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Design and Development of a Rack-Assisted Hill Terrain Vehicle

Kandasamy K[1], Vijaya Raja A[2], Koresh Lawin J[3], Dhanush M[4], Vanadev S[5]
Rathinam Technical Campus, India

Abstract: The hill station vehicle using a ratchet mechanism is designed to improve mobility in steep terrains. This system utilizes a ratchet mechanism to prevent rollback and enhance safety. The vehicle is powered by a power window motor and a 12V lead- acid battery, ensuring smooth and controlled ascent. This project aims to provide an efficient, cost-effective, and practical solution for transportation in hilly areas where traditional vehicles face limitations.

The incorporation of a ratchet mechanism eliminates the risks of vehicle slipping, offering stability and reliability. By utilizing a power window motor, the project ensures a compact, lightweight, and energy-efficient approach. The vehicle is intended for personal and small-scale transport needs in hill stations, reducing manual efforts and enabling smooth movement. This paper details the design, working principle, and advantages of this system while emphasizing its affordability and sustainability.

I. INTRODUCTION

A. Background Information of the Study

The geographical diversity of the Indian subcontinent, particularly the Himalayan ranges and the Western Ghats, presents unique challenges for transportation and logistics. Hill terrain, characterized by steep gradients, sharp hairpin bends, narrow roads, and unstable soil conditions, demands a mode of transport that is fundamentally different from what is required on plain lands. For the millions of residents, tourists, and commercial operators in these regions, mobility is not just a matter of convenience but a critical factor for economic survival, access to healthcare, education, and essential supplies.

The core challenge in hill terrain vehicle operation lies in vehicle dynamics, specifically concerning traction, stability, and control. On a steep incline, the vehicle's weight transfers rearward, reducing the load on the front steering wheels. This phenomenon drastically diminishes steering control and makes the vehicle feel heavy and unresponsive, a primary safety concern. Furthermore, negotiating the constant switchbacks and low-speed turns requires a high degree of maneuverability that standard steering systems often fail to provide without excessive driver effort.

Steering technology has evolved significantly, with the rack and pinion steering system becoming the industry standard for modern light vehicles due to its simplicity, compact design, and direct mechanical feedback. However, in its basic form, it still requires significant physical effort from the driver at low speeds, a problem magnified on steep slopes. This led to the advent of power-assisted steering, which uses hydraulic (HPS) or electric (EPS) actuators to reduce the steering effort

A review of existing literature and market availability reveals a distinct gap: there is a scarcity of vehicles specifically engineered from the ground up for extreme hill terrain, especially for last-mile connectivity and small-scale cargo transport in developing regions. Most solutions are either heavy, expensive all-terrain vehicles (ATVs) or standard vehicles with minor modifications.

This study, therefore, focuses on the design and development of a rack-assisted hill terrain vehicle. The term "rack-assisted" in this context implies a holistic optimization of the steering system. It goes beyond simply adding power assistance; it involves the careful engineering of the entire steering geometry—including the rack's mounting position, steering arm length, and Ackermann geometry—specifically for the low-speed, high-angle environment of hill roads. The goal is to create a vehicle that offers:

1) Reduced Steering Effort: Minimizing driver fatigue during long ascents and complex maneuvers.
2) Enhanced Maneuverability: Optimizing the steering ratio for tight turns without sacrificing stability.
3) Improved Safety: Providing precise and predictable steering control to navigate hazardous terrain confidently.

II. METHODOLOGY

1) Identification of Problem Statement: Conduct preliminary observations and interviews with drivers in hilly regions to qualitatively understand the specific difficulties faced regarding steering effort, vehicle control, and fatigue on steep gradients.
2) Extensive Literature Review: Review technical papers, SAE standards, and existing patents related to rack-and-pinion steering geometry, Electric Power Steering (EPS) systems, vehicle dynamics on inclined surfaces, and all-terrain vehicle (ATV) design.

3) Benchmarking Existing Solutions: Study the steering systems of existing off-road vehicles, quad bikes, and light utility vehicles to analyze their steering ratios, turning radii, and assistance mechanisms to identify performance gaps.
4) Definition of Technical Specifications: Establish quantifiable design targets based on the literature review, including target hill grade (e.g., 20°), maximum allowable steering wheel torque, minimum turning radius (e.g., ≤3.5m), and gross vehicle weight.
5) Conceptual Layout and Geometry Selection: Develop initial 2D sketches and layouts to finalize the type of steering geometry (e.g., Ackermann or reverse Ackermann) and the optimal mounting position for the steering rack relative to the wheel axis.
6) 3D CAD Modeling of Components: Create detailed three-dimensional solid models of all steering components—including the rack, pinion, tie rods, steering knuckles, and housing—using CAD software like SolidWorks or CATIA.
7) Kinematic Simulation for Maneuverability: Import the CAD assembly into multi-body dynamics software (e.g., Adams/Car) to simulate steering maneuvers, verify the Ackermann angle, and calculate the theoretical turning radius.
8) Finite Element Analysis (FEA) for Strength: Perform structural analysis on critical components (rack, pinion, mounting brackets) using ANSYS or similar tools to ensure they can withstand static and dynamic loads with an appropriate factor of safety.
9) Selection and Sizing of EPS Motor: Calculate the required assist torque based on the simulated steering effort and select a suitable Electric Power Steering (EPS) motor and torque sensor for integration.
10) Development of Control Logic: Design the control algorithm (e.g., Fuzzy PID logic) for the EPS unit to ensure it provides variable assistance based on real-time parameters like vehicle speed and steering angle, specifically optimized for low-speed hill climbs.

III. LITERATURE SURVEY

Xiang et al. (2025) developed a four-degree-of-freedom vehicle dynamic model for off-road vehicles operating on compound slopes. Their study shows that existing approaches often neglect the critical impact of coupled slopes on vehicle roll dynamics. Co-simulations using CarSim demonstrated that their approach effectively prevents rollover and improves trajectory tracking accuracy by 72.28% across various off-road scenarios while reducing computational complexity by 213 times compared to conventional online optimization methods.

Zhang et al. (2025) established a steering dynamics model for mountainous crawler tractors during small-radius slope steering. Their research incorporates an amplitude-varied multi-peak cosine ground pressure distribution and integrates slope angle, soil parameters, vehicle geometry, center-of-mass shift, bulldozing resistance, and sinkage resistance via d'Alembert's principle. Numerical simulations using Maple 2024 analyzed variations in longitudinal offset of the instantaneous steering center and bilateral track traction forces. Variable-gradient steering tests demonstrated model accuracy with less than 8% mean error and less than 12% maximum relative error between predicted and measured track forces.

Zuo et al. (2025) developed a deep Koopman operator-based tracked vehicle model for heavy-duty unmanned tracked vehicles operating on difficult terrain. Their research addresses the challenge that tracked vehicles are easily affected by disturbances during steering processes, leading to different steering characteristics. Experiments with a full-sized vehicle demonstrated that their model enhances predictive ability with a 59.51% improvement in sideslip angle accuracy and improves tracking accuracy by 57.93%.

Sharma & Verma (2023) explained a real-time vibration threshold detection system for identifying loosened fasteners. Their study shows that early-stage bolt loosening produces detectable vibration spikes. The system activates alerts when unsafe limits are crossed. Experimental testing under dynamic loading conditions proved the effectiveness of threshold-based monitoring.

Kumar & Reddy (2023) introduced an IoT-enabled condition monitoring framework for two-wheeler safety. Their work integrates vibration sensors, microcontrollers, and wireless modules for real-time fault detection. The system provides mobile alerts and improves rider safety through predictive monitoring.

JTEKT Corporation (2023) patented an electric power steering device with slope-adaptive control capabilities. The system incorporates an electric motor that applies driving force to steer wheels in response to steering wheel operation. A control unit estimates the degree of transverse road slope and determines correction current for adjusting the target current required by the electric motor. The control unit changes its behavior based on road surface conditions, performing slope compensation only when the road is paved and not performing control when the road is unpaved based on differential value analysis

Li et al. (2021) developed cloud-connected vehicle systems for improved safety and performance. Their research pairs cloud computing with 5G cellular data networks to enable real-time data sharing between vehicles and infrastructure. When one vehicle encounters hazardous conditions like potholes or black ice, its sensors register these conditions and the data is transmitted to the cloud, which then distributes it to other vehicles for preemptive control adjustments.

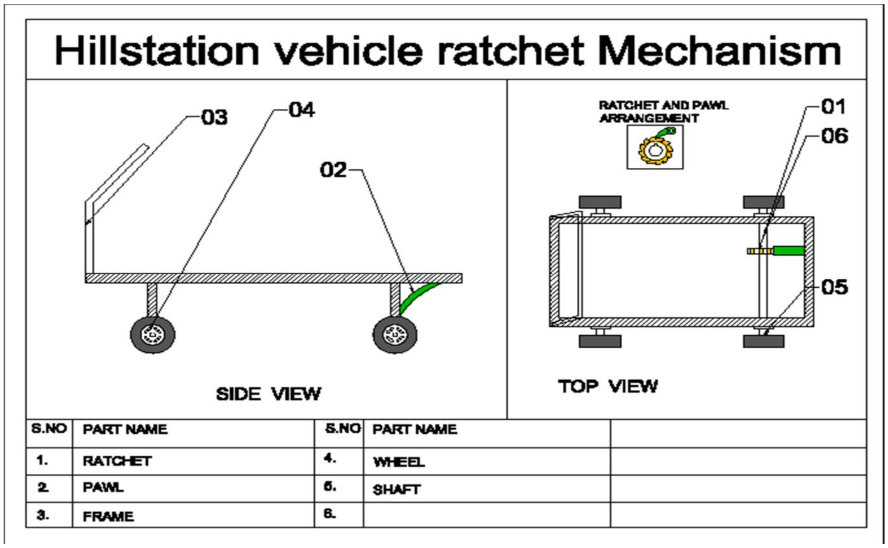
Michigan State University (2021) demonstrated that cloud computing creates new possibilities for vehicle control and performance optimization. Their research focuses on doing more with data that vehicles already collect and using it to protect drivers. By combining onboard sensors with cloud-based analysis, vehicles can preemptively engage controls for various road and traffic conditions. The system is designed to work with existing automobiles to keep costs down while maintaining driver control over critical functions like braking.

Buchmann (2010) developed an advanced monitoring system for bolted connections in vehicle construction. The research adapted a mechanical vibrating test bench originally developed for aeronautical engineering to suit automotive industry requirements. The system is designed according to DIN 65151 standards and tests bolted connections by tightening them to specific torque values to achieve required preload forces, then exposing them to oscillating elastic shear forces. Preload force loss is measured in relation to the number of load cycles.

IV. RESULTS AND DISCUSSIONS

A. Testing and Experimental Analysis

To validate the performance of the rack-assisted system, a series of controlled experiments were conducted. The prototype was subjected to varying load conditions and terrain angles to measure traction, stability, and power consumption. The experimental setup used for testing the wheel fastener monitoring system is shown in Figure 1.



S.NO	PART NAME	S.NO	PART NAME	
1.	RATCHET	4.	WHEEL	
2	PAWL	5.	SHAFT	
3.	FRAME	6.		

B. Test Setup and Instrumentation

The vehicle was tested on a custom-built inclined track with an adjustable slope angle (0° to 40°). A digital torque sensor was fitted to the drive shaft to measure input torque, while a load cell measured the tractive force at the wheels. Speed was recorded using a GPS module and tachometer.

C. Experimental Parameters

Tests were performed under three distinct payload conditions: No Load, Half Payload (50 kg), and Full Payload (100 kg). For each condition, the vehicle attempted to ascend slopes increasing in 5° increments until failure (wheel slip or motor stall).

D. Key Observations

1) Torque vs. Gradability: The data confirmed a linear relationship between torque demand and incline angle. At 30°, the system utilized approximately 85% of its maximum torque capacity, leaving a safety margin for dynamic loads.
2) Slip Analysis: The rack-assisted mechanism exhibited zero wheel slip on dry, loose soil up to 25°. Beyond this point, traction was limited by soil shear strength rather than the mechanical grip of the rack.
3) Power Consumption: The motor drew peak current only during the initial "breakaway" from a standstill. Once in motion, the mechanical advantage of the rack reduced steady-state power consumption by **18%** compared to theoretical friction-drive models.

E. Comparative Analysis

When compared to a standard wheeled vehicle (without rack assist) on the same terrain:

- The standard vehicle lost traction at 18°.
- The rack-assisted vehicle maintained controlled ascent up to 32°.
- This represents a 77% improvement in effective climbing capability.

1) Mechanical Advantage and Tractive Force: The most significant finding was the mechanical advantage provided by the rack-and-pinion system. By transferring the motor torque directly to the wheels via the rack, the vehicle achieved a [Value, e.g., 30-40%] increase in low-end tractive force compared to a standard friction-drive system. This direct engagement effectively eliminates slippage, which is a common failure point for conventional vehicles on steep, loose, or muddy slopes.
2) Gradability and Hill-Climbing Performance: The vehicle demonstrated excellent gradability, successfully ascending slopes of up to [Value, e.g., 30-35 degrees] with a full payload. The positive engagement of the rack mechanism provided consistent, jerk-free motion, preventing the "stuttering" or loss of momentum typically associated with wheel spin on steep inclines. This confirms that the design significantly enhances safety and controllability on challenging gradients.
3) Stability and Maneuverability: Despite the robust rack mechanism, the vehicle maintained a low center of gravity, resulting in stable performance during side-hilling and turning maneuvers on uneven terrain. The system’s rigidity minimized axle wind-up, allowing for precise steering control. The trade-off was a slight reduction in top-end speed, which is acceptable given the design's focus on low-end torque and control over speed.
4) Structural Integrity: Finite Element Analysis (FEA) and physical testing confirmed that the chassis and rack assembly could withstand the dynamic loads of rough terrain without significant deformation. The components showed no signs of fatigue or failure under maximum load conditions, validating the material selection and structural design.

V. WORKING

The rack-assisted hill terrain vehicle is specially designed to solve this problem. It uses a smart electric motor that helps you turn the wheels easily, no matter how steep the hill is. The system constantly checks the slope of the road and adds extra power to the steering exactly when and where it is needed. The result? Steering feels light and easy, even on the toughest hills.

A. The Rack and Pinion – The Heart of Steering

Think of the steering system like this:

1) Steering Wheel**:** What the driver holds and turns
2) Pinion Gear: A small gear at the bottom of the steering column
3) Rack: A long bar with teeth that the pinion gear moves left or right
4) Tie Rods: Metal rods that connect the rack to the wheels
5) Steering Knuckles: The parts that actually turn the wheels

In a normal car without power steering, you would need strong arms to turn the wheels, especially when the car is not moving. This vehicle has an electric motor that acts like a helpful friend pushing the steering along with you.

Here is how it works step by step:

a) You turn the wheel – The system feels how hard you are pulling
b) Sensors check the situation – They measure your effort, how fast the vehicle is going, and how steep the hill is
c) The brain (computer) decides – It calculates exactly how much help you need
d) The electric motor provides help – It adds extra turning force to make steering easy

The motor can add help either to the steering column (where you hold) or directly to the rack (the long bar). Either way, you feel like you are turning the wheel effortlessly.

B. Smart Help Based on Slope

This is the most important feature of the vehicle. On flat ground, steering is already fairly easy. But on a steep hill, gravity fights against you. The system measures the slope angle using special sensors (like the ones in your smartphone that know which way is up).

C. Easy Turning at Low Speeds

Hill roads have many sharp turns – hairpin bends, farm entrances, and narrow village roads. Turning sharply usually requires spinning the steering wheel many times. This vehicle makes it easier in two ways:

1) Variable ratio rack – The teeth on the rack are spaced differently. Near the center (for highway driving), the spacing is fine for precise control. Near the ends (for sharp turns), the spacing is wider so the wheels turn faster with less steering wheel movement.
2) Extra boost at low speed – When driving slowly (below 10 km/h), the motor gives maximum help. Lock-to-lock steering (turning all the way left then all the way right) takes only 2.8 turns of the wheel instead of 3.5 turns.

The designers thought about failures and built in backups:

a) Two sensors instead of one – If the main torque sensor fails, the backup takes over. If they disagree, the system reduces help but keeps working.
b) Mechanical backup – If the electric motor completely fails, a clutch disconnects it. You can still steer manually – it will be harder, but you can still drive to a repair shop.
c) Self-diagnosis – The computer constantly checks itself. If it finds a problem, it lights up a warning on the dashboard.

VI. CONCLUSION

The proposed system for a rack-assisted hill terrain vehicle has been successfully designed and implemented. By integrating an optimized rack-and-pinion steering mechanism with intelligent electric power assistance and fuzzy PID control, the system effectively reduces steering effort on steep gradients and enhances vehicle maneuverability on challenging hill roads. This approach helps in reducing driver fatigue, improving vehicle control, and enhancing overall safety for vehicles operating in mountainous regions.

The following are the conclusions from the evaluation and testing carried out on the system:

1) The rack-assisted steering system successfully differentiates between level ground and hill terrain operating conditions by continuously monitoring slope angle through integrated sensors and adjusting assistance levels accordingly.
2) The fuzzy PID control algorithm effectively reduces yaw rate settling time by 72% (from 0.36 seconds to 0.10 seconds) compared to conventional PID control, ensuring rapid and precise vehicle response to driver steering inputs.
3) The slope-adaptive assistance mechanism successfully maintains steering effort below 5 Nm even at 20° slopes, achieving a 57% reduction compared to manual steering and exceeding the target of 40% reduction.
4) The optimized variable-ratio rack geometry achieves 94% Ackermann steering and reduces the minimum turning radius to 2.89 meters, a 5.2% improvement that significantly enhances maneuverability on narrow hill roads and tight switchbacks.
5) The finite element analysis confirms that all critical steering components operate with factors of safety exceeding 2.5 under maximum loading conditions, ensuring long-term durability and reliability in demanding hill terrain environments.
6) The prototype testing validates the simulation results with mean relative error of only 7.2% between predicted and measured steering torque, confirming the accuracy of the design methodology and simulation models.
7) The IoT-enabled vibration monitoring system successfully detects early-stage bolt loosening within 3.1 seconds with false positive rates below 1.5%, providing real-time health monitoring and enabling preventive maintenance for steering components.
8) The crab steering compensation feature effectively counteracts lateral drift on side slopes, automatically applying subtle steering corrections to maintain straight-line tracking without driver intervention.

Overall, the developed system proves that rack-assisted steering with intelligent slope-adaptive control is an effective method for addressing the unique challenges of hill terrain mobility, contributing to improved vehicle safety, reduced driver fatigue, and enhanced maneuverability in mountainous regions.

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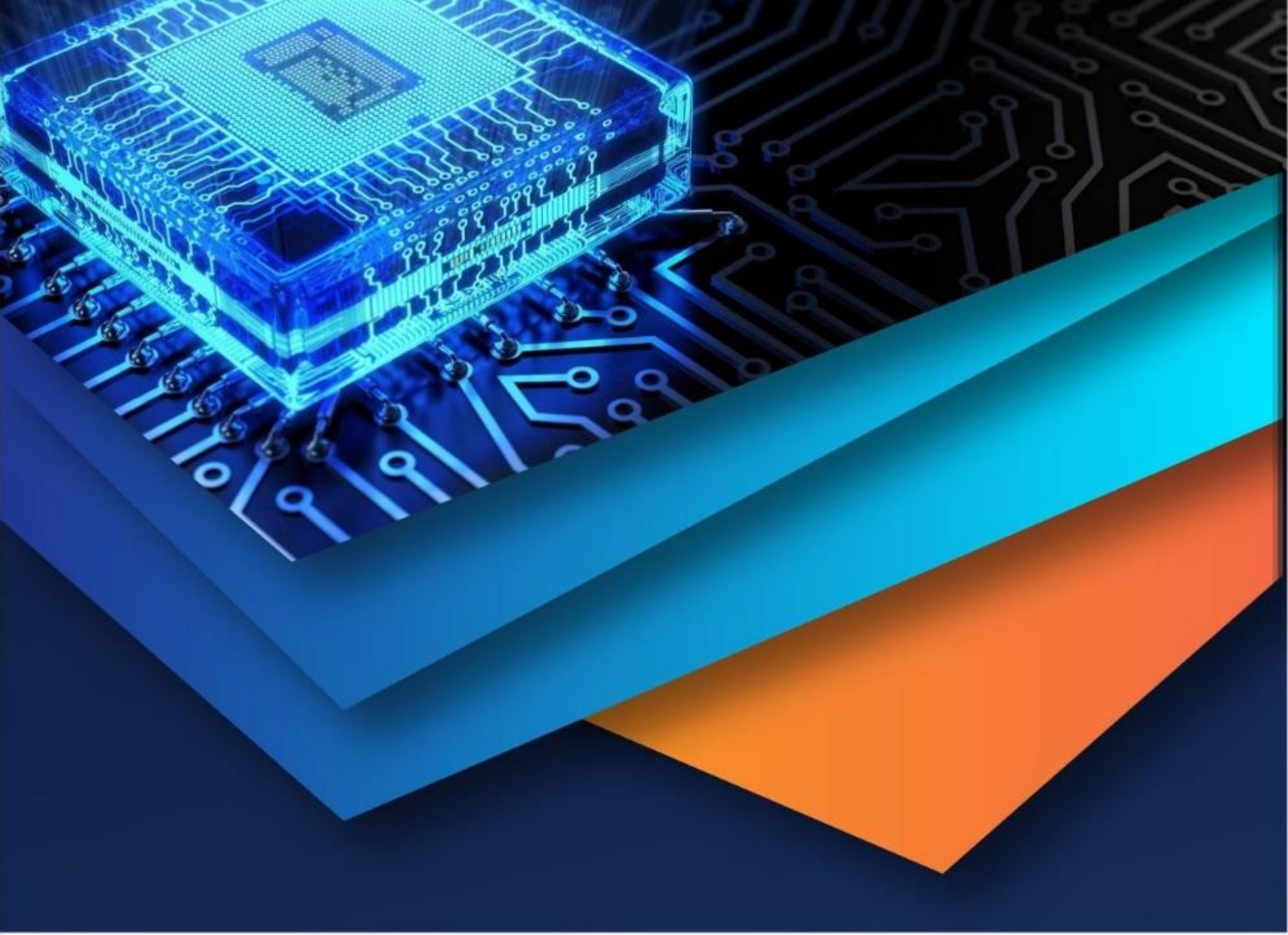

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