

REVIEWS

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Advances and challenges in electric unicycle stability: a review of structural design and control mechanisms

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Abstract

Unicycles possess inherent instability, requiring cohesive design and control mechanisms to maintain balance. This review examines various control strategies and structural designs that enhance unicycle stability. The position of the center of gravity plays a critical role, and it is influenced by factors such as chassis design, supporting structures, and battery placement. Control systems process data from sensors and make adjustments using methods that range from simple methods ranging from simple proportional-integral-derivative (PID) controllers to advanced approaches such as fuzzy logic and predictive control. Sensors, including accelerometers and gyroscopes, detect inclination and movement that maintain an upright position. The ability to perform real-time adjustments can be enhanced by components such as motors and reaction wheels. Additionally, hardware such as Arduino and SoPCs enhances stability control by providing real-time computing capabilities. This review highlights gaps in current knowledge by gathering insights from scholarly articles, research papers, and patents. This research contributes ideas and knowledge toward improving electric unicycles in terms of stability, efficiency, and suitability for real-world applications.

Keywords: Electric unicycles, Stability, Structural design, Control mechanisms

Introduction

Unicycles, being single-wheeled vehicles, exemplify the contradiction between engineering complexity and design simplicity. In contrast to multi-wheeled vehicles, unicycles do not have inherent stability, which requires the rider to constantly make adjustments for both longitudinal and lateral balance [1]. According to Chen [2], mechanical maneuvering of a unicycle comprises two components: the rotational motion of the tire axis and the translational movement occurring at the tire-ground interface. The rotational motion and translational movement are interdependent and influence one another, making them key subjects of investigation.

As electric unicycles gain popularity for personal transportation, their adoption continues to rise. However, stability remains a major challenge for everyday travel and widespread adoption [3, 4]. Electric unicycles are personal mobility devices and recent studies have focused on enhancing their stability and control. These developments include the

incorporation of detachable support tires for improved side-to-side (lateral) stability at lower speeds and the use of large, smooth, inflatable pneumatic rubber caster wheels for enhanced lateral stability [4]. Control systems typically employ gyroscopes and accelerometers to measure angle and acceleration, employing Kalman filters to reduce sensor noise [5]. The following control algorithms have been investigated: PID, LQR, and ADRC. However, LQR and ADRC have been shown to significantly improve control performance. The electric drive maintains forward and backward stability through gravity regulation, causing the unicycle to behave like an inverted pendulum [4]. These improvements have made electric unicycles easier to use and more stable across different terrains, enhancing their suitability for everyday applications [5]. Unicycle stability is influenced by structural design. The geometry and positioning of the frame, wheels, and batteries, along with material choices, determine key parameters affecting the center of gravity (CoG) and balance [6]. Additionally, innovations such as the installation of flywheels, support wheels, auxiliary supports, handles, and seats have been shown to improve stability in the lateral plane [6]. Functional features such as retractable footrests and ergonomically integrated enhancements accommodate riders of different skill levels [1]. Such structural modifications form the foundation for sustaining dynamic stability.

Advanced control systems play an important role in processing and converting sensor data into accurate corrective actions [6]. Specific hardware, including gyroscopes, accelerometers, and inertial measurement units (IMUs), are essential for mapping tilt and angular velocities, providing feedback to adjust stability [7]. Moreover, mathematical techniques such as Kalman filters are used to enhance data accuracy by filtering out noise and external interferences [5]. For general-purpose applications, traditional forms of control such as (PID) controllers are sufficient for maintaining stability. However, more sophisticated approaches such as fuzzy logic, adaptive systems, and artificial intelligence (AI)-based algorithms offer greater flexibility under different conditions. Furthermore, the integration of hardware and software platforms such as Arduino and system-on-a-chip (SoPC) enables real-time computing and control enhancing the overall performance of electric unicycles [8]. The following challenges have been identified: the need for greater stability when traversing complex terrains, an expanded body weight range that the unicycle can support, and more efficient energy use [9]. Furthermore, the integration of hardware and software systems requires careful consideration to ensure real-time feedback, especially in rapidly changing conditions [4]. Currently, there are limited studies on the stability of electric unicycles.

Table 1 presents a summary and comparison of recent review papers on micromobility and stability, highlighting their focus areas, limitations, and research gaps. The table also provides comprehensive evaluations of past investigations regarding electric unicycle stability findings related to both structural modifications and control system implementations. In essence, there are no specific review papers dedicated solely to electric unicycle stability; most studies focus on micromobility, with reviews addressing policy, user behavior, and sustainability rather than technical control development in electric unicycles.

While urban mobility research touches on basic stability control, it often overlooks the interaction between control strategies such as Proportional–Integral–Derivative (PID), Linear Quadratic Regulator (LQR), and Active Disturbance Rejection Control (ADRC)

Table 1 Summary of recent studies on micro mobility and stability: focus areas, limitations, and research gaps

Year/ref	Focus area	Limitations/gaps
2023 [10]	Discusses control algorithms like PID, LQR, ADRC. Highlights gyroscopic control and sensor integration	Limited application-oriented examples; lacks discussion on lifecycle or societal impacts.
2023 [11]	Reviews infrastructure, user behaviour, and KPIs like emissions, modal shifts, and safety	Lacks focus on stability control or in-depth technical innovations in micromobility
2023 [12]	Reviews user behavior, safety, and infrastructure influences on ePMD adoption and usage	Minimal technical exploration; limited to behavioral and policy aspects
2023 [13]	Analyzes dynamic and kinematic stability and discusses navigation techniques	Focused on robotics, lacks integration of sustainability or broader societal implications
2023 [14]	Examines control systems for stability in electric vehicles, compares stability challenges between EVs and ICEVs	Limited to vehicles with broader applications, not micromobility specific
2022 [15]	Focuses on sustainability using a Life Cycle Thinking (LCT) approach, addressing environmental, social, and economic aspects of micromobility	Limited technical exploration of vehicle dynamics or stability mechanisms
2022 [16]	Investigates functional and non-functional factors influencing micromobility adoption, emphasizing environmental and social values	Ignores stability, control systems, and technical improvements in micromobility devices
2021 [17]	Examines sustainability impacts such as energy efficiency, emissions reduction, and modal shifts due to e-micromobility	Minimal attention to control mechanisms or safety-focused stability research
2021 [18]	Explores micromobility's role in reducing car dependency and promoting sustainable urban transport	No detailed exploration of individual micromobility devices' technical features or design
2021 [19]	Reviews ADRC in robotic systems for robustness under uncertainties and disturbances	Limited focus on micromobility or personal transport devices

and mechanical designs such as shock-absorbing footrests or reaction wheels. This gap makes stability improvements more challenging. This review categorizes stability methods into passive techniques, such as shock absorbers and frame modifications, which enhance stability through their influence on structural design and control requirements, and active approaches, such as PID, which continuously adjust to maintain balance. Organizing these methods can help researchers explore new designs and improve unicycle stability. The research is guided by three key questions aimed at analyzing the stability challenges and solutions for electric unicycles, as follows:

Q1: What is the role of structural design in unicycle stability?

Q2: What is the role of control systems in contributing to dynamic unicycle stability?

Q3: What are the interplays between structural design and control systems in contributing to unicycle stability?

Based on these three questions three main objectives were identified as being highly relevant for understanding:

- i. Investigation of the role of structural design in unicycle stability
- ii. Investigation of the role of control systems in dynamic unicycle stability.
- iii. Investigation of the interplay between structural design and control systems contributing to unicycle stability.

The framework of this article is structured as follows. The methodology section (Section 2) outlines the literature review process, detailing the search method, inclusion and exclusion criteria, final selection, and the approach used to analyze the studies. The research objectives are addressed by comparing existing unicycle designs using patent articles, with comparisons guided by the research questions. Section 3 revisits structural design and its role in stability. Section 4 discusses the control algorithms used to maintain stability. Section 5 explores the interplay between design and control systems contributing to unicycle stability. Section 6 summarizes the main conclusions and identifies potential areas for future research.

Methodology

Although additional insights on local electric unicycle systems may exist in other languages, this study exclusively considers publications in English. Two types of publications are included in this research: empirical articles and patent articles. Only research articles and reviews from peer-reviewed journals are considered, while books, book chapters, and dissertations are excluded. Empirical articles are limited to journals published from 2000 to December 31, 2024, as electric unicycles gained popularity after 2000. Studies referring to unicycles before 2000 often describe them as “single-wheeled vehicles” or “one-wheel vehicles”.

The first step involved identifying relevant studies through an online search using various databases, including Scopus, Google Scholar, and ScienceDirect. Patent articles, on the other hand, were considered from 2000 to 2024, based on their publication year, and were extracted from the Lens.org database. The search strategy was applied consistently across all databases. Prior to starting the search process, a set of primary studies was identified. Primary studies refer to the identification of relevant works that ensure the defined research questions and objectives are valid while avoiding duplication of previous research.

An initial search in Google Scholar and Scopus using the term “electric unicycle” AND “stability” AND “review” resulted in 10 relevant studies. However, none of them included a review of advances and challenges in electric unicycle stability comparing patented unicycles. The query commenced by first selecting the keywords to target relevant studies, which included “electric unicycle” and “unicycle robot”, and these were set up in a search string. These search strings were used to conduct searches across all geographical areas. The results were screened using a set of eligibility criteria (filters) to focus on the most relevant publications.

The comparison of the designs is based on existing electric unicycles, identified through a patent search in the Lens.org database. A few criteria were applied to filter out irrelevant research, such as unicycles that rely on manual pedaling. The embodiment of the electric unicycle served as the main search string for patent articles used in comparisons. Exemplary existing unicycles were investigated based on the research questions.

This study uses a systematic review to find relevant patents and research on improving the stability of electric unicycles. The search focused on journal articles, conference papers, and patent databases, focusing on control systems, sensor use, and design improvements. To choose the most useful studies, clear inclusion and exclusion criteria were applied. Studies and patents were included if they focused on

balancing single-wheeled vehicles, involved sensor-based feedback or gyroscopic stabilization, or provided experimental or simulation results. Patents that introduced new mechanical or electronic stabilization methods for electric unicycles were also considered. However, studies about multi-wheeled vehicles, patents without sufficient technical details, and research focusing solely on rider skill improvement without technical solutions were not included.

The first step was identifying relevant studies through an online search using various databases. The keywords used were “electric unicycle”, “unicycle robot”. As a result, the initial research from three main databases (Scopus, ScienceDirect, and Google Scholar) for the “electric unicycle” search string (from 2000 to 2024) yielded 372 articles, while the “unicycle robot” search string (from 2000 to 2024) yielded 2,130 articles, based on the criteria initially established. According to Fig. 1, these publications have a distribution of dates that demonstrates the growing interest in electric unicycles and unicycle robots. The drop in the number of publications in 2021 is likely due to the impact of the COVID-19 pandemic, as researchers slowed down their work during the last third of the year. However, this does not indicate a declining interest in the topic in subsequent years.

Patent selection was carried out using the Lens.org database, with keywords such as “electric unicycle” and “unicycle robot” to find relevant patents. The most important patents were chosen based on several factors. First, patents that introduced new ways to improve balance, especially with active stabilization, were preferred. Technical details were also important, meaning patents with clear design diagrams, control algorithms, or test results were given priority. Another key factor was whether the patent could be used with modern unicycle systems, including microcontrollers and sensors. Finally, patents referenced in other research or used in commercial products were considered more valuable. After reviewing many patents, only those that met all the criteria were included in this study. Referring to Fig. 2, there has been a trend in patent applications for electric unicycles from 2000 to 2024. Approximately 270 patents were found, of which only 40 were available as open-access documents. Additionally, five documents were excluded due to language barriers or irrelevance to the topic, and 12 documents were excluded because they involved manual operations.

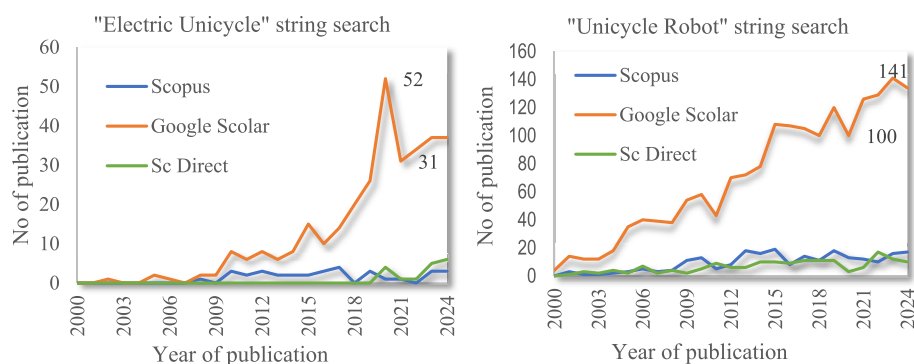


Fig. 1 Trends in publications featuring the terms “unicycle robot” and “electric unicycle” from 2000 to 2024, based on data from 3 main databases

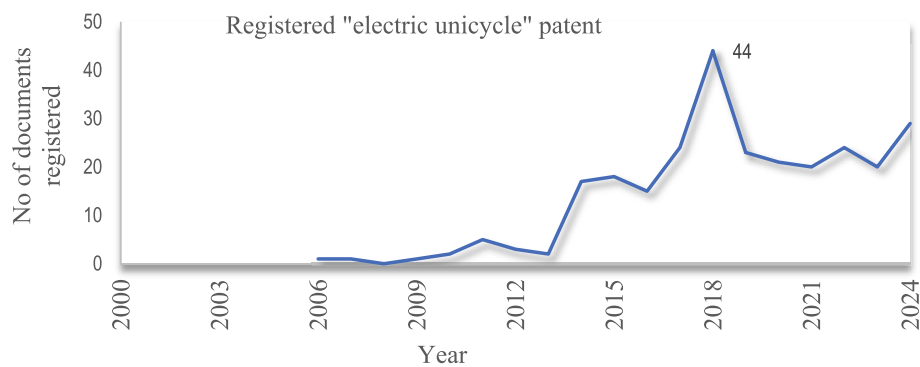


Fig. 2 List of patents published for “electric unicycle” from the Lens.org database from 2000 to 2024

The second and third stages of the methodology focus on research refinement. In the second stage, to select a shorter list from the initial research, we used the Mendeley tool to evaluate which records combined two or more of the above-listed keywords. In the third stage, we used Elicit.ai to perform the final bibliometric analysis and confirm that, after restricting the initial 625 sources to the final number of cited ones, we were still covering the entire scope and purpose of this comprehensive literature review. Once the relevant papers were identified, the final steps aimed at selecting publications, analyzing them, and reporting results. For selecting the final sample, all publications were merged, and potential duplicates were excluded. Publications that were not related to electric unicycles as defined in this study, such as scooters, bicycles, three-wheelers, or two-wheelers, were excluded. In addition, articles that were duplicated across databases, manually operated, not in English, or did not include “electric unicycle” were eliminated through title screening. The second task was to examine whether the remaining publications referred to electric unicycle stability and structural aspects by reviewing their abstracts and main text. If relevant impacts were reported in the manuscript, then the publication was retained.

Analysis and result

As illustrated in Fig. 3, a total of 2772 records were compiled through searching the keywords in the titles and abstracts. The PRISMA flow diagram in Fig. 3 presents the process, starting from the identification of the literature, through the screening process, and ending with the final set of publications. In the identification stage, duplicate studies ($n = 110$), unrelated titles, publications in other languages, or those with restricted access ($n = 2010$) were removed; thus, 492 empirical studies and 50 patent articles proceeded to the next step. Title and abstract screening excluded 2120 empirical articles and 220 patents; therefore, 385 publications moved to the full-text screening stage.

Full-text articles were evaluated, and 140 studies were selected based on the relevance of their content to the main research objectives of this study. In addition, six articles were excluded because they were classified as review articles. Ultimately, in the inclusion phase, 70 empirical articles and 20 patent articles were selected for full review in the present study.

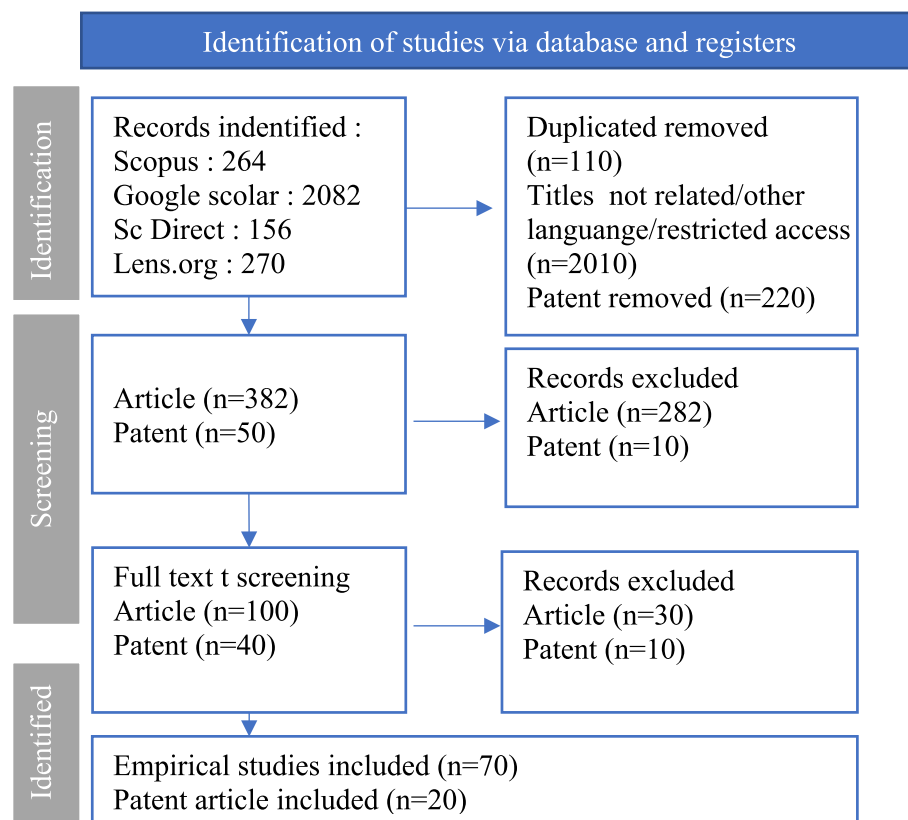


Fig. 3 Number of publications in the review process at each screening step, following the PRISMA flow diagram

The following sections will discuss three main aspects: namely structural design, control mechanisms, and the interplay between structural design and control mechanisms, as shown in Fig. 4.

Structure and component placement

This section discusses how the structure of the unicycle can help improve its stability. A comparison of additional structures was conducted among patented unicycles developed by inventors. Table 2 systematically provides a comparison of existing patents regarding structural innovations for supporting unicycle stability, with reference to the inherent instability of the single-wheel structure.

Another important invention is the use of shock absorbers, which enhance stability on rough surfaces by reducing oscillations and other destabilizing forces. In 2023, Butenko [24] proposed a dual gas–liquid shock absorber system for agile damping of uneven terrain by fine tuning the movement of the vehicle, whereas Dworzecki [26] integrated a control structure with gyroscopes, sensors, and shock absorbers to allow optimization of individual vehicle stabilizers according to environmental conditions. Moreover, Zhou [36] focused on optimizing longitudinal stability and minimizing the influence of vibration through pneumatic springs, thereby making the rider more comfortable and improving unicycle control.

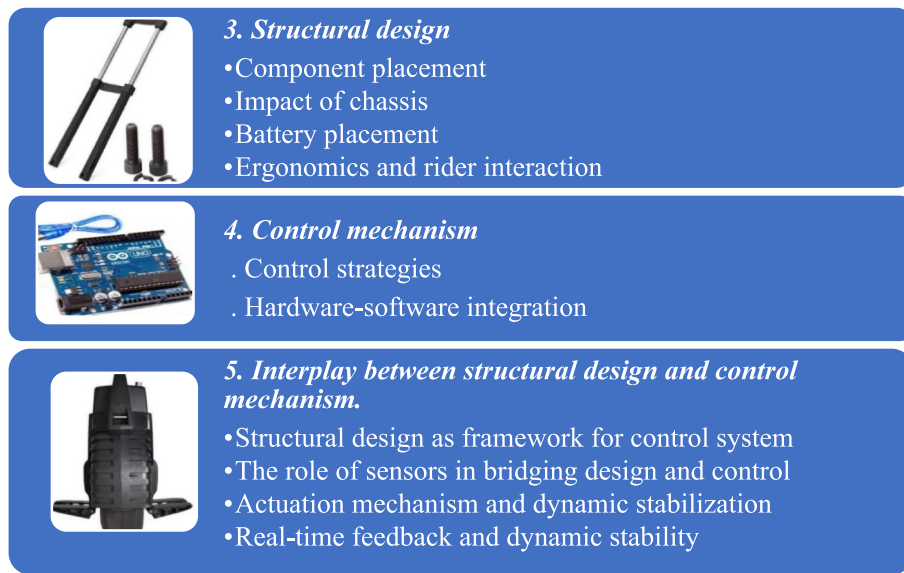


Fig. 4 Structure of the review

Table 2 Comparison of patented electric unicycles and the added mechanical structures

Inventor/ref	Year	Additional structure	Inventor/ref	Year	Additional structure
Lv [20]	2024	Minimalistic single wheel structure	Artemev [21]	2017	Auxiliary supports
Hadley [22]	2024	Shock-absorbing footrests	Simeray [23]	2016	Battery integrated in footrest
Butenko [24]	2023	Shock absorber with gas and liquid systems	Artemev [25]	2016	Single wheel, motor, platform actuator
Dworzecki [26]	2023	Shock absorbers, gyroscope, sensors	Hoffmann [27]	2014	Single wheel, gyroscopic sensors, control unit
Guo [28]	2022	Adjustable footrests	Polutnik [29]	2013	Seat-mounted damper
Liu [30]	2022	Compact unicycle and footrests	Sersic [31]	2012	Segmented/flexible single wheel
Zhou [32]	2022	Seat, pedals, footboard, handle	Polutnik [33]	2012	Rotational seat damper with spring
Butenko [34]	2021	Footrests, shock absorbers,	Verduron [35]	2012	Gyrostad-based balancing mechanism
Zhou [36]	2020	Pedals, seat, emergency brake	Alexander [37]	2011	Standing steering system
Fan [38]	2020	Foot platforms, suspension system	Shin [39]	2010	Compact frame, seat, footrests
			Simeray [40]	2019	Footrests with convex curvature

Components such as wheel supports, retractable stabilizers, and auxiliary supports provide additional or temporary stability, for instance, when the unicycle is starting, being ridden for the first time, or is at a standstill.

In 2020, Fan [38] proposed reinforcing the foot supports with suspension systems to provide riders with a stable footing while also mitigating the jolting impact of the ground. Likewise, Guo [28] created variable footrests so that the rider's posture aligns with the unicycle's axis, increasing balance and reducing pressure on the rider. The footrest design features an upward tilt and inward angle to keep the user's feet firmly in

place, particularly when the unicycle leans forward or backward. Stability on the footrests is ensured by this specific design, which actively secures the user's feet throughout unicycle operation. Surface features like grip tape on the footrests enhance stability during usage. In 2017, Artemev [21] proposed auxiliary supports that function during low velocities and periods of nonmovement, providing stability without decreasing maneuverability. The auxiliary supports provide lateral stability to the self-balancing unicycle by restricting unintended side-to-side tilting. Figure 5 illustrates how the auxiliary support is added to enhance stability.

Comfortable and easily reversible seating arrangements also ensure stability through weight distribution and balance [33]. Polutnik [29] proposed a cycling seat with mounted dampers, useful in counteracting disturbances caused by vertical and angular translations by the rider. Zhou [36] designed an ergonomic seat with adjustable pedals and handles positioned parallel to each other, ensuring that the rider's body position on the unicycle aligns with the vehicle's center of gravity for better control. Simeray [23] also pointed out downstretched footrests with a concave curvature to enhance rider convenience and stability, owing to better contact with the unicycle.

Stability is also promoted using modular and adaptive components that enable design variations based on user requirements or specific environmental conditions. In 2021, Butenko [34] proposed the addition of a modular shock absorber that makes the unicycle more durable, along with protective casing elements for rough surface. Zhou [36] used handles and footrests as components integrated into a flexible system, allowing for adaptability in the design and adjustability of the elements. Likewise, Simeray [23] integrated ergonomic footrests with a modular design; thus, perception and comfort improved, increasing recreational and competitive viability. Figure 5 illustrates the footrest positioning that helps the rider maintain stability.

Finally, a few inventors combine mechanical innovations with control system innovations, integrating them within a stabilization framework that addresses stability issues holistically. In 2023, Dworzecki [26] proposed sensors together with shock absorbers to provide a real-time adaptive stabilization solution for different surfaces. Verduron [35], in his 2012 work, described a balancing mechanism with gyroscopic stability, where lateral and longitudinal stability was enhanced using damping and gyroscopic systems. These hybrid models demonstrate how multiple technologies can be used to address the complex challenges associated with unicycle dynamics by enhancing stability and optimizing design.

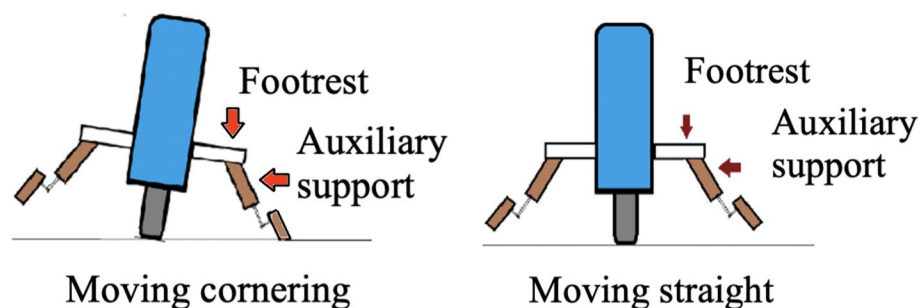


Fig. 5 Auxiliary supports added to the ends of the footrests [21]

Impact of chassis design on stability

The structural design of an electric unicycle is critical for addressing its inherent instability and ensuring safe operation. Unlike bicycles or multi-wheeled vehicles, electric unicycles rely solely on a single wheel for support and balance, necessitating precise engineering to compensate for its lack of passive stability.

Table 3 summarizes studies on structural design in various types of unicycles. There are two main factors that influence the stability of the unicycle: control algorithms and the structural design itself. The data were compiled from 20 relevant empirical articles and 21 associated patent articles focused on the structure and stability of electric unicycles. This study identified ten main structural aspects.

Few articles [1, 22, 41] mention that installing support wheels reduces the tendency to topple laterally due to the increased contact area between the wheels and the ground, while simultaneously improving the stability of the unicycle. The two small additional wheels are positioned on both sides of the unicycle and can be expanded and retracted using a control system. As shown in Fig. 6, the wheels are designed to retract and expand, controlled by a dedicated system and mounted on both sides of the unicycle. The figure also illustrates the actual fabrication, where an additional wheel is integrated.

While the installation of a reaction wheel or rotating disk is one of the additional features that help maintain stability, this is illustrated in Fig. 7. Several studies employed this element as part of the unicycle balancing system to produce an opposing torque, which counteracts unicycle tilt [42, 44, 56]. During unicycle side-tilting, the reaction wheel rotates in the reverse direction, producing a gyroscopic effect to stabilize the system and keep it upright. The lateral stability of the unicycle depends heavily on this operational system. When the unicycle sways to one side, the reaction wheel rotates in the opposite direction to generate torque that corrects the sway, preventing the unicycle from falling over. This mechanism plays an important role in controlling the lateral stability of the unicycle, which is one of the greatest challenges in designing a single-wheeled vehicle due to its high nonlinearity and oscillatory behavior. The reaction wheel generates suitable torque to balance the rolling motion and maintain the lateral stability of the unicycle. This mechanism mimics how a human rider utilizes hands and body to maintain balance while cycling a unicycle [45].

In addition, Cao [46] used two types of flywheels that support the stability of the unicycle, a lateral balancing flywheel and a steering flywheel. The lateral flywheel maintains balance, while the steering flywheel aids in maneuvering during operation. The author also stressed that flywheels are necessary for static and dynamic equilibrium, keeping the unicycle upright and moving in a straight line. Shao [47] also highlights that when the flywheel turns at a high speed, it generates resistance due to its angular momentum. This angular momentum opposes alterations to the orientation of the unicycle, especially in the lateral plane (lateral motion). Since the unicycle flywheel can spin in any direction and at any desired rate, the unicycle can actively resist forces that tend to tilt it over.

There are several inventors who have incorporated a pendulum into their unicycle. The pendulum helps stabilize the unicycle laterally by providing a means of control balance [6]. The movement of this pendulum generates a recovery torque, which assists with maintaining stability [48]. Daud [6] proposed installing the pendulum sideways, allowing

Table 3 Structural comparison between the existing electric unicycles

Ref	Support wheel	Reaction/rotating disk/wheel	Pendulum	Balancer	Seat/handle	Damper/spring	Stand	COG/weight distribution	Shock absorber	Footrest/pivot system
[1]	✓									
[6]			✓							
[36]				✓						
[21]	✓									
[22]							✓			
[23]										✓
[27]				✓						
[28]		✓		✓						
[29]				✓		✓				✓
[30]										
[31]	✓									
[33]				✓		✓				✓
[34]										
[37]				✓						✓
[38]									✓	
[40]										✓
[41]		✓								
[42]		✓								
[43]		✓								
[44]		✓								
[45]		✓								
[46]		✓								
[47]										
[48]			✓							
[49]			✓							

Table 3 (continued)

Ref	Support wheel	Reaction/rotating disk/wheel	Pendulum	Balancer	Seat/handle	Damper/spring	Stand	COG/weight distribution	Shock absorber	Footrest/pivot system
[50]			✓							
[51]									✓	
[52]					✓					
[53]		✓								
[54]								✓		
[55]					✓					
[55]		✓								

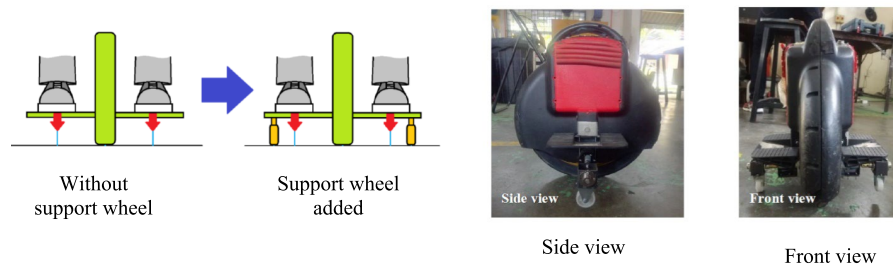


Fig. 6 Fabricated unicycle with retractable support wheel [1]

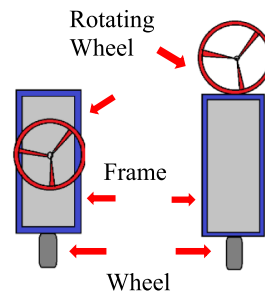


Fig. 7 Unicycle with reaction wheel [46] and [51]

it to swing and generate a restoring torque to counterbalance the tendency of the unicycle to topple over. These findings illustrate that the unicycle can maintain an upright position and achieve lateral stability by varying the angle and motion of the pendulum. This mechanism emulates the motion of a rider stabilizing a unicycle through shifts of body weight, thus improving dynamic stability and mobility of the system.

Divya [49] and Daud [50] emphasized that controlling the roll angle provides a definite means of achieving stability by using a swinging mechanism such as a pendulum. The pendulum torque, controlled by the pendulum motor, maintains the balance of the unicycle by preventing it from falling when unbalanced moments occur. The balance weight attached to the pendulum rod maintains the roll angle by producing the correct amount of torque. This mechanism mimics the way a human rider balances a bicycle by swaying the arms and trunk for correcting the unicycle's balance [48]. If tilted, the position of the pendulum shifts the center of mass to the unicycle's balance [50].

From the literature, one researcher used a balancer as one of the supporting structures for maintaining the stability of the unicycle [44]. The balancer counteracts the mass of the DC motor, which is placed on the opposite side of the wheel. This ensures that the center of mass is correctly positioned and prevents the unicycle from tilting excessively. The balancer has a similar weight to the DC motor and stabilizes the system, allowing the unicycle to stand and move on one wheel.

The installation of a seat, handle, or both is another effective method to enhance the stability of a unicycle while in operation. Seven existing unicycles were found to have a seat and handle installed. Meanwhile, Maddukuri [57], installed both a seat and handlebars on his unicycle, the I-Cycle. The researcher emphasized that these additional features play crucial roles in improving stability. The seat installation is designed to ensure that the combined center of gravity (CoG) of the I-Cycle and rider are vertically aligned

over the hub motor's axle line, which is essential for maintaining upright balance. The connection between the seat and seat post is adjustable in both angular and longitudinal directions, allowing for optimal mass distribution and stability. Kadis [52] designed a unicycle called Micycle, with a seat and pole mounted at the top of the main plate for the rider. In addition, Chen [55] stated that the seat on the electric unicycle improves stability because there is a point to lean on while riding. This supporting arm, coupled with a handling rod used for maneuvering, assists with shortening the supporting arm length compared to the swing arm length. These geometries enhance the solidity of the unicycle, ensuring that undesirable body oscillations in the front and rear are quickly controlled or eliminated when over-swing or an attitude problem occurs. Based on this design, the unicycle is considered more stable and easier to maneuver compared to other designs that do not incorporate a supporting seat.

Polutnik [29], an inventor from the United States, identified that the seat and handle enhance the structural support and balance of the unicycle in a way that improves the rider's control. The short seat design allows the rider to sit in a comfortable position while keeping the center of gravity stable, and the longer handle or handlebars provide additional security. The handle is useful for controlling the direction of the ride. Furthermore, several researchers, Hoffmann, Verduron, and Polutnik [27, 29, 35] found that the seat increases rider comfort while also enhancing stability due to a lower center of mass. The handlebars are convenient to hold and allow the rider to maneuver and balance the unicycle more easily.

Additionally, some researchers chose to install a damper to absorb the vibrations of the unicycle during operation. The damper element was implemented as a fluid damper and was placed between the lower and upper parts of the unicycle. Its primary function is to absorb vibrations, thereby enhancing the stability of the ride. The damper minimizes oscillations, which helps achieve a more stable ride, making it easier to balance and steer the unicycle [54]. Meanwhile Polutnik, an inventor from the USA, [33] emphasized that vibration damping controls forces that arise during riding from uneven ground or sudden motions experienced by the unicycle. This, in turn, minimizes shaking and swaying that may affect the rider.

Another feature that helps the rider start the ride is the stand. The kickstand (as illustrated in Fig. 8) is an accessory that supports the unicycle, allowing it to be balanced and parked with considerable stability when idle. It has collapsible functionality when not in use, enabling it to fit onto the body of the unicycle as a clip-on or within the frame for storage. Hadley [22] invented a unicycle with a stand and stated that it stabilizes the unicycle when not in use, allowing it to be parked upright using a kickstand. A kickstand may be deployed only when needed, and its position can be a compact, cylinder-like attachment placed either outside or inside the body of the unicycle. It provides structural support so that, in the event of a stop, the unicycle does not fall over or tilt to one side.

There are a few inventors who installed a so-called absorber in their design [23, 34, 38, 51]. The inventors agreed that the absorber is instrumental in enhancing the stability of the unicycle, thanks to its ability to minimize vibration and oscillation after crossing rough terrain. They achieve this using a first shock absorber containing shock-absorbing gas, and a second one containing shock-absorbing liquid. These shock absorbers

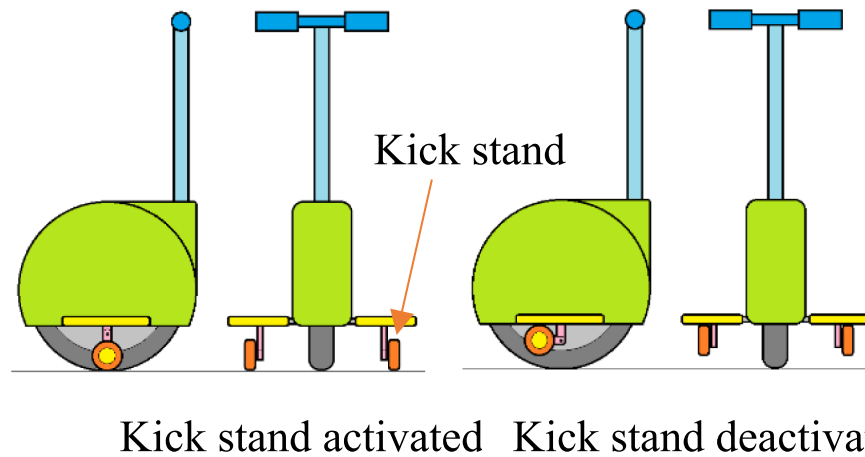


Fig. 8 Unicycle with kickstand

minimize the magnitude of mechanical vibration transmitted from the wheel section to the footrests so that the user maintains a stable position and does not fall off easily. Additionally, due to the welded link between the footrests and the frame, it is possible to maintain constant control of the unicycle while making turns.

The installation of a footrest and pivot system is one example of improving the stability of the unicycle. According to studies, nine researchers and inventors chose to install these features on their unicycles. Guo [28] stated that the footrests integrated into the powered unicycle also apply the concept of stability, as the user's feet rest on the framework. The footrests are made with a slight upward and inward incline and slide forward and backward, preventing the user's feet from slipping off when the seat tilts forward or backward. This design helps balance and control the unicycle while ensuring reliable and steady contact between the user's feet and the footrests.

Additionally, the footrests themselves incorporate mechanical design features, such as a grip strip along the working surface, to prevent slippage. Another inventor Simeray [40] emphasized that the installed footrests are made from soft materials, which help absorb bumps and maintain stability. On the other hand, these footrests may also contribute to stability, although they may appear ornamental, they also function as landing gear, particularly when addressing stability while the unicycle is stationary. This makes it possible for the user to step onto the footrest if it is on the ground when the rider's leg is placed on it.

The inventor also revealed that the footrest functions similarly to a convex surface, with a concave underside, aligning proper anterior–posterior force distribution without the need for electrical controllers. Regarding the convex shape, the footrest acts as a fulcrum that assists in initiating the stabilization process. In addition, it functions as a plumb line, enabling the user to keep the footrest vertical, ensuring a secure position while standing. Simeray [40] also stated that the footrest helps trigger stabilization when the second foot touches the other footrest, activating the motor to counteract longitudinal tilt, bringing equilibrium. This feature allows the user to manipulate and adjust longitudinal stability conveniently while remaining on the ground.

Depending on the chosen frame design, its modularity becomes highly effective in increasing stability as new elements, such as stabilizers, sensors, and actuators, can be easily incorporated without affecting the structural rigidity of the unicycle. These designs allow modifications to the unicycle's geometry for different riders or terrains, enabling balance to be restored across various conditions [9].

Battery placement

Energy systems play a key role in enabling the stability of electric unicycles, as they continually supply power to the actuators, sensors, and control units. Such systems have a direct impact on the performance of balancing mechanisms, which in turn determine the stability of the unicycle under dynamic and realistic conditions, particularly in terms of the center of gravity (COG).

Regarding the structural design of the unicycle, instead of installing additional features, battery placement is also a significant factor in stability. As inventor Simeray [40] mentioned, there are several ways in which the position of the battery can help maintain stability. The placement can help lower the center of gravity by positioning the batteries, motor and transmission in the footrest area, directly beneath the middle of the wheel. This lowers the center of gravity, thereby improving stability.

Simeray [40] also highlighted that, in another approach, battery placement can contribute to a tighter profile, allowing the user's legs to be positioned closer to the contact point with the flat surface of the floor. This reduces the possibility of the frame experiencing lateral torque when the user balances laterally. In addition, the placement of the batteries supports a flexible rim and rollers, where the wheel comprises a flexible rim controlled by at least three rollers. This setup enables the wheel to minimize vibration and operate stably, even when compressed under the user's weight. Furthermore, battery placement can also contribute to the gyroscopic effect, where the high inertial momentum of the rim and tire, combined with the freedom of motion between the device and the user's legs, provides greater lateral stability. Altogether, these design elements help the electric self balancing unicycle remain upright while in use, making it easier for the rider to control and enhance safety. Battery location is also critical for stability. By placing the batteries near the center of gravity, the rotational mass is lowered, which results in a decreased reaction time for making corrections during dynamic activities [23]. Guo [28] mentioned that placing the battery in an appropriate location can enhance stability in various ways, as it helps lower the center of gravity while simultaneously making the unicycle less prone to tipping over.

The strategic placement can also help balance the weight distribution among the rider, batteries, and motor. As mentioned by Artemev [25], two batteries are installed on both sides of the unicycle to create a balanced distribution of volume and weight. Such structural weight distribution benefits the stability and balance of the unicycle. In addition, the placement contributes to secure retention, as the internal bracket that holds the battery ensures the batteries do not shift within the unicycle during operation. If the battery were to move, it could cause instability and discomfort while riding. As for the comparison of existing electric unicycles, the data was summarized in Table 4.

Expanding on the stability features, there is also the discovery of the balance wheel, which is hinged at the top part of the unicycle frame to assist in balance, particularly

Table 4 Battery placement comparison between the existing electric unicycle

Ref/battery placement	Near the wheel axis	Near central axis	Within the wheel hub	In the footrest	Inside the lower frame	Distributed along the frame	Within motor compartment	Centralized near motor	Between frame and wheel
[24, 33, 54, 58, 59]		✓							
[23, 28]				✓					
[25, 60, 61]									✓
[31, 36, 39, 40, 56]			✓						
[26, 27, 32, 62]								✓	
[29, 36, 63]							✓		
[35, 52]	✓								
[22, 27, 37, 38, 62, 64]					✓				
[7, 34, 51]						✓			

sideways. This feature helps reduce the chances of toppling over, especially when traversing inclined surfaces or performing maneuvers [65]. Similarly, ensuring that the offset center plane corresponds with the spindle's middle plane guarantees wheel centering in relation to the rider, thereby eliminating any disturbance due to misalignment [57]. In addition, firmly linking the wheel to the brushless DC motor's rotor ensures that the unicycle remains balanced in the lateral direction by maintaining steady and controlled movement [48]. All these design features work together to enhance electric unicycles, making them more dependable and safer for different applications. With the proper arrangement of the wheels' position and the addition of the inverted pendulum system, engineers can improve unicycle stability and response to disturbances, thereby making the ride more comfortable for the user. Together, these design features, combined with proper wheel alignment and an inverted pendulum system, significantly enhance unicycle stability and rider comfort.

Ergonomics and rider interaction

Several ergonomic factors influence the design of the unicycle, especially regarding how the rider can effectively manipulate the setup to achieve balance. Therefore, stability depends not only on internal configuration and system properties but also on the rider's capacity to guide the system. Additionally, adjustable seat height, handlebars, and footrests help provide comfort and safety for both short and tall riders, ensuring an optimal unicycling experience. The retractable footrest is an ergonomic feature that provides support in certain circumstances, serving as a strong stabilizing point. These components provide support during stationary stops or when stepping on and off the unicycle, minimizing the likelihood of tilting [21]. For beginners, they offer an easier way of cycling, as they assist in stabilizing and maneuvering.

They also bear a significant part of the load in stabilizing the rider, which is why there are many types of footrests. Therefore, in accordance with the tool-location concept, footrests are placed near muscle balance points to optimize body weight distribution, which is necessary for achieving desired stability. Furthermore, rough-surfaced or

cushioned footrests provide a better grip, preventing slippage when the device pad shifts at specific velocities [23]. There are also handlebars that vary according to the rider, as well as tensioning mechanisms that assist with the rider–unicycle interface. These aspects make it easier for the rider to control the unicycle, especially in dynamic environments [66].

Summary of structural design of the unicycle and the effect on its stability

The findings reported in this review show that unicycle stability depends on structural design, with lateral and longitudinal balance being key factors. Structural variables such as the unicycle's geometrical parameters, weight distribution, and wheel type all have a significant impact on the unicycle's overall stability when operating in various settings. The position of the center of gravity is extremely significant; a low center of gravity improves stability while minimizing the likelihood of capsizing but makes it difficult to turn. However, a higher center of gravity increases the likelihood of instability, even though it makes the unicycle more maneuverable.

Other comparable structures have been integrated into the frame, significantly improving stability. A variable, automated, or retractable footrest, for example, allows the rider's weight to be distributed more evenly when braking hard or cornering. Likewise, the use of low-mounted batteries or weighted sections minimizes the risk of falling over by enhancing the unicycle's stability against toppling. This could be attributed to frames with involute damping mechanisms built directly into the frame, translating into improved control, particularly on rough patches, and a better overall ride quality. While the structural design provides the foundation for stability, effective control strategies are essential for maintaining dynamic balance. The next section explores these control mechanisms and their role in compensating for disturbances during motion.

Control mechanism for dynamic stability

Control strategies

Stability in unicycles is highly sensitive because of their single-wheel design, and it requires continuous processing of sensor data and appropriate movements to actively control instabilities. As illustrated in Fig. 9, the diagram of the control system for an electric unicycle shows how different components work together to maintain balance and stability. The flowchart highlights the interplay between sensing, computation, and actuation units.

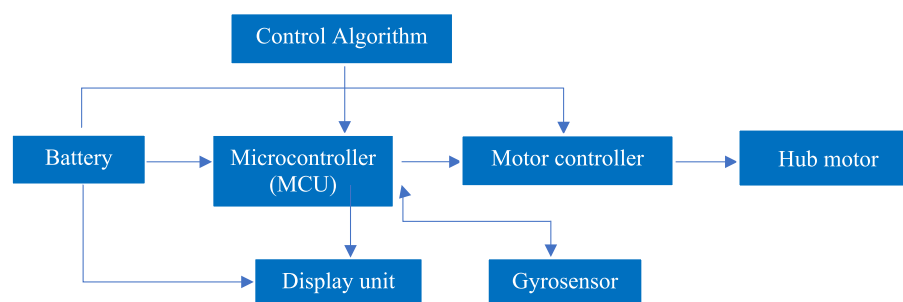


Fig. 9 Basic component flowchart of an electric unicycle showing the interaction between power supply, sensing, control, and actuation units

actuation, and rider feedback. The microcontroller (MCU) is the central processing unit that interprets data obtained by the gyrosensor and other devices to identify a tilt angle, acceleration and rider input. According to this feedback, the control algorithm (i.e., PID, MPC) calculates corrective measures and transmits signals to the motor controller which then uses the hub motor to stabilize the unicycle.

The battery feeds both the MCU and the motor controller, ensuring continuous operation. The display and control unit informs the rider in real-time with system status, battery level, and error alerts, and lets the user make simple inputs. This feedback mechanism will make sure that the balance is not lost (indicated by the sensors) and the hub motor will correct the situation immediately under the supervision of the MCU, which ensures the balance of the rider.

Detailing these relationships, the diagram shows that the stability of the unicycle lies in a feedback-control loop running continuously, and not in isolated parts. As summarized in Fig. 9, stabilization is a closed loop: IMU $\rightarrow$ MCU (state estimation/control) $\rightarrow$ motor controller $\rightarrow$ hub motor $\rightarrow$ vehicle dynamics $\rightarrow$ IMU. Figure 9 explicitly shows the connection between the MCU and the motor controller within the closed-loop system.

The system is powered by a battery management unit, which provides energy to all components. There is also a display and control unit that shows important information such as battery life and system status. Together, these parts help the unicycle balance itself and move smoothly. Current control techniques include the frequently used PID control, known for its stability and reliability in addressing steady-state errors in classical control strategies. These controllers continuously calculate the error signals between the desired and actual angles of tilt and then manage the motors to stabilize the system [43].

Nonetheless, a PID controller exhibits some drawbacks in dealing with non-linearities and sharp disruptions. Due to this, new control approaches such as fuzzy logic systems have been proposed to enhance adaptive control. Fuzzy logic control (FLC) uses a method analogous to human-like decision-making processes, enabling it to work flexibly under varying conditions without necessarily requiring the mathematical model of the system [67]. This makes FLC especially useful when dealing with risks that are inherent in real-world applications.

Table 5 presents a comparative analysis of different control strategies for unicycle stabilization. It evaluates key performance attributes such as accuracy, response time, robustness, adaptability to environmental changes, and efficiency. Additionally, the table highlights the limitations of each approach, providing insights into their suitability for various riding conditions. This comparison serves as a valuable reference for researchers and engineers aiming to enhance unicycle stability through optimized control mechanisms.

In choosing a controller, accuracy is one of the most important specifications, as the more accurate it is in terms of following a specific mode of behavior or desired stability, the more accurate the overall system will be. Zhang [64] used an adaptive fuzzy controller in his unicycle, which demonstrated satisfactory performance by handling non-linearities and uncertainty through logical rules and equations. This makes it especially applicable in applications that require real-time control, such as roads with variations in slope and changing loads. As for Chiu [68], he used an Adaptive Interval Type-2 Fuzzy Controller (AIT2FC), based on interval type-2 fuzzy logic systems, to enhance accuracy

Table 5 Comparative controller for electric unicycle

Attribute/controller	Adaptive fuzzy controller [64]	(AIT2FC) [68]	LQR controller [69]	LQG Controller [47]	PID [58]	IT2FNN [70]	Linear PD [52]
Accuracy	High accuracy	Accurate within modelled scenarios	Precise tracking and balancing	Moderate for high dynamic coupling	Basic accuracy	Fast with online learning	Fast
Response time	Moderate	Moderate	Fast	Fast	Moderate	Fast	Fast
Robustness and reliability	High resistance to disturbance	High due to adaptive rules	Reliable over varying terrains and rider weights	High under low disturbance level	Basic robustness	High,	Moderate
Adaptive capability	Adapts to external disturbance	Dynamic tuning and online parameter adjustment	Adapts to friction changes and rider weight variations	Limited adaptive response to environment changes	Limited adaptation to sudden environment changes	High, adaptive to rider and terrain	Minimal
Efficiency	Energy-efficient with adaptive control for disturbance	Efficient with adaptive learning	Efficient for varying terrains	Moderate due to computation needs	Basic efficiency; simple design	Highly accurate for diverse terrains	Basic accuracy for stabilization
Limitations	Requires precise sensor calibration	Complex design and computationally intensive	Sensitive to modeling accuracy	Limited response to abrupt disturbance	Less effective for complex maneuvers	Computationally intensive due to online learning	Less effective for complex maneuvers

by incorporating an additional level of uncertainty handling. This provides high accuracy in cases where general measures are uncertain, making it suitable for implementation in systems that operate under ambiguous or uncertain environments.

On the other hand, the inventor, Rashid [54] used the LQR controller, which can track and balance a given system by minimizing a quadratic cost function. It stands out as a highly powerful tool when the systems and the domain are clear-cut, sequential, and predictable, capable of providing accurate models of the goal and search space. The LQG controller has reasonable accuracy, which is sufficient for a dynamical system with low levels of dynamic coupling; however, the algorithm may fail when handling significant nonlinearities or dramatic changes [47]. Even for a simple yet critical balancing process, such as the one demonstrated in this paper for a pendulum, the PID controller provides only basic accuracy, which is insufficient for highly developed functional systems [58]. In contrast, the IT2FNN is characterized by a fast adaptive response and requires low computational time to achieve high accuracy, making it suitable for fast-changing environments [70]. Meanwhile, the Linear PD Controller can deliver fast, simple, and accurate responses but remains ineffective for oscillating systems with high versatility and profound changes due to its rigidity [64].

Response speed remains a vital requirement for controllers to manage disturbances effectively. The adaptive fuzzy controller, together with AIT2FC, achieves precise control but exhibits slower performance due to its complex algorithmic requirements [68] while LQR- and LQG-based controllers demonstrate fast response times by using sophisticated feedback mechanisms for signal-based real-time modifications.

Kadis [52] mentioned that rise times are under 0.25 s and overshoot levels remain low according to the design, making it appropriate for human-controlled self-balancing unicycle operation. The linear PD controller shows reasonable stability only in simple operational areas [54].

Robustness, together with the reliability of a controller, depends on its performance when exposed to interference and non-ideal operating scenarios. The adaptive fuzzy controller effectively resists both disturbances and nonlinear system reactions, thus delivering dependable performance across various conditions [64]. Through an adjustable rule system, AIT2FC maintains stability when interacting with unpredictable conditions [68]. Under various riding conditions, the LQR Controller demonstrates consistent operation, delivering reliable results in actual cycling environments [54]. Significant disturbances remain a challenge for the LQG Controller because their operation depends heavily on linear and Gaussian conditions [47].

In addition, Tsai [70] mentioned that IT2FNN shows exceptional resilience through their ability to navigate dynamic uncertainties, including changing rider weights and shifting terrain conditions. IT2FNNs possess a simple structure, good local approximating performance, resolvability, and function equivalence to a class of nonlinear functions, making them effective in modeling and controlling nonlinear systems. Real-time adaptation to uncertainties through IT2FNNs enables consistent driving performance across conditions, which improves the robustness of the seatless electric unicycle control system.

Controller systems require adaptable control mechanisms to maintain stable performance levels when conditions change. AIT2FC offers superior control capability

through its online performance tuning, which exceeds that of the adaptive fuzzy controller in its ability to adjust dynamically [68]. LQR and LQG controllers function less effectively than other controllers in unstable situations, yet remain reliable for fixed scenarios despite their lack of adaptability [47, 69]. The PID/PD controllers perform well in static conditions, yet fails to adapt when environments become dynamic [58]. The IT2FNN system demonstrates a fast adaptation response to rider actions, terrain patterns, and system operational elements, leading to successful real-world implementation [70]. In environments with basic static operation and stable conditions, the linear PD controller demonstrates peak efficiency but exhibits limited adaptability [69]. The power efficiency of these electric unicycles depends heavily on energy conservation features. Using an adaptive fuzzy controller creates stable control that helps maximize energy efficiency and reduce energy waste while extending operating time. AIT2FC boosts efficiency through real-time learning technology, which optimizes energy utilization, making it suitable for energy-constrained applications.

The LQR controller maintains stable energy consumption across different terrains, although their precise tuning parameters require adjustment due to operating condition fluctuations [69]. The LQG controller maintains moderate efficiency yet requires greater processing resources when operating in changing environmental conditions [47]. PID/PD controllers provide basic energy management, though fall short for advanced process requirements [58]. IT2FNN demonstrates strong adaptability combined with real-time learning abilities, delivering high efficiency in power consumption management across multiple operating environments [70]. The linear PD controller achieves acceptable energy management when stabilizing basic systems; however, it proves inadequate for energy-intensive complex applications [52].

Due to complicated implementation requirements and sensitive sensor calibration needs, AFC remains impractical for systems operating with minimal computing resources. AIT2FC faces implementation challenges because of their high design complexity combined with high computational requirements, which restrict their deployment in simple or low-cost systems [68]. The LQR controller demonstrates excellent steady-state accuracy, though their parameter adjustment requirements are extensive, making this approach unsuitable for variable operating environments [70]. Because the PID/PD controllers work best for basic low-order control problems, they manifest inefficient behavior when applied to higher-order systems [59]. IT2FNN maintains high accuracy and strong power capabilities, yet their time-consuming online learning methods conflict with the needs of systems with constrained processing environments.

Linear PD controllers demonstrate high performance during basic actions, yet present limited capabilities in complex motion tasks under predictable conditions [52]. The various controllers exhibit diverse characteristics, providing different levels of strength. The accuracy levels of the AFC, along with AIT2FC are comparable to IT2FNN when enhanced with adaptation features [64]. Basic processes only required PID and Linear PD control [58]. The combination of high accuracy with balanced response rates defines LQR, LQG, and IT2FNN, while AFC and AIT2FC demonstrate medium response times and accurate output [68]. The controller combination of adaptive fuzzy with AIT2FC exhibits powerful resistance against interferences, yet LQR maintains stability across different terrains, and IT2FNN effectively addresses dynamic uncertainties.

Among these controllers, LQR requires careful power–performance tuning, whereas PID/PD highlight fundamental efficiency characteristics [52]. AIT2FC and IT2FNN require higher computational resources, and both LQR- and LQG-based models are sensitive to model accuracy, while PID/PD control is oversimplified for complex systems [68].

Sensors and actuators and hardware-software integration

The tight coupling of hardware and software ensures that control strategies are executed in real time, and the ensuing data processing of sensors, decision-making, and subsequent action implementation occur simultaneously [47]. Arduino and System-on-a-Chip (SoPC) platforms enable this integration by incorporating powerful computational units capable of real-time computations [8].

Arduino systems are commonly used in prototyping, primarily because they are flexible and interoperable with diverse sensors and actuators. They are most suitable in areas that require cost-effective alternatives to sophisticated designs. On the other hand, SoPC platforms, which integrate microprocessors with programmable logic for multi-purpose control, are suitable for complex applications such as AI control strategies [8]. The function of control systems in unicycles begins with sensing and control, which are subcomponents of the overall control system. A gyroscope, accelerometer, and inertial measurement unit (IMU) are some of the key elements used to measure tilt, angular velocity, and linear acceleration. This information enables the system to track the orientation of the unicycle and detect instability from its balanced position [20].

The gyroscope measures rotational movement, while the accelerometer detects changes in linear motion, thus providing invaluable data for stability. In IMUs, such sensors enable highly accurate multi-axis tracking of motion, which is crucial for triggering timely corrective actions [21]. However, raw sensor data is noisy and computationally demanding; therefore, superior filtering methods, such as Kalman filters, are applied to mitigate problems resulting from external interferences [5].

Actuators convert input data from sensors into mechanical responses that correct balance. Reaction wheels produce counteracting force in the form of torque to counter tilt, and high torque motors actively change the speed of the wheel to maintain alignment with the rider's center of mass. The proximity of these actuators to the center of mass of the unicycle enhances response speed while reducing the energy required to maintain balance [12]. Over the last few years, progress has been made in augmenting body-based sensors, such as CMOS cameras, to provide vision-based feedback alongside the original sensor modalities. At the same time, dynamic robustness has been enhanced to support maneuvering in more complex environments [7].

Summary of controlled algorithm effect on its stability

Control algorithms are critical for maintaining unicycle balance stability due to the many challenges that arise from the device's single point of contact with the ground. Proportional-Integral-Derivative (PID) controllers continue to be widely used for real-time process stabilization. However, their performance is limited under rapidly varying signals or conditions requiring precise tuning since small parameter adjustments may lead to instability. Both lateral and longitudinal planes benefit from advanced algorithms

like Linear Quadratic Regulators (LQR), which control stability by managing deviations across these planes. These algorithms excel in minimizing oscillations and preserving stability during switching operations, allowing for greater computational capability and reasonable system modeling.

Advanced and learning-type algorithms, such as neural networks and fuzzy logic, have shown promise in enhancing stability under uncertain and dynamically changing conditions. These technologies allow the system to adjust parameters dynamically in response to rider weight, slope, or external disturbances. Other methods are also used, such as sliding mode control, which accommodates system uncertainty, and extremum seeking control, which efficiently handles nonlinear systems across diverse scenarios.

In conclusion, specific control processes significantly impact the stability of unicycles, depending on how the system responds to dynamic and external interferences. Further studies should explore enhancing such algorithms with advanced sensing and adaptation to achieve even greater stability in practical applications. With the control strategies and hardware systems in place, it is crucial to assess their effectiveness in improving stability. The next section presents an evaluation of the combined impact of design, control, and hardware implementation on overall unicycle stability.

Interplay between design and control system contribution to the unicycle stability

Unicycles are inherently unstable systems, requiring a seamless integration of structural design and advanced control systems to achieve dynamic balance and maneuverability. This interplay defines the ability of unicycles to respond to varying terrains, rider dynamics, and operational constraints. Insights from empirical articles provide a comprehensive understanding of how these two domains combine in enabling stability.

Structural design as a framework for control systems

The structure of a unicycle is the foundational core upon which all other control systems are built. The placement of additional components, including reaction wheels, pendulums, and gyroscopes, directly influences the overall control approach. For example, Azizi [1] identifies parameters such as retractable stabilizing wheels operated electrically to increase surface contact and provide improved left and right stability. Likewise, Rizal [56] utilized a turntable and reaction wheel to isolate roll and yaw, thereby reducing control complexity and enhancing multiple-degree-of-freedom (DOF) control.

The function of mass turnover is also highlighted. For example, Zeini [71], showed that arranging internal components to optimize the center of gravity reduces instability, allowing control systems to operate at a micro level rather than focusing on correcting gross center of gravity imbalances. These examples illustrate that structural changes reduce the computational and operational load on control systems.

The role of sensors in bridging design and control

For control to be successful, sensing must be precise, and the integration of sensors with the system's structure has a direct impact on performance. IMU systems were examined by Ramadhan [72], who incorporated both accelerometers and gyroscopes to provide real-time tilt and angular velocity data, supporting excellent control under different

conditions. Correspondingly, Ho [44] showed that by carefully positioning tilt sensors, adaptive neural network controllers become more responsive. One study [5] explored a dual IMU approach to reduce noise, increase tilt-angle estimation accuracy, and demonstrating how sensor placement influences the feedback loop. Such integration of sensors within the structure allows control systems to adapt structural behavior to environmental and rider excitation in real time while remaining stable.

Actuation mechanisms and dynamic stabilization

Stabilization requires movement control facilitated by actuators such as reaction wheels, gyroscopes, and pendulums. Shao [47] described a two-rod configuration in which the spin motor manages lateral movements using a hanging flywheel, while the drive motor controls forward and backward movements. This illustrates how mechanical advancements reduce the computational load on control systems by incorporating inherent stability. Jin [73] discussed the gyroscopic precession effect, where high-speed gyroscopes generate large stabilizing torques to counter sideways disturbances. The incorporation of this mechanism leverages inherent physical properties to simplify control algorithms thereby improving system reliability. Likewise, Xu [48] examined pendulum mounted arrangements that embody sideways recovery torque, demonstrating how mechanical motion and torque changes are interconnected for motion control.

Optimizing control algorithms through design

The reduction of system complexity and the use of compact designs are known to improve control systems. Vizi [3] employed the Appellian approach, a compact dynamics formulation with pseudovelocities, to obtain compact equations, enabling controllers to perform maneuvers such as lane changes and sharp turns at small computational costs. Similarly, Kadis [52] showed how the structural separation of roll and pitch dynamics facilitates the application of LQR and PD control designs. Rizal [56] followed a similar approach, using structural features such as turntables and reaction wheels with gain scheduling algorithms to adapt control parameters dynamically to changing conditions.

Structural simplifications for computational efficiency

When structural dynamics are simplified, the computational burden is reduced, allowing control systems to focus on critical stability functions. Using the Appellian approach by Vizi [3], compact nonlinear equations motion for unicycles were formulated. This structural fragmentation makes it easier to integrate feedback controllers into the model, thereby facilitating the efficient execution of complex movements such as weaving maneuvers and tight turns.

Modular design for controller adaptability

Modular and adaptable structural designs ensure controllers can effectively respond to changing conditions. Hofer [4] demonstrated that the use of lightweight, rechargeable batteries reduces structural inertia, improving feedback control efficiency. This modularity guarantees that control algorithms respond optimally to rapid changes, such as rider inputs or terrain irregularities. Furthermore, Thar [74] demonstrated how structural

architectures, including gyroscopic systems and gain-scheduling, cooperate to produce longitudinal and lateral stability.

Enhanced control through structural alignment

Achieving conformity between structural characteristics and control goals enhances the performance of algorithmic systems. Shao [47] proposed doubling the actuators by featuring both a drive motor and a spinning motor. This placement removes complications that could otherwise arise between longitudinal and lateral motions, allowing control algorithms to function independently along its axis. This alignment increases stability while simultaneously reducing the computational load on controllers.

Design-driven optimization techniques

Sophisticated methods for improving control algorithms rely on structural design parameters. Kadis [52] explained how LQR controllers are designed with structural constraints such as actuator saturation and weight allocation in mind. This approach ensures robust stability under various conditions despite low power consumption. In turn, Ramadhan [72] investigated how integrated IMU systems contribute to algorithm development, providing excellent tilt details that simplify dynamic modeling and allow real-time tuning.

Feedback-enhanced control performance

Structural sensor placement enhances control algorithms by providing real-time feedback mechanisms. As shown by Radin [5], an interleaved dual IMU configuration demonstrates that data captured from two orientations improves noise reduction and enhances the response of feedback controllers. This configuration ensures that control algorithms adjust accurately to external interferences and internal design fluctuations.

Adaptive control for structural variability

Contemporary control methods are proactive, adapting to structural and environmental changes. Shao [47] highlighted that the gain scheduling algorithms were incorporated to adjust control parameters based on terrain and rider variations, ensuring stability in different situations. As noted by Sánchez [9], who stated that lighter, rechargeable batteries reduce structural inertia, enhancing feedback integral control. As explained by Ramadhan [72], the use of sophisticated Kalman filters for sensor fusion highlights the symbiotic relationship between structure and control. These systems allow control algorithms to remain balanced even in noisy environments by providing strong, noise-free data.

Real-time feedback and dynamic stability

Bidirectional communication is the critical link connecting structure and control, allowing unicycles to dynamically counterbalance as adjustments are made in real-time in response to environmental changes and rider behavior. This aspect emphasizes the acquisition and processing of relevant data at the right moment in the stability process.

Sensor placement and feedback loops

The placement and attachment of sensors are critical in determining the accuracy and responsiveness of feedback loops within the unicycle structure. Ramadhan [72] demonstrated how integrated IMU systems, combining accelerometers and gyroscopes, calculate tilt angles and angular velocities. The actual implementation of an extended Kalman filter in this setup eliminates sensor noise, providing accurate data for control action adjustments even under changing road conditions. Likewise, Radin [5] described how multiple IMU configurations, where sensors are integrated in an interleaved format, to improve tilt-angle estimation accuracy. This configuration reduces interference and achieves high-resolution feedback, allowing quick control system adjustments for unicycle dynamics.

Feedback-driven actuation

Implementing real-time feedback directly feeds adjustments to actuators during operation, stabilizing the system. Shao [47] explained a system that uses a drive motor for acceleration in the forward and backward directions and a spin motor for left and right adjustments using a suspended flywheel. This configuration relies on feedback to control torque and manage movement along the longitudinal and lateral axes. Additionally, Kadis [52] presented how integrated steering mechanisms combined with control systems dynamically adapt to rider inputs. Sensor data ensures roll stability in the steering mechanism, while the control system stabilizes pitch.

Adaptive controllers using feedback

Sophisticated controllers use real-time feedback to adjust to variations in the system effectively. Hofer [4] presented small rechargeable batteries with low mass, reducing structural inertia for faster feedback control. This interaction between structure and control further stabilizes the system during extreme mode changes. One approach involves gain-scheduling algorithms that adjust actuator control values based on gyroscopic feedback, as described in [74]. These modifications maintain consistent force application when encountering changes in height or uneven terrain in both lateral and longitudinal planes.

Interaction between feedback and environmental conditions

Feedback systems are crucial for adapting to varying environmental conditions. Sánchez [9] explained how Kalman filters are used to mitigate noise arising from rough terrain that affects sensor readings. These filters enable control systems to remain stable despite external disturbances, proving the effectiveness of real-time feedback incorporation. Lastly, Rizal [56] demonstrated how control systems use real-time data to regulate intricate relationships between structural components, such as turntables and reaction wheels. Automatic adjustments via feedback loops prevent overshooting and enhance stability during sharp maneuvers.

Self-stabilization and advanced feedback techniques

Real-time feedback is important for the process of self-stabilization. Vizi [3] introduced the Appellian approach to obtain compact dynamic equations describing a unicycle's behavior. This model enables controllers to fine-tune vehicle behavior, ensuring stability even during complex maneuvers such as lane changes.

From Table 6, the results demonstrate how different structural modifications impact the performance and complexity of the control system. For example, adding a pendulum introduces natural stability, which reduces the need for the control system to make frequent corrections. This simplifies the control algorithm and reduces the computational workload, although it can increase mechanical complexity. Similarly, a reaction wheel generates torque to stabilize the system, but it often requires precise, high-frequency control, which can increase computational demands. On the other hand, a shock absorber dampens vibrations, smoothing out the system's response and reducing the need for rapid adjustments, making the control system's job easier, though it adds weight and cost.

The stability of the system can be optimized and simplified by refining frame geometry. However, it may restrict design flexibility. Although it increases weight and mechanical complexity, adding a balancer helps distribute weight uniformly, thereby lowering the requirement for active balancing control. By lowering the necessity for active stabilization, components such as the handle, seat, and footrest enhance user stability and comfort, thereby simplifying the job of the control system. These additions, meanwhile, introduce trade-offs such as additional weight and design restrictions. While reducing the need for active control, a stand offers a consistent base and reduces the

Table 6 Comparison of structural modifications and their impact on stability and control complexity in electric unicycles

Structural modification	Effect on stability	Impact on control system	Reduction in computational complexity?
<i>Support wheel</i>	Supports the unicycle when stationary, reducing external tilts	Provides a stable base for the system	Yes; reduces the need for active balancing control
<i>Pendulum mechanism</i>	Shifts center of gravity for passive stability	Reduces need for frequent corrective actions	Yes; reduces high-frequency updates
<i>Shock absorbers</i>	Dampens road disturbances and sudden impacts	Lessens sudden instability, allowing lower update rates	Yes; reduces the need for rapid control adjustments
<i>Balancer</i>	Adds mass distribution for better balance	Improves passive balance, reducing active control effort	Yes; enhances natural stability
<i>Handle and seat</i>	Provides rider stability, reducing sudden shifts	Stabilizes user movements, reducing control fluctuations	Yes; minimizes rider-induced instability
<i>Footrest</i>	Helps in weight distribution, improving lateral stability	Minimizes unintended tilting, reducing rapid control corrections	Yes; reduces lateral instability
<i>Stand</i>	Supports the unicycle when stationary, reducing external tilts	Provides a stable base for the system	Yes; reduces need for active balancing control
<i>Reaction wheel/rotating disk</i>	Creates gyroscopic stabilization, improving balance	Requires an additional control system	No; increased the number of control subsystems

device's portability. Finally, the reaction wheel or rotating disk stabilizes the system using gyroscopic forces; however, high-frequency control is necessary, which raises energy consumption. In essence, each structural change involves trade-offs, and understanding these interactions enables engineers to balance structural complexity with control efficiency.

Summary of interplay

The interplay between design and control systems in unicycles showcases a sophisticated synergy, transforming these inherently unstable vehicles into dynamically stable, adaptable systems. Structural innovations, such as reaction wheels, gyroscopes, pendulums, and optimized sensor placements, form the backbone of control, while advanced techniques like gain-scheduling, LQR, and neural networks dynamically adapt to rider variability, terrain changes as well as environmental disturbances.

Real-time feedback, powered by integrated IMUs and gyroscopes, bridges structural dynamics with control algorithms, enabling precise adjustments to torque, tilt, and velocity. This co-design approach, where structural simplicity reduces computational demands while advanced controllers enhance mechanical designs, plays a pivotal role in achieving multi-axis stability, maneuverability, and efficiency. By aligning structural adaptability with intelligent control, this synergy not only ensures robust performance but also lays the foundation for future innovations in autonomous and micromobility systems, highlighting a transformative path for single-wheeled vehicle technologies.

Conclusion

This review study will benefit both researchers and the community by critically evaluating structural design and control methods to address key concerns in unicycle stability. For researchers, it serves as an ideal reference database, compiling cutting-edge research, identifying weaknesses, and anticipating the progress of future studies. As a result, this research provides a theoretical basis for integrating engineering, robotics, and control systems through the description of how structural adaptations interact with control strategies.

Additionally, this study offers practical recommendations on potential technologies, such as the combination of high-performance sensors and integrated control techniques which encourage the development of new approaches to improve stability. In the general pursuit of sustainable and effective transportation systems for communities, this paper makes several significant contributions. By expanding the research area of unicycle stability, it enables the development of safer, more reliable, and user-friendly personal transport systems. The potential applications of current technological advancements in automotive manufacturing can reduce reliance on traditional conventional vehicles, thereby alleviating road congestion and pollution. Furthermore, the findings of this research could contribute to improved mobility solutions in urban environments and for individuals with impairments. This work aligns academic and industry knowledge with global policy to create realistic, sustainable, and socially responsible solutions for current mobility demands.

Structural design plays a foundational role in unicycle stability by influencing the system's center of gravity, dynamic behavior, and overall robustness. Innovations such as

lightweight materials, modular frames, and adaptive geometries enhance maneuverability and balance, while emerging trends like multifunctional frames and smart materials promise further optimization. Various design strategies have been proposed to improve stability. While several aspects of structural design are well-studied, the structure itself remains a primary contributor to stability alongside control systems.

Control systems are the operational core of stability, transforming sensor data into corrective actions to counteract the inherent instability of single-wheeled vehicles. Traditional PID controllers are effective for basic stabilization, but modern approaches, including fuzzy logic, AI-driven algorithms, and hybrid strategies, offer enhanced adaptability to nonlinear dynamics and external disturbances. Despite these advancements, challenges remain in computational efficiency, scalability to diverse environments, and integration with evolving hardware platforms.

This review also identifies several research gaps, including the need for improved performance on uneven terrains, scalability to diverse rider profiles, and seamless integration of hardware and software components. Addressing these gaps requires a multidisciplinary approach, combining advancements in material science, control algorithms, and energy technologies.

Future research directions

The present research effort on improving electric unicycle stability still requires advancements to enhance safety, performance, and operational reliability. The combination of artificial intelligence technology with sensors and modern computing systems could support better operational success under actual conditions by solving current implementation obstacles.

AI-based control systems show great potential as an emerging research area. Almost perfect stability has been demonstrated in controlled environments using methods such as PID and Model Predictive Control (MPC); however, these approaches often struggle with unexpected conditions, such as road irregularities or rapid steering maneuvers. Reinforcement learning within AI enables unicycles to adapt autonomously by learning environmental patterns in real time. Kuntal [10] noted that AI-driven controllers use several types of controllers to manage different aspects of vehicle dynamics and control. Further research should investigate how to deploy AI technologies effectively in electric unicycles while also designing systems that balance rapid response with low power consumption to extend battery life. Researching rechargeable flow batteries could expand sustainable, low-emission energy storage options. Energy efficiency remains a vital key focus area. Through AI management of power usage, unicycles may maintain stability while reducing risks of sudden battery depletion. Through regenerative braking technologies braking energy can be harvested and stored, thereby extending the battery's operational lifespan. These enhancements could improve the practicality and usability of electric unicycles for daily use.

Various obstacles remain to be solved. The successful operation of AI systems depends on both system complexity and substantial amounts of available data. The acquisition of data presents challenges; however, researchers are working on methods involving synthetic data development and dataset improvement techniques to overcome this limitation. Security features should be built into these systems because

they must respond properly to unforeseen circumstances without endangering users. Modifying these areas of development could enable electric unicycles that are stable, efficient, and easy to operate. The development of electric unicycles toward practical and popular modern transportation usage remains a goal.

Future studies should further improve these systems by incorporating adaptive control driven by artificial intelligence, which enables the footrest to adapt to rider behavior. Investigating cutting-edge materials, including shape-memory alloys or carbon fiber, could help lower weight without sacrificing durability. Using energy-efficient actuation, such as electromagnetic or piezoelectric systems, is another promising way to reduce power consumption. Including IoT connectivity could further improve the system by allowing real-time monitoring and mobile application customization. Finally, recognizing how various riders fit the system and how it influences their comfort and riding confidence depends on conducting ergonomic and human-centered studies. By tackling these features, future innovations can advance electric unicycles toward safer, more practical, and broadly accessible daily mobility solutions.

Abbreviations

PID	Proportional integral derivative
LQR	Linear Quadratic Regulator
LQC	Learning Quadratic Controller
ADRC	Active Disturbance Rejection Control
FLC	Fuzzy Logic Control
AIT2FC	Adaptive Interval Type-2 Fuzzy Controller
IT2FNN	Interval Type-2 Fuzzy Neural Network
Linear PD	Linear proportional-derivative control
CMOS	Complementary metal-oxide-semiconductor
CoG	Center of gravity
IMU	Inertial measurement unit
SoPC	System on a Programmable Chip
ePMD	Electric Personal Mobility Device
EVs	Electric vehicles
ICEVs	Internal Combustion Engine Vehicles
IPS	Inverted Pendulum System
DC	Direct current
MCU	Microcontroller unit
AI	Artificial intelligence

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Authors' contributions

All authors contributed equally to the development of this review. Noorhidayah Ramli conducted the literature search, performed the analysis, and drafted the manuscript. The supervisors provided guidance on research direction, critical revisions, and overall editorial support. All authors read and approved the final version of the manuscript.

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Data availability

The authors confirm that all data supporting the findings of this study are included within the article.

Declarations

Competing interests

The authors declare that they have no competing interests.

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