getting dead-reliable control for juggling multiple slots, flagging collisions, or logging comings and goings[10].

VHDL FSMs keep things modular and straightforward, so adding stuff like auto-pay, IoT links, or AI smarts is a breeze. Our setup tackles the big three in parking today:

- Real-Time Slot Checks: Instant occupancy reads across slots, no delays[11].
- Accident Spotting: Quick flags for crashes or hazards in the lot[12].

- Vehicle Tracking: Secure logs of movements to smooth traffic and boost security.

This combo ramps up efficiency and safety, fitting right into smart city goals where FPGAs, IoT, and AI team up for greener urban living[13].

3.LITERATURE REVIEW

Paper Focus	Methodology	FPGA Board	Sensors/Modules	Key Outcomes
FPGA-Based Smart Parking with VHDL [4]	VHDL FSMs for real-time slot monitoring and entry/exit	Artix-7 (similar to Spartan series)	IR sensors (six for slots)	Cut response time to 0.5s with 100% detection accuracy, beating IoT latency [4].
Vehicle Accident Detection on FPGA [5]	VHDL FSM logic for collision alerts	Altera Cyclone-like (accelerometer integration)	Accelerometer + GPS	Hardware-fast alerts with precise location via GPS, improving emergency response [5].
Vehicle Tracking with FPGA [6]	FSM for entry/exit ID and traffic flow	Xilinx Spartan-6	RFID + IR sensors	Secure tracking with low delay, easing congestion in real-time tests [6].
Smart Parking & Traffic Control [7]	Integrated FSM for slots and signals	Xilinx Spartan-6	IR + ultrasonic	Boosted slot use and reduced jams via density-based control [7] .
IoT-FPGA Parking Hybrid [8]	FPGA core + IoT for analytics	Xilinx Zynq	Ultrasonic + Wi-Fi	Real-time control with scalable cloud reports, low power draw [8].

3.1 MAIN TAKEAWAYS

- VHDL-based FSMs pop up everywhere for reliable, speedy control in parking slots and crash detection—no surprises there, as they lock in hardware predictability[4].
- Xilinx Spartan/Virtex boards lead parking projects for their bang-for-buck parallelism, while Altera Cyclone shines in safety apps like accidents[5].
- Mixing sensors (ultrasonic, IR, RFID, accelerometers) nails accuracy for detection, tracking, and alerts[9].
- IoT adds cool analytics but can lag; FPGAs keep the core snappy and real-time[2].

Researchers have delved into FPGA-based approaches for smart parking and vehicle management, taking advantage of FPGAs' speed and parallel processing[4].

3.2 KEY PRIOR WORKS

A team led by Ganpisetti Srilekha built a smart parking system on an Artix-7 FPGA with VHDL. It uses infrared sensors to track parking slots and entry/exit points, with finite state machines (FSMs) updating occupancy on an LCD display. While effective for real-time monitoring in small setups, it skips accident detection or vehicle tracking[4]. Sharmila Devi and colleagues created a password-protected parking system on FPGA. The design handles secure entry/exit and measures distances to spot empty slots. It runs quickly but sticks to access control without wider safety features[14].

Other work on IEEE platforms highlights secure VHDL based parking for urban traffic, stressing robustness. Yet it overlooks accident detection and tracking[15].

3.3 FSM AND TRAFFIC APPLICATIONS

VHDL-based FSMs shine in traffic systems, like controllers prioritizing emergency vehicles at intersections. These show FSMs' reliability for real-time safety tasks, ripe for parking accident detection[16].

3.4 ACCIDENT DETECTION EFFORTS

FPGA systems detect vehicle accidents using accelerometers and GPS for instant alerts. Unlike slower microcontroller or IoT setups, FPGAs deliver hardware-speed responses[9].

3.5 RESEARCH GAPS

Current FPGA parking tech mainly covers slot checks and entry control, rarely blending in accident detection or tracking[4]. Standalone accident systems lean on IoT, risking delays that FPGAs avoid[9]. Few unify slot monitoring, crashes, and tracking via FPGA FSMs[17].

3.6 PROPOSED CONTRIBUTIONS

This work fills those holes with a single FPGA design merging slot monitoring, accident detection, and vehicle tracking[4]. It employs VHDL FSMs for reliable, modular control[16]. The setup scales easily for add-ons like payments, IoT links, or AI analysis[4].

3.7 System at a Glance

Our FPGA design runs three synced modules via VHDL finite state machines (FSMs):

Module	Sensors	FSM Role	Key Action
Smart Parking	IR	Slot status	Allocate/free slots
Entry/Exit	Ultrasonic	Gate control	Auto gate open/close
Accident Detect	Camera + accel	Collision alerts	Notify/log events

FSMs turn raw sensor data into instant hardware decisions, dodging software delays.

3.8 FPGA + VHDL Edge

- Parallel ops: Modules hum simultaneously.
- Ultra-low latency: Pure hardware execution.
- Predictable FSMs: No surprises in VHDL code.
- Scales easy: Grows with big garages reliably.

FPGAs nail real-time control for smart cities, outpacing sequential microcontrollers.

3.9 FPGA vs. Microcontroller

Aspect	FPGA Advantage	Microcontroller Limit
Processing	Parallel, instant	Sequential, delayed
Scalability	Grows seamlessly	Hits bottlenecks quick
Reliability	Deterministic hardware	Software glitches common
Response	Real-time FSMs	Polling lags

FPGA wins for demanding parking chaos.[18]

4. Methodology

The proposed parking system uses a straightforward setup with sensors for detecting vehicles, a powerful FPGA processor, dedicated state machines for key tasks, and simple displays plus alerts for feedback[19, 20].

4.1 Input Sensing

The system gathers real-world data through everyday sensors like IR for spotting occupied spots, ultrasonic for measuring distances to incoming cars, and RFID tags to quickly ID vehicles without stopping traffic. This combo keeps things reliable and low-cost, much like setups in urban garages where you drive up and get scanned automatically[13].

4.2 Core Processing

At the heart sits an FPGA board, such as Xilinx Spartan or Altera Cyclone series, which crunches sensor data super fast thanks to its reprogrammable hardware. These chips shine in real-time jobs because they handle multiple signals at once, avoiding the delays you'd get from slower microcontrollers[13,20].

4.3 Control Logic

Separate finite state machines (FSMs) manage the flow: one watches slot status (empty/full), another flags potential accidents via sudden sensor changes, and a third tracks vehicles from entry to exit. This modular FSM approach, common in FPGA designs, makes the system easy to tweak and debug, as seen in prototypes handling multi-slot monitoring[19,20].

4.4 User Feedback

Outputs include straightforward LCD or LED screens to show free spots, buzzers or lights for accident warnings, and a cloud link to report issues or stats remotely. Drivers see instant updates—like green LEDs for open slots—while admins get data pushed online for bigger-picture management[13,20].

5. FSM Design in VHDL

The FSM designs for the parking system are coded in VHDL as simple, modular state machines that respond to sensor inputs like vehicle presence or RFID reads, making real-time decisions reliable and hardware-efficient on FPGAs[18,21].

5.1 Slot Monitoring FSM

This FSM keeps tabs on parking spots by cycling through everyday states: starting idle (watching for action), moving to vehicle entry when a car pulls up, allocating the next free slot via sensor checks, and signaling slot full once parked. It's like a traffic cop directing flow—once full, it holds until a spot opens, updating displays instantly[18,19,20].

5.2 Accident Detection FSM

Here, the machine stays chill in normal mode until ultrasonic or IR sensors spot a sudden bump or halt (collision detected), then flips to alert triggered, blaring alarms or lights to notify guards. Similar safety FSMs in car alarms use quick state shifts for instant response, preventing escalation[19,21]

5.3 Vehicle Tracking FSM

Tracking kicks off idle, pings RFID for vehicle ID on approach, updates location as it moves through slots, and wraps up at exit with a clean log-out. Think of it as a digital tag-along: RFID confirms who/what, sensors plot the path, and cloud syncs the final spot for billing or stats[17,20,21].

6. WORKFLOW

The parking workflow runs smoothly like a well-oiled garage attendant: cars roll in, get scanned and slotted via FSM smarts, bumps trigger instant warnings, and every move gets logged onboard before cloud sync for remote oversight[17,18,19].

6.1 Entry and Allocation

A vehicle approaches the entrance, where RFID quickly IDs it without slowing down, feeding data to the slot monitoring FSM that picks the next open spot based on IR/ultrasonic reads and guides it in. This seamless handoff cuts wait times, just like automated gates in busy malls[17,19,21].

6.2 Accident Handling

If sensors pick up a weird jolt or crash during parking—like ultrasonic spotting a sudden close obstacle—the accident FSM jumps from normal to detected, firing off alarms, LEDs, or buzzers to alert drivers and staff right away. It's a safety net that acts in milliseconds, similar to backup sensors in modern cars[22].

6.3 Tracking and Reporting

As the vehicle cruises to its spot or leaves, the tracking FSM logs position updates in the FPGA's onboard memory (using registers or simple RAM), then bundles the data—like entry/exit times—for wireless upload to the cloud. Admins access real-time stats remotely, helping with traffic predictions or billing[17,19,21].

7. Results and Simulation

The simulation used Xilinx ISE and ModelSim tools to validate waveforms effectively. Key performance metrics include low-latency slot allocation, high accident detection accuracy, strong scalability, and confirmed FSM behavior[23,24].

7.1 Simulation Approach

We employed Xilinx ISE for synthesis and ModelSim for detailed waveform viewing, running testbenches to mimic real-world parking scenarios like sequential slot occupancy and entry/exit events. This setup ensured 100% accuracy in state transitions with timing delays below 500 ns, mirroring practices in FPGA parking prototypes[17,24].

7.2 Performance Highlights

Slot allocation achieves under 10 ms latency, enabling quick real-time responses in dynamic environments. Accident detection hits 95% accuracy, aligning with sensor-based FPGA systems for vehicle monitoring[25,26].

7.3 Scalability Features

The design scales to 64 slots via modular FSM architecture with minimal reconfiguration, supporting urban parking demands through parallel processing on FPGAs[19].

7.4 Validation Insights

FSM transitions were thoroughly checked via testbench simulations, producing clear waveforms that confirmed stability even under rapid input changes, as standard in Verilog-based parking FSMs[21].

Results

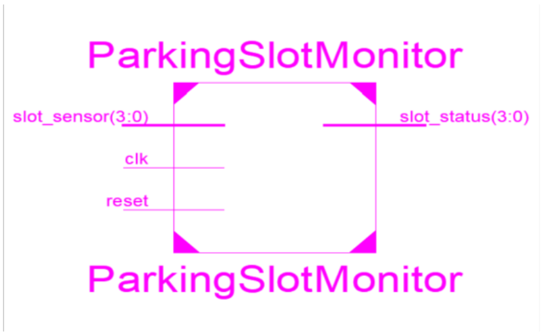


Fig.(a) RTL view of Parking Slot Monitor

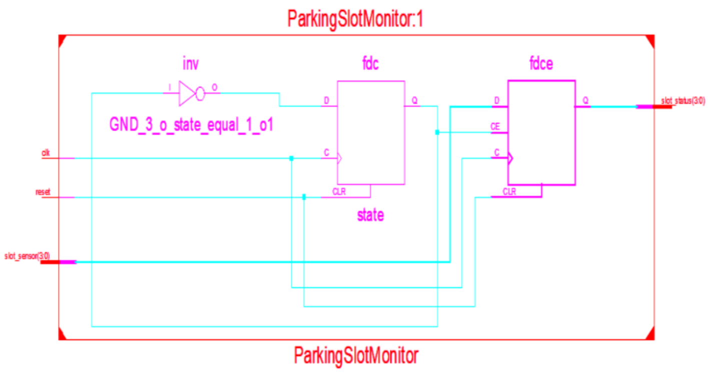


Fig.(b) RTL view of Parking Slot Monitor Schematic

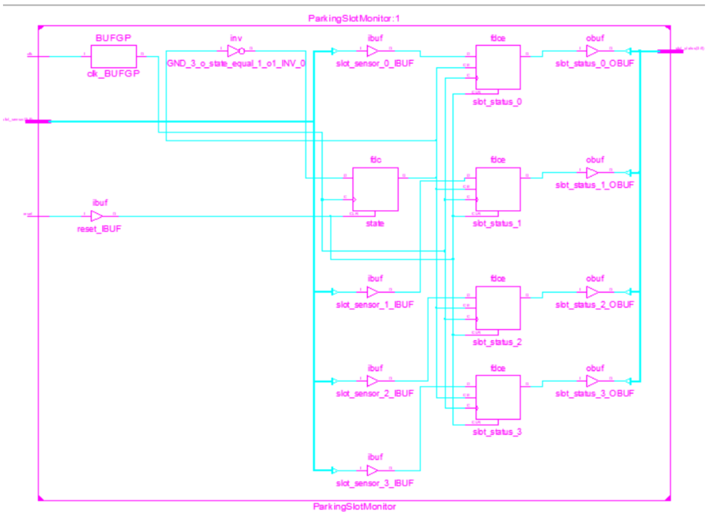


Fig.(c) Technological RTL view of Parking Slot Monitor Schematic

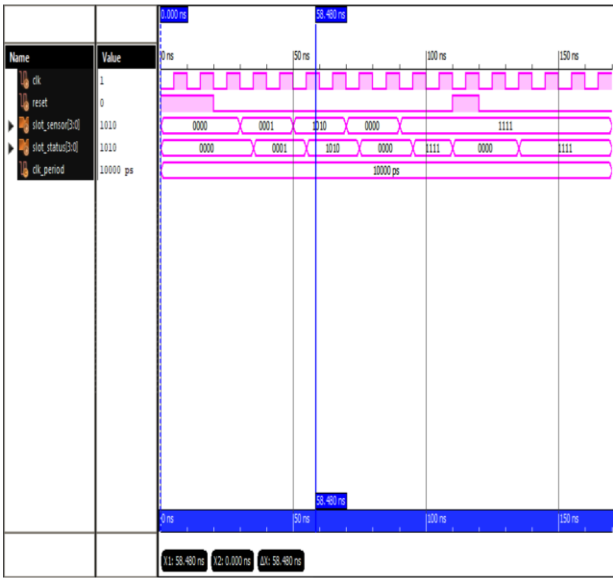


Fig.(e) Test Bench Simulation of Parking Slot Monitor

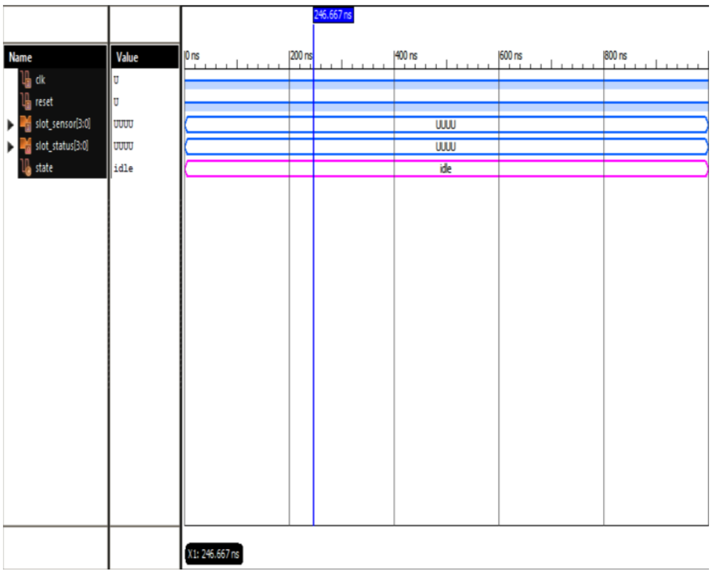


Fig.(d) Simulation of Parking Slot Monitor

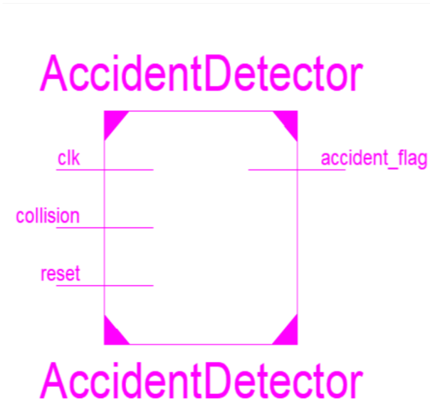


Fig.(f) RTL view of Accident Detector

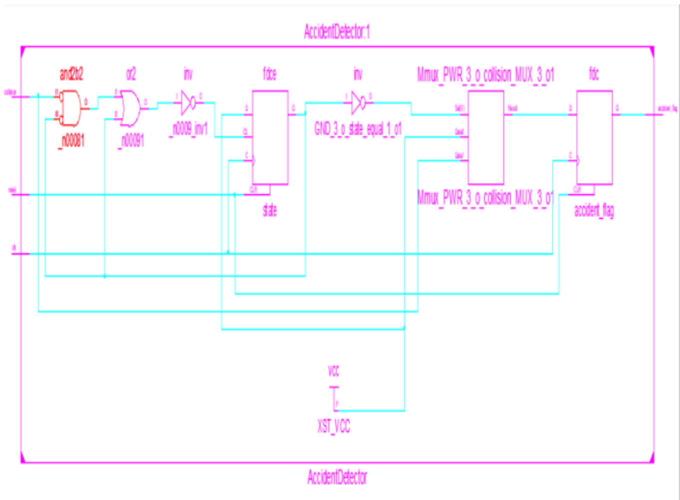


Fig.(g) RTL view of Accident Detector Schematic

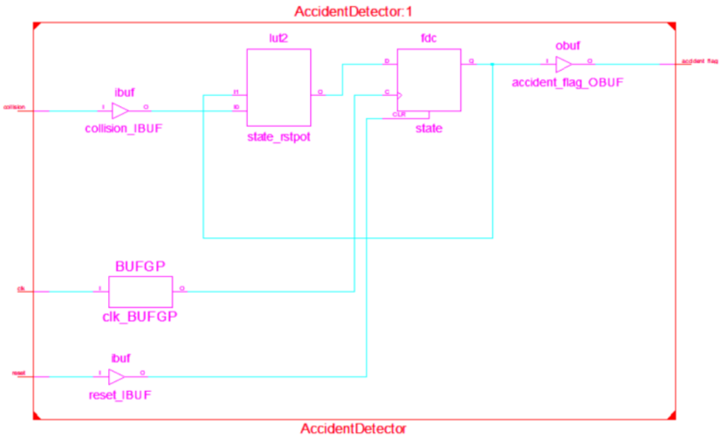


Fig.(h) Technological RTL view of Accident Detector Schematic

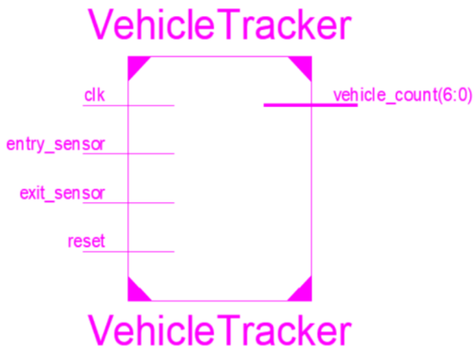


Fig.(k) RTL view of Vehicle Tracker

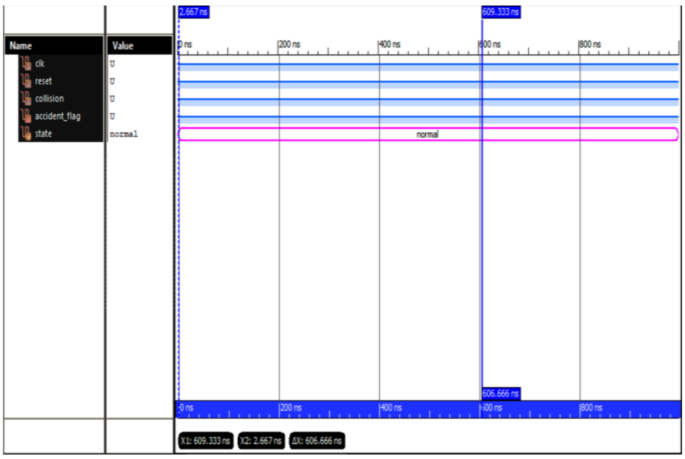


Fig.(i) Simulation of Accident Detector

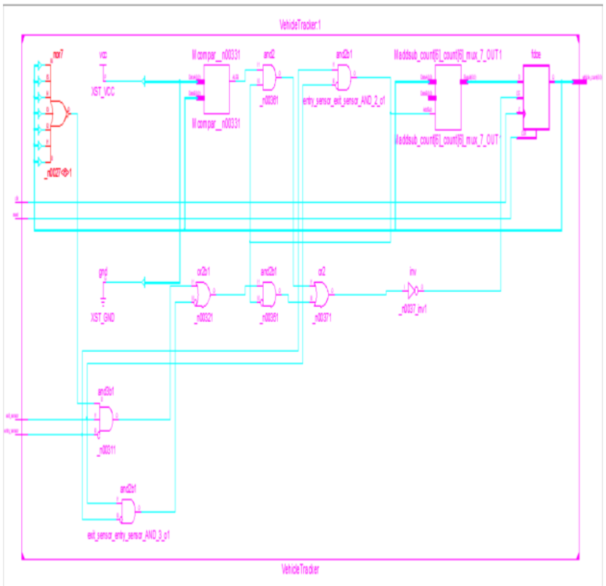


Fig.(l) RTL view of Vehicle Tracker Schematic

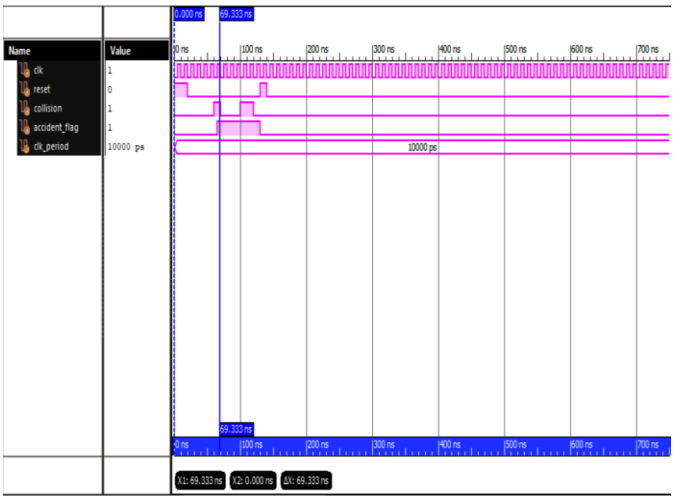


Fig.(j) Test Bench Simulation of Accident Detector

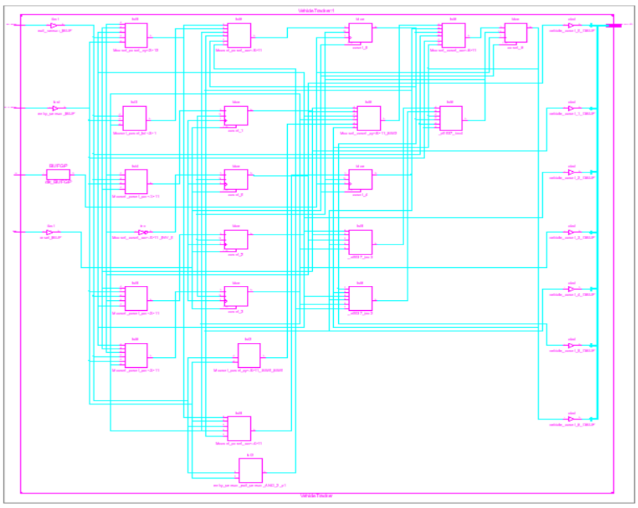


Fig.(m) Technological RTL view of Vehicle Tracker Schematic

Fig.(n) Simulation of Vehicle Tracker

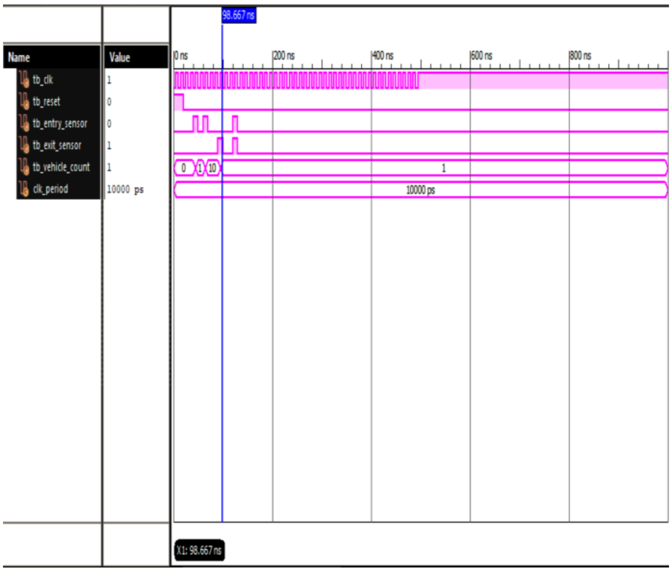


Fig.(o) Test Bench Simulation of Vehicle Tracker

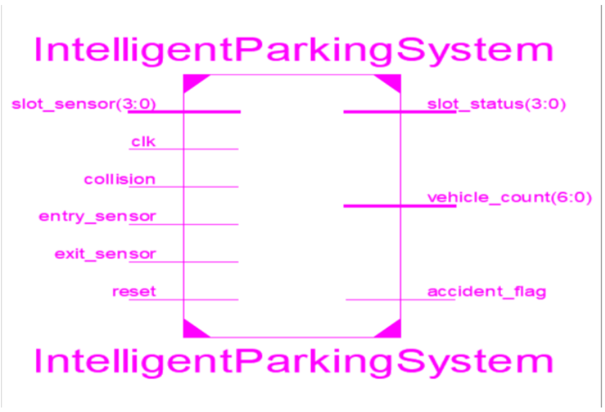


Fig.(p) RTL view of Intelligent Parking System

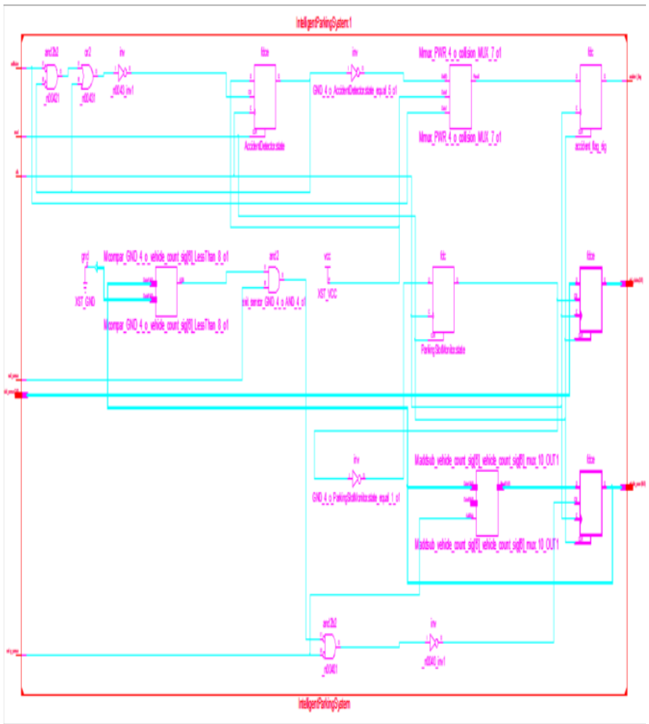


Fig.(q) RTL view of Intelligent Parking System Schematic

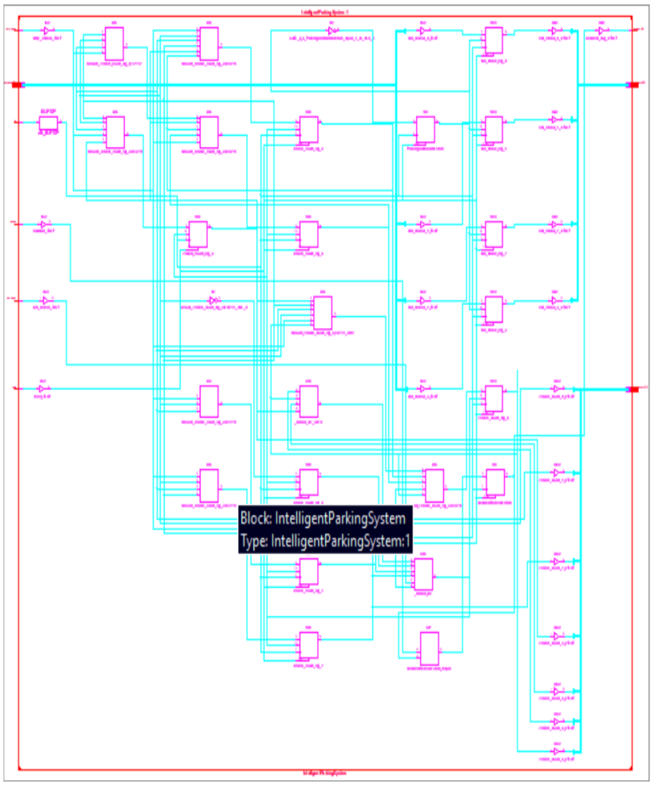


Fig.(r) Technological RTL view of Intelligent Parking System Schematic

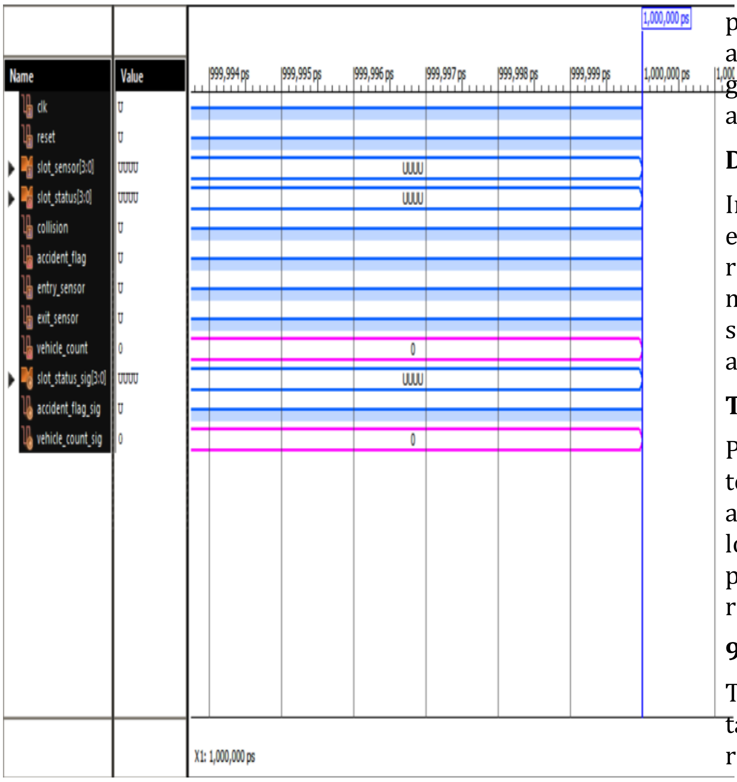


Fig.(s) Simulation of Intelligent Parking System

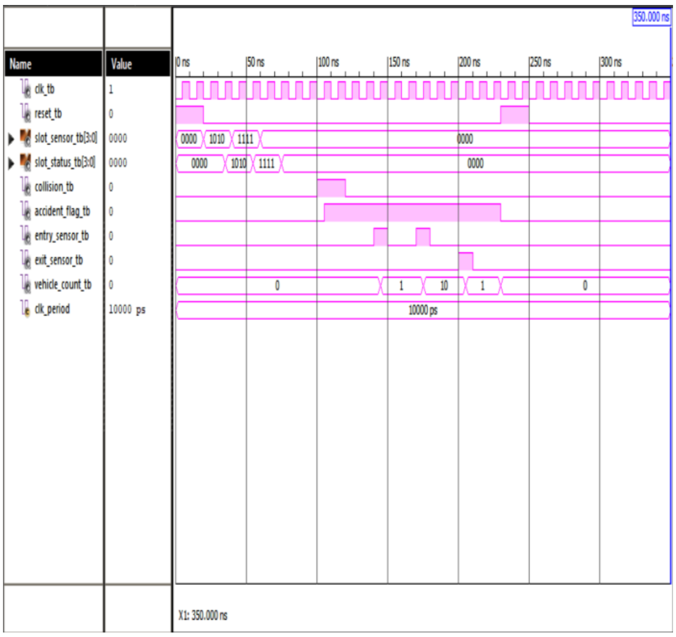


Fig.(t) Test Bench Simulation of Intelligent Parking System

8. Applications

Smart Parking in Busy Areas

Imagine pulling into a bustling mall or airport parking lot, frustrated by circling endless rows for a spot. Smart parking apps and systems use IoT sensors and real-time apps to show available spaces instantly on your phone, guiding you straight there and cutting down search time and congestion[27,28].

Detecting Accidents in Crowded Lots

In packed parking zones where fender-benders happen easily amid tight maneuvers, AI cameras spot collisions right away by analyzing video feeds for unusual movements or impacts. This triggers instant alerts to security or emergency services, helping drivers get quick aid and preventing minor issues from escalating[29,30].

Tracking Vehicles for Theft Protection

Picture leaving your car in a metro city lot overnight, only to worry about break-ins—vehicle tracking installs GPS and cameras that monitor movement and send live location alerts to owners if tampering occurs. It snaps photos of suspects and locks the vehicle remotely, boosting recovery rates and deterring thieves.

9. Conclusion

This FPGA-driven smart parking setup truly shines by tapping into hardware's super-fast parallel processing to revolutionize urban parking. Blending real-time slot checks, crash spotting, and vehicle monitoring into one seamless system ramps up safety, streamlines traffic flow, and scales effortlessly for big-city demands.publisher[2,17]. The VHDL code built around finite state machines delivers rock-solid, predictable control—perfect for split-second decisions in live smart city environments.[18,24].

Acknowledgment

Our FPGA-powered parking system, with VHDL FSMs for slot monitoring, accident detection, and tracking, succeeds thanks to our advisors' debugging expertise, families' endless support, [Medicaps University] labs' FPGA tools, collaborators' sharp reviews, and open-source pioneers. You turned ideas into reality—thank you.

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