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Geofenced Predictive Safety for Autonomous Logistics Vehicles: MATLAB Simulation and Arduino Hardware-in-the-Loop Validation in High-Risk Urban Zones

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Abstract: The dynamic advancement of intelligent transportation systems holds the promise of a better future with higher levels of road safety and efficiency. Nevertheless, the interaction between intelligent logistics vehicles and other vulnerable road users in high-risk areas remains a major challenge. This project brings the promise of a better future concerning road safety to life through the design of an intelligent system for "geofencing." Geofencing describes an intelligent system that uses intelligent boundaries to improve road safety. It involves establishing boundaries in areas of greater road-safety concern. Often, such boundaries intended to alert drivers of impending danger. However, in the project's design, the predictive intelligent system ensures that, once intelligent transportation systems detect an intelligent boundary layer, the vehicle slows down as it drives through it. The predictive intelligent system was developed using simulations in MATLAB, integrated with an Arduino hardware-in-the-loop. This research postulates that a layer of automated protection woven into the transportation network does not constrain mobility but provides additional reliability for autonomous logistics, especially in protecting the most vulnerable sectors of the population.

Keywords: Predictive safety, Geofencing, Autonomous vehicle, Boundaries, Fleets management

I. INTRODUCTION

The introduction of autonomous vehicles is predicted to revolutionize road transportation, especially by reducing error rates and optimizing flow. As the rate of urbanization increases, the introduction of autonomous vehicle fleets into road networks is increasingly becoming a tangible reality. However, the shift to fully autonomous vehicles is hindered by numerous hurdles, particularly in road safety. For instance, while autopilot on the highway has reached some levels of maturity, in urban areas, especially in "sensitive zones," there is a need for autonomous vehicles with some kind of "intelligence" in terms of awareness. Sensitive zones may include schools and residential areas. In both developing and developed nations, the observance of speed limits, particularly in these critical areas, is known to be abysmal. For example, it has been mandated by the respective governments in regions such as India, where in the speed limits should be restricted to 25-30 km/h, particularly in zones such as schools, which are grossly ignored due to the negligence and lack of understanding on the part of the drivers, as revealed from the statistics about this issue wherein it has been revealed that thousands of cases are filed near schools, thereby causing fatal accidents, thus revealing the critical deficiency of the prevalent passive signals and signs.

A. Problem Definition and Scope

The main problem addressed in this work is the inability of traditional traffic management systems to ensure speed compliance for logistics vehicles entering high-risk areas. Current driver-assistance systems often rely on reactive sensors—braking only when an obstacle has been detected. Itself is not sufficient for "preventative safety," in which speed needs to be reduced before there is even a chance that a potential hazard will come into view, given the environmental context.

The existing methods, which include conventional cruise control and vision-based recognition of speed signs, are inadequate for the following reasons:

1) Sensor Limitation: Vision-based systems have limitations, like bad weather, insufficient light, or obstacles, which prevent them from recognizing a speed zone in time [2].

2) Latency: The reactive systems using detection of pedestrians tend to react too late, as the vehicle may be traveling at an unsafe speed initially [3].
3) Human Factors: The driver may choose to override the warning due to fatigue and driving habits in different cultures, which may emphasize speed over safety factors [4].

B. Contributions

This paper proposes the Predictive Safety Geofencing System. This system will be achieved using Global Positioning System (GPS) technology, which will be used to set virtual boundaries that induce different vehicle behaviours as follows:

1) Development of a Proactive Control Framework: A logic-based algorithm is advanced that will override default throttle control to implement a hard speed limit, say, 20 km/h, immediately upon entry into a geofenced coordinate, irrespective of external visual cues.
2) Simulation and Hardware Validation: This paper outlines the process for simulating the vehicle dynamics with the help of MATLAB's Automated Driving Toolbox. Additionally, this paper outlines a hardware-in-the-loop prototype using an Arduino board.
3) Improved Situational Awareness: This system will feature visual mapping as well as the logging of statuses to give the operators real-time information on the state of the zones.

II. RELATED WORK

A. Autonomous Vehicle (AV) Control Strategies

The foundation of any AV safety system lies in its control algorithms. More classical approaches, such as Proportional-Integral-Derivative (PID) controllers and Pure Pursuit algorithms, are widely used for lateral and longitudinal control to ensure vehicles track their intended paths accurately [5]. While these algorithms are effective for path tracking, they typically treat speed as a reference setpoint derived from a planner, rather than a safety constraint imposed by infrastructure. More advanced techniques, such as flatness-based control, attempt to manage vehicle dynamics by exploiting the mathematical properties of the system model. However, these often require precise parameter identification, which can be difficult in real-world scenarios [6]. Our work differs in that it implements a supervisory control layer that dictates the maximum allowable reference speed based on geolocation to lower-level controllers, acting essentially as a higher-authority safety governor.

B. Simulation and Risk Assessment

Simulation plays a significant role in the development of AV technology, as testing physical vehicles is highly expensive and risky. Charlton et al. stress the need to simulate crowds and autonomous vehicles in shared spaces to conduct thorough research on the interaction processes and potential phenomena that emerge in these conditions [7]. Jasour et al. further discussed the demonstration, the need for efficient non-sampling techniques for risk assessment, particularly when assessing the unpredictable behaviour of other agents using deep neural networks [8]. While this research draws on the essential approaches of dynamic obstacle avoidance and crowd psychology, it focuses on static environmental constraints. This applies simulation techniques not only to obstacle detection and avoidance but also to determining conformance to regulatory boundary limitations (or geofences).

C. Socio-Technical Challenges and Connectivity

Not only is the implementation of AVs a technical problem, but also a socio-technical one. Questions related to the social trust and cultural acceptability of the technology are important factors in its social acceptance [4]. Moreover, the need for the internet for geofencing purposes, hence the "Internet of Autonomous Vehicles" (IoAV), is dependent on the infrastructure and structure of the network itself [9]. However, there is potential for security risks, as adversaries may manipulate geofence information or AVs, underscoring the need for cybersecurity strategies [10]. This research acknowledges the challenges by developing a system that is dependent on GPS and seeks to promote trust through the maintenance of a high level of safety while driving, hence addressing the "usability vs. safety" trade-off, which has been well-examined within game-theoretic analyses of social interactions related to the safety of the roadway [3].

III.METHODOLOGY

The proposed system has been devised as a framework composed of three subsystems. These subsystems are Perception Module (Simulated GPS), Decision Logic (Geofencing Core), and Control Actuation (Vehicle Interface). Moreover, this system functions on the principle of continuous spatial monitoring. The system architecture is shown in Fig 1.

A. Perception Module

We use MATLAB's Mapping and Automated Driving Toolboxes to simulate the vehicle as it is equipped with a Positioning System, and this module continuously provides the vehicle's current state vector.

B. Decision Logic

This is the main "Predictive Safety" engine. The system maintains a database of "sensitive zones" characterized by a centre point and a safety radius. The logic simply uses the Haversine distance between the vehicle and the zone's centre point.

1) Condition: If the vehicle is flagged as "Inside Zone."
2) Action: The target velocity is clamped to (e.g., 20 km/h).

C. Control Actuation

The decision applies to the actuation of the vehicle during manufacturing. In the hardware simulation, this is exemplified by an Arduino interface with Pulse Width Modulation (PWM) to actuate a DC motor.

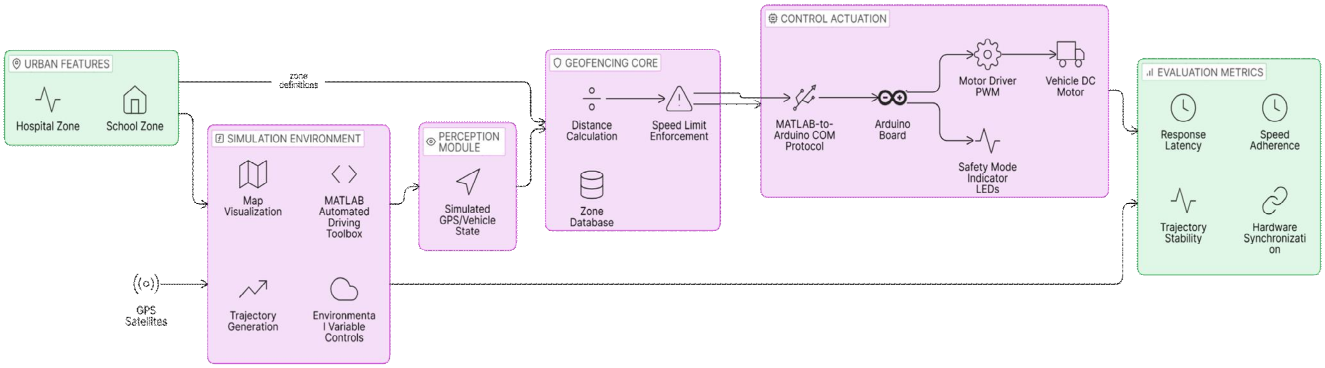


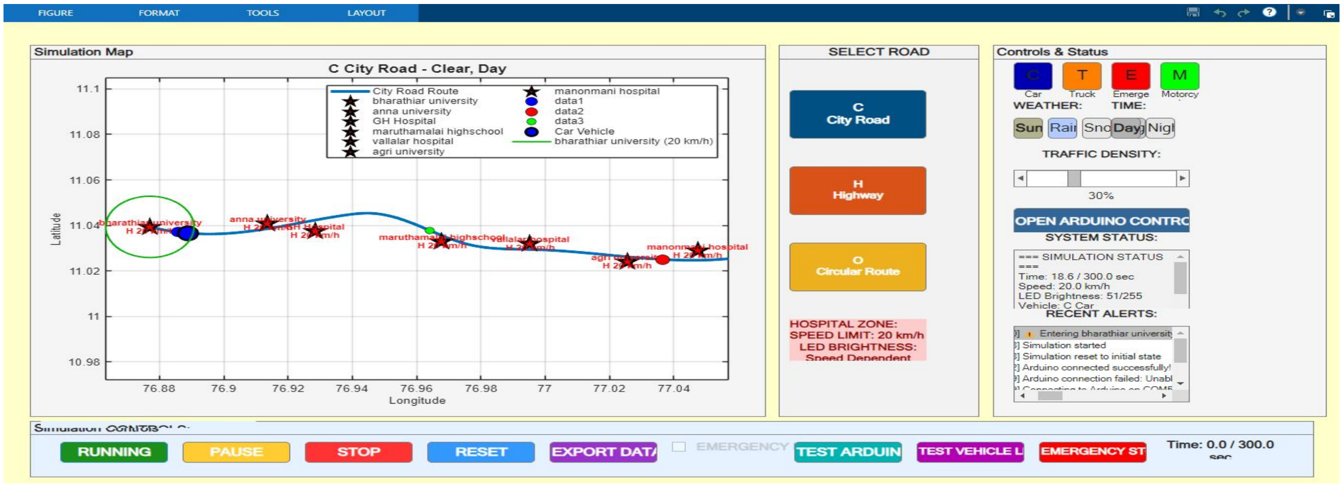
Fig. 1 Proposed System Architecture

IV. RESULTS AND DISCUSSION

A. Simulation Environment Design

A Graphics user interface (GUI) created in MATLAB as a flexible environment for modelling shown in Fig 2.

1) Map Visualization: The framework displays a virtual map with the geofenced areas (schools, hospitals) represented with circular shapes.
2) Trajectory Generation: Users can select predefined routes such as Highway, City Route, and Circular Path to test the vehicle's responses at different road types.
3) Environmental Variables: The simulation allows the modification of the weather and the traffic density, making it possible to test the geofencing logic with different theoretical constraints.



HOSPITAL ZONE:
SPEED LIMIT: 20 km/h
LED BRIGHTNESS:
Speed Dependent

```
=== SIMULATION STATUS
===
Time: 18.6 / 300.0 sec
Speed: 20.0 km/h
LED Brightness: 51/255
Vehicle: C Car
```

```
] ⚠ Entering bharathiar universit
] Simulation started
] Simulation reset to initial state
] Arduino connected successfully!
] Arduino connection failed: Unabl
```

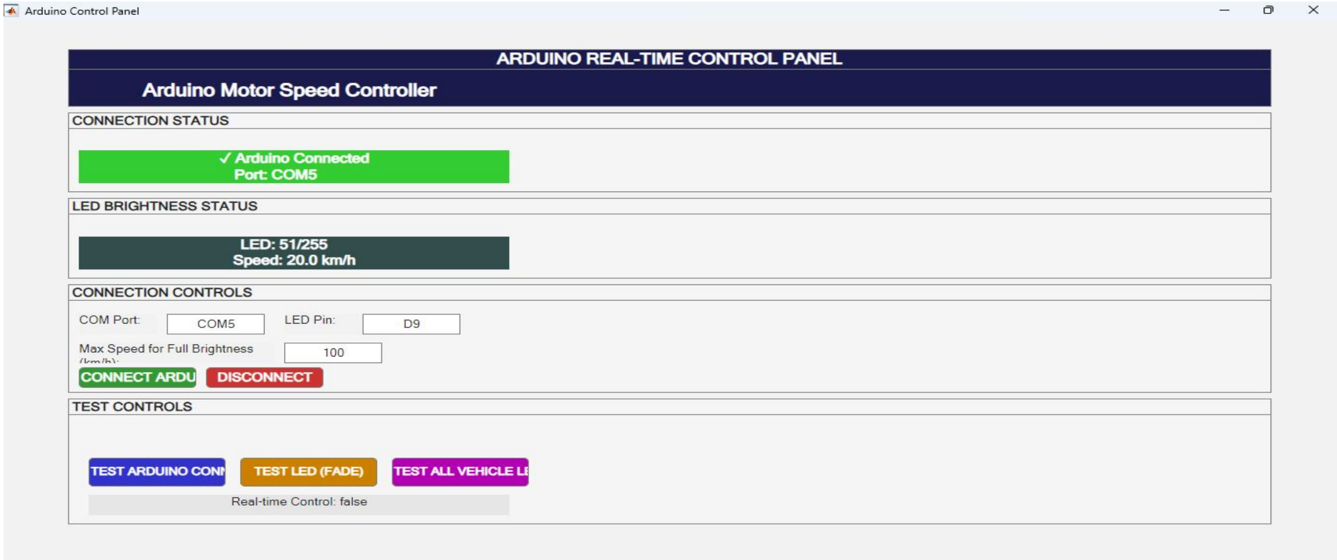
Time: 0.0 / 300.0 sec

Fig. 2 Designed GUI for simulation

B. *Hardware-in-the-Loop (HIL) Validation:*

To bridge the gap between the two concepts of simulation and implementation, the Arduino Mega 2560 used as the controller.

1) Communication: The Arduino receives motor speed data from MATLAB via a serial port using arduino control panel as shown in Fig 3.



Arduino Control Panel

ARDUINO REAL-TIME CONTROL PANEL

Arduino Motor Speed Controller

CONNECTION STATUS

✓ Arduino Connected
Port: COM5

LED BRIGHTNESS STATUS

LED: 51/255
Speed: 20.0 km/h

CONNECTION CONTROLS

COM Port: COM5
LED Pin: D9
Max Speed for Full Brightness: 100

TEST CONTROLS

Real-time Control: false

Fig. 3 Designed Control Panel

2) Motor Control: An L293D IC is used to control the motor by receiving the PWM signals from the Arduino (D9). The ratio of the duty cycle and the speed of the simulation is proportional to one another. Rough prototype for testing is shown on Fig 4.

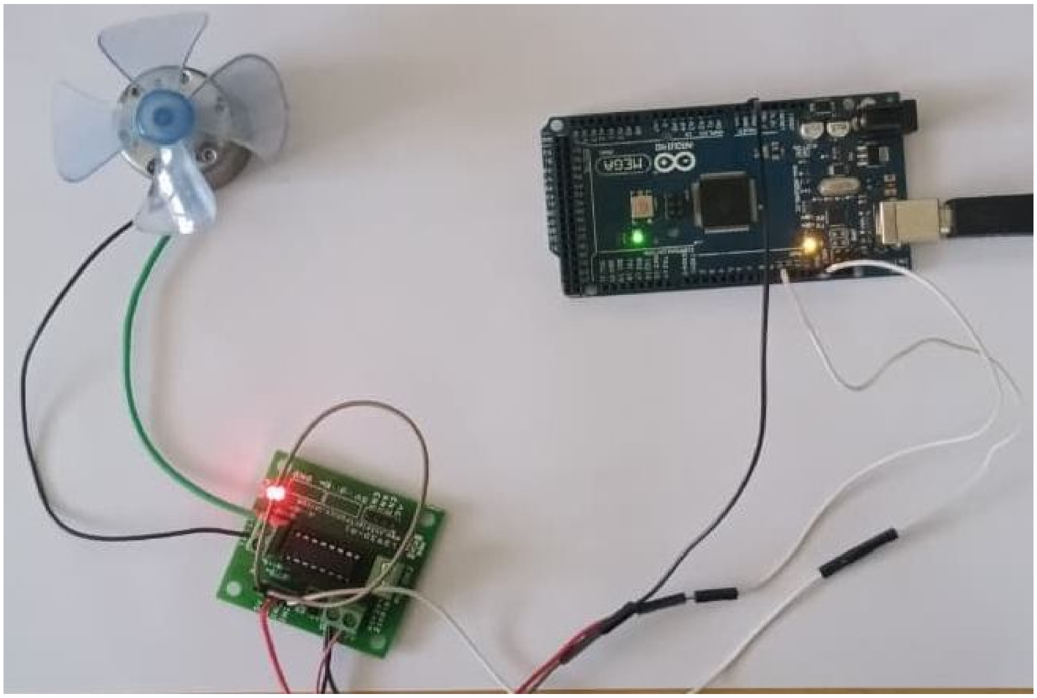


Fig. 4 Testing Model

3) Feedback Mechanism: Once the simulation detects the vehicle entry into the geofence, the command sent to the Arduino is automatically throttled. LED indicators provide the hardware rig to visually verify the “Safety Mode” function (dimmed LEDs indicating slower speed/intensity).

C. Evaluation Plan

The following metrics are defined to verify the efficacy of the system, which is implemented hypothetically in the simulation:

1) Response Latency: Time difference between the vehicle crossing the geofence boundary and the start of deceleration.
2) Speed Adherence: The % of time the vehicle stays below 25 km/h as it travels through the sensitive zone.
3) Trajectory Stability: Check if the sudden reduction in speed introduces instability in the vehicle's lateral control, using concepts of PID control stability [5].
4) Hardware Synchronization: Confirming that the actual motor response is well-matched with the required speed profile for the virtual vehicle.

D. Practical Implications and Deployment:

Integration of predictive geofencing into autonomous logistics fleets will have serious implications for urban planning: speed limits can now be digitized, and traffic rules dynamically adjusted without physical infrastructure changes. For example, a virtual low-speed zone could be defined around a construction site or during certain hours in the vicinity of specific schools. It aligns with the spirit of the Internet of Autonomous Vehicles, in which infrastructure-to-vehicle communication establishes a telematic safety net [9]. Moreover, such systems can feather traffic by preventing "stop-and-go" waves from propagating due to hard human braking at an obstruction; autonomous agents would smoothly begin to decelerate well in advance of the virtual boundary condition [1].

E. Limitations and Failure Modes:

Despite this advancement in technology, there exist the following limitations:

1) GPS Dependency and Accuracy: The system relies on accurate localization. In the presence of urban canyons, or tall buildings, GPS signals may be degraded enough to cause the vehicle to believe it is outside of a zone when it is inside. As mentioned in a literature review, one of the key barriers to full autonomy readiness today is the use of only one sensor modality.
2) Cybersecurity Risks: Since the system depends on digital maps and external coordinates, it is prone to spoofing attacks. A malicious attacker can, in principle, shift or remove a geofence. Bhemavarapu notes that cybersecurity breaches in AVs put passengers and pedestrians at risk [10].
3) Clash between drivers of algorithm-deployed vehicles vs manual vehicle: An autonomous truck that rigidly sticks to 20 km/h in a zone where human drivers normally drive 40 km/h may create tailgating risks or road rage incidents. Game-theoretic models suggest that human drivers may exploit AVs' cautious nature, dominate the road, and create new safety hazards [3].

F. Ethical Considerations

Guidance on ethical issues related to control can be sought from the literature.

1) Autonomy vs. Paternalism: To what extent might the system remove autonomy from the driver in semi-autonomous modes of driving? Although programmed to protect the driver, the system cannot automatically account for situations where speeding might be necessary, such as fleeing a landslide or a fire.
2) Liability: In an event where an accident occurs within a geofenced zone despite the speed limit having been enforced (e.g., due to a child running out instantaneously), the issue of liability becomes complicated. Is it attributed to the speed control, sensor sensitivity, or actions of the pedestrian.

V. CONCLUSION AND FUTURE WORK

The idea has been successfully implemented as a project, proving not only its feasibility but also its necessity for ensuring predictive safety in autonomous logistics, especially given its implementation as a combination of MATLAB programming and Arduino. Essentially, it was able to show, as a proof of concept, how a vehicle could be made to slow down to a speed of only 20 km/h once it is inside a high-risk zone, thus proving how it could be interpreted as a fundamental step towards a transport system that prioritizes, first and foremost, safety, especially for those that it is most needed – at a time when there is a clearly defined gap in how to most effectively address safety concerns, especially in areas where there is a high rate of accidents, especially around schools and hospitals.

Future iterations of this research should focus on:

1) V2X Integration: Going beyond simple GPS geofences and leveraging the concept of Vehicle-to-Everything (V2X) communication to enable the zone to "communicate" with the vehicle about itself.
2) Advanced Prediction Models: The concept involves improving pedestrian prediction models in zones by integrating "probabilistic models which predict pedestrian behaviour at the zone edges, rather than reacting to the line."

3) Robust Control Algorithms: Using model-free control algorithms to cope with changing loads, such as an empty or a loaded truck, without the need to fine-tune parameters in the control system.

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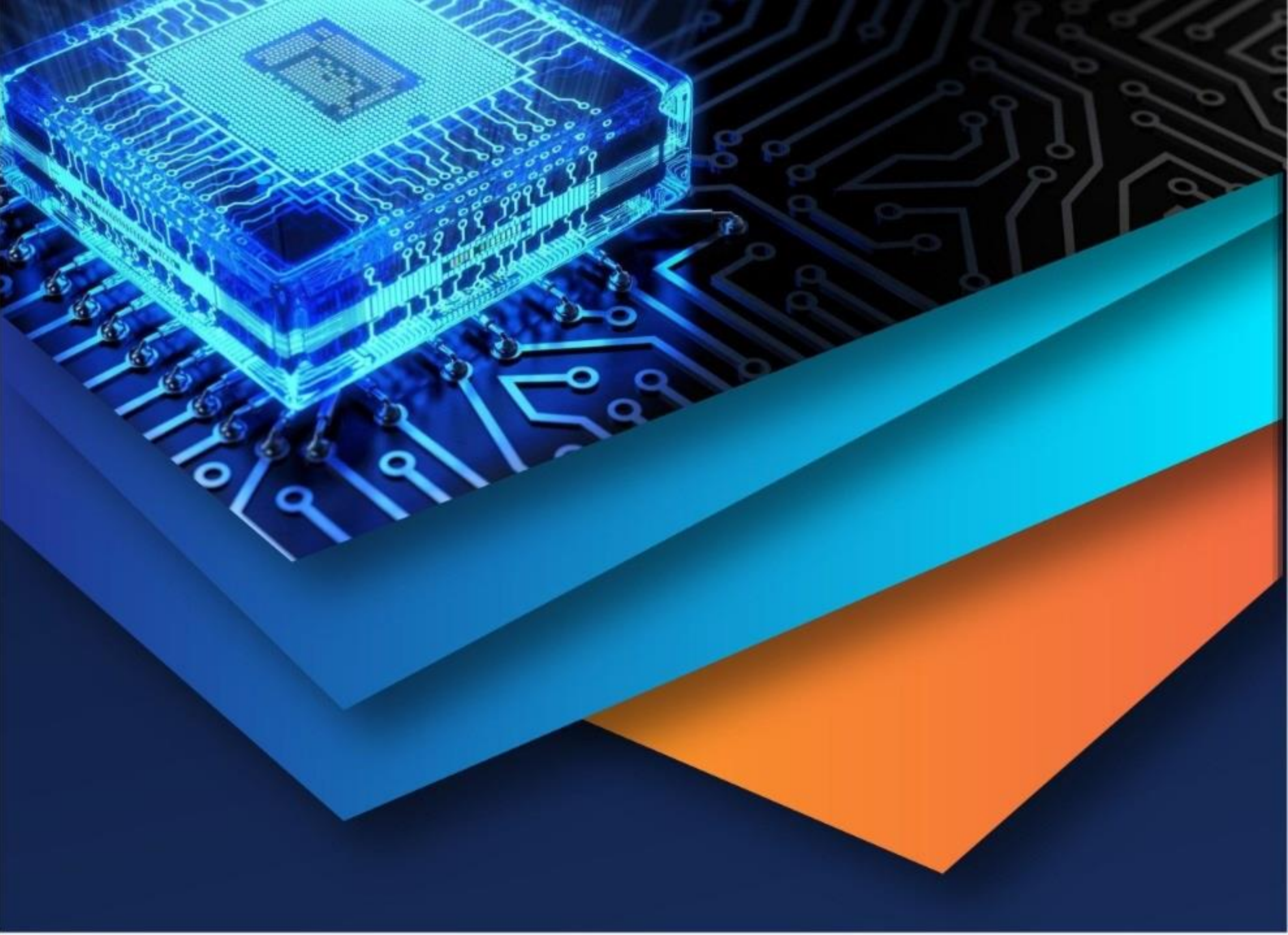

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