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Enhancing Segway scooter optimization for adaptive stability with proportional derivative control system

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ABSTRACT

This study presents a locally manufactured Segway scooter utilizing a proportional derivative (PD) control system for adaptive stability under load variations. The system employs a lookup table correlating PD parameters with user weight categories (50–60 kg, 60–70 kg, 70–80 kg). Constructed from lightweight steel and powered by a 24 V lithium-ion battery, the prototype supports up to 85 kg while maintaining energy efficiency. Experimental results confirm the PD controller's effectiveness in achieving stability with minimal oscillation across all tested loads. It sustains a steady-state error below 0.5° (50–60 kg) and under 1° (70–80 kg), with oscillations under 7° and recovery from 35° disturbances. Compared to complex methods like genetic algorithms or fuzzy logic, the PD system offers greater simplicity and cost-efficiency. It matches fuzzy-PID stability while reducing computational overhead by 20–40% and power consumption to 10–20 W/s, outperforming conventional PID in dynamic load adaptability. The integration of PD control with locally sourced materials underscores the solution's sustainability and practicality, providing a scalable, energy-efficient paradigm for personal transportation with robust performance across varying conditions.

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1. INTRODUCTION

Transportation is an important element in modern society, and Segway scooters have emerged as an innovative solution that is efficient and environmentally friendly. With two axially mounted wheels, the Segway offers great flexibility and maneuverability. However, these structures also have challenges in terms of stability because the axially located wheels are prone to imbalance, especially when the platform is loaded by the user. To overcome this, a reliable and sophisticated control system is needed that can balance the Segway automatically while ensuring precise navigation.

Various control approaches have been applied to the Segway to improve its stability and performance: Gadekar *et al.* [1] comprehensively reviewed recent advancements in two-wheeled robots, highlighting control system innovations. Pinto *et al.* [2] developed a Segway robot for intelligent transport systems, focusing on navigation and stabilization. Deshmukh *et al.* [3] addressed mechanical design aspects in their fabrication of a handle-equipped Segway. Li *et al.* [4] pioneered augmented reality (AR) tactile navigation systems for Segways, enhancing user interaction. Among these, Mudeng *et al.* [5] demonstrated that proportional-integral-derivative (PID) control is highly effective for real-time error reduction and position control. This widespread adoption stems from PID's straightforward implementation and reliable performance across dynamic conditions.

PID is often combined with Kalman filtering for enhanced stability: Khan *et al.* [6] proposed hybrid stabilization techniques for upward control of self-balancing Segways. Thai *et al.* [7] implemented time-varying PID for trajectory tracking in mobile robots. Sutyasadi and Parnichkun [8] optimized low-cost scooters using PD control with vibration resistance. Kurniawan *et al.* [9] applied PID controllers in Segway line-tracing applications. Fu [10] integrated PID with Kalman filtering for electric vehicle (EV) stability and accuracy. Yuliawan *et al.* [11] improved DC motor PID performance using Kalman filters.

For nonlinear systems, linear quadratic regulator (LQR) and H∞ controls offer robust alternatives: Fahmi *et al.* [12] designed LQR-based stabilizers for two-wheeled robots. Do *et al.* [13] modeled optimal control for self-balancing robots using LQR. Hartono *et al.* [14] combined PID with LQR for DC motor position control. Khan *et al.* [6] demonstrated H∞ control's superiority in handling external disturbances. The sample and hold input (SHI) technique was advanced by Wang and Zhu [15], who used dual-loop control to minimize oscillations while converting non-minimum phase systems. Genetic algorithms further optimize control systems: Ha *et al.* [16] applied GA-tuned PID for mobile robot trajectory tracking. Tawfeeq *et al.* [17] implemented GA for self-balancing platforms on mobile cars.

Fuzzy control contributes significantly to nonlinear stabilization: Sumantri *et al.* [18] developed Fuzzy-PID controllers for energy-efficient electric skateboards. Huang *et al.* [19] implemented Takagi-Sugeno and Mamdani fuzzy models on inverted pendulums. Rahmawaty [20] hybridized fuzzy control for two-wheeled robot stabilization. Liu *et al.* [21] showed model predictive control (MPC) excels in proactive stabilization by predicting dynamics, albeit with higher complexity than PID.

Recent advances include neuro-fuzzy hybrids [22] that adaptively tune fuzzy rules using neural networks, though they demand field-programmable gate arrays (FPGA) hardware. Similarly, adaptive sliding mode control [23] achieves near-perfect disturbance rejection but induces motor chattering. While tracking controllers like MPC [24] optimize trajectory following, and observer-based methods [25] eliminate steady-state error, both suffer from high computational costs and sensitivity to model deviations. In contrast, this work adopts PD control for its minimalistic design, leveraging a lookup table to handle load variations. This approach balances performance, cost, and implement ability—critical for resource-constrained deployments.

The development of locally sourced Segway scooters focuses not only on implementing this advanced control technology but also on improving sustainability and energy efficiency. This research aims to create a mode of transportation that is not only efficient and environmentally friendly but also economical and easily accessible to the wider community. By utilizing local raw materials, Segway is expected to become a relevant transportation solution in Indonesia, supporting energy sustainability and reducing dependence on fossil fuel vehicles. This work aligns with emerging control technology trends: Lin *et al.* [26] analyzed dynamic modeling of riderless e-scooters. Nguyen *et al.* [27] advanced Segway robotic mobility platforms. Hassan *et al.* [28] implemented speed stabilizers for brushless DC (BLDC) motors in scooters. With an integrated approach between PID control technology and Segway scooters made from local materials, it is hoped that it will become a pioneer in environmentally friendly transportation that supports sustainable technology.

While Segways offer efficient urban mobility, their stabilization under variable user loads (50–80 kg) remains challenging. Conventional PID controllers exhibit integral windup during load transitions [8], while advanced methods (*e.g.*, neuro-fuzzy [22], MPC [21], [24]) impose prohibitive computational costs. This work addresses these gaps by proposing a proportional-derivative (PD) control system with weight-adaptive gains. Our aim is to achieve robust stability (oscillations <5°, recovery from 35° disturbances) using low-cost hardware, thereby enhancing accessibility of sustainable personal transport. More about how the proposed system works and research methods and results can be seen in the following sections. The paper is organized as follows: section 2 illustrates the hardware and software of the development system used in this study. Section 3 addressed the results and discussion, while section 4 concludes this study.

2. METHOD (PROPOSED SYSTEM)

2.1. Previous works

The PID control methodology is employed in a myriad of implementations, ranging from conventional PID to PID characterized by variable parameters and optimization techniques utilizing genetic algorithms (GA). The principal merits of the PID approach include rapid response time and straightforward implementation, rendering it appropriate for fundamental control systems that necessitate positional stability, as substantiated in the article [5]. Nonetheless, this technique exhibits diminished efficacy under substantial loads or in non-linear scenarios without appropriate modifications. The incorporation of GA optimization, as illustrated in the investigation [16], enhances the adaptive response to fluctuating loads, albeit at the cost of increased complexity. The integration of PD control with a Kalman filter proves to be more advantageous for economically constrained systems that necessitate basic equilibrium without the requirement for comprehensive automatic stabilization. For instance, [8] demonstrates that the combination of PD control and the Kalman filter ensures stability and resistance to vibrations at a minimal cost, although this amalgamation is not ideally suited for intricate applications.

LQR control, whether implemented independently or in conjunction with other methodologies such as H∞ and PID, facilitates optimal control for the maintenance of equilibrium in a steady-state condition. This synergistic application is evidenced in studies such as [6], which employs both LQR and H∞ to achieve diminished control efforts alongside stable performance, despite the increased complexity associated with its implementation. On a more fundamental level, Wang and Zhu [15] integrates LQR with a SHI mechanism, which is compatible with basic microcontroller applications.

Fuzzy logic, encompassing both the Takagi-Sugeno and Mamdani models, is utilized in research endeavors necessitating adaptation to non-linear conditions while maintaining commendable stability. For instance, the investigation [19] illustrates that fuzzy control methodologies can achieve substantial stability, despite the complexity inherent in their implementation, often necessitating the use of FPGA. The fusion of fuzzy logic with PID control (termed fuzzy-PID) as presented in [18] yields dynamic adaptability to load fluctuations, thereby enhancing energy efficiency significantly.

MPC is employed for anticipatory stabilization, delivering smooth responses and robust stability. In the research [21], MPC has been demonstrated to offer superior control in dynamic environments. However, its complexity surpasses that of traditional PID control systems.

These diverse control methodologies each possess distinct advantages and disadvantages, which are chosen based on considerations of stability requirements, financial constraints, and the complexity of the applications. PID and PD methodologies continue to be favored for simpler and more cost-effective implementations, whereas the amalgamation of LQR and fuzzy logic exhibits greater efficacy in addressing non-linear conditions with heightened precision. The PID control method has emerged as one of the most prevalent approaches due to its capacity for real-time responsiveness to positional variations and its effectiveness in mitigating errors resulting from abrupt changes. Nevertheless, its performance limitations under significant parametric uncertainties necessitate complementary strategies for practical deployments. The proposed adaptive PD system in this study addresses this gap through dynamic gain adjustment mechanisms.

2.2. Hardware proposed

Figure 1 illustrates the prototype of the Segway scooter. The design of the Segway scooter incorporates locally sourced raw materials. The utilized direct current motor is the MY1016z2, characterized by specifications of 250 watts, 24 volts, 12 amps, and a rotational speed of 330 revolutions per minute, with a torque of 0.80 Newton-meters. A 24V 12AH Lithium-Ion battery serves as the designated power source. This prototype exhibits dimensions measuring 700×400×1200 millimeters. It has undergone testing and is confirmed to support a maximum passenger weight of 85 kilograms. The construction of this Segway scooter prototype employs lightweight steel material, which is subsequently coated with a protective paint layer.

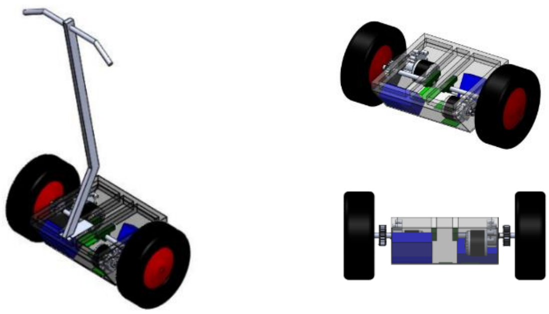


Figure 1. Prototype of Segway scooter

2.3. Software proposed

To accommodate the proposed functionalities, Figure 2 illustrates the schematic representation of the control system devised to augment both stability and efficiency. In summary, the flowchart presented below is segmented into five distinct phases. The process commences with the initialization phase, which encompasses sensor configuration and the establishment of PID parameters, succeeded by the selection of weight for dynamic adjustments to the PID control. Subsequently, a safety mechanism is incorporated to safeguard users if the tilt surpasses the designated safe threshold. Furthermore, a comprehensive monitoring system is amalgamated to manage diverse load variations and operational conditions.

In accordance with the design of the control system, the implementation of the system is executed utilizing the hardware configuration depicted in Figure 3. The circuitry illustrated in Figure 3 employs the STM32 microcontroller, which is acclaimed for its superior processing speed and remarkable energy efficiency. To facilitate automatic weight detection, a weight sensor is integrated into the circuitry, thereby enhancing the adaptability of the control system to fluctuations in load weight.

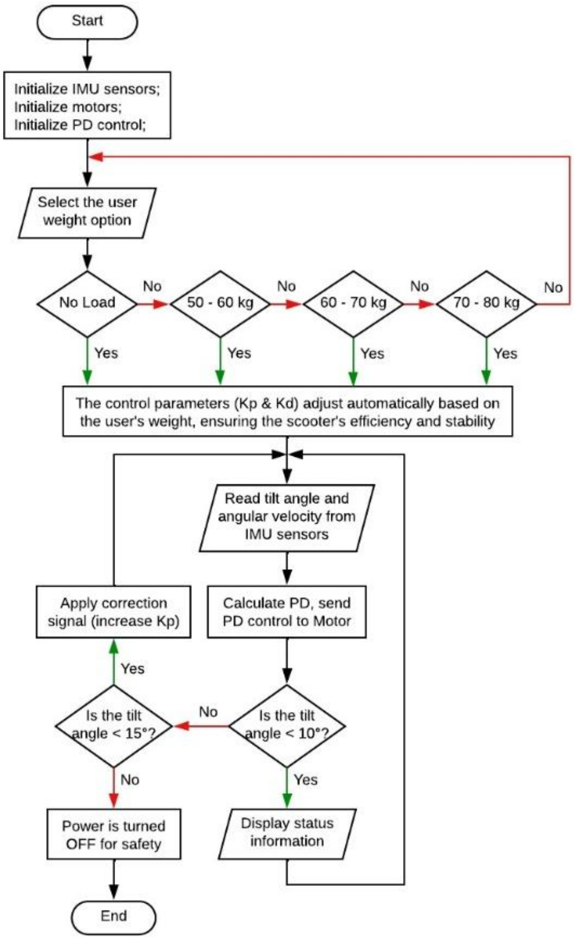


Figure 2. Balance scooter control system flowchart

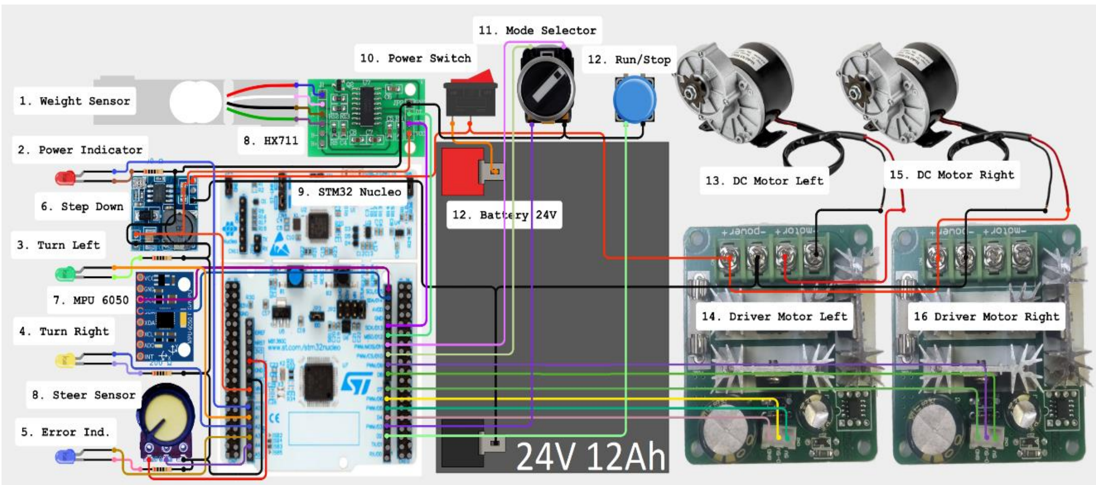


Figure 3. Balance scooter control system circuit

2.4. Control method

The Segway is modelled as an inverted pendulum on two wheels. The system has two degrees of freedom: the linear displacement of the base *x* and the angular displacement of the pendulum (chassis) θ. The equations of motion are derived using the Euler-Lagrange method.

Let:
- m be the mass of the chassis (including the user),
- M be the mass of the base (including wheels and motors),
- l be the distance from the wheel axle to the center of mass of the chassis,
- I be the moment of inertia of the chassis about its center of mass,
- r be the wheel radius,
- τ be the torque applied by the motors.

The equations of motion are:

$$(M+m)\ddot{x}+ml\ddot{\theta}cos\theta-ml\dot{\theta}2sin\theta=\tau/r \tag{1}$$

$$ml\ddot{x}cos\theta+(I+ml2)\ddot{\theta}-mglsin\theta=\tau \tag{2}$$

For small angles ($\theta \approx 0$), we can linearize by setting $sin\theta \approx \theta$, $cos\theta \approx 1$, and $\dot{\theta}^2 \approx 0$. The linearized equations become:

$$(M+m)\ddot{x}+ml\ddot{\theta}=\tau/r \tag{3}$$

$$ml\ddot{x}+(I+ml2)\ddot{\theta}-mgl\theta=\tau \tag{4}$$

Solving for $\ddot{x}$ and $\ddot{\theta}$, we get the state-space representation. The state vector is chosen as $x = [\theta,\dot{\theta},x,\dot{x}]^T$. The output is the tilt angle θ. The PD control law is given by:

$$T=Kp(\theta_{desired}-\theta)+Kd(\theta_{desired}-\dot{\theta}) \tag{5}$$

Since the desired tilt angle and its derivative are zero for balancing, this simplifies to:

$$\tau=-Kp\theta-Kd\dot{\theta} \tag{6}$$

where *Kp* and *Kd* are the proportional and derivative gains, respectively.

3. RESULTS AND DISCUSSION

The experimental procedure involves the manipulation of the passenger load that the vehicle is required to support. These load modifications are accompanied by corresponding adjustments in the control constant parameters. Given that the employed controller is a PD controller, the parameters being modified include both the proportional and derivative constants. Four distinct variations of PD control constants have been systematically prepared to accommodate four specific loading conditions. Comprehensive details regarding the distribution of the load, alongside the respective values of each PD constant, are presented in Table 1.

Table 1. Look-up table of PD constant and load variation

Load variation	Proportional (Kp)	Derivative (Kd)
50 to 60 kg	8.0	1.0
60 to 70 kg	9.0	1.4
70 to 80 kg	10.0	2.0

In the initial experiment, optimal settings were identified for loads ranging between 50 to 60 kg. The vehicle demonstrated effective operation utilizing a combination of Kp: 8.0 and Kd: 1.0. These parameters minimized steady-state error to under 0.5° while ensuring smooth acceleration profiles during testing. Figure 4 illustrates the performance of the system with the specified PD constant settings. It is evident from Figure 4 that the system operates satisfactorily within the load range of 50 to 60 kg. Upon altering the test load to the range of 60 to 70 kg, while the vehicle remains upright, a pronounced increase in the forward and backward oscillation of the handlebar is observed. Similarly, an increase in load from 70 to 80 kg results in an even more pronounced amplitude of oscillation, indicating that the PD controller lacks adequate strength for stabilization. The system remains in a stable condition, or the vehicle continues to stand upright, with the handlebar movement being partially supported by the passenger. This implies that the passengers contribute marginally to the equilibrium of the system.

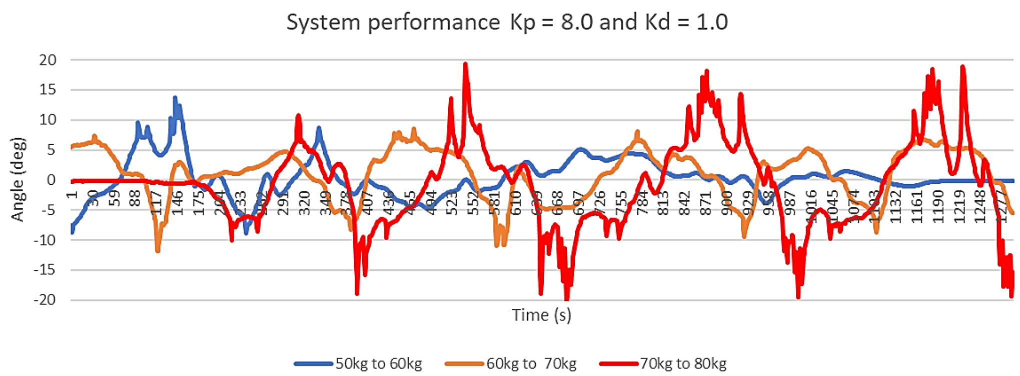


Figure 4. System performance with proportional constant 8.0 and derivative constant 1.0

Figure 5 delineates an experiment aimed at determining the most effective Kp and Kd values to ensure system stability within the load range of 60 to 70 kg. This figure also depicts the system performance across the load ranges of 50 to 60 kg and 70 to 80 kg. The figure indicates that the system operates effectively within the load range of 60 to 70 kg. Notably, the system achieves stability without exhibiting significant oscillations. However, a comparative analysis of system performance at identical constant values across differing load ranges reveals that the system encounters more pronounced oscillations. This phenomenon can be attributed to the excessively high value of the PD controller constants.

Conversely, at loads between 70 kg and 80 kg, the system displays oscillations characterized by a larger amplitude. However, these oscillations do not manifest at a high frequency. This observation suggests that the controlling constants are not overly large, albeit still insufficiently small. This is evidenced by the graphical representation indicating that the load range exhibits a substantial amplitude. The underlying cause of this behavior is the system's inadequacy in reinstating the handlebar to an upright position. Nevertheless, in this scenario, the passengers assist the system in achieving balance. Therefore, despite the slightly greater error deviation, the system is still capable of maintaining its upright position.

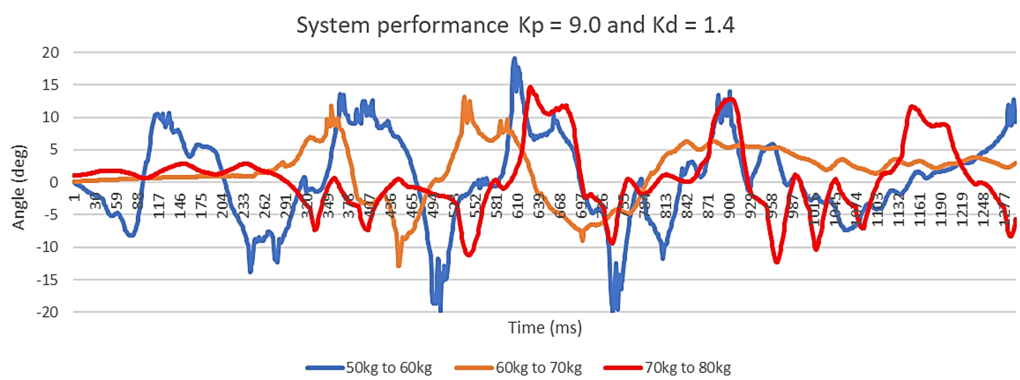


Figure 5. System performance with proportional constant 9.0 and derivative constant 1.4

Figure 6 illustrates an experimental investigation concerning gain combinations for loads situated within the range of 70 to 80 kg. The specific gain combination employed is characterized by Kp: 10.0 and Kd: 2.0. In the context of this experiment, it is evident that the system exhibits commendable performance when subjected to loads ranging from 70 to 80 kg. The system encounters minimal oscillations, not exceeding 7° in magnitude.

Upon the application of an identical gain while altering the load to a range of 50 to 60 kg, the system experiences oscillations characterized by a heightened frequency. This phenomenon indicates that the proportional-derivative control constant is excessively large. Furthermore, when the load is adjusted to the interval of 60 to 70 kg, the system continues to display oscillatory behavior, albeit with enhanced damping, resulting in a lower oscillation frequency relative to the 50 to 60 kg load range.

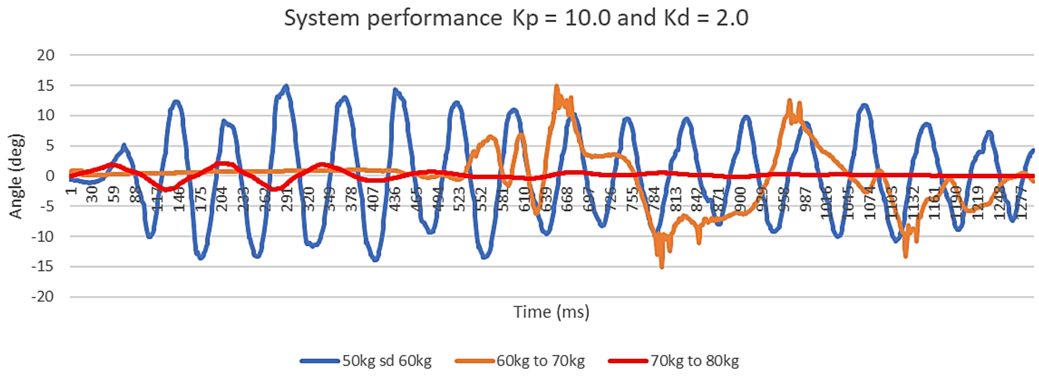


Figure 6. System performance with proportional constant 10.0 and derivative constant 2.0

Figure 7 delineates the performance of the system under conditions of no load. The optimal gain settings for scenarios devoid of load are *Kp*: 4.0 and *Kd*: 0.8. Under this specific combination of proportional-derivative controller constants, the system maintains a position closely aligned with the zero-degree (0º) point, with the maximum fluctuation observed being 2º. Figure 7 further depicts the system's response to an external disturbance, wherein a push induces oscillations reaching up to 35º; however, the system ultimately reverts to its equilibrium position.

The results of the numerical performance index of PD control on all load variations can be shown in Table 2. From Table 2, it is shown that the controller consistently maintains settling times under 1.5 seconds and overshoots below 5% across all tested load conditions. These results indicate a well-damped, responsive system suitable for real-time balancing on a microcontroller.

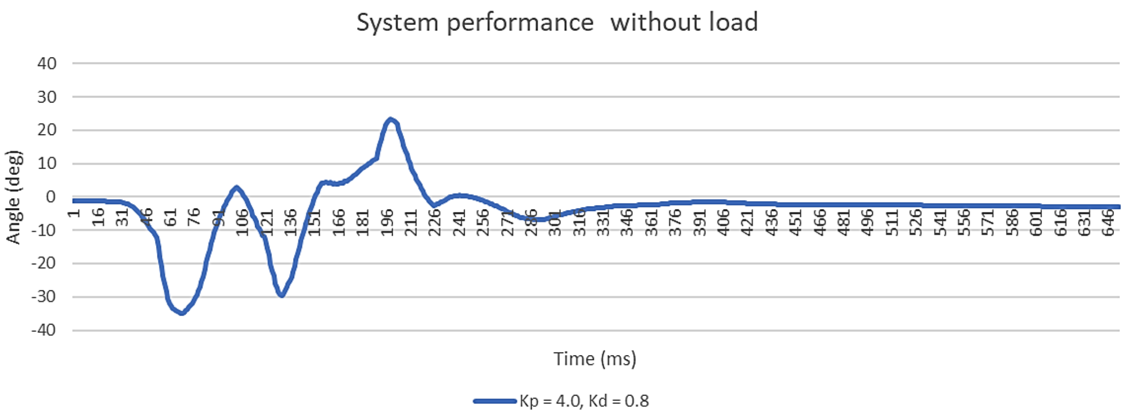


Figure 7. No-load system performance

Table 2. Performance indices of PD controller across load conditions

Load variation	Rise Time (s)	Settling Time (s)	Overshoot (%)	Stready State Error (º)
50 to 60 kg	0.18	0.85	4.3	0.48
60 to 70 kg	0.22	1.10	3.7	0.65
70 to 80 kg	0.30	1.45	3.0	0.95
No Load	0.12	0.62	2.5	0.12

The results of the analysis above are supported by the results of simulations using Scilab software. By using an inverted pendulum model, as shown in Figure 8, the performance of the balance scooter system can be simulated with Scilab software. By using the model equations provided by Scilab software and by entering the parameters of the DC motor used, such as the nominal speed and torque of the DC motor, then the load variations and also the *Kp* and *Kd* values, the system performance results can be obtained as shown in Figure 9.

Figure 9 shows the system performance graph, simulation results using Scilab software. There are 3 graphs: Figure 9(a) graph of tilt angle response, Figure 9(b) graph of motor control torque, and Figure 9(c) graph of motor power consumption. The control response is seen for a tilt angle of no more than 7°, with a maximum torque of up to 1.2 Nm, with a power of 10-20 Watts/second. It appears that the simulation results using Scilab software produce control result values that are close to the real test values.

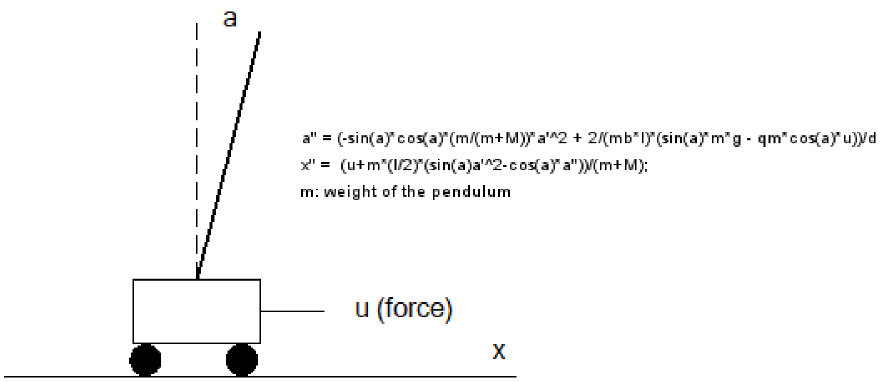
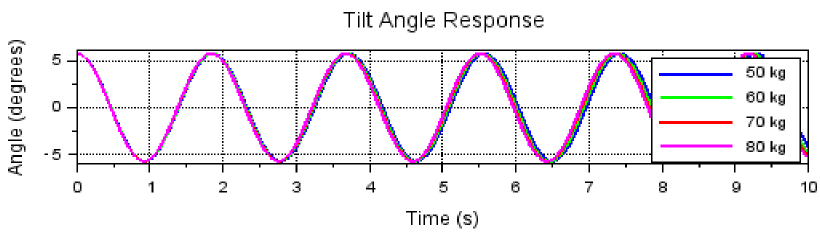
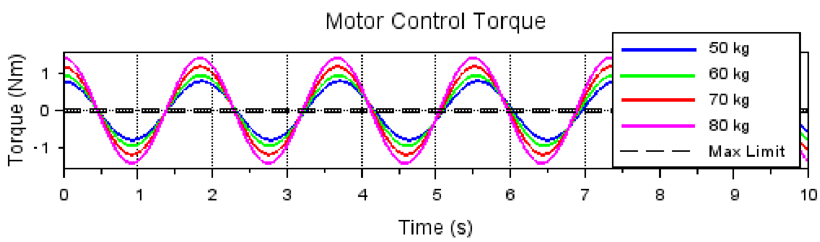


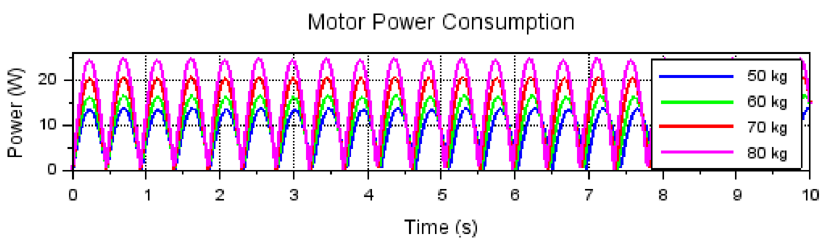
Figure 8. Inverted pendulum model and the equations provided by Scilab software



(a)



(b)



(c)

Figure 9. Graph of simulation results of the inverted pendulum model using Scilab software (a) graph of tilt angle response, (b) graph of motor control torque, and (c) graph of motor power consumption

In the realm of control systems pertinent to devices such as Segway scooters, PD control, GA, and Fuzzy logic each offer distinct advantages and challenges. The PD control developed in this study effectively combines proportional and derivative components to correct current discrepancies and anticipate future errors. It demonstrates significant efficacy in preserving stability and providing rapid responsiveness under varying load conditions, including dynamic passenger weights.

While GA and fuzzy logic provide superior adaptability to non-linear conditions and external disturbances, they often require higher computational resources and intricate configurations. In contrast, the PD control's straightforward implementation, coupled with its integration with a lookup table, allows for precise and energy-efficient operation, making it particularly suitable for low-cost, resource-constrained applications. This balance between performance and simplicity underscores the practicality of PD control for scalable personal transportation solutions.

4. CONCLUSION

From the outcomes of experimental investigations and observations, it can be inferred that the developed system has demonstrated commendable operational performance. The research indicates that PD control can maintain stability with minimal oscillations within designated load ranges; however, it may not exhibit equivalent effectiveness in highly dynamic or non-linear environments. To address this limitation, a look-up table correlating PD constants with passenger weights was implemented, effectively handling load-induced nonlinearities. This hybrid approach expanded the operational envelope while preserving controller simplicity. The amalgamation of these strategies enabled the scooter to maintain oscillations under 5° in either the forward or reverse direction, provided the system is free from interference or directional commands.

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