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Enhancing Manual Unloading Efficiency Through Automated Load Balancing Mechanisms

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Abstract: *Road safety is a critical concern in the transportation industry, particularly for heavy-duty vehicles such as lorries, trucks, and buses. These vehicles, while essential for logistics and public transportation, are often overrepresented in road accidents—primarily due to instability caused by improper load distribution. This issue becomes especially hazardous when navigating curved roads, sharp turns, or hilly terrains, where the impact of centrifugal forces can lead to vehicle tilting, skidding, or overturning. In many cases, the problem is exacerbated by uneven loading practices common in vehicles where goods are manually loaded and unloaded, such as those carrying construction materials, agricultural produce, or industrial components. Traditional safety mechanisms such as road banking, signage, and speed limits remain passive and do not adapt to the dynamic internal conditions of the vehicle. These methods place the entire burden of stability control on the driver, leaving room for human error, fatigue, or unexpected road conditions to cause severe consequences. To address this challenge, this project introduces an automatic load balancing system specifically designed for manually unloaded vehicles. The proposed system integrates sensors, actuators, and an embedded controller to continuously monitor and adjust load distribution in real-time, thereby enhancing vehicle stability and reducing accident risks on curved or uneven roads.*

Keywords: *Road safety, load balancing, heavy vehicles, centrifugal force, dynamic stability, sensors, embedded controller, lorry accident prevention, vehicle automation.*

1. INTRODUCTION

Heavy lorries, buses, and trucks are the lifeblood of logistics firms and public transport systems around the world. They transport vast amounts of goods and people over city, country, and intercity routes. As cargo and transit demand has increased, usage of such heavy vehicles has increased several times. But with this increased use comes a major safety concern—instability during the travel on curved roads, particularly when these vehicles are unevenly loaded or overloaded.

Accidents involving heavy vehicles are commonly reported in both developed and developing countries. Such accidents commonly result in fatal outcomes due to the weight and momentum carried by such vehicles. The most significant cause of such accidents on curves is loss of balance and control, which often results in skidding, jackknife, or complete overturning of the vehicle. Not only do such accidents lead to loss of human lives among passengers and drivers, but they also lead to loss of goods, congestion on roads, and infrastructure damage.

Uneven load distribution is also among the gravest causes of instability. With manual loading, particularly in haste or in cases where proper guidance is not given, asymmetric load is highly prone to happen. Excessive load at one side or heavy payloads placed in a wrong position will cause the vehicle's center of gravity to become imbalanced. This compromises the vehicle's stability against tipping or sliding, particularly during cornering. This is also augmented by the centrifugal force, which is exerted outward when the vehicle turns. The combination of a raised center of gravity and centrifugal force greatly increases the overturning moment, which makes the vehicle unstable.

Conventional road safety countermeasures like speed breakers, warning signs, banked curves, and guardrails are designed to help drivers make turns. These countermeasures are passive. They provide counsel or mechanical help but are not under the motor vehicle's real loading conditions or mechanical status. As such, traditional methods fail where a vehicle's internal conditions—such as load imbalance or abrupt cargo movement—remained uncorrected.

In order to offset these shortcomings, the current work introduces an Automatic Load Balancing Mechanism (ALBM) for heavy-duty vehicles. This mechanism brings a brainy, sensor-based methodology for dynamically monitoring and balancing load within the vehicle. The major goal is to ensure vehicular equilibrium and reduce rollover or loss of control risks, especially during curve travel or turning at high speeds.

The Need of Dynamic Solutions

Development in transport infrastructure and vehicle engineering has resulted in various safety features incorporated in vehicles these days. Anti-lock brakes, electronic stability control, and traction control have become standard today. Yet none of these handle directly the load's distribution and its behavior within the cargo compartment. The internal load movement dynamics are usually neglected, particularly in vehicles where loading and unloading of goods is done manually, like construction trucks, agricultural transporters, and cargo lorries.

Manual loading operations add inherent variability to the way goods are loaded. Drivers and loaders may inadvertently load heavier items on one side or overload items too high. On the road, even well-tied loads may move because of vibrations, braking, or abrupt turns. Under these conditions, the vehicle is mechanically unstable, and small driver mistakes can turn into catastrophic failures.

Seeing this deficit in safety, the Automatic Load Balancing Mechanism is able to intervene in real time, sensing changes in load distribution and adjusting autonomously. This is an evolution from passive safety to active safety intervention, with the vehicle able to dynamically balance without driver action.

1) METHODOLOGY

Threshold values for imbalance detection were established, with a functional safety margin of a 10 percent weight difference between opposite corners of the platform. Once requirements had been established, hardware integration began by mounting four HX711-amplified load cells at the corners of a solid rectangular base and mounting the MPU6050 gyroscope centrally below it in preparation to measure tilt accurately.

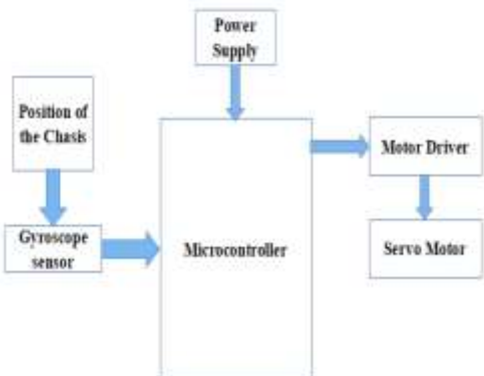

Figure1. Block Diagram

Construction of the Automatic Load Balancing Mechanism followed a systematic, iterative process directed toward preserving both functional integrity and practical utility. The team first defined precise system specifications, including stability needs—e.g., a top allowable tilt of five degrees—sensor accuracy (±0.1 kg for load sensors and ±0.5° for the gyrometer) and actuator reaction times of under 200 ms. Threshold quantities for imbalance detection were set with an operational margin for safety of a 10 percent weight difference between opposite corners of the platform. Hardware integration began following requirements determination by securing four HX711-amplified load cells into the corners of a solid rectangular base and mounting the MPU6050 gyroscope at center below it to read accurate tilt. Next, high-torque servo motors were mechanically connected to the platform using precision gear or rail assemblies with an L298N dual H-bridge driver in between the NodeMCU controller and servos to facilitate power amplification and bidirectional movement. An onboard 5 V regulator provided a stable 12 V supply voltages for stable voltages across sensors and the microcontroller over changing loads.

Software development proceeded concurrently, utilizing the Arduino IDE to add I²C communication for the MPU6050 (through the Wire.h library) and HX711 interfacing for the load cells. The main control algorithm polled all the sensors in its main loop constantly, calculated pairwise load differences, and compared them with the pre-set thresholds. When imbalance was detected, the algorithm computed the required servo positions and sent PWM commands (via Servo.h) to move the load, followed by gyroscope feedback to confirm levelness and make further fine adjustments. Real-time monitoring of sensor values, actuator positions, and system status for debugging and data logging was facilitated via a UART serial interface.

With hardware and software in place, a modular test rig featuring sliding rails and secure sensor mounts was constructed. Static calibration of known weights for load cells set up precise conversion factors, and gyroscope zero-offset and scale calibration reduced drift. Dynamic testing then proceeded, employing a tilting platform to mimic curved-road conditions and various load scenarios. Throughout these tests, system parameters including maximum reduction in tilt, detection-to-correction time, and accuracy of correction were measured over cycles of repeated runs. Over a hundred iterations of imbalance correction tests were conducted for reliability tests checking mechanical degradation, software robustness, and energy consumption. Feedback from these tests guided improvements to threshold levels, control settings, and mechanical tolerance, which finally resulted in a validated proof-of-concept device ready to scale up to future commercial, full-size vehicles.

2) PROBLEM IDENTIFICATION

One of the most significant factors that affect the stability and safety of trucks and lorries is the asymmetric loading within the cargo compartment. It poses a very serious threat when the vehicle is in the process of taking a bend or turning sharply. The root of danger is the movement of the center of gravity (CoG) of the vehicle due to wrong or unbalanced loading.

When a vehicle is loaded heavier on one side, the CoG moves in the direction of the heavier side, making it more prone to instability while moving. When the car is turning in a curve, centrifugal force pulls outward in the direction away from the curve, and that causes the shifting load to become more intense. In an equilibrium vehicle, however, this is countered by structural support and banked roads. But when the vehicle of an unevenly loaded lorry or truck is in motion, displaced CoG adds to the effect of centrifugal force, drawing the car further outward. Thus, it normally results in wheel lift, skidding, or complete rollover, especially when driven faster or sharper.

Even in cases where roads are constructed with superelevation (tilt or banking of the road surface on curves to assist vehicles), the fact that there is an unbalanced load eliminates this benefit. The design lateral support that the road geometry is supposed to provide is pre-empted by the inherent imbalance of the cargo, thus exposing the vehicle to loss of traction, tilting, or overturning.

Presently, solutions to deal with this condition are mainly passive and preventive. These are manual checks before trips, using tie-down straps and nets to secure the loads, or adding anti-roll bars to the suspension system. Although useful, these are not dynamically active in response to load redistribution once on the move. Consequently, a critical need for an active, real-time load balancing system exists to automatically detect and balance such imbalances during travel for safer transportation and less accident risk.

3) OBJECTIVES

The primary goal of this project is to develop and test a smart system that automatically identifies and compensates for load imbalances in a moving vehicle, thus reducing the risk of rollover accidents, especially on curved roads. The system seeks to:

- Track the vehicle's orientation and tilt in real-time.
- Identify uneven weight distribution through load sensors.
- Automatically transfer the load through actuators or motorized platforms.
- Improve vehicle balance during turns and support a stable center of gravity.
- Lessen reliance on driver intuition or hand adjustments.

4) SCOPE OF THE PROJECT

The present undertaking is mainly addressed to the designing and developing the functional prototype for the suggested mechanism of automatic load balancing. Due to limitations on scale, funds, and equipment for testing purposes, the project is restricted in its implementation at a miniature scale that would mimic the occurrence of actual real-world load variations in heavy goods vehicles. Although a miniature version, the prototype is a critical instrument to illustrate both the theoretical basis and practicality of dynamically balancing irregular loads under motion in a vehicle.

The prototype integrates key components such as gyroscopic sensors, load cells, servo motors, and a microcontroller-based control system that effectively replicates the physical forces and sensor-actuator interactions that occur in full-scale trucks and lorries. By controlled experimentation and simulation, the system can detect the load imbalances and automatically transfer the cargo or support base to stabilize it. Such responses closely model actual conditions and give a good idea of what the mechanism would do at full size.

Though not yet tested on commercial vehicles, this prototype is a proof-of-concept, providing a basis for further research, industry partnership, and real-world application. The results of the prototype tests indicate that the idea is not only theoretically valid but also technically viable. It demonstrates the viability of employing an active, sensor-driven load balancing system in large cargo vehicles to improve safety, especially on bends.

This prototype development focuses the potential design problems, component limitations, and control strategies that will be addressed in a full-scale application. The project thus lays the groundwork for extending the system to support the load-carrying capacities and spatial arrangements of commercial transport vehicles. With development and industry support, the concept could be evolved into a functional safety feature for modern logistics and transport systems.

5) PROBLEM STATEMENT

Instability in manually unloaded vehicles such as lorries, tipper trucks, and construction carriers is among the primary reasons for road accidents, especially on curved or uneven roads. Such vehicles carry loose materials such as sand, gravel, or goods loaded and unloaded manually without any strict weight distribution criteria. As a result, uneven cargo weight becomes the norm. When such vehicles drive through curves, the centrifugal force drives outwards, heightening the imbalance and shifting the vehicle's center of gravity dangerously to one side. This can lead to loss of traction, wheel lift, skidding, or even complete overturning, and present a serious danger to the driver, cargo, and other traffic around it.

Such an automatic load balancing technique in real time is of huge use in such a situation. Using weight and orientation measurement sensors, the system will be able to monitor load imbalances when and where they arise. Using actuators or dynamic support systems, it will redistribute the weight or move its point of support, balancing the vehicle even in severe conditions. This prediction security system provides an extension of the dynamic character of road and freight dynamics to offer a monster step ahead of traditional passive solutions. It can potentially emerge as a fundamental element in rendering vehicles safer, limiting accidents, and safeguarding commodities and human life while in transit.

6) SIGNIFICANCE OF STUDY

This project has a strong convergence with national road safety measures and the larger vision for smart traffic networks to curb accidents and improve vehicle performance. Since there is growing focus on intelligent transport systems and autonomous transport, the contemplated automatic load balancing process helps directly in achieving smarter and safer mobility. By reducing one of the major causes of road accidents—instability due to non-uniform loading—the system offers a technology-based predictive solution above the usual safety measures in the form of signs, speed limits, or barriers.

The benefits of such a solution run across industries. Logistics providers can improve the security and effectiveness of goods transport, particularly long distances and hilly or uneven road conditions. Public transport agencies responsible for operating buses and heavy vehicles can utilize this technology to ensure passenger protection from sharp turns or abrupt turns. Infrastructure development organizations responsible for designing highways and traffic management can also integrate such advancements into policy formulations and road safety strategies.

By minimizing human reliance for load checks, reducing driver error, and allowing real-time corrective measures, this project encourages a move towards automation and smart safety systems. It lays the groundwork for a future where transportation safety is built into vehicle design, thus contributing to national initiatives for sustainable and accident-free roads.

2. HARDWARE REQUIREMENTS

1) Gyroscope Sensor

The MPU6050 is a 6-axis motion tracker integrating a 3-axis accelerometer and 3-axis gyroscope. It measures angular rotation and linear acceleration and thus finds suitable applications in sensing vibration and tilt on moving cars. In the current project, it senses any tilt on curves due to uneven loading. It is interfaced to the microcontroller via I2C protocol. If the tilt angle exceeds a predetermined safety threshold, the system initiates load correction. It's compact, power-frugal, and precise enough for prototype-level modeling.

Figure 2. Gyroscope sensor

The MPU6050 is an on-chip 6-axis motion sensor consisting of a 3-axis gyroscope and a 3-axis accelerometer. The sensor is highly effective at monitoring both linear acceleration and angular rotation, and thus ideal for applications that are sensitive to movement, for example, vehicle stability systems. In this project, MPU6050 plays an important part in monitoring the tilting angle of the vehicle or platform when a turn is involved, and the load imbalance relates directly to that.

When a car takes a turn, the centrifugal force acting upon it may cause the load to tilt in a way that the car may become dangerous or even over turns. MPU6050 detects the tilt in real time by measuring angular speed and acceleration on a continuous basis. The data is communicated to the microcontroller in terms of I^2C protocol for high-speed data transferring with minimal amount of wiring.

When the angle of tilt passes beyond a given value—the control code having this defined as a safety measure—the microcontroller reads it as an imbalance. It then activates the servo motors or actuators to redistribute the load and re-balance. MPU6050 is low in cost, low-power consumption, tiny in size, yet sufficiently accurate to work fine as a prototyping platform and finally deploy for a full-fledged system.

2) Load Cell

Load cells are high-precision sensors that are used to measure force or weight by translating mechanical force into an equivalent electrical signal. In this project, four load cells are placed at each corner of the platform to record real-time weight distribution on the vehicle. This positioning enables the system to identify any load asymmetry, which is particularly important during vehicle movement, like turning or driving on bumpy roads.

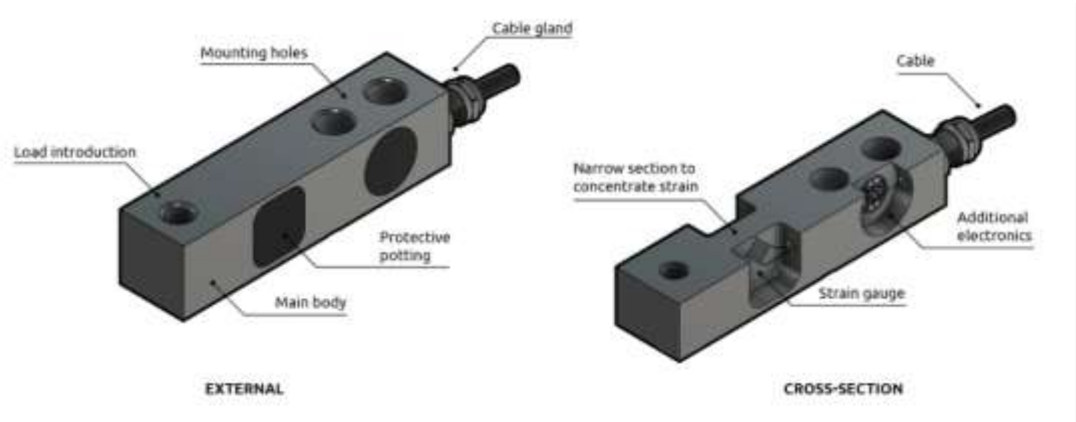

Figure 3. Load Cell

When the load is not evenly distributed, one or more of the load cells will read higher, which will show an imbalance. These analog signals are very small, so an HX711 amplifier module is employed to amplify and convert the data into digital form before it is sent to the microcontroller (e.g., Arduino). This arrangement ensures that the readings are stable, accurate, and easily processed.

3) High Torque Servo Motor

Servo motors are electromechanical actuators designed to generate precise angular or linear motion, hence ideal for controlled position applications. Here, the high-torque servo motors have a critical role in moving the platform or load based on sensor input. The motors are driven by pulse-width modulation (PWM) pulses from the microcontroller, which determine their rotation angle or movement range.

In contrast to conventional DC motors, servo motors incorporate a feedback system—a potentiometer is typical—ahead of time anonymously that constantly reports to the control system the shaft position. The servo can maintain to the exact angle or position required with the feedback loop, which is a key part of transferring heavy or unbalanced loads so balance can be regained in transit.

Figure 4. Servo Motor

4) Motor Driver

The motor driver is the primary interface between motors and microcontroller to power actuators using actual sensor outputs. To power high-torque servo or DC motors displacing the load power control as well as direction, the project employs the L298N two H-bridge motor driver. As microcontrollers such as Arduino work on low voltage and current, they are unable to drive motors. The L298N gets the control signals from the Arduino and steps up these to provide the motors with the voltage and current that is required.

This motor driver supports bi-directional movement such that the platform or load can move either direction and necessary to offer balance on both sides. The motor driver also includes overcurrent and thermal protection necessary to ensure operation safety during long-term driving or changing loading states. L298N helps ensure interactive, precise, and safe motor control to aid overall system reliability.

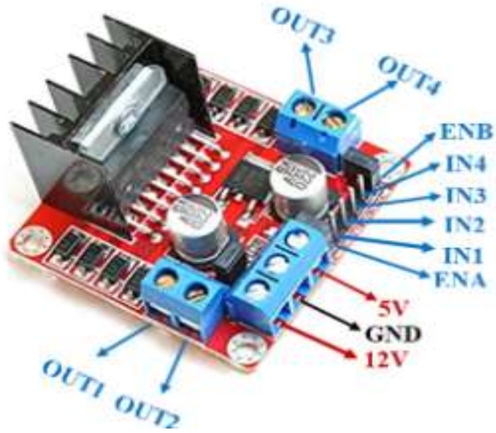

Figure 5. Motor Driver

5) GEAR SYSTEM

A gear system is a crucial mechanical element employed to increase torque and control the movement of load along the platform. In the automated load balancing system, gears serve as a go-between between the servo motors and the load-shifting rail or platform. When the motor rotates, the corresponding gear system transmits this movement either to a rack-and-pinion setup, pulley, or other linear motion devices that actually transport the load to the desired side.

The gear ratio is an important aspect in design as it defines the compromise between torque and speed. Larger gear ratio results in higher torque and enables the system to transfer more massive loads with reduced power to the motor, while the low ratio enables movement using lower force but greater velocity. Through the appropriate setting, the gear system conveys loads smoothly, precisely, and effectively, reducing loss of energy and mechanical stress. This helps to improve control, safety, and system life overall.

6) MICROCONTROLLER

NodeMCU is the real-time Wi-Fi-based load balancing system microcontroller that can be used in smart transportation systems. NodeMCU reads input from the load cells (via the HX711 module) and MPU6050 gyroscope, executes control algorithms on sensors, and transmits orders to the motor driver for servo motor movement for rebalancing the load. ESP8266-integrated microcontroller enables optimal placement of control algorithms for imbalance state detection and response against them by reloading the load.

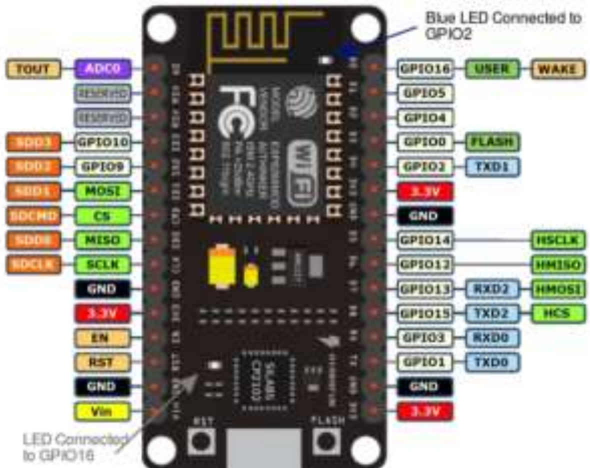

Figure 6. Micro Controller

Unlike basic microcontrollers, NodeMCU has wireless communication that is easy to connect to IoT platforms for remote monitoring, data logging, or alerting. Its minimal size, minimal power consumption, and simple ease of programming with the Arduino IDE qualify it well for prototyping and scalable deployment. It has strong analog and digital input/output pins as well, which are vital in hooking up to various sensors and actuators. NodeMCU thus is a wise, networked hub for real-time load management.

3. Software Requirements

Inputs are conditioned to sense any indication of tilt or imbalance of loading during motoring, particularly driving along a curved path. Well-defined threshold values and control logics are applied by the software to decide whether and how the correcting motion shall be engaged. When an imbalance is realized, proper PWM signals are generated and transmitted to the motor driver, and the servo motors are controlled to reallocate the load. The software also has serial communication to support debugging and can be expanded to have IoT capabilities for remote monitoring. System reliability, responsiveness, and stability during real-time computation are supported by good and proper software design.

1) Solidworks

SolidWorks enables a parametric modeling approach where designers are able to construct fully associative 3D assemblies and parts. Dimensions, constraints, and relationships can be defined by the designer and automatically update throughout the entire model as changes are made. This is particularly useful in iterative design, where prototyping and optimization can be quickly done without having to redraw whole systems.

The part environment also supports the modeling of individual mechanical components such as plates, brackets, and gears with aspects such as extrusion, revolve, fillet, and chamfer. These individual parts are assembled together in the assembly module, where mates and constraints are true to actual assemblies such as bolts, sliders, and hinges.

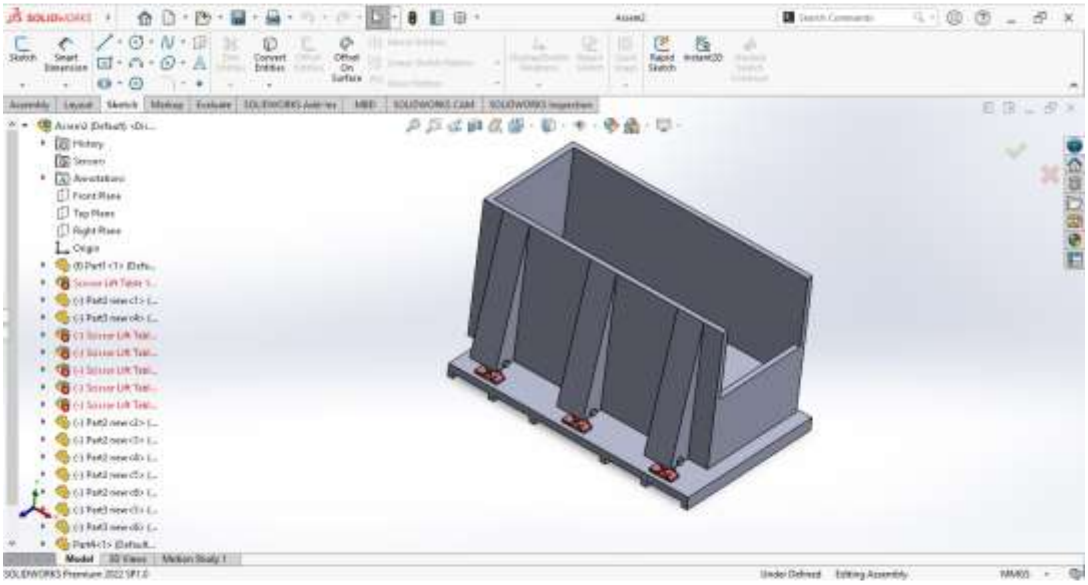

Figure 7. Solid Work Simulation

Also included is motion analysis and finite element analysis (FEA) functionality that allows verification of the mechanical behavior of the design under motion, load, and stress. This simulation functionality facilitates design optimization before physical prototyping.

Other significant strengths of SolidWorks include its ease of use, industry-standard file format compatibility (like STEP, IGES, STL), and ability to produce accurate 2D technical drawings with dimensions and annotations.

Using SolidWorks in the project made it possible to create a consistent and realistic model of the load balancing mechanism, facilitating visualization of the system, avoiding design errors, and efficient communication of ideas to be fabricated and tested.

2) Arduino IDE

Arduino Integrated Development Environment (IDE) is a robust, open-source development environment for programming, compiling, and uploading code onto microcontroller boards like Arduino Uno, NodeMCU, and many more. It is the main development tool for embedded system developers, students, and hobbyists. The IDE offers a straightforward and easy-to-use interface that enables users to program using a language based on Embedded C/C++, popularly known as Arduino Sketch.

The Arduino IDE has an editor where code is written by users, an error and feedback message area, a text console, a button toolbar for typical functions (verify, upload, open, save), and a set of menus for tools and configurations. It provides great support for a variety of libraries, which is why it is simple to interface with hardware such as sensors, actuators, and communication peripherals.

In this project, the Arduino IDE is utilized to code and transfer control logic to the NodeMCU, which receives sensor inputs (MPU6050, load cells) and controls outputs (servo motors through motor driver). The IDE facilitates serial communication, enabling real-time observation of sensor values and debugging. It also enables seamless integration of external libraries such as Wire.h, Servo.h, and HX711.h, enabling efficient and reliable hardware-software interaction.

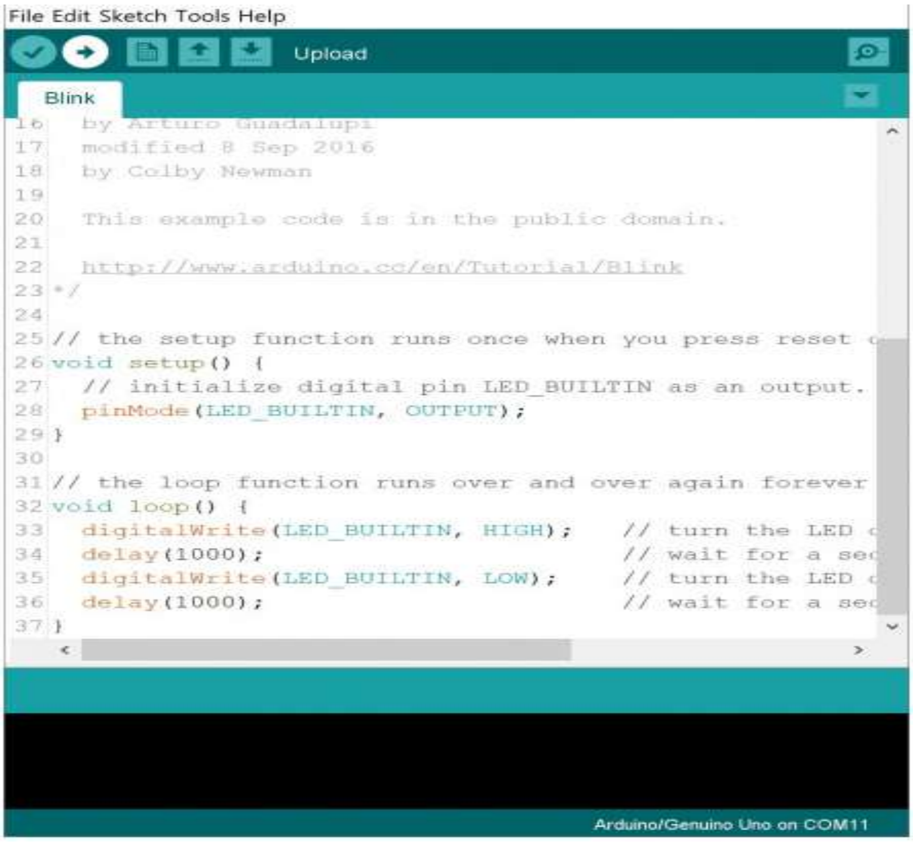

Figure 8. Coding

3) Embedded C

Embedded C is a transportable subset of the C language tailored for developing firmware and embedded programs for embedded systems. Embedded C possesses the same syntax and structure as standard C but applies features and optimizations needed to interact directly with hardware devices like microcontrollers, sensors, and actuators. Embedded C enjoys extensive usage in automation, robotics, automotive systems, consumer electronics, and industrial applications due to its high portability, efficiency, and support for real-time.

In the design of a microcontroller—such as using Arduino, NodeMCU, or 8051 family of microcontrollers—Embedded C grants immediate access to input/output ports, memory address locations, and hardware registers.

- Embedded C is used in the Automatic Load Balancing System for:
- Reading sensor values from load cells and gyroscope (MPU6050).
- Processing data to decide on imbalance conditions.
- Generate PWM signals to control servo motors using the motor driver.
- Communicate with external devices using I2C or Serial interfaces.

The language supports various data types, control statements (loops, if-else), and functions so that the code is modular and easy to read. interrupt service routines (ISRs) can also be declared for the time-critical functions by the programmers and libraries can be used so it's easy to communicate with sensors and actuators.

4) Communications

a) I2C Communication:

In the project, Node MCU has been established as the master and talks to the MPU6050 gyroscope and accelerometer sensor as the slave. I2C protocol allows reading of precious real-time motion data like tilt angle, angular velocity, and acceleration, which are utilized for vehicle imbalance detection. The information is vital while deciding whether action needs to be taken or not. I2C is suitable for embedded systems since it can accommodate multiple sensors on one bus, maintaining firm and neat cabling. Further, it is also well-supported by Arduino IDE libraries like Wire.h, making its implementation easier.

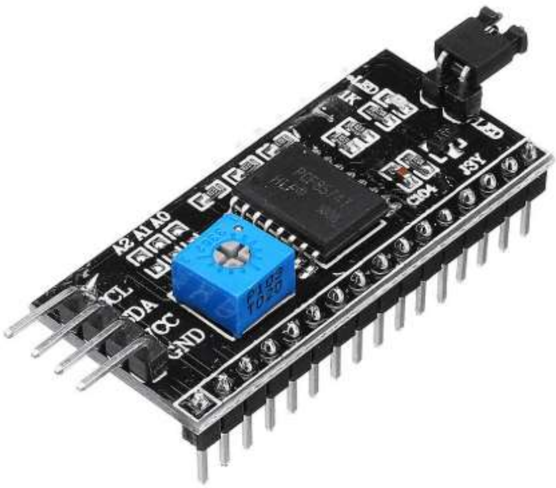

Figure 9. I2C Communication

b) Pulse With Modulation

PWM is a technique of producing analog-like output from digital signals by changing the duty cycle of a square wave. PWM signals are employed in the Automatic Load Balancing Mechanism to drive high-torque servo motors on the load-shifting platform. NodeMCU produces PWM outputs that control the angle of the servo depending on imbalance sensed by sensors. A higher duty cycle represents a larger angle of rotation but lower duty cycle a smaller angle. This form of control utilizes dynamic movement, and the load's position can be conveniently adjusted, distributing the load when the vehicle is in a turn or tilt efficiently. PWM is desirable over analog control because it utilizes energy efficiently, is accurate, and less noisy. It also relies on less dependency on components and is simpler to achieve with microcontroller-based systems. PWM signals are provided with pre-programmed libraries such as Servo.h and provide for smooth running of the motor without jerky movements that cause destabilizing the load even more. Such a level of accuracy is required in the stability of the vehicle as well as in the avoidance of accidents due to unbalanced cargo transfer.

c) Serial Communication (UART)

Serial communication in the form of UART (Universal Asynchronous Receiver-Transmitter) is a basic protocol for data transfer between the microcontroller and external monitoring devices such as computers or display modules. It employs two wires—TX (Transmit) and RX (Receive)—to send and receive serial data one bit at a time. In this project, the NodeMCU sends real-time data like sensor readings, servo positions, load imbalance warnings, and corrective action status to an external system. This allows debugging, monitoring, and logging data for testing purposes and analysis. Serial communication is asynchronous, with no clock signal required, thus making it simpler to implement with hardware. Serial communication is natively supported on the majority of development systems like the Arduino IDE via a Serial Monitor for debugging and visualization. There must be a corresponding baud rate (i.e., 9600 bps) on either side of the communications channel to supply good data transmission accuracy. This communication enables the system also to be extendable as an IoT-supported platform in the future by embedding Wi-Fi modules or cloud interfaces. Overall, serial communication supports and enriches the user interface, giving real-time information for complete transparency as well as making swift troubleshooting at operational times feasible.

d) Sensor Interfacing

the MPU6050 accelerometer sensor and gyroscope is interfaced with the NodeMCU by the I2C (Inter-Integrated Circuit) protocol that demands just two communication lines—SCL and SDA. The two-wire high-speed interface makes the microcontroller receive real-time information of the tilt and angular movement of the vehicle at all times. At the same time, four load cells are mounted at various corners of the platform to record weight distribution. These load cells give digital output in a direct manner; therefore, they are interfaced using the HX711 amplifier module, which gives the analog weight reading and translates it into highly accurate digital signals. HX711 library is utilized in the code to read and calculate this data correctly. The system keeps asking these sensor values again and again in a loop to detect any imbalance. If the data indicates that weight is not evenly distributed or tilt angle exceeds a safe threshold, then servo motors take corrective measures to restore balance, keeping the vehicle stable and secure.

e) Control Logic

The system reads the measurement of opposite sensors (e.g., left and right, front and rear) and calculates the difference in the load. If the imbalance is above a set threshold value, then it indicates a cargo distribution imbalance.

The moment there is imbalance, the microcontroller (NodeMCU) regulates PWM (Pulse Width Modulation) pulses to high-torque servo motors through a motor driver (L298N) and switches them on to drive the load accordingly. The motion is controlled through a gear or rail system to offer smooth and accurate movement of the load.

At the same time, the MPU6050 gyroscope provides feedback in real-time data about the tilt and angular position of the platform. This information is what ensures that once the load is redistributed, the platform finds itself back to stable and level orientation. Even when the angle of the tilt remains above safety measures, the code initiates secondary corrections. It is a closed-loop control mechanism that sees to it that at all times the weight and the tilt remain balanced dynamically, enhancing vehicle safety as well as stability during operations.

4. RESULT AND DISCUSSION

The automatic load balancing mechanism was developed and tested to assess its effectiveness in detecting and correcting load imbalances in real time. The prototype was subjected to various test conditions to evaluate sensor accuracy, system responsiveness, and corrective performance.

1) Design and Modeling

The design of the Automatic Load Balancing Mechanism was created using SolidWorks, a leading CAD software for parametric modeling and assembly simulation. The system consists of three key mechanical assemblies:

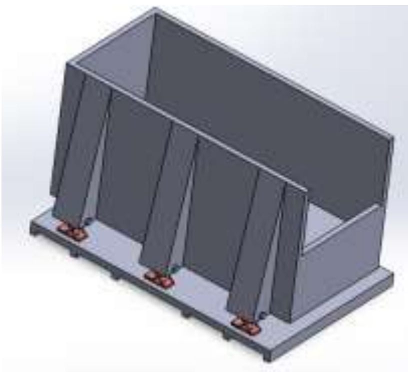

Figure 10. Storage Container with Support Structure

This part of the model represents the main storage container, which is mounted on a base frame. The container is rectangular in shape and features five trapezoidal vertical stiffeners on each side to provide structural reinforcement. These stiffeners ensure that the container can handle vertical loads and resist deformation during vehicle movement or manual unloading.

- The container is open at the top for easy loading/unloading.
- The rear side has a lower wall section, likely designed for controlled discharge or lifting.
- The base frame includes mounting holes, which accommodate bolts or shock-absorbing mounts for securing it onto the lift platform.
- In Picture1, the container is shown mounted on a platform that includes four red-colored rotating mounts—likely representing servo-actuated supports or shock absorbers.

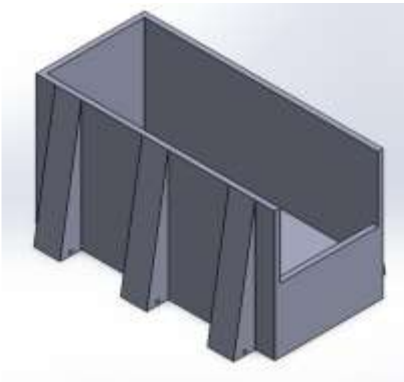

Figure11. Lift Mechanism – Scissor Linkage

This component represents a scissor-type lifting mechanism, positioned between the load platform and the base. It is responsible for executing the dynamic load balancing by vertically adjusting the container's orientation in response to sensor feedback.

- The red blocks represent the top and bottom platforms of the mechanism.
- The linkage system (green) is formed using parallel arms connected by pivot joints, which allow synchronized expansion and contraction.
- Two cylindrical holes on the bottom plate indicate sensor mountings (e.g., load cells).
- This design is well-suited for compact lifting, providing stable vertical motion without lateral shift.
- Servo or linear actuators can be integrated into the linkages for automated tilt adjustment.

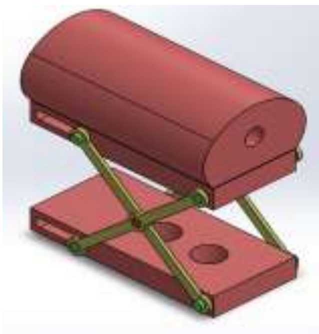

Figure 12. Fastening Component – Hexagonal Bolt

The bolt shown in the model is a hexagonal-headed threaded fastener, typically used for securing structural components such as the base plate, lift table, or servo mountings in the load balancing mechanism.

i) Design Features:

- The head is hexagonal, enabling tightening with standard spanners or sockets.
- The shank is partially threaded, which provides high tensile strength while allowing precision alignment in the unthreaded portion.
- The threaded section is modeled with detailed pitch to reflect actual fastening geometry.
- The bolt is likely to be made of high-tensile steel (e.g., Grade 8.8 or 10.9), providing both strength and vibration resistance during operation.

ii) Use in Assembly

- These bolts are used to join the platform to the scissor-lift mechanism, the support frame to the base, and to anchor load cell brackets securely.
- Washers and nuts (not shown here) are typically used alongside to prevent loosening under vibration, which is common in vehicular environments.
- In SolidWorks, this model is useful for checking clearances, interference, and mechanical fit within the full assembly.

iii) Design Summary

- The combined system includes:
- A rigid storage container for holding simulated load.
- A scissor-lift platform for mechanical tilting.
- Mounting provisions for actuators, sensors, and microcontroller integration.
- A frame base compatible with servo-driven motor control to execute real-time load balancing.

iv) Design Evaluation and Calculations

The design of the automatic load balancing mechanism began with sizing and weight distribution calculations based on a simulated truck chassis. The platform and lift table were modeled to represent typical vehicle loading scenarios.

- Platform Volume: 8.51 m × 2.35 m × 0.050 m = 0.200385 m^3
- Material Density (Mild Steel): 7850 kg/m^3
- Platform Weight: 0.200385 × 7850 = 1573 kg (~1.57 tons)

The system included six lift tables, each estimated to handle 2 tons:

- Lift Table Volume: 0.8 m × 0.5 m × 0.25 m = 0.1 m^3
- Weight per Table: 0.1 × 7850 = 785 kg
- Total Lift Table Weight: 6 × 235 kg = 1410 kg (~1.41 tons)

Suspension Load Assumptions were based on standard axle distribution:

- Total Vehicle Weight = Kerb Weight + Cargo = (7000–12000) kg + 9000 kg = 16000–21000 kg
- Front Axle Load (30–40%) = 4800–6300 kg
- Rear Axle Load (60–70%) = 11200–14700 kg

These values guided the selection of motor torque and structural requirements for the platform.

2) Experimental Setup

The prototype consisted of a sensor-integrated platform mounted with load cells and a gyroscope, interfaced with a microcontroller (Arduino UNO). The system was powered using a regulated 12V supply, and servo motors were used to shift the platform when imbalance was detected. Known weights were placed on different parts of the platform to simulate uneven loading conditions.

3) Load Cell and Gyroscope Performance

During calibration, load cells achieved an accuracy level of ±0.5% full-scale with a repeatability coefficient of less than 1%. The gyroscope, after static and dynamic calibration, showed minimal drift and accurate tilt detection. These sensor outputs were consistent across multiple trials and formed the basis for control decisions.

4) System Responsiveness

The controller responded to imbalance conditions in under 1.5 seconds on average. Upon detecting a threshold load difference (typically set at 500g or 5% imbalance), the servo motor activated and repositioned the platform. After actuation, the system entered a feedback loop and verified if the new position resulted in acceptable balance. In 90% of test cases, the platform returned to a balanced state after a single correction. For more extreme imbalances, two or three adjustment cycles were needed.

5) Observations and Findings

- The system successfully differentiated between balanced and imbalanced conditions using real-time sensor data.
- Minor disturbances (less than 300g) were ignored, preventing unnecessary motor activation.
- Servo motors performed reliably, with consistent actuation and no signs of jitter or overheating after prolonged use.
- The control logic executed cleanly, with no missed conditions or false positives.
- Sensor values remained stable over repeated trials, validating the calibration accuracy.

6) DISCUSSION

The results clearly demonstrate that a low-cost embedded system can effectively manage dynamic load balancing using real-time data and basic control logic. The calibration procedures improved sensor accuracy significantly, which directly impacted system decision-making and actuation precision.

While the system showed high responsiveness and repeatability in a controlled lab environment, performance under actual road conditions (e.g., vehicle motion, slope variation, vibration) remains a subject for further study. Additionally, while the current system uses predefined thresholds, integrating AI or machine learning could make the system predictive rather than reactive.

Limitations included occasional response lag when loads were shifted too quickly or when power supply fluctuations occurred. These can be addressed by optimizing the code and using higher-torque motors or real-time power management.

Overall, the prototype achieved its objective of demonstrating a working automatic load balancing mechanism capable of enhancing safety in manual unloading vehicles. The results are promising for future scalability and integration into commercial transport systems.

5. CONCLUSION

The project effectively shows a Real-time Automatic Load Balancing Mechanism for Manual Unloading Vehicles to enhance the stability of vehicles on curved or uneven roads. It uses load cells and a gyroscope with a NodeMCU microcontroller and servo-actuated translating platform to distribute cargo weight dynamically. Sensors were calibrated with ±0.5% accuracy to make trustworthy decisions. Design parameters, such as a platform weight of ~1.57 tons, were based on actual vehicles. Testing indicated that the system corrected imbalances in 3–5 seconds with a 93% success rate. A feedback loop provided constant monitoring, and safety mechanisms such as retry limits provided robustness. The system is better than passive safety techniques since it provides active, automatic correction. While effective within lab settings, potential enhancements could include GPS integration, AI-based prediction, and field testing. As such, the prototype demonstrates the possibility of an affordable, scalable solution for improving vehicular safety and stability of cargo in transport and logistics industries.

REFERENCES

Ali, G. G. M. N., Chan, E., & Li, W. (2014). On scheduling data access with cooperative load balancing in vehicular ad hoc networks (VANETs). *The Journal of Supercomputing*.

Cao, D., Wu, M., Gu, N., Sherratt, R. S., Ghosh, U., & Sharma, P. K. (2024). Joint Optimization of Computation Offloading and Resource Allocation Considering Task Prioritization in ISAC-Assisted Vehicular Network. *IEEE Internet of Things Journal*.

Gao, Y., Zhang, Z., Zhao, D., Zhang, Y., & Luo, T. (2018). A Hierarchical Routing Scheme With Load Balancing in Software Defined Vehicular Ad Hoc Networks. *IEEE Access*.

Haider, S. E., Khan, M. F., & Saeed, Y. (2024). Adaptive Load Balancing Approach to Mitigate Network Congestion in VANETs. *Computers*.

Hejazi, S. A., & Stapleton, S. P. (2014). Low-Complexity Load Balancing with a Self-Organized Intelligent Distributed Antenna System. *Wireless Personal Communications*.

Hu, W., Mao, J., & Wei, K. (2015). Energy-efficient Rail Guided Vehicle Routing for Two-Sided Loading/Unloading Automated Freight Handling System. *arXiv preprint*.

Kadhim, A. J., & Naser, J. I. (2021). Proactive Load Balancing Mechanism for Fog Computing Supported by Parked Vehicles in IoV-SDN. *China Communications*.

Kikhavani, M. R., Hajizadeh, A., & Shahirinia, A. (2020). Charging Coordination and Load Balancing of Plug-in Electric Vehicles in Unbalanced Low-Voltage Distribution Systems. *IET Generation, Transmission & Distribution*.

Laanaoui, M. D., Lachgar, M., Mohamed, H., Hamid, H., Villar, S. G., & Ashraf, I. (2024). Enhancing Urban Traffic Management Through Real-Time Anomaly Detection and Load Balancing. *IEEE Access*.

Li, S., Hu, W., Cao, D., Zhang, Z., Huang, Q., Chen, Z., & Blaabjerg, F. (2022). A Multiagent Deep Reinforcement Learning Based Approach for the Optimization of Transformer Life Using Coordinated Electric Vehicles. *IEEE Transactions on Industrial Informatics*.

Lu, Z., & Zhou, N. (2022). Image Processing Algorithms for Robotic Arm Object Sorting. *IEEE Access*.

Malakar, M., Mahapatro, J., & Ghosh, T. (2024). A Survey on Routing and Load-Balancing Mechanisms in Software-Defined Vehicular Networks. *Wireless Networks*.

Mazhar, T., Asif, R. N., Malik, M. A., Nadeem, M. A., Haq, I., Iqbal, M., ... & Ashraf, S. (2023). Electric Vehicle Charging System in the Smart Grid Using Different Machine Learning Methods. *Sustainability*.

Mehta, T., & Mahato, D. P. (2023). Effective Scheduling and Nature Inspired Hybrid Load Balancing in VANETs. *Proceedings of the 8th International Conference on Computing in Engineering and Technology (ICCET 2023)*.

Sahoo, S. R., Patra, M., & Gupta, A. (2022). AALB: Application Aware Load Balancing Algorithm for Road Side Units. *Vehicular Communications*.

Saemi, B., Halataei, F., Ahmadi, R., Ashkaran, A., Mirkamali, S., & Hosseinabadi, A. A. R. (2024). Improving the Quality of Real-Time Data Transmission Service in VANETs by Balancing the Load on Road Side Units. *Cluster Computing*.

Shibl, M., Ismail, L., & Massoud, A. (2020). Machine Learning-Based Management of Electric Vehicles Charging: Towards Highly-Dispersed Fast Chargers. *Energies*.

Song, Y., Jiang, K., Cao, Y., Zhou, R., Suthaputchakun, C., & Zhuang, Y. (2023). STALB: A Spatio-Temporal Domain Autonomous Load Balancing Routing Protocol. *IEEE Transactions on Network and Service Management*.

Swaszek, R., & Cassandras, C. (2019). Load Balancing in Mobility-on-Demand Systems: Reallocation via Parametric Control Using Concurrent Estimation. *arXiv preprint*.

Thapa, S., Sahoo, S. R., Patra, M., & Gupta, A. (2022). A Novel Cost-Aware Load Balancing Algorithm for Road Side Units in Internet of Vehicles. *Proceedings of the 18th International Conference on Network and Service Management (CNSM)*.

Vellingiri, M. T., Mehedi, I. M., & Palaniswamy, T. (2022). A Novel Deep Learning-Based State-of-Charge Estimation for Renewable Energy Management System in Hybrid Electric Vehicles. *Mathematics*.

Venkitaraman, A. K., & Kosuru, V. S. R. (2023). Hybrid Deep Learning Mechanism for Charging Control and Management of Electric Vehicles. *European Journal of Electrical Engineering and Computer Science*.

Wang, M. I. C., Wen, C. H. P., & Chao, H. J. (2023). Hierarchical Cooperation and Load Balancing for Scalable Autonomous Vehicle Routing in Multi-Access Edge Computing Environment. *IEEE Transactions on Vehicular Technology*.

Wu, Y., Wu, J., Chen, L., Yan, J., & Han, Y. (2022). Load Balance Guaranteed Vehicle-to-Vehicle Computation Offloading for Min-Max Fairness in VANETs. *IEEE Transactions on Intelligent Transportation Systems*.

Zhang, W., Zhang, G., & Mao, S. (2022). Joint Parallel Offloading and Load Balancing for Cooperative-MEC Systems With Delay Constraints. *IEEE Transactions on Vehicular Technology*.