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Design and fabrication of an Autonomous Anti-Rollback System

Brihadish JB[1], Sajith N[1], Lokesh P.N[1], S. Thulasi[2], and V.R. Sarma Dulipala[3]

[1]Final Year Student, Dept. of Automobile Engineering, University College of Engineering BIT Campus, Anna University, Tiruchirappalli, India
[2]Assistant Professor, Dept. of Automobile Engineering, University College of Engineering BIT Campus, Anna University, Tiruchirappalli, India
[3]Assistant Professor (Sr. Gr), Dept. of Physics, University College of Engineering BIT Campus, Anna University, Tiruchirappalli, India

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Abstract - *Unintended vehicle rollback on inclines remains a significant safety risk. Contemporary solutions, notably Hill Hold Assist, rely on co-opting the vehicle service brakes via the ABS controller, introducing hydraulic complexity and potential brake wear. Manual systems require driver intervention and are prone to error. This paper details the design, fabrication, and validation of a novel autonomous anti-rollback system that overcomes these limitations by introducing an independent, electro-pneumatically actuated mechanical lock. The proposed system integrates a robust ratchet and pawl mechanism with an Arduino-based control unit. An MPU6050 accelerometer provides real-time inclination data, which the microcontroller processes to autonomously trigger a 5 by 2 solenoid valve. This valve governs a pneumatic actuator to engage the pawl, mechanically preventing rollback. Finite Element Analysis was employed to validate the system mechanical integrity and guide material selection. This analysis confirmed structural steel as insufficient, leading to the selection of AISI 4140 low-alloy steel. The final design was validated to withstand forces exceeding 20,000 Newtons, far exceeding the 7500 Newton operational load, with a maximum equivalent stress of 360.15 MPa and strain of 0.0017 remaining well within the allowable limits of 393 MPa and 0.002. Experimental validation of the fabricated prototype confirmed its efficacy, demonstrating a rapid response time of 1.00 to 1.25 seconds and a greater than 99 percent engagement success rate. This research validates a low-cost, reliable, and fully autonomous mechatronic solution that serves as a viable alternative to brake-dependent systems, demonstrably enhancing vehicle safety.*

Key Words: **Autonomous Anti-Rollback System (AARS), Vehicle Safety, Ratchet and Pawl Mechanism, Finite Element Analysis (FEA), Hill hold Assist, Gear Design and Fabrication.**

1. INTRODUCTION

Unintended vehicle rollback on inclined surfaces is a persistent and significant safety concern in automotive engineering. Such incidents, often occurring during uphill starts or parking manoeuvres, can lead to collisions, property damage, and personal injury [1]. This risk is particularly pronounced in vehicles with manual transmissions, where the driver must coordinate the clutch, throttle, and brake.

To mitigate this, automotive manufacturers have implemented two primary solutions: the manual handbrake and electronic Hill Hold Assist (HHA). The manual handbrake, while mechanically simple, is entirely dependent on driver intervention. Its effectiveness is contingent on human factors, such as being correctly engaged with sufficient force, and it is prone to human error [2, 4].

Modern vehicles increasingly adopt electronic HHA (also known as Hill Start Assist or HSA). These systems, however, are typically software-based functions that co-opt the vehicle's existing Anti-lock Braking System (ABS) and Electronic Stability Control (ESC) modules. HHA holds the vehicle by applying hydraulic pressure to the service brakes, temporarily preventing rollback after the driver releases the brake pedal. While effective, this approach relies on a complex network of sensors and hydraulic controls, adds potential electronic failure points, and contributes to the wear of the service brakes.

The literature reflects a clear need for a more robust and reliable alternative. Research has explored various mechanical anti-rollback mechanisms, including ratchet and pawl designs, to improve safety [6, 9]. Some proposals have focused on integrating these mechanisms within the disc brake assembly [9], while others have suggested automating existing manual levers [5]. While these efforts validate the interest in mechanical solutions, a gap remains for a cost-effective, mechatronic system that is *both* fully autonomous (like HHA) and mechanically independent from the primary braking system.

This paper details the design, fabrication, and multi-stage validation of a novel Autonomous Anti-Rollback System (AARS) that directly addresses this gap. The proposed system introduces a robust, independent mechanical lock based on a ratchet and pawl mechanism. This lock is not reliant on the vehicle's hydraulic brakes; instead, it is autonomously controlled by a dedicated mechatronic system. An Arduino microcontroller, processing real-time

data from an MPU6050 accelerometer, engages the lock via an electro-pneumatic actuation system. This choice of pneumatic actuation is notable for its high force output and reliability, and it offers significant adaptability. While the prototype was developed for mid-size cars, the system architecture is inherently suitable for heavy commercial vehicles, which already possess on-board air brake systems that can be readily tapped.

This paper presents the complete mechatronic design, the critical role of Finite Element Analysis (FEA) in guiding material selection from structural steel to AISI 4140, and the quantitative performance results from a fully fabricated prototype. The validated system demonstrates a reliable, low-cost, and independent solution, offering a viable alternative to existing systems and enhancing overall vehicle safety across multiple vehicle classes.

2. LITERATURE REVIEW

Existing research on vehicle incline safety is largely bifurcated, focusing on two distinct challenges: the structural optimization of mechanical locking mechanisms [6, 9] and the parallel development of autonomous, sensor-driven actuation to eliminate driver error [4, 5].

In the first domain, the ratchet and pawl mechanism is well-established as a robust mechanical lock. Collate et al. [6] explored the design and development of such mechanisms, validating their high reliability while noting the associated challenges of manufacturing complexity and cost-effectiveness. Prakash et al. [9] further investigated this concept by proposing a mechanical anti-roll system (ARS) that integrated the ratchet and pawl mechanism directly within the vehicle's disc brake assembly. This highlights a common design choice of attempting to integrate the safety lock with existing wheel components.

In the second domain, the literature demonstrates a strong consensus that manual engagement is a key point of failure. Both Joshi et al. [4] and Benssin et al. [5] identified the limitations of manual hill hold levers and proposed automatic actuation based on gradient sensors. This validates the core principle of using sensor data—such as from an accelerometer—to trigger an anti-rollback mechanism, thereby reducing driver workload and minimizing the risk of human error.

Despite these advancements, a distinct gap persists. Current research either focuses on purely mechanical locks that require integration into existing, complex assemblies [7, 9] or on electronic systems that rely on the primary service brakes (as discussed in the Introduction). There is a clear lack of research that successfully integrates a robust, independent mechanical lock (like a ratchet and pawl) with a cost-effective, autonomous mechatronic control system (like an Arduino and electro-pneumatics). This research directly addresses this void by creating a hybrid system that combines the mechanical reliability from one field of study with the autonomous control from another, resulting in a novel and independent safety architecture.

3. METHODOLOGY

The development of the AARS followed a systematic mechatronic design methodology, visualized in Fig. 1. This process integrated virtual design, computational analysis, and physical fabrication to ensure system integrity. Initial concepts were translated into 3D models using CATIA V5, which then served as the basis for Finite Element Analysis (FEA) in ANSYS. This computational phase was critical for component-level validation *prior* to fabrication, especially for material selection. The process concluded with physical prototyping, sensor integration, and performance testing.

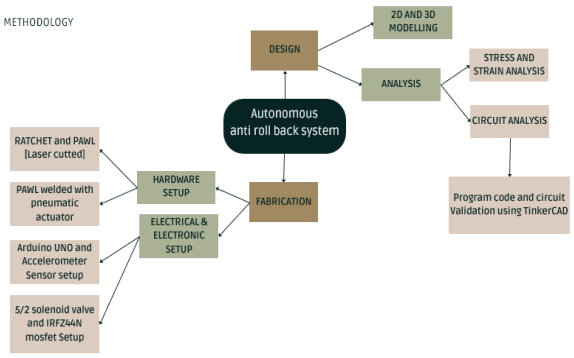


Fig -1: The systematic design methodology, integrating virtual modelling, computational analysis, fabrication, and validation.

The system's architecture is a hybrid mechatronic design composed of three primary sub-systems: the mechanical lock, the electronic control unit, and the pneumatic actuation circuit.

3.1 Mechanical Sub-System: Ratchet and Pawl

The core of the AARS is an independent mechanical lock, separate from the vehicle's service brakes. This system employs a robust ratchet wheel and a corresponding pawl. The ratchet wheel is designed to be affixed to a component of the vehicle's driveline (e.g., the axle or wheel hub), allowing free rotation in the "forward" direction. The pneumatically-driven pawl is designed to engage with the ratchet's teeth, creating a positive mechanical stop that instantly prevents any reverse rotation (i.e., rollback).

3.2 Electronic Control Sub-System

The system's "brain" is an Arduino UNO microcontroller. This unit processes real-time inclination data from a 3-axis accelerometer sensor (MPU6050/GY-521). The control logic is programmed to continuously monitor the vehicle's tilt. When the accelerometer detects an incline that surpasses a pre-defined threshold (e.g.,>3-5 degrees), the microcontroller interprets this as a rollback risk and immediately outputs a "high" signal to the actuation sub-system. Conversely, it deactivates the system

when the incline is non-critical or when a signal from the reverse gear selector is detected, allowing for intentional reverse manoeuvres, as shown in the simulation environment in Fig - 2.

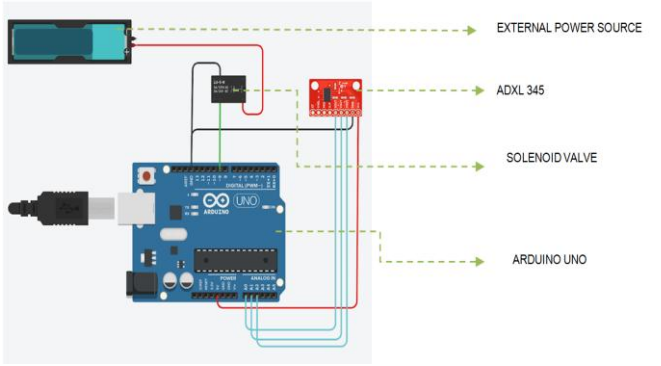


Fig -2: Hardware test setup in Tinker CAD

3.3 Electro-Pneumatic Actuation Sub-System

The microcontroller's logic signal is routed to an IRFZ44N MOSFET, which acts as a digital switch capable of handling the current required to drive a 5/2-way solenoid valve. This industrial-grade solenoid valve functions as the interface between the electronic and pneumatic systems. When activated, the solenoid directs compressed air to a pneumatic actuator (cylinder). This actuator converts the air pressure into a precise linear force, driving the pawl into engagement with the ratchet wheel. When the signal is removed, the solenoid vents the air, and the pawl retracts, disengaging the lock. The complete mechatronic control loop is illustrated in the system schematic in Fig. 3.

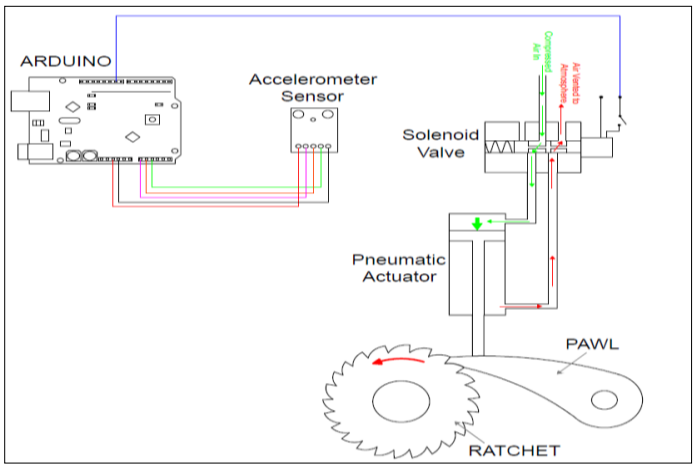


Fig -3: System architecture schematic, illustrating the control loop from the accelerometer to the electro-pneumatic actuation of the pawl.

3.4 Fabrication and Material Selection

The primary mechanical components, the ratchet and pawl, were fabricated using precision laser cutting to ensure tight tolerances. Based on the FEA results (discussed in Section 4), these components were fabricated from AISI 4140 low-alloy steel. This material was selected for its high tensile strength (655 MPa), high fatigue strength, and hardness (approx. 22 HRc) compared to standard structural steel. Its density is 7850 kg/m^3. The assembled experimental prototype is shown in Fig. 4.

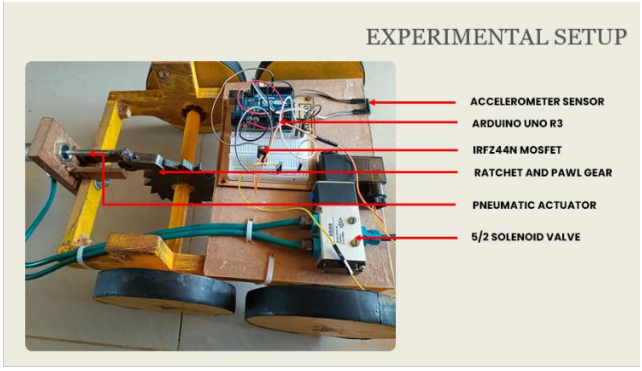


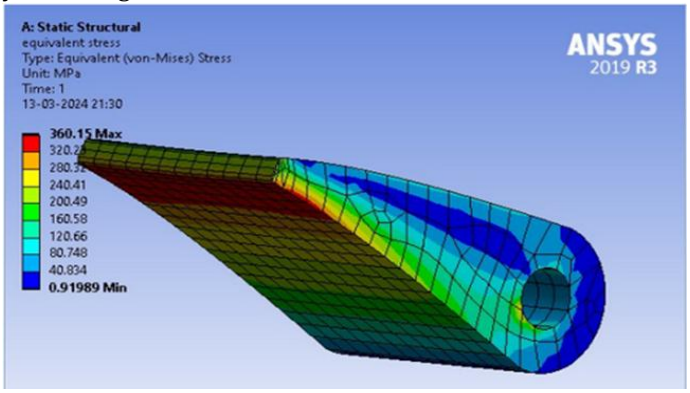
Fig -4: Assembled Experimental Setup of AARS

4. RESULTS AND DISCUSSION

The system's performance was validated through a two-stage process: first, a computational validation of the mechanical design using FEA, and second, an experimental validation of the fabricated prototype's mechatronic performance.

4.1 Computational Validation

The system's mechanical integrity was validated computationally using ANSYS to ensure the ratchet and pawl components could withstand operational loads. The primary objective was to validate the design for a mid-size vehicle, with a calculated rollback force of 7500 N. Initial simulations performed on standard structural steel revealed that this material was insufficient, failing to meet the load requirement. This analysis mandated a material change to AISI 4140 low-alloy steel. The final design, using AISI 4140, was then subjected to a simulated load of 10,000 N to ensure a robust safety margin. The results confirmed the design's integrity. The maximum equivalent (von Mises) stress, which occurred at the high-contact root of the pawl, was 360.15 MPa (with the ratchet at 280.11 MPa). This remained well below the material's allowable yieldstrengthof393MPa.



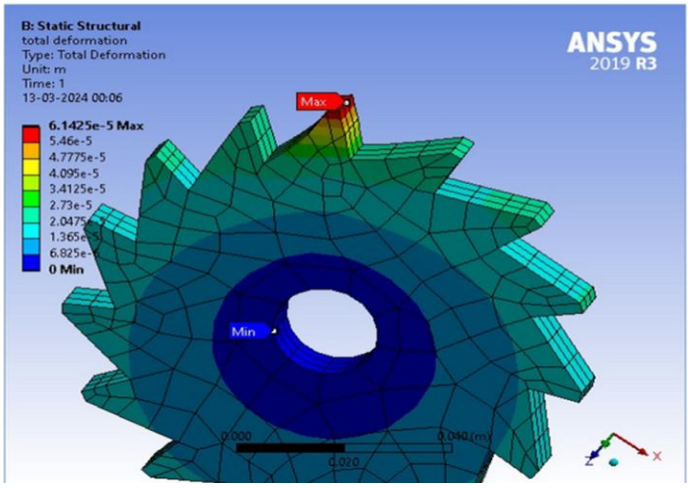


Fig -5: FEA results (A) equivalent (von Mises) stress on the pawl, and (B) total deformation of the ratchet.

The analysis yielded a safety factor of 1.1 for the pawl and 1.4 for the ratchet. Similarly, the maximum equivalent strain on the pawl was 0.0017, which was safely below the material's allowable strain limit of 0.002. These data points, summarized in Fig. 6, computationally validated that the mechanical design is robust and will not fail under the anticipated operational loads.

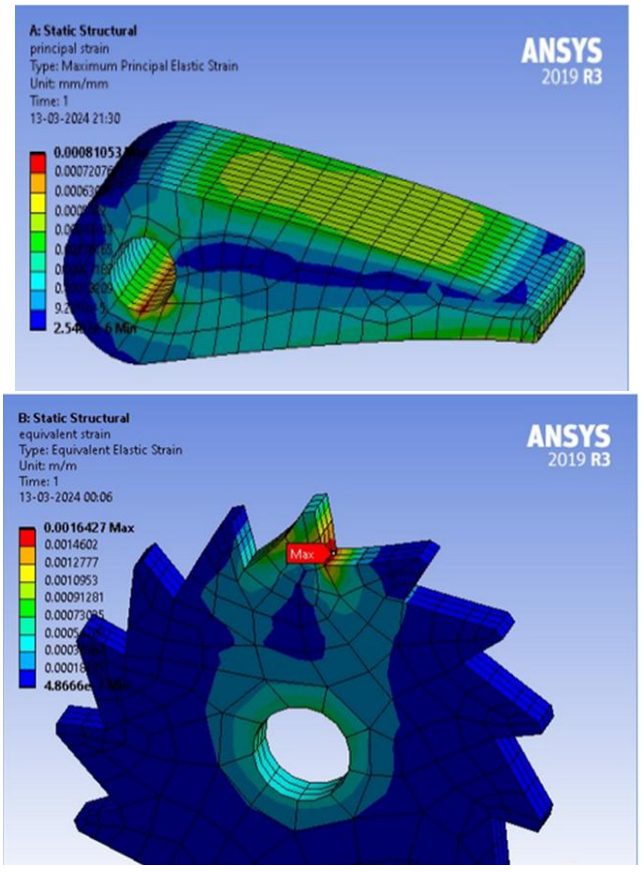


Fig -6: Summary of FEA results, (A) strain on pawl, (B) strain on the ratchet.

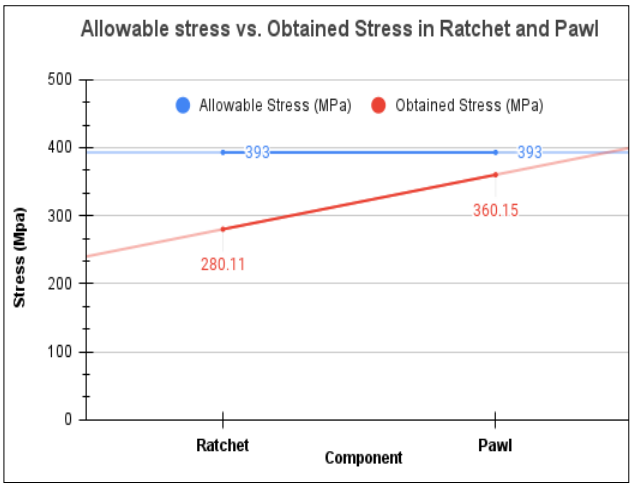


Fig -7: Equivalent stress in the ratchet and pawl against the allowable limits of AISI 4140 steel.

4.2 Experimental Validation

Following computational validation, a physical prototype (as shown in Fig. 4) was fabricated and subjected to experimental testing to validate the mechatronic system's real-world performance. Two primary metrics were evaluated: system response time and engagement reliability.

System Response Time: This was measured as the total duration from the moment the accelerometer's incline threshold was crossed to the full, positive engagement of the pawl. The system consistently demonstrated a rapid response time in the range of 1.00–1.25 seconds.
Engagement Reliability: Reliability was assessed over numerous test cycles, simulating incline stops. The system achieved a >99% success rate in correctly engaging the pawl and preventing rollback.

4.3 Discussion

The results from both computational and experimental validation confirm the efficacy of the AARS. The FEA data confirms the *robustness* of the mechanical design and the critical importance of material selection (AISI 4140). The experimental data confirms the *effectiveness* of the autonomous mechatronic control system. A sub-1.25-second response time combined with >99% reliability proves that this hybrid electro-pneumatic system is a viable and highly effective alternative to existing HHA systems. It successfully provides fully autonomous operation while remaining mechanically independent of the vehicle's service brakes.

5. CONCLUSION AND FUTURE SCOPE

This research successfully demonstrated and validated a novel Autonomous Anti-Rollback System (AARS) that

provides a robust, independent mechanical lock, addressing the limitations of brake-dependent HHA and manual handbrakes. A two-stage validation process confirmed the system's efficacy: Finite Element Analysis (FEA) was essential in guiding the material selection to AISI 4140 steel (SF 1.1-1.4), while experimental testing of the fabricated prototype confirmed a rapid response time (1.00-1.25s) and high reliability (>99%). This work thus validates a low-cost, autonomous mechatronic solution that enhances vehicle safety by remaining independent of the primary braking system.

Future research, which is currently underway, is focused on replacing the pneumatic system with a high-torque electric linear actuator. This investigation is also optimizing the mechanical integration to engage the differential/rear axle shaft directly and expanding the control logic to function as a fully autonomous, sensor-based parking brake.

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