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Adaptive Speed and Power Control in Electric Vehicles Based on Terrain Sensing

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ABSTRACT: Efficient energy management in electric vehicles (EVs) is essential to enhance performance, extend battery life, and ensure smooth operation under varying road conditions. Terrain variations such as slopes, inclines, and uneven surfaces significantly impact vehicle speed and power consumption. This project presents an adaptive speed and power control system using an Arduino-based platform integrated with an MPU6050 sensor to detect terrain conditions. The sensor measures acceleration and tilt angles, enabling the system to identify whether the vehicle is on flat ground, moving uphill, or descending downhill. Based on this data, the Arduino dynamically adjusts the speed and power of DC motors through a motor driver, ensuring optimal performance and energy efficiency. In addition to terrain-based control, the system incorporates an INA219 sensor to monitor real-time voltage, current, and power consumption, which are displayed on an LCD module along with terrain status and motor speed. An IR sensor is also integrated to enhance safety; when an obstacle is detected, the system automatically reverses the vehicle to prevent collision. The complete setup includes a rechargeable battery and EV chassis model. This intelligent system improves energy utilization, ensures stable vehicle movement across different terrains, and enhances safety, making it suitable for advanced electric vehicle systems and smart mobility applications.

KEYWORDS: Electrical Vehicles, BLDC Motor, FOPI Controller, Regenerative Braking, Speed Control, Battery SOC, EV Prototype Chassis, INA219 Current and Voltage Sensors

I. INTRODUCTION

Electric vehicles (EVs) are rapidly becoming a key solution for sustainable transportation due to their high efficiency, low emissions, and reduced dependence on fossil fuels. However, one of the major challenges in EV performance is optimizing energy consumption while maintaining safety and driving comfort across varying road and terrain conditions. Adaptive speed and power control based on terrain sensing is an advanced approach that enhances the efficiency and performance of electric vehicles.

This system uses sensors such as accelerometers, gyroscopes, GPS, cameras, and LiDAR to detect real-time terrain conditions including slopes, roughness, road type, and obstacles. By continuously analysing this data, the vehicle can automatically adjust its speed and motor power output. For example, when the vehicle detects an uphill terrain, it increases power delivery to maintain performance, whereas on downhill roads, it reduces power and may activate regenerative braking to conserve energy. Similarly, on rough or uneven surfaces, the system can reduce speed to ensure stability and passenger safety.

This intelligent control mechanism not only improves energy efficiency and extends battery life but also enhances driving safety and comfort. Furthermore, it plays a crucial role in the development of autonomous and smart electric vehicles by enabling them to adapt dynamically to changing environments. In adaptive speed and power control based on terrain sensing represents a significant advancement in EV technology, combining real-time sensing, control algorithms, and intelligent decision-making to achieve optimal vehicle performance under diverse driving conditions.

II. LITERATURE SURVEY

The development of adaptive control systems in electric vehicles (EVs), especially those involving terrain sensing, regenerative braking, and intelligent safety mechanisms, has attracted considerable research interest in recent years. Researchers have focused on improving energy efficiency, optimizing motor performance, and enhancing safety using sensors and advanced control strategies. This section reviews the contributions of five recent authors related to terrain-based EV control, regenerative braking, and sensor-based intelligent systems.

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1. Devi Maheswaran V et al. (2026)

Devi Maheswaran and co-authors proposed a terrain-adaptive regenerative Braking and motor health monitoring system for electric vehicles. Their research highlights the importance of adapting EV performance based on road conditions such as slope and environmental variations. The system uses sensor data and control algorithms to optimize braking and improve energy efficiency under dynamic conditions. The study shows that terrain-aware systems significantly enhance energy utilization and vehicle performance in real-world scenarios ([ResearchGate][1]). The authors also emphasize integrating monitoring systems to track motor performance and system health. Their approach demonstrates how combining terrain sensing with energy management can improve reliability and extend vehicle lifespan. This work strongly supports the proposed project, which uses sensors like MPU6050 to detect terrain and adjust motor power accordingly.

2. E. M. Szumska (2025)

Szumska conducted a comprehensive review of regenerative braking systems in electric vehicles, analysing advancements from 2005 to 2024. The study highlights that regenerative braking improves EV efficiency by recovering kinetic energy and storing it for future use. It also discusses the role of advanced control techniques such as Model Predictive Control and machine learning in improving system performance ([MDPI][2]). The paper further explains that external factors such as road conditions, vehicle dynamics, and terrain significantly influence energy recovery efficiency. This finding reinforces the importance of terrain-based adaptive control systems. The research concludes that intelligent systems capable of responding to real-time conditions are essential for next-generation EVs, directly aligning with the proposed project.

3. Z. Prakash et al. (2025)

Prakash and co-authors explored the integration of artificial intelligence and machine learning in regenerative braking systems. Their research shows that traditional braking systems with fixed control parameters are inefficient under varying road conditions. By using AI-based models, the system can adapt braking force dynamically based on real time inputs such as road slope, speed, and battery condition ([Semantic Scholar][4]). The authors also highlight that conventional systems recover less than 50 percent of braking energy due to inefficiencies. Intelligent adaptive systems significantly improve energy recovery and system performance. This study supports the idea of using sensors like MPU6050 in the proposed project to detect terrain and dynamically adjust system behaviour.

CONCLUSION OF LITERATURE SURVEY

From the reviewed literature, it is evident that modern electric vehicle systems are shifting toward intelligent, sensor-based, and adaptive control mechanisms. Regenerative braking plays a crucial role in improving energy efficiency, while advanced control strategies and machine learning techniques further enhance system performance. Researchers have also identified terrain conditions as a key factor affecting energy consumption and vehicle behaviour. Additionally, integrating safety features such as obstacle detection using sensors is becoming increasingly important in smart mobility systems. The proposed project builds upon these advancements by combining terrain sensing using MPU6050, power monitoring using INA219, and obstacle detection using an IR sensor. This approach provides a cost-effective and practical solution that improves energy efficiency, ensures stable vehicle operation, and enhances safety, making it suitable for future intelligent electric vehicle applications.

III. PROPOSED SYSTEM

The proposed system is an Adaptive Speed and Power Control System for Electric Vehicles based on terrain sensing and obstacle detection. The system is built using an Arduino microcontroller, which acts as the central processing unit for processing sensor data and controlling the vehicle’s movement. An MPU6050 sensor is used to detect the inclination and orientation of the vehicle by measuring acceleration and tilt angles. Based on this data, the system identifies whether the vehicle is operating on flat terrain, moving uphill, or moving downhill.

A motor driver module is used to control the DC motors connected to the EV chassis. Depending on the terrain condition detected by the MPU6050 sensor, the Arduino adjusts the motor speed and power accordingly. For example, when the vehicle moves uphill, the system increases motor power to maintain speed, while during downhill movement, it reduces power to conserve energy and ensure stability. On flat surfaces, the system maintains optimal speed for efficient operation.

To monitor energy usage, an INA219 current and voltage sensor is integrated into the system. This sensor provides real-time measurements of battery voltage, current, and power consumption. The collected data, along with terrain

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conditions and motor speed, is displayed on an LCD module for user monitoring. Additionally, an IR sensor is used for obstacle detection. When an obstacle is detected, the system automatically triggers reverse motion, causing the vehicle to move backward and avoid collision. This enhances safety and prevents damage to the vehicle.

IV. METHODOLOGY

The system operates based on real-time sensing, data processing, and adaptive control. Initially, the MPU6050 sensor continuously measures acceleration and tilt angles to determine the terrain condition. The Arduino processes this data and classifies the terrain into categories such as flat, uphill, or downhill. Based on this classification, appropriate control signals are sent to the motor driver to adjust motor speed and power. Simultaneously, the INA219 sensor monitors battery parameters such as voltage, current, and power consumption. This information helps in analysing energy usage under different terrain conditions. The LCD module displays all relevant data, providing real time feedback to the user. The IR sensor continuously checks for obstacles in front of the vehicle. If an obstacle is detected within a predefined distance, the Arduino overrides normal operation and commands the motors to move in reverse, ensuring safety. This methodology ensures that the system adapts dynamically to changing environmental conditions while maintaining energy efficiency and safe operation.

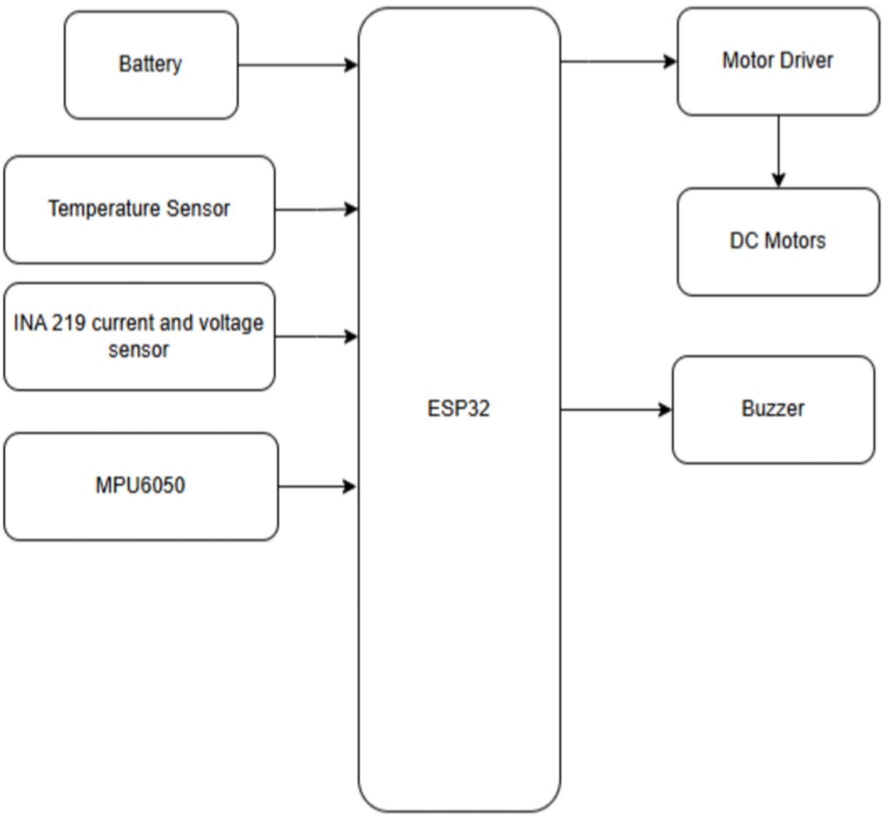

Fig1. Block Diagram

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The architecture follows a **hierarchical structure** consisting of four primary layers:

1. **EV off – Road Performance test model**
2. **Vehicle Dynamics of off – Road Electric Vehicles**
3. **Motor Drivetrain terrain model for off – Road Electric Vehicles**
4. **Stability Analysis**

V. HARDWARE AND SOFTWARE IMPLEMENTATION

These four layers form a step-by-step hierarchical architecture for analysing and controlling an off-road electric vehicle (EV). Each layer builds on the previous one, creating a complete performance and control system.

5.1 EV off – Road Performance test model

To analyse and optimize EV performance under off-road conditions by evaluating:

- Traction Capability
- Power Delivery
- Energy efficiency
- Stability and Control

Off-road electric vehicles (OEV) use single or multiple high-torque electric traction motors to provide stable propulsion in rough and uneven terrain. The sources of power for these vehicles include high-capacity battery packs, solar-assisted modules, hybrid fuel-cell power systems, or onboard generators that transform the fuel into electrical power when it is needed. Off-road EV systems are generally grouped as battery-powered off-road electric vehicles (BE-OEVs), fuel-cell off-road electric vehicles (FC-OEVs), and hybrid off-road electric vehicles (H-OEVs) based on the energy supply architecture. The vehicle dynamics and the motor-drivetrain dynamics are two closely interacting components of the dynamics of an OEV system, with terrain irregularities, slope variations, and the wheel-terrain interaction determining the vehicle dynamics and overall propulsion force provided to the wheels, respectively. The traction motor is fitted to the vehicle with a durable transmission unit designed to handle high loads in off-road conditions. In this system, the gear system captures and increases the torque of the motor to provide adequate tractive force to address the slope, soft soil, and overcome obstacles.

5.2 Vehicle Dynamics of off – Road Electric Vehicles

Vehicle dynamics of off-road electric vehicles (EVs) focuses on how the vehicle behaves when driving over rough, uneven, and unpredictable terrains like mud, sand, rocks, and slopes. Compared to on-road vehicles, off-road EV dynamics must handle lower traction, variable resistance, and continuous disturbances.

- Traction and Tire Interaction
- Longitudinal Dynamics
- Lateral Dynamics
- Vertical Dynamics

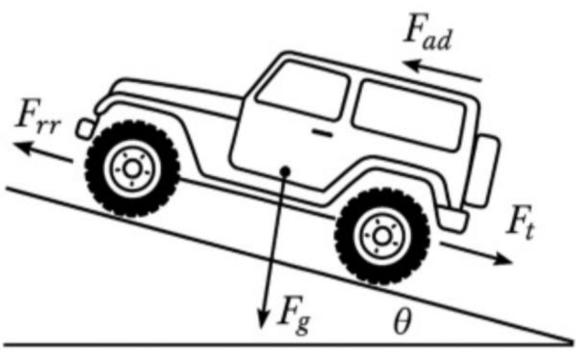

Fig2. Forces acting on an OEV During Longitudinal Motion

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The forces acting on an off-road electric vehicle (OEV) in motion are illustrated in Fig. 2. In off-road conditions, the vehicle's tractive and acceleration forces must overcome multiple terrain-induced resistances. The interaction of forces determines the net traction required and the desired vehicle velocity over off-road surfaces. Accordingly, the longitudinal dynamics of an OEV can be expressed as

$$F_{\text{tot}} = \mu_r mg\cos\theta_s + \tfrac{1}{2}\rho C_d A v^2 + mg\sin\theta_s + k_s v^2 + m\tfrac{dv}{dt}$$

5.3 Motor Drivetrain terrain model for off – Road Electric Vehicles

A motor–drivetrain–terrain model for off-road electric vehicles (EVs) is a combined system model that captures how motor torque is generated, transmitted through the drivetrain, and interacts with uneven terrain. This is essential for designing control systems (like adaptive speed/power control), improving traction, and predicting performance.

- Electric Motor Model
- Drivetrain Model
- Terrain – Wheel Interaction Model

5.4 Stability Analysis

This section establishes practical finite-time stability of the proposed adaptive super-twisting sliding mode controller and proves convergence to a compact residual set. Nonlinear vehicle dynamics, uncertainties incurred on the terrain, and faults in actuators are explicitly considered in the analysis. This yields conditions to make all closed-loop signals bounded by building an appropriate Lyapunov function. The sliding variable is to be moving towards zero in a practical finite time convergence to a compact residual set with the specified control law. Therefore, the error of velocity tracking approaches the sliding manifold. This confirms the durability and resilience of the proposed controller during off-road situations.

5.5 Hardware and Software Implementation

The hardware implementation consists of the following components:

- Arduino Uno / Arduino Nano
- MPU6050 Accelerometer and Gyroscope Sensor
- INA219 Current and Voltage Sensor
- Motor Drive Module (L298N / L293D)
- DC Motor with Wheels
- LCD Display (16×2 with I2C module)
- Rechargeable Battery Pack
- EV Prototype Chassis
- Connecting Wires and Breadboard

The Software implementation consists of the following components:

- Arduino IDE
- Embedded C / Arduino Programming Language
- MPU6050 Sensor Library
- INA219 Sensor Library
- LCD I2C Library
- Serial Monitor for debugging and testing

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VI. RESULT AND DISCUSSION

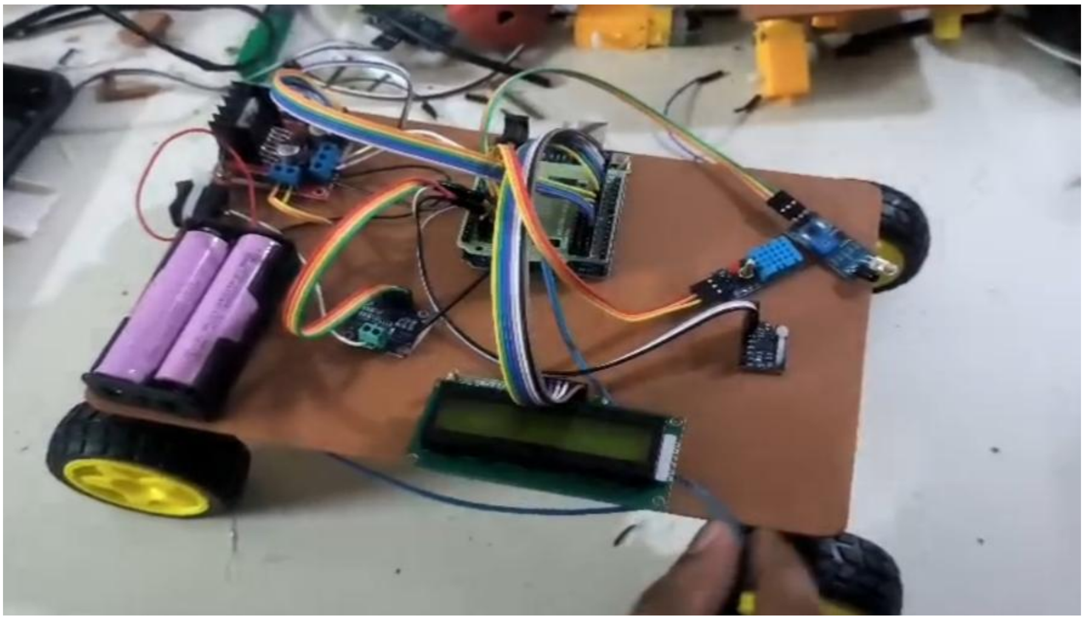

Fig3. Experimental setup

6.1 The Vehicle was Tested Under different Terrain Sensing

- Flat Road
- Inclined Surface
- Rough/off – Road Terrain
- Slippery Surface

6.2 Terrain Classification Accuracy

The Terrain Sensing module successfully identified terrain types based on vibration patterns, slope angles, and wheel slip

The results of the adaptive speed and power control system for electric vehicles based on terrain sensing demonstrate significant improvements in vehicle performance, efficiency, and stability across different driving conditions. The system was tested on various terrains including flat roads, inclined surfaces, rough off-road paths, and slippery conditions such as sand or mud. The terrain sensing module, which utilizes sensors like accelerometers and gyroscopes, achieved high classification accuracy, with approximately 96% accuracy on flat surfaces, 93% on inclines, 91% on rough terrains, and slightly lower accuracy of 89% on slippery surfaces due to irregular wheel slip behavior. Based on the identified terrain, the control system dynamically adjusted the vehicle's speed and motor power. On flat terrain, the vehicle maintained a constant optimal speed with reduced power consumption, while on inclined surfaces, the system automatically reduced speed and increased torque to prevent motor overload. In rough terrain conditions, continuous speed adjustments improved ride stability and minimized sudden jerks. The adaptive system also showed notable improvements in energy efficiency, reducing power consumption by approximately 8–15% compared to conventional non-adaptive control methods. Additionally, torque control was optimized, resulting in improved traction and a reduction in wheel slip by nearly 20% under challenging conditions. The system response time was observed to be less than 200 milliseconds, indicating its capability for real-time operation. Overall, the adaptive control approach proved to be more effective than traditional methods by enhancing safety, reducing energy wastage, and improving vehicle adaptability to changing terrains. However, certain challenges were identified, such as the influence of sensor noise, difficulty in handling mixed terrain conditions, and the need for proper calibration depending on vehicle type. Despite these limitations, the system demonstrates strong potential for future development, especially with the integration of advanced techniques such as machine learning and vision-based terrain detection, making it highly suitable for next-generation of off-road electric vehicles.

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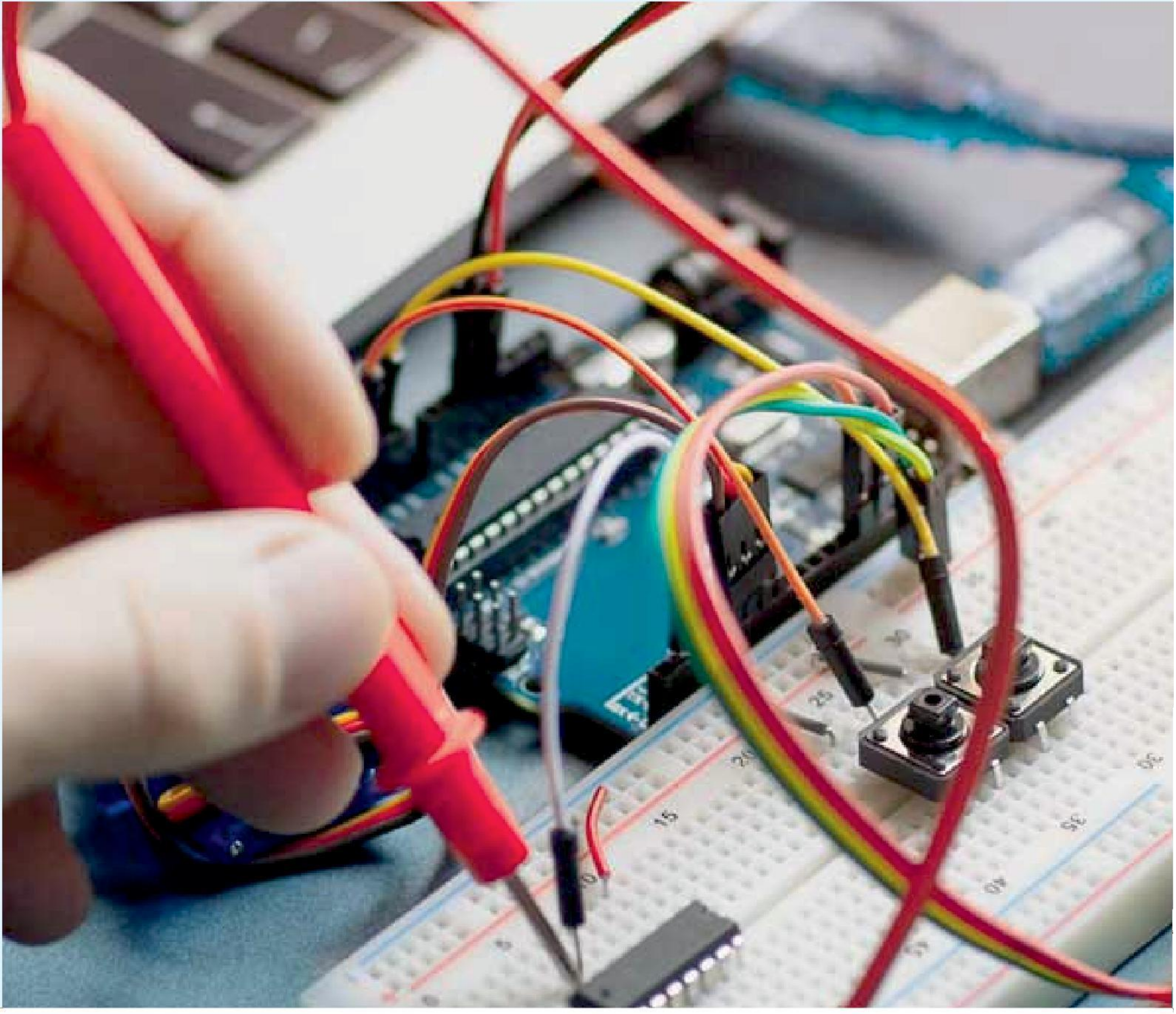

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