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A Glance Review on Self-Balancing Motorbike

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ABSTRACT – *In recent years, significant advancements have been achieved in two wheeled transportations known as motorbikes specifically on self- balancing motorbikes. This achievement is the result of new technologies' advancement, artificial intelligence, electric powertrains, and their integration. Considerable research and academia around the globe have reported their research on adopting and adapting this new technology. For these reasons, it is important to highlight new findings and approaches in this domain that are relevant to assist in advancing this new revolution. This article presents a glance review of historical advancements in self-balancing motorbikes, the relationship between motorbike geometry and self-balancing, and key technologies involved in self-balancing systems in motorbikes. The aim is to contribute to this rapidly growing field of self-balancing research by exploring the latest research findings on the solution approach, to help expedite future research, and to give some future direction that needs to be considered as a path to produce a standardized dynamic self-balancing motorbike.*

KEYWORDS: Self-balancing, motorbike, two-wheeled, electric vehicle, autonomous vehicle

1. INTRODUCTION

Self-balancing motorbikes represent a groundbreaking innovation within the realm of two- wheeled transportation. These vehicles integrate sophisticated technological advancements to autonomously sustain stability and balance, thereby mitigating the risk of the motorcycle tipping over while stationary or operating at reduced speeds. The primary objective of self-balancing motorbikes is to bolster safety, curtail accidents, and enhance the overall riding experience. This type of innovation is particularly advantageous for novice riders and individuals navigating complex urban landscapes. It's also redefining convenience and accessibility and signifies a substantial progression toward the future of intelligent and adaptive transportation systems (Liu et al., 2024).

The historical trajectory of self-balancing motorbikes is firmly anchored in the evolution of robotics and gyroscopic technology, which has been incrementally advancing over several decades. In 1903, an Irish Australian inventor, Louis Grennan, was the first to patent a gyroscopically balancing vehicle. In 1912, Russian inventor Dr. Pyotr Shilovsky, in collaboration with Louis Grennan, developed and designed a two-wheel car with a gyroscope sitting in the middle of the body of the car for maintaining stabilizing force (Gadola et al., 2019; Vasilevski et al., 2023). The self-balancing and two-wheel robot SEGWAY HT is commercially available, and it was invented by Dean Kamen, who has designed more than 140 systems (Vasilevski et al., 2023). Initial concepts about self-balancing vehicles surfaced during the mid-20th century with the advent of gyroscopic stabilizers for motorcycles, although practical applications were constrained by existing technological limitations. The contemporary evolution commenced in the 2000s, propelled by the emergence of self- balancing robots, exemplified by the Segway, which underscored the feasibility of gyroscopic stabilization (Sawant et al., 2021). By the 2010s, manufacturers such as Honda and BMW began unveiling prototypes of self-balancing motorbikes. Honda's Riding Assist technology, revealed in 2017, utilized robotic control systems to uphold balance without dependence on conventional gyroscopes. Concurrently, BMW's Vision Next 100 concepts presented a futuristic interpretation of self-balancing motorcycles crafted to enhance rider safety and convenience (Gadola et al., 2019; Vasilevski et al., 2023).

In 2021, Honda launched an enhanced iteration, Riding Assist 2.0, which incorporated an independent swingarm system to further bolster stability at reduced speeds. Yamaha subsequently introduced its own variant, the Advanced Motorcycle Stabilization Assist System (AMSAS), which utilizes sensors to effectuate adjustments and preserve balance during low-speed maneuvers (Sawant et al., 2021). Although these motorcycles exhibit remarkable technological progress, they predominantly remain within the prototype stage. Firms such as Lit Motors have initiated preorders for their own electric self-balancing motorcycles. At present, the widespread adoption of self-balancing systems in the motorcycle industry remains limited. Nevertheless, recent advancements indicate a promising future in which such technology could become a standard feature. The integration of sensor technology, control systems, and electric powertrains is facilitating the development of motorbikes capable of achieving dynamic self-stabilization (Qiu et al., 2023).

This article will provide a glance overview of bike geometry and self-balancing motorbikes, focusing on the technical aspects that underpin their functionality. Key technologies that facilitate the operation of self-balancing motorbikes include gyroscopic sensors, control algorithms, and electric motors. Finally, conclusions and future directions that need to be considered as a path to produce a standardized dynamic self-balancing motorbike.

2. LITERATURE REVIEW

2.1 Relationship Between Motorbike Geometry and Self-Balancing

Motorcycle geometry plays a critical role in determining the stability, maneuverability, and overall performance of a motorbike (Figure 1). Key geometrical parameters such as wheelbase, rake angle, trail, and caster angle significantly influence the behaviour of the motorcycle under various riding conditions (Sawant et al., 2021).

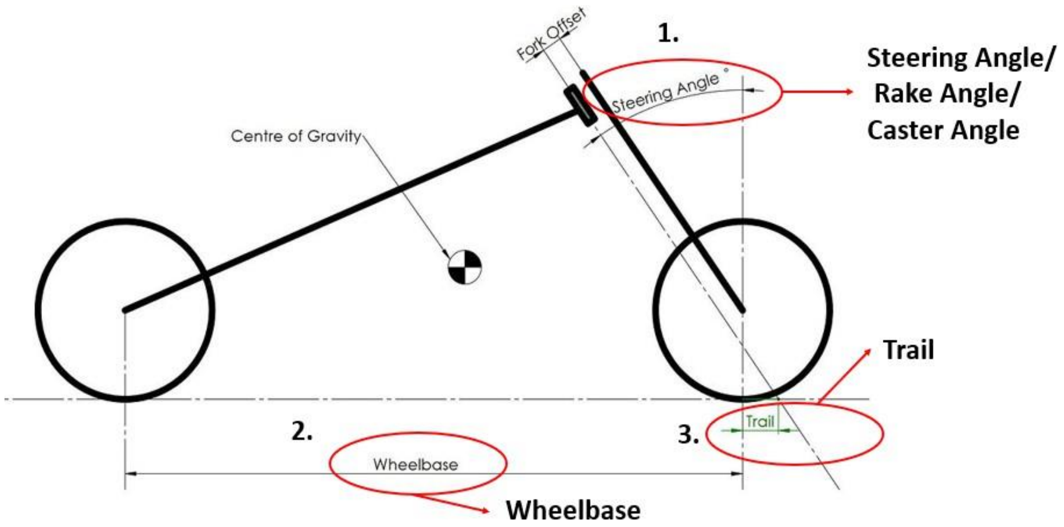

FIGURE 1: Main parameters of motorcycle chassis geometry (Gadola et al., 2019)

The wheelbase of a motorcycle is the distance between the centers of the front and rear wheels. It is a fundamental parameter that affects both stability and maneuverability. A longer wheelbase generally enhances stability by providing a larger moment arm to resist destabilizing forces, but it can compromise maneuverability due to the increased turning radius (Roe & Thorpe, 1980). Conversely, a shorter wheelbase allows for tighter turns and better agility, which is often preferred in racing environments, but it may reduce high-speed stability (Roe & Thorpe, 1980).

The rake angle, also known as the caster angle, is the angle between the steering axis and the vertical plane. It is measured from the front wheel's axis to the steering head. A larger rake angle (more upright) generally increases stability at high speeds by reducing the tendency to wobble, but it can make the motorcycle more difficult to maneuver at low speeds (Wilson-Jones, 1951; Sakai, 2024). A smaller rake angle (more inclined) enhances maneuverability by allowing quicker steering inputs, but it may lead to instability at higher speeds (Sharma et al., 2015). Studies have demonstrated that the rake angle is closely linked to the trail, and both parameters must be considered together to achieve optimal handling. For example, a motorcycle with a larger rake angle may require a shorter trail to maintain maneuverability, while a smaller rake angle may necessitate a longer trail to ensure stability (Wilson-Jones, 1951; Sharma et al., 2015).

The trail is the distance from the point where the steering axis intersects the ground to the contact patch of the front tire. It is a critical parameter for stability, as it determines how the motorcycle responds to steering inputs and external disturbances. A longer trail generally improves stability by providing a greater restoring moment when the motorcycle leans, but it can make the bike more resistant to steering inputs, reducing maneuverability (Wilson-Jones, 1951; Sharma et al., 2015). Conversely, a shorter trail allows for quicker steering and better agility but may compromise stability, especially at high speeds. Research has shown that the trail is highly dependent on the rake angle and wheelbase, and optimizing these parameters together is essential for achieving a balance between stability and handling (Roe & Thorpe, 1980).

Self-balancing in motorcycles is the ability of the bike to return to its upright position after being disturbed. This property is influenced by geometrical parameters, particularly the rake angle, trail, and wheelbase. At low speeds, self-balancing is challenging due to the inherent instability of single-track vehicles, but at higher speeds, gyroscopic effects from the rotating wheels and the trail contribute to automatic stabilization (Liu et al., 1992). The interaction between the rake angle and trail is particularly important for self-balancing. A larger rake angle and longer trail enhance the restoring moment, making the motorcycle more stable at high speeds. However, these same parameters can make the bike more difficult to maneuver at low speeds (Sharma et al., 2015).

Stability in motorcycles refers to the bike's ability to maintain its equilibrium and resist deviations from its intended path. This can be categorized into two types: directional stability and lateral stability. Directional stability is influenced by the rake angle, trail, and wheelbase, while lateral stability is affected by factors such as the center of mass, tire properties, and suspension characteristics (González & Vasquez, 2023). Research has shown that directional stability can be enhanced by increasing the rake angle and trail, but this may come at the cost of reduced maneuverability. Lateral stability, on the other hand, is influenced by the distribution of mass and the lateral stiffness of the frame and suspension. A stiffer frame and optimized suspension settings can improve lateral stability without compromising handling (Ye et al., 2022).

Maneuverability refers to the ease with which a motorcycle can change direction and navigate tight corners. It is primarily influenced by the rake angle, trail, and wheelbase. A smaller rake angle and shorter trail allow for quicker steering inputs and tighter turning radii, making the motorcycle more maneuverable (Sharma et al., 2015). However, excessive maneuverability can compromise stability, particularly at high speeds. Therefore, the geometrical parameters must be carefully optimized to achieve a balance between stability and maneuverability. For example, a motorcycle designed for racing may prioritize maneuverability with a smaller rake angle and shorter trail, while a touring bike may emphasize stability with a larger rake angle and longer trail (Wesley & Venkatesan, 2002). Research has shown that the wheelbase, along with other parameters like rake angle and trail, must be carefully optimized to achieve a balance between stability and handling. For instance, a study on high-performance motorcycles highlights that a shorter wheelbase, combined with a stiffer frame and optimized suspension, can improve both stability and maneuverability without compromising rider comfort (Roe & Thorpe, 1980).

TABLE 1: Summary of the parameters and their effects on stability and maneuverability

Parameters	Effects on Stability and Maneuverability
Wheelbase (Roe & Thorpe, 1980; Ye et al., 2022)	Longer wheelbases enhance stability but reduce maneuverability.
Rake Angle (Wilson-Jones, 1951; Sharma et al., 2015)	Larger rake angles improve stability at high speeds but reduce maneuverability at low speeds.
Trail (Wilson-Jones, 1951; Sharma et al., 2015)	Longer trail enhances stability but makes the motorcycle more resistant to steering inputs.
Self-Balancing (Wilson- Jones, 1951; Liu et al., 1992)	Influenced by rake angle, trail, and wheelbase; gyroscopic effects enhance stability at high speeds.
Stability (Forouhar & Packard, 1994) ("Influence of aerodynamic lift and center of pressure position in motorcycle stability", 2023) (Ye et al., 2022)	Directional stability is enhanced by larger rake angle and trail; lateral stability is influenced by mass distribution and suspension.
Maneuverability (Wilson-Jones, 1951; Sharma et al., 2015)	Enhanced by smaller rake angle and shorter trail, allowing quicker steering inputs and tighter turns.

Based on the review, the author found that the geometrical parameters of a motorcycle, including wheelbase, rake angle, and trail, play a crucial role in determining its stability and maneuverability. These parameters must be carefully optimized to achieve a balance between the two, ensuring the motorcycle performs well under various riding conditions.

2.2 Technologies Involved in Self-Balancing Systems in Motorbikes

Self-balancing systems in motorbikes are complex technologies that integrate multiple components to maintain stability. The physics behind self-balancing motorcycles combines several mechanisms and principles such as sensors, control algorithms, and mechanical interventions that work together to achieve what riders do naturally. Motorcycles need two different mechanisms to stay balanced (Zhang & Wu, 2019). The wheels act as gyroscopes that provide natural stability at high speeds. Additional systems must step in to prevent tipping at lower speeds or when the bike stands still.

Gyroscopic sensors are essential for self-balancing systems, measuring a motorbike's orientation and angular velocity. These sensors are typically complemented by accelerometers and sometimes inclinometers to provide a comprehensive understanding of the bike's state. Gyroscopes measure the angular velocity of the motorbike, which is critical for detecting lean angles and changes in orientation. To improve accuracy, gyroscopic data is often fused with accelerometer data. Techniques such as Kalman filtering or complementary filtering are employed to combine these measurements effectively. Ji et al. (2014) present a design for a self-balancing two-wheeled vehicle that utilizes an STM32 F microcontroller and a digital motion sensor (MPU-6050) to achieve stability and control in movement. It implements a Kalman-filtering algorithm to effectively fuse gyroscope and accelerometer signals, providing an optimal estimate of the vehicle's attitude angle and angular velocity, which is crucial for maintaining balance. (Mahler & Haase, 2013) present a drift compensation controller that effectively integrates data from both gyroscopes and accelerometers to provide an accurate estimation of the bike's tilt angle. Besides that, in some cases, inclinometers are used alongside gyroscopes to measure the bike's roll and pitch angles. These measurements are particularly useful for maintaining balance during dynamic maneuvers. Andreev (2016) uses a combination of gyroscopes and inclinometers to maintain stability during cornering.

Besides sensor data, additional systems need to be integrated to prevent tipping at lower speeds or when the bike stands still. Control algorithms are the brain of self-balancing systems, processing data from sensors and commanding actuators to maintain balance. Current approaches to motorcycle stability incorporate various control mechanisms, including linear controllers such as PID (Proportional-Integral-Derivative) (Vasilevski et al., 2023) as well as nonlinear methods and intelligent control techniques (Choi et al., 2019). Traditional control methods have notable limitations. PID controllers are commonly used for balance control, but require precise modelling and tuning, and their effectiveness is limited to small leaning angles due to reliance on linearization (Glushchenko et al., 2018; Vijaya Lakshmi & Manimozhi, 2024). Fuzzy logic is sometimes integrated with PID controllers to improve flexibility and robustness. Ma et al. (2024) combine fuzzy logic with Kalman filtering to optimize the state estimation and balancing performance of a two-wheeled vehicle. Even though Nonlinear control techniques like Fuzzy Logic Controllers (FLC) provide better stability and adaptability but come with complexities in rule formulation (Kharola et al., 2016). Additionally, combining FLC with neural networks improves system stability. Overall, traditional methods often struggle to handle the nonlinear and under-actuated dynamics of motorcycles, especially under external disturbances and model uncertainties (Vijaya Lakshmi & Manimozhi, 2024). Recently, advancements in Deep Neural Networks have made Reinforcement Learning (RL) as one of the most important and valuable technologies that can interact with an unfamiliar environment, choose actions, and gradually uncover the dynamics of that environment (Anjana et al., 2020; Naeem et al., 2020). Vijaya Lakshmi & Manimozhi (2024) present the implementation of a Deep Deterministic Policy Gradient (DDPG) algorithm within the framework of Reinforcement Learning (RL) to achieve self-balancing in motorcycles. The DDPG agent engages in iterative interactions with the motorcycle environment to formulate an optimal control policy, leveraging various state variables such as position and velocity, in conjunction with actions including motor torque. A comparative analysis with a traditional Proportional-Derivative (PD) controller illustrates that the DDPG approach yields faster response times, superior disturbance rejection, and enhanced adaptability in the face of uncertainties. The findings underscore the significant potential of reinforcement learning algorithms in advancing motorcycle control systems, ultimately contributing to safer and more efficient operational outcomes.

Furthermore, together with sensor data and control systems, it is important to choose the right actuators that execute the commands. The choice of motor type and its control strategy significantly impact the system's performance. Brushless DC (BLDC) motors are commonly used due to their high efficiency in terms of high torque and precise control, and reliability in terms of lightweight, low maintenance, and critical performance and long-term durability in motorcycles (Ehsani et al., 2018; Zeraoulia et al., 2006). Zero motorcycles, Harley-Davidson LiveWire, Energica, and NIU Electric Scooters are some of the commercial motorcycles using brushless motors. Yetayew & Tesfaye (2021) employ BLDC motors controlled by a Super Twisted Sliding Mode Controller to adjust the scooter's tilt angle ("Genetic Algorithm Tuned Super Twisted Sliding Mode Controller (STSMC) for Self-balancing Control of a Two-Wheel Electric Scooter", 2022). Field-Oriented Control (FOC) is an advanced motor control strategy that optimizes torque and efficiency. Tu et al. (2023) use FOC to control the flywheel motor, enabling precise balance control. Besides a brushless motor and FOC control strategy, Horoub et al. (2023) introduce a novel method for achieving self-balancing in two-wheeled vehicles using electric ducted fans, which blow air in the opposite direction of the fall to maintain equilibrium. This innovative approach allows for stability while reducing the weight of the two-wheeler. It details the implementation of a Proportional-Integral-Differential controller that utilizes an Inertial Measurement Unit sensor and a nonlinear complementary filter to accurately determine lean angles, ensuring the vehicle remains at a required upright 0° lean angle. The effectiveness of this controller is validated through theoretical and experimental testing on both small-scale and large-scale models.

The geometry of the motorbike plays a critical role in the stability of the self-balancing system. Optimizing these parameters can enhance the effectiveness of the self-balancing system. Besides the wheelbase and center of gravity, the suspension system and dynamic geometry adjustment system are other critical systems to adjust the bike's geometry to maintain balance. The suspension system is designed to absorb shocks while maintaining the bike's balance. Panzani et al. (2021) proposes a gyroscopic stabilizer that works in conjunction with the suspension system to improve roll stability at low speeds and enhance safety and comfort for riders. It introduces a multi-objective optimization problem that facilitates the joint design of the actuator and its control law, allowing designers to effectively steer parameter choices and resulting in a prototype that has been manufactured, installed on a motorcycle, and experimentally validated under various conditions. Another system, called dynamic geometry adjustment, adjusts the bike's geometry to maintain balance. Andreev (2016) describes a supporting device that allows independent movement of the wheels, enhancing stability on uneven terrain. The author proposed a two-wheeled gyro-stabilized vehicle that features a stabilizing two-stage gyroscope that allows the frame to rotate freely relative to the body about a vertical axis, enhancing stability during motion over rugged terrain while reducing the overall dimensions of the vehicle. The vehicle includes a sensor that detects the angle of rotation of the gyroscope frame, which works in conjunction with a control system to maintain stability by adjusting the speed of the vehicle wheels, ensuring that the angle between the gyroscope rotor's axis of rotation and the vehicle's direction of movement remains at ninety degrees

3. DISCUSSION

This section wraps up the findings from the review in the previous section. Based on the review, it was found that motorbike balancing could be achieved by the combination of motorbike geometry and an active self-balancing system. Motorbike geometry plays a significant role in natural self-balancing, especially at higher speeds, and it also affects the efficiency and effectiveness of active self-balancing systems at low speeds. The geometry of a motorbike includes parameters such as wheelbase, rake angle, trail, and center of gravity (CoG), all of which directly affect balance and maneuverability. A longer wheelbase enhances stability but can reduce maneuverability. Self-balancing systems must exert more effort to correct imbalances in bikes that have shorter wheelbases. Rake and trail affect how the front wheel responds to steering inputs. A larger trail contributes to natural stability at high speeds, which reduces the workload on a self-balancing system. Additionally, lower CoG generally improves balance and helps the bike remain upright. Self-balancing systems are designed with the dynamic center of gravity (CoG) in consideration.

Self-balancing systems in motorbikes are a synergy of advanced sensors, sophisticated control algorithms, precise actuator responses, and optimized motorbike geometry. Gyroscope sensors measure the angular velocity of the motorbike for detecting lean angles and changes in orientation. The data from the gyroscope sensor is fused with the accelerometer to improve the accuracy of detection and combined with the IMU sensor to achieve stability and control in movement. Current approaches to motorcycle stability incorporate various control mechanisms, including linear controllers, nonlinear methods, and intelligent control techniques to ensure precise balance control. Reinforcement Learning (RL) offers valuable solutions that can interact with an unfamiliar environment, choose actions, and gradually uncover the dynamics of that environment. Together with sensor data and control systems, it is important to choose the right actuators that execute the commands. BLDC motor, FOC control strategy, and EDFs approach could be integrated to provide both precise torque control and directional thrust, which may enhance stability in extreme or edge cases. Finally, the geometry of the motorbike, including the suspension system and dynamic geometry adjustment, plays a critical role in stability. Optimizing these parameters can enhance the effectiveness of the self-balancing system.

4. CONCLUSION

This article provides a glance review of self-balancing motorbikes. The article highlighted the historical advancement in self-balancing motorbikes, the relationship between bike geometry and self-balancing, and key technologies involved in self-balancing systems in motorbikes that need to be considered as a path to producing a standardized dynamic self-balancing motorbike. Based on the review, it was found that motorbike balancing could be achieved by the combination of motorbike geometry and an active self-balancing system. Motorbike geometry plays a significant role in natural self-balancing, especially at higher speeds, and it also affects the efficiency and effectiveness of active self-balancing systems at low speeds. Self-balancing systems include advanced sensors, sophisticated control algorithms, precise actuator responses, and optimized motorbike geometry, which need to be integrated together to maintain stability in extreme and edge cases.

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