iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 Issue: VIII Month of publication: August 2026

DOI: https://doi.org/10.22214/ijraset.2026.84549

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VIII Aug 2026- Available at www.ijraset.com

Self-Balancing Electric Unicycle

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Abstract: The design and development of a self-balancing electric unicycle (EUC) aimed at improving safety, durability, and user customization compared to existing personal electric vehicles is presented in this paper. Current commercially available unicycles often prioritize cost reduction and mass production, resulting in limited repairability, reduced structural integrity, and insufficient user-centered design features. To address these limitations, a multidisciplinary engineering approach integrating mechanical and electrical designs is presented in this paper.

The EUC was designed around an architecture that incorporates a programmable brushless motor controller derived from the 100V/250A variant of the open-source VESC project. The controller was designed to support a maximum phase current of 300A and a maximum battery current of 120A. Real-time balance control is achieved using an inertial measurement unit (IMU) to measure pitch angle and angular velocity. A closed-loop proportional–integral–derivative (PID) control algorithm processes sensor data and regulates motor current to implement balance and acceleration. It uses a 24s battery configuration with a maximum operating voltage of 100.8 V and EVE 40PL "tabless" 21700 lithium-ion cells. The robust aluminum frame used in the design improves its structural reliability while maintaining manufacturability and cost efficiency. Additionally, a modular accessory system was employed to enhance utility, including features such as storage integration, ergonomic improvements, and customizable external components. Computer-aided design tools, specifically Fusion 360, were used extensively to model the system and evaluate component integration. Electrical subsystems, including an LED lighting system and power distribution, were designed and validated through schematic development. Analytical modeling and subsystem validation indicated that the design met all its intended performance objectives. The maximum speed was estimated to be around 43mph / 70kmh. It weighs about 35kg and has a capacity exceeding 140kg. A road test of the final design was successfully performed.

Keywords: Electric Unicycle, LED, Battery box, Kick stand, 3D Printer

I. INTRODUCTION

Personal electric vehicles, particularly designed as a self-balancing electric unicycle, in urban environments suitable for short distance commuting is becoming extremely popular. Urban commuters and college students require a transportation solution that is affordable, portable, and capable of handling a variety of real-world conditions. These unicycles have a minimal environmental impact, as they do not burn fossil fuels, contributing to the goal of achieving zero emissions for global warming. A detailed comparative study of carbon emissions generated due to EUC's, and other automobiles is presented in [1]. Their study shows significant reduction in greenhouse gas emissions due to the use of EUC's. By reducing road congestion, especially in densely populated areas, electrical unicycles facilitate efficient movement of emergency service vehicles, ensuring timely response during emergencies. Physically, riding an electrical unicycle strengthens core muscles and improves physical balance, prompting overall wellbeing.

EUCs therefore provide a compact and efficient transportation solution, especially in areas where traditional vehicles are impractical. As more individuals acquired the necessary skills and gained a deeper understanding of unicycles, their popularity surged due to the improvement in speed and enhanced safety features. However, despite their growing adoption, many existing designs still suffer from critical shortcomings related to safety, durability, and maintainability. Many of these issues stem from material cost cutting and an overreliance on plastics.

The first electric unicycle ever patented is by Charles L. Gabriel [2]. A commercial site showing a variety of available EUCs is presented in [3]. This site shows the very simplest models all the way to the most advanced ones. A prototype EUC with an aluminum structure with a low gravity center for its balance, using a three-phase synchronous Brushless motor with permanent magnet rotor and two lateral platforms is presented in [4]. Their design used a lithium-iron-phosphate battery (12V) and a gyroscopic sensor that sends the signals to a Brushless electric motor of 500W.

An electric unicycle design using a 215 W brushless DC motor is presented in [5]. They used circular pipes for the fabrication of the frame. The vehicle can attain a maximum speed of 15–20 km/hr and travel up to 10 km in a single charge. It weighs approximately 40 kg and its load carrying capacity is around 100 kg. A study conducted by a hospital in Korea noticed that out of the fifty patients injured by isolated e-scooter accidents, 45 (90%) had fallen off their e-scooter due to a simple loss of balance [6]. This highlights the importance of balancing the unicycle. A thorough review that examines various control strategies and structural designs that enhance unicycle stability is presented in [7]. A modified design of electric unicycle with a focus on stability and usability is presented in [8]. They added two small wheels on both sides of the unicycle thereby reducing the tendency of toppling to the lateral direction. Through research and observation, it became evident that many commercially available unicycles are designed with a focus on cost reduction rather than long-term reliability. Design choices such as the use of proprietary fasteners, limited accessibility to internal components, and reliance on poorly constructed balance control loops create challenges for users when maintenance or repairs are required. Additionally, these products often lack user-centric features such as seats and power pads that vastly improve comfort, usability, and customization. Hence there is a clear need for a safer, more dependable, and more accessible personal electric vehicle. Existing solutions often present several limitations, such as prohibitive cost for dependable models, limited repairability and access to components, poor adaptability to different terrains, lack of beginner-friendly control features, and limited customization options. These shortcomings negatively impact user experience and contribute to safety concerns. Furthermore, users are often dependent on manufacturers for repairs and system maintenance, which further highlights the need for a more user-focused and serviceable design. In this research, we focus on exploring a more practical and engineering-focused approach to unicycle design, emphasizing simplicity, reliability, and improved user experience. Improving electric unicycles in the context of public health, safety, and welfare is our primary focus. Since unicycles ae typically used on sidewalks, a traffic system is essential to ensure harmony with pedestrians. This would include bright lights, special signaling systems, and GPS guidance to help users navigate crowded areas to reach their destination safely.

II. FUNCTIONAL DESCRIPTION

The self-balancing electric unicycle is designed as an integrated electromechanical system that combines mechanical support, electrical power delivery, and real-time control to maintain rider stability. The system operates by continuously monitoring the rider's center of gravity and dynamically adjusting motor torque to maintain balance. Figure 1 shows a functional flow of the unicycle [9]. The main components comprise a brushless DC motor, rechargeable lithium-ion batteries, gyroscopic sensors, accelerometers, and a microcontroller for processing inputs to regulate balance. At the core of the system is a high-voltage electrical architecture, designed to support efficient power delivery to both the motor and auxiliary subsystems. Real-time data from an internal inertial measurement unit (IMU) which includes gyroscopic and accelerometer inputs is fed to the microcontroller. The microcontroller processes the data and controls the motor controller, which maintains the balance of the unicycle. This allows the system to detect changes in rider position and instantly respond with corrective torque.

The mechanical structure consists of an aluminum frame that supports the motor, battery system, and external components. The frame is designed to minimize deformation under load while maintaining a compact and lightweight form factor. Structural integrity is essential for both safety and performance, particularly during acceleration, braking, and turning.

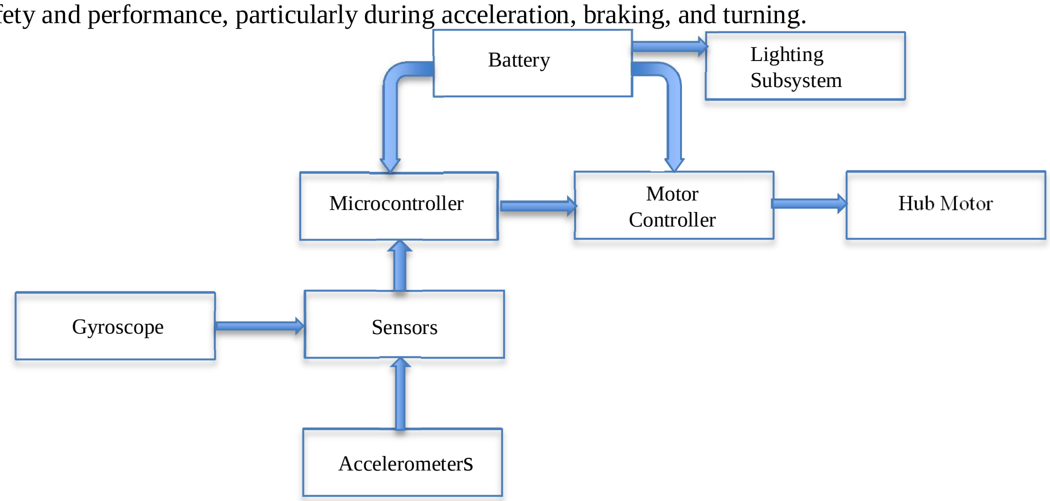

Fig. 1 A functional flow of self-balancing electric unicycle [9]

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In addition to the primary drive system, the unicycle includes a dedicated LED lighting subsystem for visibility and safety. The LED system is powered through a constant-current driver and includes both front-facing lights and a rear LED strip. The system incorporates a step-down voltage module to regulate voltage for lower-power components, ensuring safe and efficient operation across all electrical loads. The system is also designed with user interaction in mind. External features such as accessory mounts, ergonomic surfaces, and modular components enhance usability and allow for customization. These features contribute to a more practical and user-friendly design, particularly for everyday commuting applications. Overall, the system functions as a closed-loop control system, where electrical, mechanical, and software components work together to maintain balance, ensure safety, and provide a smooth riding experience.

III. DESIGN

A. Design Approach

Our preliminary design phase explored multiple configurations of the unicycle, with an emphasis on user-centered design and customization. Rather than limiting the design to a single configuration, several conceptual models were developed to evaluate how unique features would impact usability, comfort, and functionality. Fusion 360 was used as the primary CAD tool to visualize and refine these concepts. The goal of this phase was not only to define the structural layout of the system, but also to explore how additional features could enhance the overall user experience.

A robust aluminum frame is used as a primary structural skeleton, selected specifically for its high strength-to-weight ratio and excellent corrosion resistance, which ensures the chassis can support the weight of the motor and battery system without excessive mass. Stainless steel is strategically integrated into high-stress mounting points and fasteners were added to provide superior mechanical durability and resistance to fatigue. To complement this metallic core, additive manufacturing is employed for external housing and specialized components; ABS (Acrylonitrile Butadiene Styrene) provide rigid, impact-resistant enclosures that maintain dimensional stability near heat-generating electronics, while TPU (Thermoplastic Polyurethane) is utilized for gaskets and vibration dampening. By combining the precision of 3D-printed polymers with the rigidity of an aluminum and steel framework, the design achieved a balance of accessibility, ease of manufacturing, and professional-grade structural integrity.

B. Mechanical Design

The mechanical system consists of a central aluminum frame, motor mounting plates, battery enclosure, and external housing components. The frame is designed to withstand dynamic loads during operation, including rider weight, acceleration forces, and external impacts. Structural components were designed to minimize deformation while maintaining a compact form factor. Fusion 360 was used extensively to model the system and ensure proper integration of all components.

CAD models were used to verify component fit and spacing, optimize structural geometry, and to plan assembly and manufacturing processes. The initial CAD design was made in Fusion360 and then imported into ANSYS to check what the general behavior of the structure was under expected forces. The initial frame was noted to exhibit stress concentrators on the design.

After the frame's design was discovered to be structurally sound in ANSYS and the stress values discerned, the base frame design was finalized, made dimensionally accurate and re-evaluated in ANSYS. This is shown in Figure 2. The frame is designed to withstand dynamic loads during operation, including rider weight, acceleration forces, and external impacts. Structural components were designed to minimize deformation while maintaining a compact form factor. The final frame designed is shown in Figure 3. Because the critical control electronics are mounted directly to the aluminum chassis, a custom-engineered cover plate was developed to serve as both a protective barrier and a primary ergonomic interface as shown in Figure 3. This creates a secure, weather-resistant enclosure that isolates sensitive circuitry and wire harnesses from external debris and mechanical impact, while maintaining a streamlined profile. Beyond protection, the plate's geometry was accurately calculated to elevate the top surface to a standardized ride height, ensuring that the center of mass remains optimized for self-balancing stability without compromising rider comfort. This elevated deck provides a robust, flat mounting plane designed with integrated hardpoints to support modular external hardware. By establishing this structural surface, the design allows for the seamless addition of a seat assembly or auxiliary storage racks, transforming the unicycle from a standing platform into a versatile, multi-modal transportation device. These design considerations ensure that the integration of the internal electrical systems does not dictate a compromise in the vehicle's external utility or aesthetic finish.

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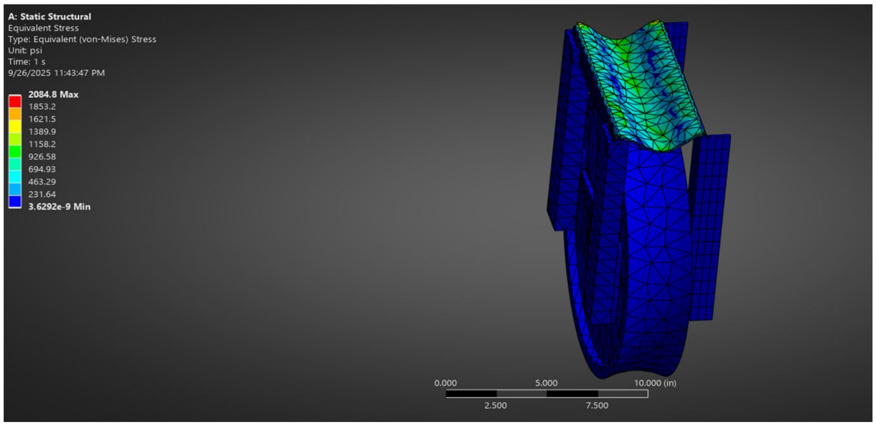

Tabular Data

	Time [s]	Minimum [psi]	Maximum [psi]	Average [psi]
1	0.2	7.2203e-010	416.96	11.19
2	0.4	1.4488e-009	833.92	22.379
3	0.7	2.539e-009	1459.4	39.163
4	1.	3.6292e-009	2084.8	55.948

Fig. 2 The dimensionally accurate frame model in ANSYS and von mises stress

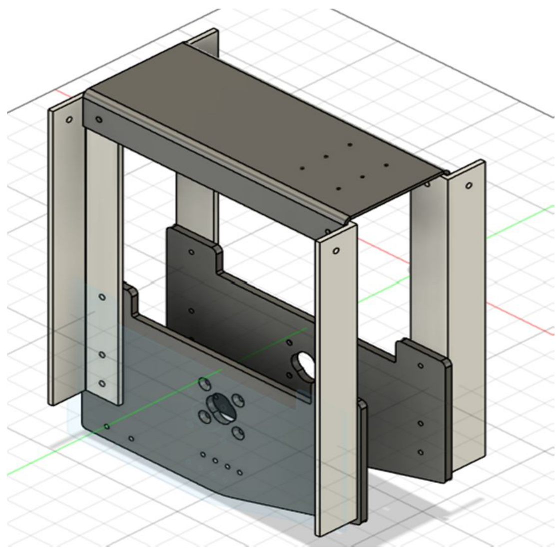

Fig. 3 The final frame

1) The Battery Box

The 21700 lithium cells were chosen to form the basis for the battery due to their higher cdr and power rating compared to 18650. The batteries were spot welded onto 0.2mm thick nickel connectors and placed in a printed circuit board (pcb). The pcb was then placed into a 3D printed frame, via an undersized groove so it can be friction fit into the housing. The box shown in Figure 4 was designed to fit the sides of the Unicycle and create further space for the battery to sit. The battery enclosure is positioned to maintain proper weight distribution, which is critical for balance and stability. Additional structural components were designed to support accessory integration and future modifications. The final battery box is shown in Figure 5.

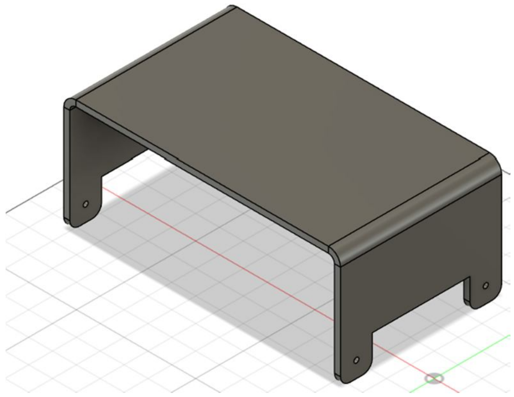

Fig. 4 Cover plate

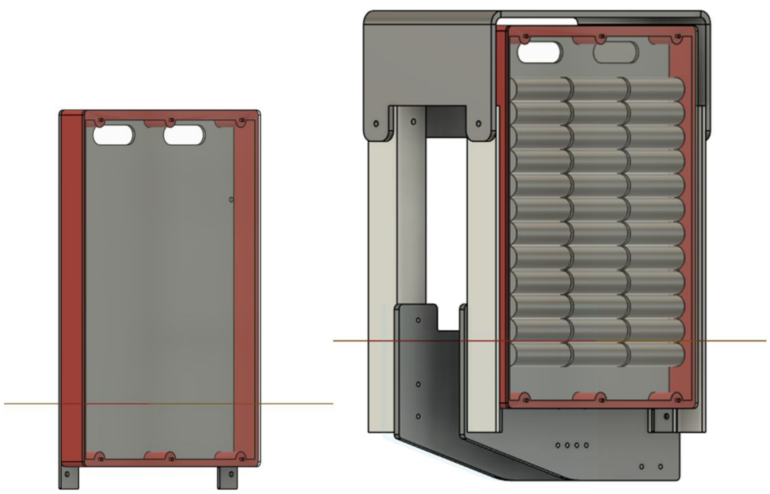

Fig. 5 Battery box

2) The Mudguard and Kickstand

The Mudguard and Kickstand assembly shown in Figure 6 was designed to be one piece, capable of holding the weight of the unicycle. The kickstand assembly is made of milled aluminum and provides rigidity for the mudguard. The mudguard is printed out of abs and has a contact surface which is offset from the central axis of the unicycle. This ensures that the unicycle has a place to rest when not in use. The full rear assembly is shown in Figure 7.

3) Pedal Spacers

The pedal spacers were milled out of aluminum and countersunk to ensure that the mounting screws would not interfere with the comfort of the rider.

The final design of the self-balancing electric unicycle is a sophisticated synthesis of structural reliability, seamless electrical integration, and ergonomic, user-focused features. Developed within the Fusion 360 CAD environment, the assembly underwent a rigorous iterative refinement process to optimize the spatial arrangement of the high-torque motor, high-density battery pack, and control electronics. The final CAD design of the unicycle is shown in Figure 8. An iterative approach ensured a low center of gravity for enhanced stability while validating the mechanical integrity of load-bearing components through simulated stress analysis. The internal architecture was also meticulously organized to facilitate efficient thermal management and organized cable routing, preventing interference between power lines and sensitive sensor data.

By bridging the gap between theoretical modeling and functional prototyping, the design iterations consolidated parts to streamline the assembly process. The design produces a cohesive system where every geometric choice supports the overarching goals of durability, responsiveness, and intuitive operational safety.

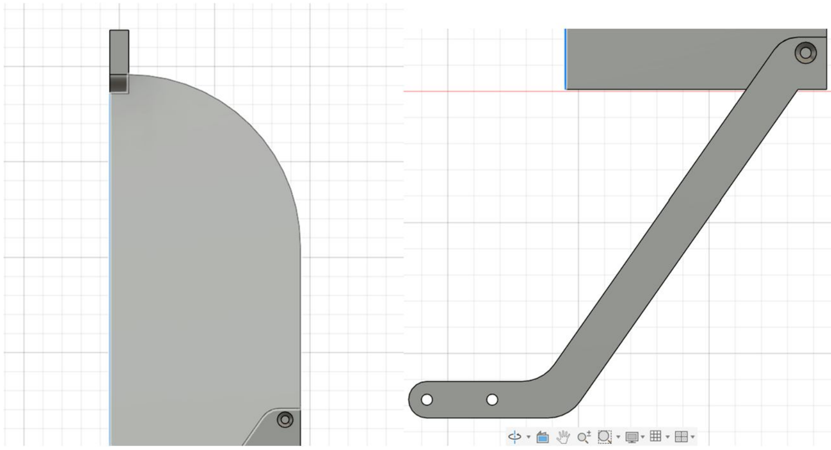

Fig. 6 Kickstand(right) and mudguard (left)

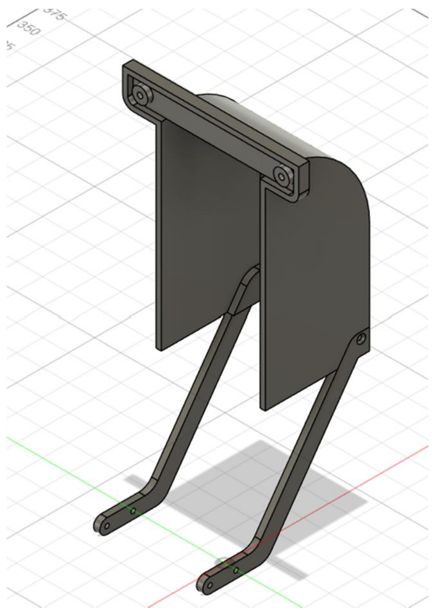

Fig. 7 Full rear assembly

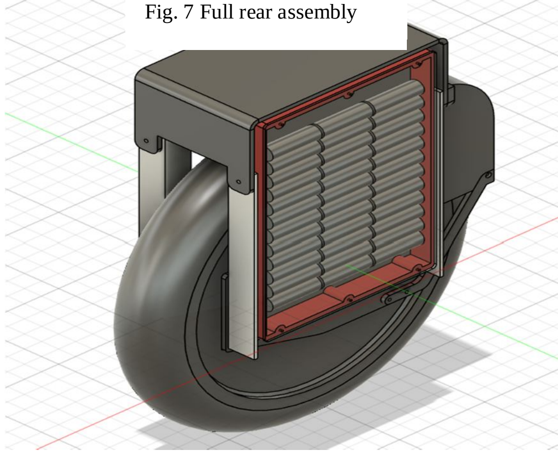

Fig. 8 Final CAD design of unicycle in fusion 360

C. Electrical System

The electrical system is based on a 100-volt architecture, designed to support both the motor and auxiliary subsystems. The key components include a high-voltage battery system (~100 V), a programmable motor controller with integrated IMU, a LED lighting system with constant-current driver, and a voltage step-down module for feeding low-voltage components.

1) Motor controller

The motor control system uses the Tronic 250R, which is a high-power VESC-based BLDC motor controller. VESC is an open-source motor controller platform, allowing the controller to be configured, programmed, and tuned for the specific motor and battery system [10]. The Tronic 250R is designed for high-current motor control, with a phase current capability of up to approximately 250A peak, making it suitable for high-power electric vehicle applications. It controls the speed and torque of the motor by regulating power delivery from the battery to the BLDC motor. The FOC drive allows smooth and efficient BLDC motor operation. It also uses PID-driven current control to regulate motor current thereby improving the response during acceleration and load changes. A 24S battery pack is used with a maximum voltage of approximately 100.8V when fully charged. This voltage level is also suitable for high-power motor operation. The controller includes Bluetooth connectivity, which is used for programming, configuration, and telemetry monitoring. It also supports multiple communication protocols, including CAN, UART, ADC, and PWM.

2) Low Voltage Accessories

The low voltage accessory system uses an ESP32-C6 Mini for peripheral control. It manages the headlight, taillight, optional telemetry logging, and future expansion for devices such as screens. The ESP32-C6 Mini uses Wi-Fi to provide an access panel for configuration and system monitoring.

The LED subsystem includes front-facing lights and a rear LED strip, improving visibility and safety. The use of a constant-current driver ensures consistent brightness and protects the LEDs from electrical fluctuations. Figure 9 presents a high-level architecture of the LED control system. The diagram shows how power is distributed to the lighting subsystem and how the control signal is passed through the microcontroller and interface circuitry to drive the front and rear LED lights. The front headlights use a constant current LED driver LDH-45A-500 with 500 mA rated output current at an operating voltage around 70V. A low-side 12V switched output is used for the taillights. This allows the ESP32-C6 Mini to switch the output and provide PWM dimming. A PCB layout was developed from the schematic design, which reflects the physical placement of components and routing of traces needed to create a compact, organized, and manufacturable printed circuit board. The board supports future expansion of low-voltage accessories such as screens or additional interface devices through an exposed UART port.

D. Prototype Development

A physical prototype of the unicycle was partially constructed to validate the design. The prototype demonstrated the feasibility of the design and provided a foundation for further testing and refinement. The Battery box was printed using a 3D printer. The cells are arranged in groups of three, which make up our “p-groups” (parallel groups). These p-groups are wired up in series to form the 24-series, 3-parallel battery pack. Each side of the unicycle holds a 12-series, three parallel pack, which are connected in series to form the complete pack. The final prototype is shown in Figure 10.

IV. DESIGN PERFORMANCE

The performance of the self-balancing electric unicycle was evaluated through a combination of analytical modeling, subsystem validation, and design verification. The system was designed around a high-voltage architecture (~100 V), allowing for improved power delivery and efficiency across a wide operating range. The selected motor and controller configuration provides sufficient torque and responsiveness to maintain balance under varying rider loads and terrain conditions. The inclusion of the programmable controller with an integrated IMU enabled real-time feedback control, which is essential for maintaining stability in self-balancing systems.

From a mechanical perspective, the aluminum frame provided a strong and durable structure capable of supporting loads up to approximately 300 lb, as defined in the design requirements. The structural layout minimized deformation and ensured consistent performance during acceleration, braking, and turning.

The LED lighting system contributed to the overall safety by improving visibility in low-light conditions. The use of a constant-current driver ensured reliable operation and protected the lighting system from electrical inconsistencies.

Table 1 summarizes the performance of the system.

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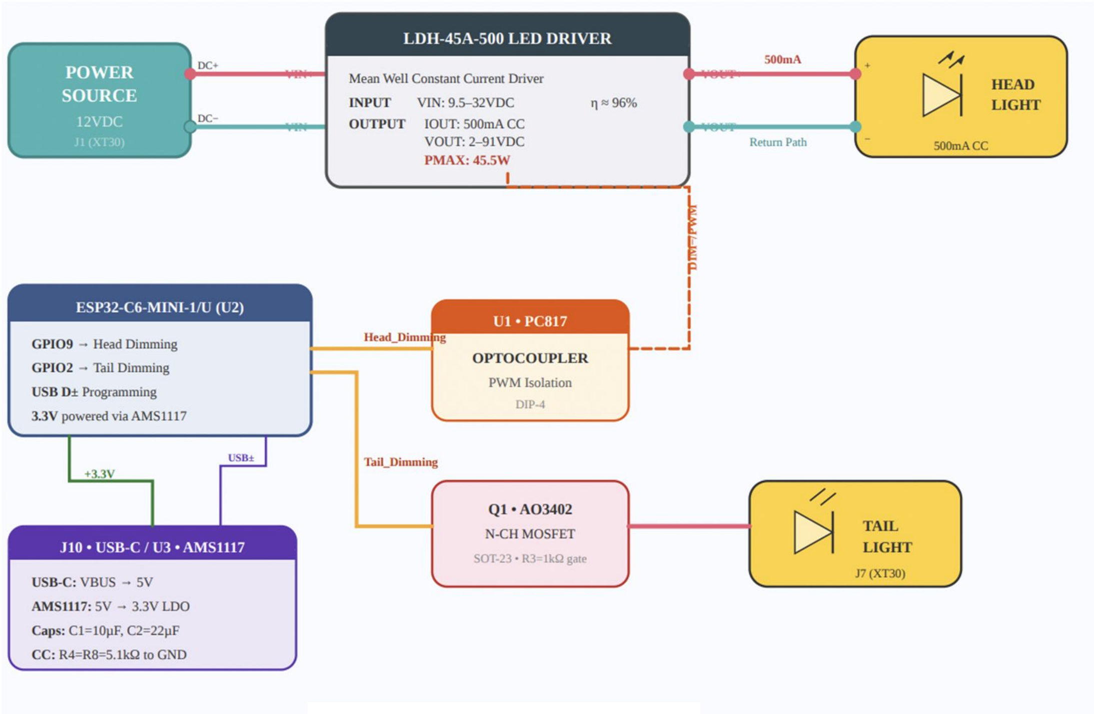

Fig. 9 High-Level LED system diagram


Fig. 10 Prototype of unicycle

A formal risk assessment was conducted to identify potential technical, safety, and project management risks. These include an identification of potential design and testing risks, mitigation strategies for component failure, ethical considerations related to safety and design integrity, and transparency in engineering decision-making. These considerations helped guide responsible engineering practices throughout the design of the unicycle.

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Table I. System Performance

Function	Qualification	Performance as Tested
Rideability	Stable self-balancing, angle remains predictable	Expectations met
Safety	Supports up to a 300lb static load	Expectations exceeded
Practicality	Daily usability and compact size	Expectations met
Acceleration	Smooth and controlled acceleration to 15mph	Expectations met
User Interface	Easy to control device settings	Almost met expectations
Maneuverability	Quick response to user inputs, small turning radius	Expectations exceeded

V. CONCLUSIONS

This project successfully demonstrates the design and development of a self-balancing electric unicycle that addresses key limitations found in existing personal electric vehicles. By integrating mechanical, electrical, and control systems, the design achieves a balance between performance, durability, and usability.

The use of an aluminum structural frame improved strength and reliability, while the high-voltage electrical system enabled efficient power delivery. The incorporation of a programmable controller with real-time feedback allowed the system to maintain balance and respond dynamically to user input. In addition to technical improvements, user-centered design is emphasized through the development of customizable features and ergonomic enhancements. This approach differentiates the design from existing solutions and highlights the importance of considering both engineering performance and user experience. Analytical validation and subsystem development indicated that the design met all its intended objectives. The final prototype was road-tested and was found to operate successfully. Our system can draw about 8.8KW out of the battery, with the limit being the motor controller. The maximum speed was estimated to be about 43mph / 70kmh based on the motor Kv (velocity constant), the tire diameter and the battery voltage. It weighs about 35kg and has a capacity exceeding 140kg. Advancements in battery technology are expected to enhance performance, reducing charging times, and extending battery life.

While the current design demonstrates strong potential, several areas can be improved in future development phases. PID tuning can be refined further for smoother and more responsive balancing behavior. The development of external housing and accessory integration features can be improved further. Heat dissipation for the battery and controller systems can be improved for better thermal management. Implementing a fully functional display system and user controls will make it a more user-friendly mode of transportation. Future work may also include additional features such as suspension systems for improved ride comfort, smartphone connectivity and app integration, GPS tracking and real time monitoring and expanded modular accessory systems. Overall, this project provides a solid foundation for future development and highlights the potential for improved, user-focused micro-mobility solutions.

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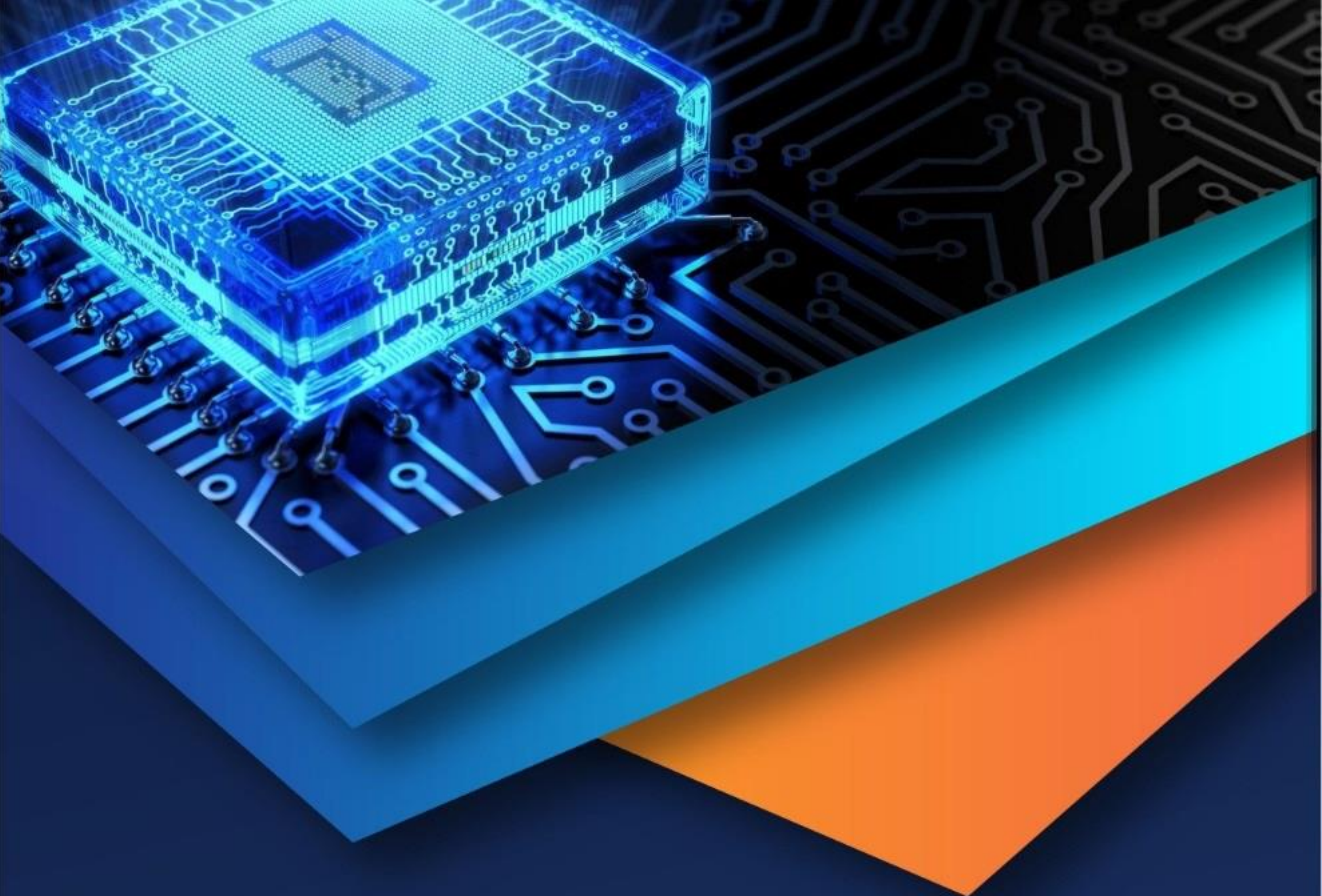

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