

Experimental Evaluation of Regenerative Braking Performance in a Small Four-Wheel-Drive Mobile Robot Under Variable Operating Conditions

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ABSTRACT

Electric and hybrid vehicles commonly use regenerative braking to improve energy efficiency, recovering kinetic energy during deceleration and converting it into reusable electrical energy. The concept has been extensively studied in large-scale vehicles, but far less research has examined how it functions in smaller robotic platforms under variable operating conditions. This study addresses that gap by investigating how regenerative braking affects energy recovery and efficiency in a 4WD mobile robot as speed, payload mass, and incline angle were varied. An INA219 current and voltage sensor, integrated with an Arduino Uno R3 for data acquisition, measured energy consumption and recovery throughout testing. Each of the three variables was tested at three levels with three repeated trials per condition, and every regenerative braking trial was compared against a non-regenerative control trial to isolate the effect of energy recovery. Across every condition tested, regenerative braking recovered measurable energy and improved efficiency relative to the control trials. Recovered energy also increased consistently as speed, payload mass, and incline angle increased, suggesting that energy recovery scales predictably with the amount of mechanical energy available. Rather than demonstrating improvements under only a single operating condition, the results showed consistent performance across all variables investigated. Collectively, these findings indicate that regenerative braking can improve energy recovery and efficiency in small mobile robotic platforms, pointing to its potential for broader use in energy-constrained robotic applications. In addition, this study provides a validated experimental platform that future researchers can use to further investigate regenerative braking at small scale.

INTRODUCTION

Greater energy efficiency within vehicles can allow for the development of new energy sources and fuels. Utilizing currently available technologies has been projected to increase average fleet fuel economy by up to 40 percent [1]. Within automobiles, energy efficiency can aid in preventing emissions of harmful

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greenhouse gases into the atmosphere. In 2021, oil-powered vehicles contributed roughly 29% of total U.S. greenhouse gas emissions, compared to approximately 2% from electric and hybrid vehicles [4]. Despite the environmental benefits offered by electric vehicles, their performance remains heavily dependent on battery efficiency and longevity. Electric vehicle batteries are often engineered and implemented to maximize operational lifespan. In spite of these efforts, battery performance inevitably declines over time due not only to repeated use, but also to internal battery design and environmental conditions [2]. As a result, mechanisms that can minimize energy loss and significantly improve overall energy utilization have become increasingly important. One such approach, common within nearly all modern hybrid and battery-electric vehicles in the United States, is regenerative braking [3].

Traditional friction braking applies, through mechanical brakes, a frictional force which converts a moving vehicle's existing kinetic energy into heat energy, later dissipated and lost into the atmosphere. Regenerative braking aims to recover kinetic energy during deceleration by transforming it into a reusable form of energy, such as pneumatic, electrical, or hydraulic, depending on the system configuration [5]. Electric motors primarily function to provide torque that propels a vehicle during normal operation. During regenerative braking, this process is reversed, causing the motor to operate as a generator rather than a power consumer. As the vehicle decelerates, the wheels continue rotating the motor, which converts the vehicle's kinetic energy into electrical energy. As the motor rotates during deceleration, a counter electromotive force (CEMF), commonly referred to as back electromotive force (back EMF), is induced, allowing the motor to generate electrical energy instead of consuming it [6]. This electrical energy is then redirected to an onboard energy storage device, such as a supercapacitor, where it can be stored for future use. Energy stored within a supercapacitor can be used to supplement vehicle power demands, ensuring a uniform power supply while optimizing performance [7]. Due to its demonstrated advantages, regenerative braking has become the focus of extensive research aimed at improving energy recovery efficiency.

Regenerative braking has consistently demonstrated improvements in energy efficiency within electric vehicles. Beyond improving overall energy efficiency, regenerative braking has also been shown to reduce mechanical brake wear and extend vehicle driving range by recovering energy that would otherwise be dissipated during braking. A system utilizing integrated high-yield supercapacitors along with an adaptive control algorithm captured roughly 92.5% of kinetic energy during deceleration, first directing it to supercapacitors for instant storage, then later the primary battery. This system was tested against real-world driving conditions, such as stop-and-go traffic along with downhill braking [8]. In addition, recent studies have tested the implementation of AI to replace conventional regenerative braking strategies; utilizing regression models, swarm intelligence, and deep reinforcement learning have demonstrated measurable improvements in energy recovery and efficiency [10]. Beyond system architecture, previous research has also demonstrated that regenerative braking performance is influenced by several operating conditions. Factors including brake pressure, motor torque, and vehicle speed have all been shown to affect overall recovery efficiency [9]. Although significant progress has been made in improving regenerative braking systems, continued research remains essential to better understand their performance across different applications and operating environments.

Despite these advances, several limitations persist within the existing body of literature. Much of the published research centers on full-scale electric and hybrid vehicles, with a substantial portion of that work directed toward control algorithm design or simulation-based modeling rather than physical experimentation. Comparatively few studies have experimentally validated regenerative braking performance on small mobile robotic platforms, and those that do often emphasize specific system architectures or individual performance characteristics. This gap is particularly relevant because small robotic platforms are increasingly common in autonomous systems research, robotics education, and low-cost prototyping, and understanding how regenerative braking behaves at this scale has direct relevance to those applications. Controlled laboratory-scale platforms also offer a practical way to validate theoretical energy-recovery predictions against real, measurable performance rather than relying on simulation alone. This study addresses that gap by developing a 4WD robotic platform to experimentally evaluate regenerative braking against a non-regenerative control under multiple operating conditions. A system was designed using an INA219 sensor and Arduino microcontroller to measure voltage and current during braking events, allowing the resulting experimental data to be compared with theoretical energy-recovery predictions. By evaluating regenerative braking within a controlled small-scale robotic system, this study contributes to the limited body of experimental work at this scale and provides a scalable framework for future research and educational use.

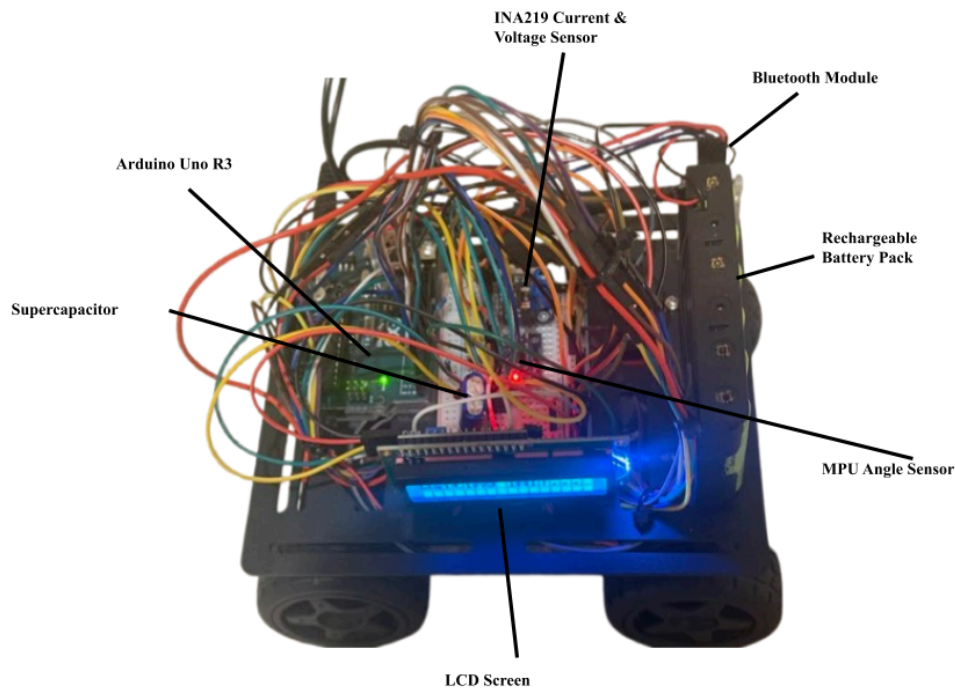
MATERIALS AND METHODS

2.1 Aim

The purpose of this study was to experimentally evaluate the effect of regenerative braking on energy recovery in a small-scale four-wheel-drive (4WD) robotic platform. While regenerative braking is well established in full-scale electric and hybrid vehicles, its behavior at a smaller, robotic scale has received comparatively little direct experimental testing. Most robotic platforms of this size dissipate braking energy as heat rather than recovering it, and a validated small-scale model would help determine whether the underlying principles of regenerative braking remain applicable and scale predictably, outside of a full-size vehicle. This study addressed the following research question: How can regenerative braking be experimentally validated in a small-scale robotic platform to improve measurable energy recovery and scale to real-world applications? The corresponding hypothesis was that increases in speed, incline angle, and load mass would each increase the measured regenerative energy recovery, since all three raise the amount of kinetic or gravitational potential energy available to be captured during braking. To test this, a 4WD robotic platform was built with a regenerative braking circuit and evaluated against a non-regenerative control across a matrix of operating conditions - three levels each of speed (PWM - Pulse Width Modulation level), load mass, and incline angle - with energy recovery measured directly using an INA219 current and voltage sensor. Results were then compared with the theoretical gravitational potential energy for each incline condition to assess how much of that available energy the system actually recovered.

2.2 Experimental Platform

The experimental platform was designed to replicate the fundamental operating principles of regenerative braking in a compact, modular robotic system while providing sufficient flexibility for controlled laboratory experimentation. The completed platform integrated mechanical, electrical, sensing, and energy storage subsystems into a single architecture capable of quantitatively evaluating regenerative braking performance under varying operating conditions, as shown in **Figure 1**.



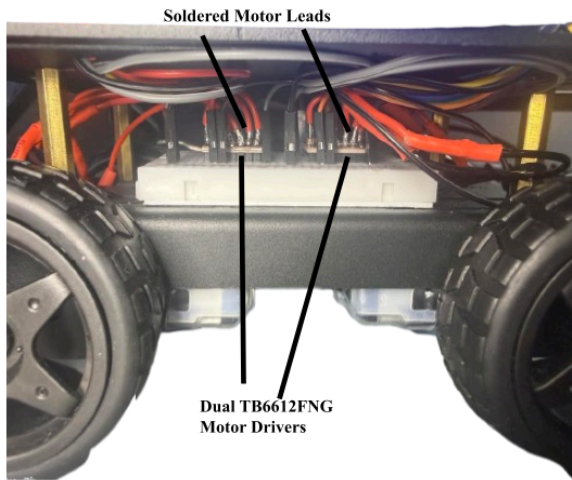


Figure 1. Annotated views of the completed regenerative braking platform. The upper image (a) shows the integrated control, sensing, and energy storage components, while the lower image (b) illustrates the finalized underside wiring configuration with dual TB6612FNG motor drivers and permanently soldered motor connections.

2.2.1 Mechanical Platform

The robot was built around a commercially available 4WD chassis with four DC gear motors, chosen in a four-wheel-drive layout for better traction and even weight distribution - both of which were essential for maintaining consistent vehicle stability during payload and incline testing. The chassis also had room to mount the sensors, the supercapacitor, and the interchangeable test masses used across trials. The motors initially lacked the torque to climb the steeper inclines. To address this limitation, the gearboxes were disassembled and fitted with custom replacement gears to increase the reduction ratio (1:48 to 1:120). That change boosted torque output enough for the robot to climb the higher incline angles reliably, thereby expanding the experimental operating range and enabling reliable testing across steeper incline conditions.

2.2.2 Control and Electronics

The primary hardware components incorporated into the experimental platform and the rationale for their selection are summarized in **Table 1**. Collectively, these components formed the mechanical, sensing, control, and energy-storage subsystems required to implement and evaluate regenerative braking. An

Arduino Uno R3 served as the system's controller, generating the PWM signal for the motors and coordinating data collection from the sensors. It was chosen for its I/O flexibility and straightforward compatibility with the sensor hardware used. Motor control started with L298N drivers, but early testing showed it dropped too much voltage and lost power internally, which distorted the energy readings. The L298N motor drivers were subsequently replaced with TB6612FNG dual H-bridge drivers after preliminary testing identified excessive voltage drop and internal power losses. The higher efficiency of the TB6612FNG reduced electrical losses within the drive system and substantially improved the accuracy of regenerative energy measurements. A Bluetooth communication module was integrated with the Arduino, enabling wireless command transmission from a mobile application. This eliminated the need for a continuous USB connection during testing, improving experimental efficiency and allowing untethered operation throughout repeated trials.

Component	Function	Reason Selected
Arduino Uno R3	System controller	Reliable sensor integration and flexible I/O
TB6612FNG Motor Driver	Motor control	Higher efficiency and lower voltage drop
INA219 Sensor	Current and voltage measurement	High-resolution power monitoring
MPU6050 IMU	Incline measurement	Accurate digital angle sensing
HC-05 Bluetooth	Wireless communication	Untethered remote operation
I ² C LCD	Real-time system feedback	Immediate status visualization
7.2 V NiMH Battery	Primary power source	Consistent output under repeated testing
5.5 V 1 F Supercapacitor	Regenerative energy storage	High power density and rapid charge/discharge

Table 1. Primary hardware components and selection rationale

2.2.3 Energy Recovery and Sensing

Energy recovered during braking was routed to a 5.5 V 1 F supercapacitor rather than the battery. Supercapacitors were selected because of their high power density and rapid charge-discharge behavior - batteries charge more slowly and don't handle a short, sudden burst of current the way a braking event produces. The supercapacitor could absorb that burst efficiently, then release it back into the system afterward. An INA219 high-side current and voltage sensor recorded measurements throughout each braking event, which made it possible to calculate total recovered energy directly rather than estimating it. An MPU6050 IMU was added to confirm ramp angle during testing, keeping the incline consistent across repeated trials. A 7.2V NiMH rechargeable battery pack supplied primary power, and an I²C LCD gave a live readout of system status while trials ran.

2.2.4 System Architecture

The mechanical, electrical, and sensing components worked together as one system. During normal driving, the battery powered the motors through the driver as usual. During braking, the motors reversed roles and acted as generators, converting the wheels' rotational energy into electrical energy that was sent to the supercapacitor. At the same time, the Arduino logged voltage and current through the INA219 sensor, which let the recovered energy be quantified and checked against theoretical predictions. The setup was built so that speed, payload, and incline could each be changed independently, without touching the wiring or the underlying circuit - which was essential given how many different condition combinations the same platform had to run through while staying consistent trial to trial. The simplified electrical power distribution architecture of the experimental platform is illustrated in **Figure 2**.

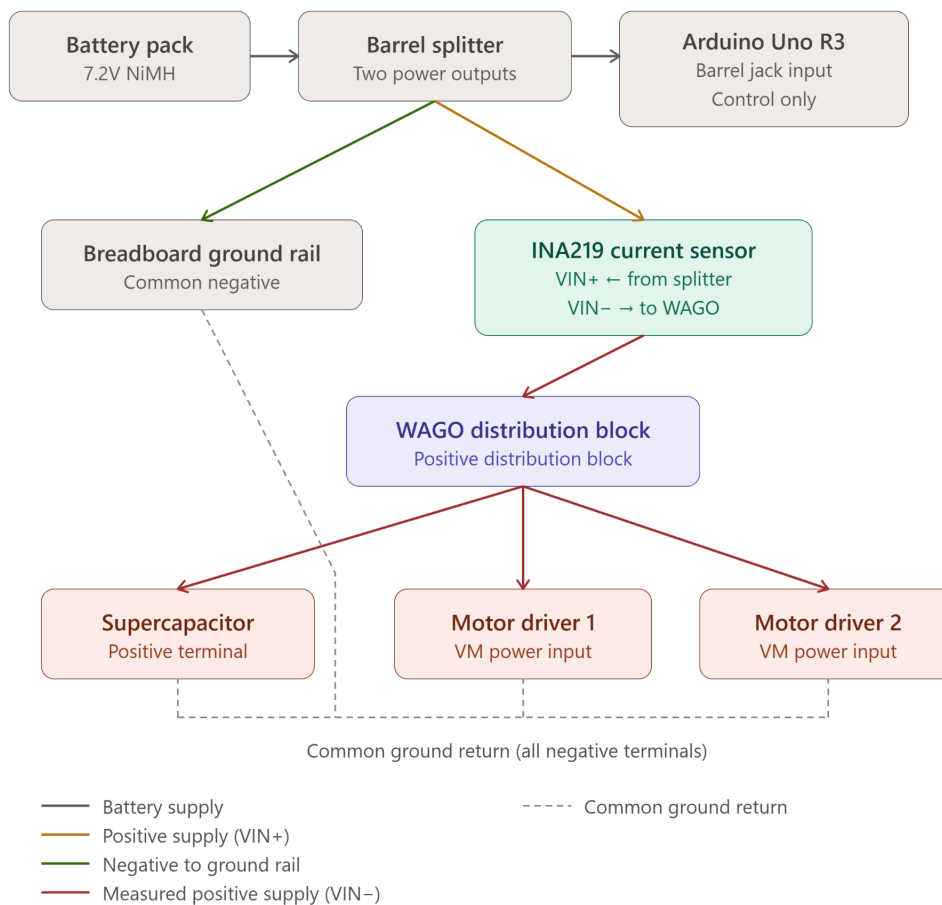


Figure 2. Simplified electrical power distribution architecture of the regenerative braking platform. The battery supply is divided between the Arduino control system and the regenerative braking measurement circuit. Power supplied to the motor drivers and supercapacitor passes through the INA219 current sensor before being distributed by the WAGO distribution block (positive distribution block), while all components share a common ground return.

2.2.5 Electrical Wiring Architecture

The electrical wiring architecture was designed to provide stable power distribution while maintaining reliable communication between the control, sensing, and energy recovery subsystems. Power from the 7.2 V NiMH rechargeable battery pack was distributed through a centralized power distribution network to the Arduino Uno, TB6612FNG motor driver, sensing modules, and regenerative energy storage circuit. High-current motor wiring was physically separated from the low-voltage communication lines to

minimize electromagnetic interference and improve the accuracy of voltage and current measurements recorded during regenerative braking events. Following prototype validation, the electrical system was transitioned from a breadboard prototype to a permanent soldered configuration. The DC motor leads were soldered directly to the outputs of the TB6612FNG motor driver, reducing connection resistance and eliminating intermittent electrical contact associated with removable jumper-wire connections. The remaining electrical connections were secured using WAGO distribution terminals and cable ties to prevent wire movement, reduce mechanical strain on solder joints, and maintain a consistent wiring configuration throughout repeated experimental trials.

As illustrated in **Figure 2**, all power supplied to the motor subsystem was routed through the INA219 current sensor before reaching the WAGO distribution block. The battery supply first passed through a barrel splitter, with one branch powering the Arduino Uno independently and the other feeding the regenerative braking circuit. This second branch entered the INA219 through VIN+ and exited through VIN-, where the WAGO distribution block routed power to the motor driver VM inputs and the positive terminal of the supercapacitor. Because all electrical power supplied to the motor subsystem passed through the sensor, the INA219 continuously measured voltage and current during both normal operation and regenerative braking. A shared ground through the breadboard ground rail provided a common electrical reference for all components, ensuring consistent electrical measurements throughout repeated experimental trials.

2.3 Experimental Design

2.3.1 Experimental Test Setup



Figure 3. Experimental test setup showing the four-wheel-drive robotic platform positioned at the top of the adjustable wooden ramp prior to each trial. The adjustable ramp enabled controlled evaluation of regenerative braking under multiple incline conditions while maintaining a consistent test surface.

Testing was conducted on an adjustable wooden ramp, as shown in **Figure 3**, which enabled incline angles to be varied while maintaining a consistent test surface throughout all experimental trials. The completed four-wheel-drive robotic platform described in Section 2.2 was positioned at the top of the ramp prior to each trial and allowed to descend under controlled operating conditions. The adjustable design of the ramp made it possible to evaluate regenerative braking performance across multiple incline angles while maintaining consistent travel distance, surface conditions, and vehicle orientation. Voltage, current, and recovered energy were displayed in real time on the onboard LCD during each trial, permitting continuous monitoring of system performance, while the Arduino simultaneously recorded the corresponding data for subsequent analysis.

2.3.2 Experimental Variables

The experiment was designed to isolate the effects of operating conditions on regenerative braking performance by systematically varying one independent variable at a time while holding all other conditions constant. Three independent variables were investigated: motor speed, payload mass, and incline angle. For the motor speed experiments, testing was conducted on a level surface without any additional payload. During the payload experiments, motor speed was maintained at 180 PWM on a level surface while the payload mass was varied. During the incline experiments, motor speed was maintained at 180 PWM without any additional payload while the incline angle was varied. The primary dependent variable was the net electrical energy recovered during regenerative braking, expressed in milliwatt-hours (mWh), as calculated from measurements recorded by the INA219 current sensor. The initial bus voltage was also recorded before each trial to verify consistent starting electrical conditions. The independent, dependent, and controlled variables used throughout the experiment are summarized in **Table 2**.

Category	Variable	Levels/Description
Independent Variables	Motor Speed	120 PWM, 180 PWM, 255 PWM
	Payload Mass	100 g, 200 g, 500 g
	Incline Angle	10°, 20°, 30°
Dependent Variables	Recovered Electrical Energy	Net Recovered Energy (mWh)
	Initial Bus Voltage	Measured Before Each Trial (V)
Controlled Variables	Robot Platform	Same 4WD Robotic Platform

	Battery	Same 7.2 V NiMH Battery Pack
	Supercapacitor	Same 5.5 V 1 F Supercapacitor
	Motor Drivers	Same TB6612FNG Dual H-Bridge Drivers
	Ramp Surface	Same Adjustable Wooden Ramp
	Travel Distance	Full Ramp Length for All Trials
	Control Software	Same Arduino Program
	Number of Trials	Three Trials per Condition

2.3.3 Experimental Procedure

Each trial began with the 7.2 V NiMH battery pack fully charged and the 5.5 V, 1 F supercapacitor discharged, so every experiment started from the same electrical baseline. The ramp was set to the incline required for that trial, and the angle was verified using the onboard MPU6050. Once the correct payload had been mounted, the Arduino program was started and bus voltage was checked on the LCD before testing began.

The robot was placed at the same fixed starting point at the top of the ramp for every trial. After motor speed was set to one of three PWM values, the robot descended the ramp under that condition without further intervention. At a fixed location along the ramp, the Arduino triggered the regenerative braking sequence, and the DC motors shifted from propulsion into generator mode. This transition converted the drivetrain's rotational energy into electrical energy, which was routed through the regenerative circuit to the supercapacitor.

Voltage and current were measured continuously by the INA219 sensor throughout each braking event, with the Arduino logging this data at the same time. The LCD displayed voltage, current, recovered energy, and system status in real time as each trial progressed. Once braking was complete, the recorded data were saved and recovered energy was calculated in milliwatt-hours (mWh).

The experimental design varied only one independent variable per trial while the remaining two variables were maintained at their baseline values. Three motor speeds (120, 180, and 255 PWM), three payload masses (100 g, 200 g, and 500 g), and three incline angles (10°, 20°, and 30°) were evaluated using this approach. Each condition was repeated three times, and the average recovered energy was used for

subsequent analysis to reduce the influence of random experimental variation. Both regenerative and non-regenerative braking configurations were evaluated under every condition to enable direct comparison of their energy recovery performance.

2.4 System Validation and Calibration

Prior to formal experimentation, the electrical measurement system was validated to verify the accuracy and reliability of the experimental platform. Following assembly of the electrical system, a calibrated digital multimeter was used to verify continuity, confirm that no short circuits or unintended electrical connections were present, and measure key supply voltages throughout the regenerative braking circuit. Voltage and current measurements reported by the INA219 sensor were then compared with multimeter readings under identical operating conditions. Measurements were collected across multiple motor operating states, and the close agreement between the two instruments confirmed that the INA219 provided sufficient accuracy for experimental use. The MPU6050 inertial measurement unit was also used to verify incline angle of the ramp prior to testing. These validation procedures ensured that both the electrical hardware and sensing system operated reliably and produced repeatable measurements throughout the experimental trials.

2.5 Data Collection and Analysis

During each regenerative braking event, the Arduino continuously acquired voltage and current measurements from the INA219 sensor while simultaneously displaying the measurements on the onboard LCD and logging them for subsequent analysis. The Arduino software calculated the supply voltage from the INA219 bus voltage and shunt voltage measurements before determining the instantaneous electrical power at each sampling interval. Recovered electrical energy was then calculated by numerically integrating the instantaneous power over the duration of the braking event and expressing the result in milliwatt-hours (mWh). All calculations were performed automatically by the Arduino during each trial.

Each experimental condition was repeated three times, and the average recovered energy was used for subsequent analysis to reduce the influence of random experimental variation. For the incline experiments, the theoretical gravitational potential energy available during descent was calculated from the robot mass, gravitational acceleration, and vertical height change. The percentage of gravitational potential energy captured by the regenerative braking system was then determined by comparing the experimentally recovered electrical energy with the corresponding theoretical gravitational potential energy. A paired t-test was conducted to determine whether the difference in recovered energy between regenerative and non-regenerative trials was statistically significant. The processed data were subsequently organized in Microsoft Excel, where averages, standard deviations, recovery efficiencies, and graphical comparisons were generated for presentation in the Results section. The calculations performed throughout the analysis are summarized in **Equations (1) - (3)**.

$$E = \sum(P_i \Delta t) \quad (1)$$

$$PE = mgh \quad (2)$$

$$\%PE_{\text{captured}} = \left(\frac{E}{PE} \right) \times 100 \quad (3)$$

Where the variables are defined as follows:

E = net recovered electrical energy (mWh)

P_i = instantaneous electrical power at sample i (mW)

Δt = sampling interval (h)

PE = theoretical gravitational potential energy (mWh)

m = total robot mass (kg)

g = gravitational acceleration (9.81 m/s²)

h = vertical height change (m)

RESULTS

The regenerative braking system produced measurable energy recovery under all experimental conditions investigated. Recovery performance was evaluated as a function of motor speed, payload mass, and incline angle, with each condition repeated three times to assess measurement consistency. The results are presented below using regression analyses to illustrate the relationship between each independent variable and the measured recovered energy, followed by an overall comparison between regenerative and non-regenerative braking performance.

3.1 Effect of Motor Speed on Energy Recovery

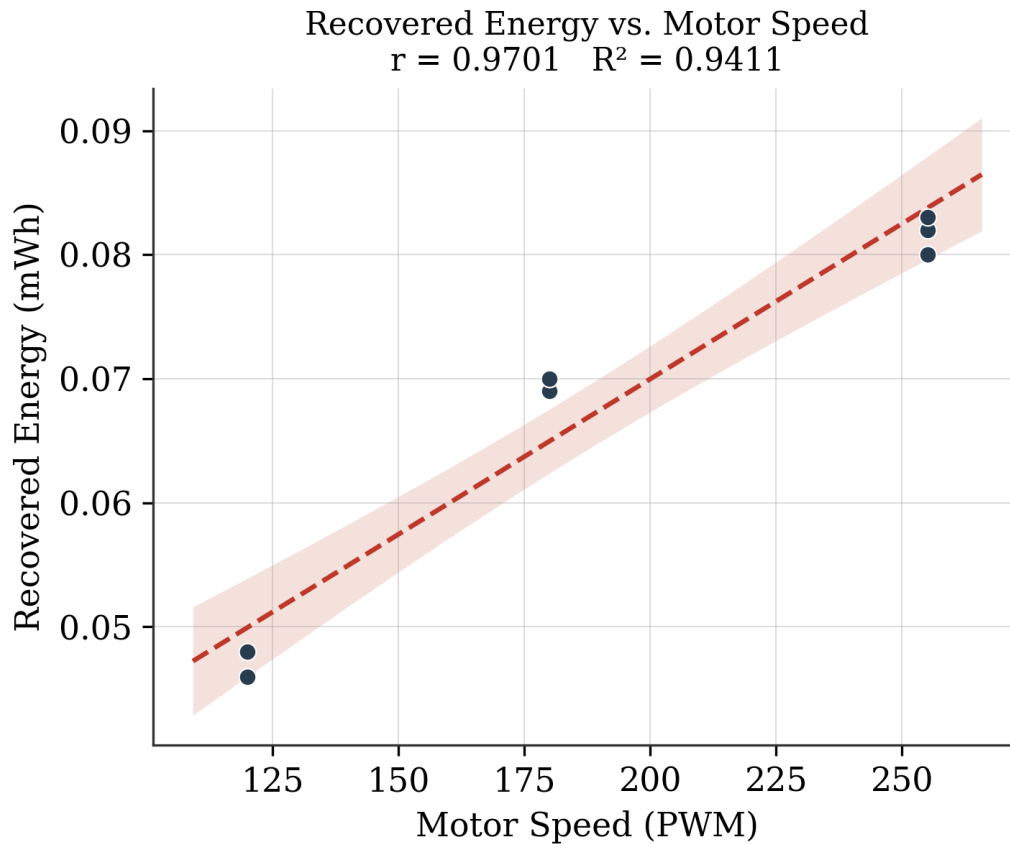


Figure 4. Relationship between motor speed and recovered electrical energy. Individual data points represent three repeated trials at each PWM setting. The dashed line indicates the linear regression, and the shaded region represents the 95% confidence interval.

As shown in **Figure 4**, recovered electrical energy increased with motor speed across all tested PWM values. Average recovered energy increased from approximately 0.047 mWh at 120 PWM to 0.069 mWh at 180 PWM, reaching 0.082 mWh at 255 PWM. The experimental data exhibited a strong positive linear relationship between motor speed and recovered energy ($R^2 = 0.941$). The relatively small variation among repeated trials indicates good repeatability of the experimental measurements.

3.2 Effect of Payload Mass on Recovered Energy

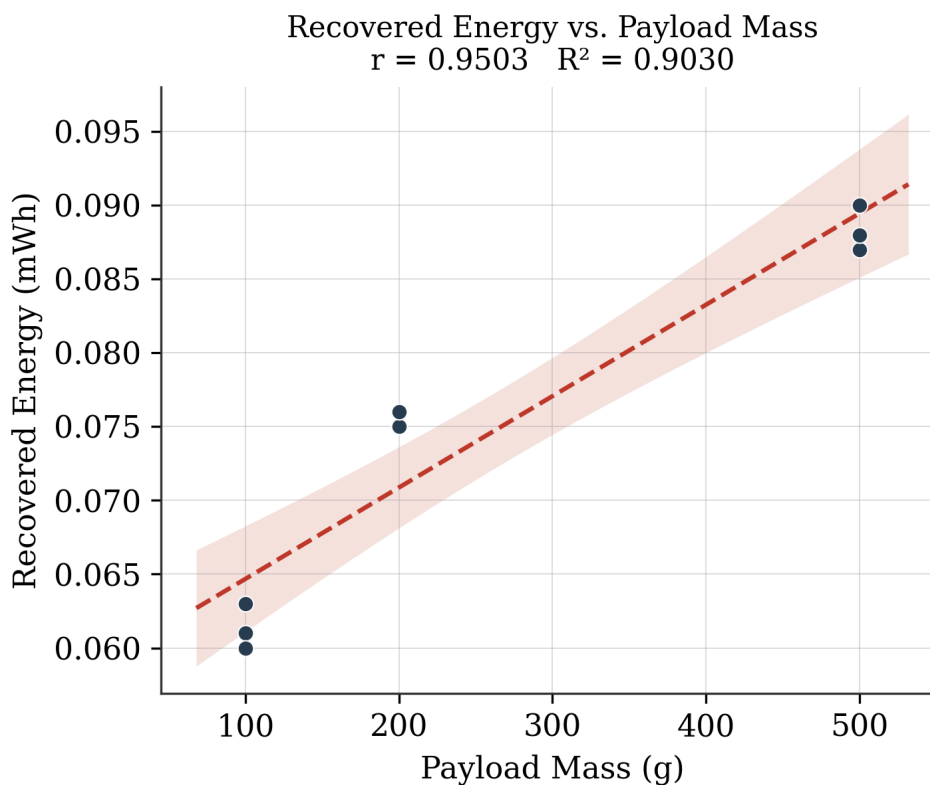


Figure 5. Recovered electrical energy as a function of payload mass. Points show individual trials (three per payload level); the dashed line is the linear regression fit, with the shaded band representing the 95% confidence interval.

As shown in **Figure 5**, Payload mass and recovered energy increased together across all three conditions - 0.061 mWh at 100g, 0.076 mWh at 200g, and 0.088 mWh at 500g. The trend was strongly linear ($R^2 = 0.903$), and with trials at each mass staying close together, the measurements remained constant across repeated trials.

3.3 Relationship Between Recovered Energy and Incline Angle

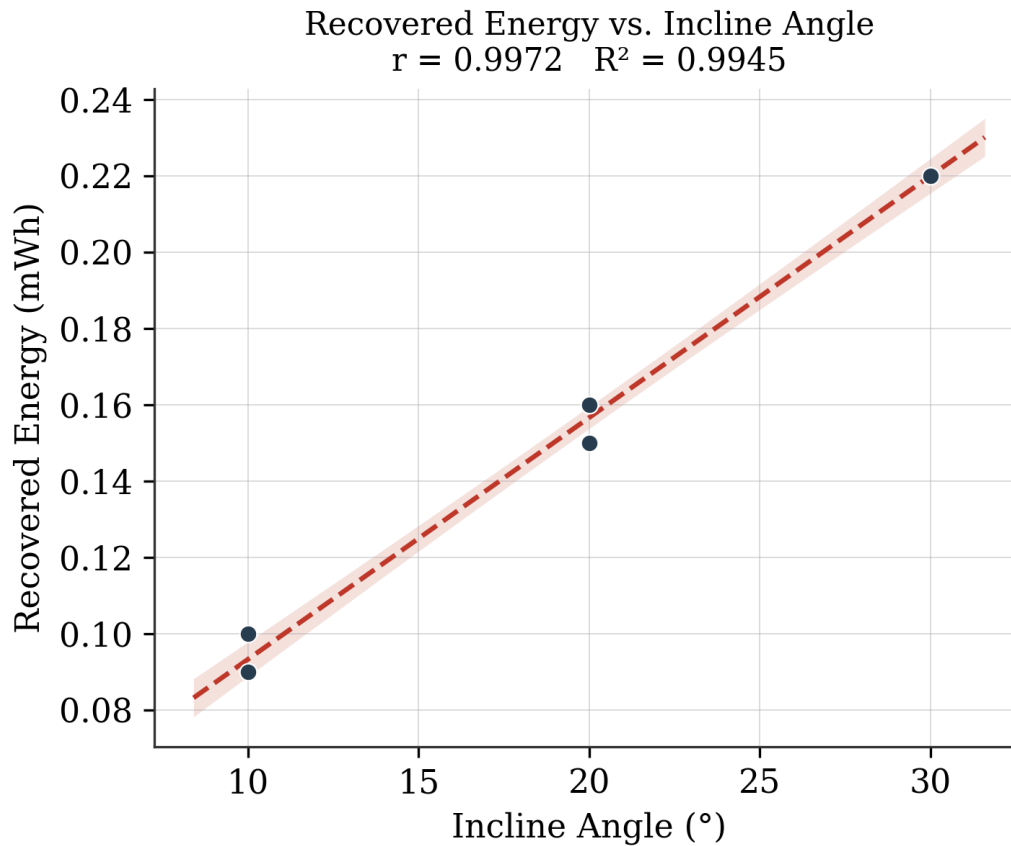


Figure 6. Relationship between incline angle and recovered electrical energy. Individual data points represent three repeated trials at each incline angle. The dashed line indicates the linear regression, and the shaded region represents the 95% confidence interval.

As shown in **Figure 6**, recovered energy rose steadily with incline angle, from about 0.095 mWh at 10° to 0.155 mWh at 20° and 0.220 mWh at 30°. The relationship was close to linear ($R^2 = 0.995$), and the three trials at each angle were closely grouped, which points to good repeatability across all three incline conditions.

3.4 Comparison with Theoretical Gravitational Potential Energy

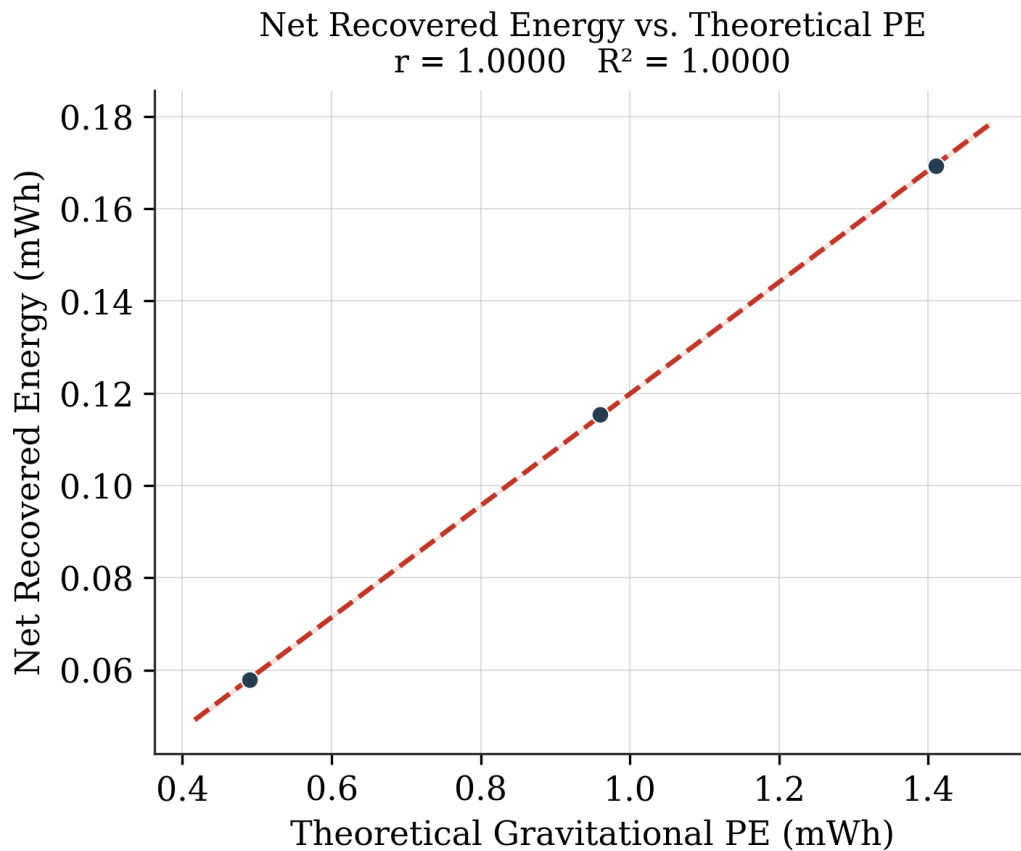


Figure 7. Recovered electrical energy as a function of theoretical gravitational potential energy across the tested incline conditions. Each point represents the average of three trials at a given theoretical energy value; the dashed line is the linear regression fit, with the shaded band representing the 95% confidence interval.

Figure 7 compares the experimentally recovered electrical energy with the theoretical gravitational potential energy available during descent. Recovered energy increased proportionally as the available gravitational potential energy increased across the three incline conditions. The linear regression produced an R^2 value of 1.000, indicating that the averaged measurements closely followed a linear relationship within the tested range. Despite this strong relationship, the experimentally recovered energy remained substantially lower than the total theoretical energy available during descent, with the system recovering approximately 12% of the available gravitational potential energy on average. This gap reflects

unavoidable mechanical and electrical losses within the system, including motor efficiency, drivetrain friction, rolling resistance, electrical resistance, and power conversion, each of which reduces the amount of energy that ultimately reaches the supercapacitor. Because recovery efficiency remained relatively consistent across all three incline conditions rather than varying substantially, these losses appear to scale proportionally with the amount of energy processed by the system, rather than being concentrated at any single operating condition.

3.5 Comparison of Regenerative and Non-Regenerative Braking Performance

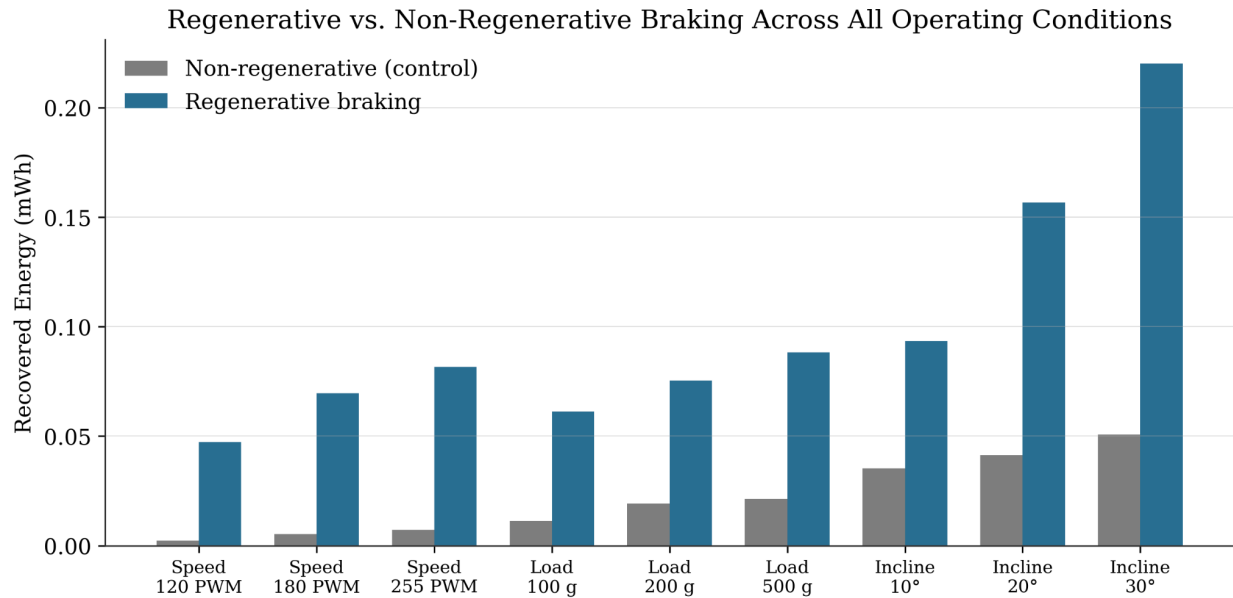


Figure 8. Comparison of average recovered electrical energy under regenerative and non-regenerative braking configurations across all tested motor-speed, payload-mass, and incline-angle conditions. Bars represent the mean of three repeated trials for each operating condition.

As shown in **Figure 8**, the regenerative braking configuration produced greater measured electrical energy than the non-regenerative control under every operating condition tested. The difference between the two configurations generally increased at higher motor speeds, payload masses, and incline angles. The largest absolute difference was observed during the 30° incline condition, which also produced the greatest overall recovered energy. These results demonstrate that the regenerative configuration consistently increased measurable energy recovery relative to the control across the full range of experimental conditions. A paired t-test comparing recovered energy across all regenerative and non-regenerative trials confirmed that this difference was statistically significant ($t(26) = 10.48$, $p < .001$), indicating that the increase in recovered energy under the regenerative configuration was unlikely to be due to random variation.

3.6 Experimental Variability and Repeatability

Recovered Energy (Mean $\pm$ SD) Across Independent Variables

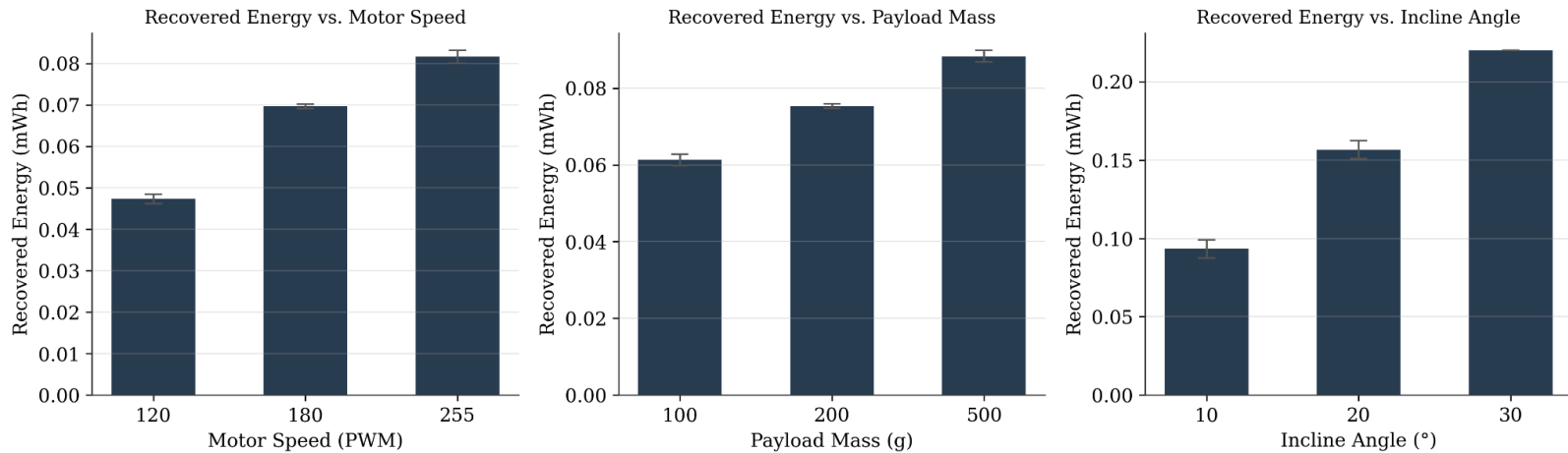


Figure 9. Mean recovered electrical energy under varying (a) motor speed, (b) payload mass, and (c) incline angle conditions. Bars represent the mean of three repeated trials at each operating condition, and error bars represent ± 1 standard deviation.

Figure 9 presents the mean recovered electrical energy and corresponding standard deviation across the tested motor-speed, payload-mass, and incline-angle conditions. The relatively small error bars indicate limited trial-to-trial variability and generally consistent measurements across repeated trials. Variability was lowest for the payload-mass conditions and remained small across the motor-speed conditions, while the 10° and 20° incline conditions exhibited slightly greater variation. Despite these differences, the standard deviations were small relative to the corresponding mean values and did not alter the increasing trends observed for any of the three independent variables. Overall, the results demonstrate good experimental repeatability across the evaluated operating conditions.

Overall, recovered electrical energy increased with motor speed, payload mass, and incline angle. Comparisons with theoretical gravitational potential energy and the non-regenerative control further demonstrated the consistent performance and repeatability of the regenerative braking system under the tested operating conditions.

DISCUSSION

4.1 Overall Performance of the Regenerative Braking System

The results demonstrate that the regenerative braking system consistently recovered electrical energy under all operating conditions investigated. Increasing motor speed, payload mass, and incline angle each resulted in greater energy recovery, indicating that the system responded predictably to changes in the mechanical energy available during braking. Although each variable influenced the system through a different mechanism, all three ultimately increased the amount of kinetic energy available for conversion into electrical energy. The strong linear relationships observed throughout the experiment further suggest that the regenerative braking system operated consistently within the tested operating range.

The increase in recovered energy with motor speed is consistent with the operating principles of DC motors during regenerative braking. As rotational speed increases, the motor generates a greater back electromotive force (back EMF), allowing a larger amount of electrical energy to be produced during deceleration [11]. Similarly, increasing the payload mass resulted in greater recovered energy because the additional mass increased the mechanical energy that the braking system was required to dissipate. Instead of being entirely lost as heat, a portion of this energy was converted into electrical energy and stored in the supercapacitor [12].

Incline angle produced the greatest increase in recovered energy because steeper slopes increased the gravitational potential energy available prior to descent. As the robot traveled down the ramp, this additional potential energy was converted into kinetic energy, providing more energy that could be recovered during braking. The nearly perfect linear relationship observed between theoretical gravitational potential energy and experimentally recovered electrical energy indicates that the regenerative braking system responded proportionally to increases in the available mechanical energy, despite recovering only a fraction of the theoretical maximum.

The observed gap between measured recovery and theoretical gravitational potential energy was anticipated, as motor efficiency, drivetrain friction, rolling resistance, electrical resistance, and power conversion each account for a portion of the energy lost before it reaches the supercapacitor [13]. Across all three incline conditions, the system recovered approximately 12% of the theoretical gravitational potential energy, indicating that the conversion efficiency remained relatively constant over the operating range investigated. Despite these losses, the regenerative configuration outperformed the non-regenerative control across every condition tested, indicating that energy which would otherwise have dissipated during braking was instead recovered.

Although the amount of recovered energy was modest, the results demonstrate that regenerative braking can provide measurable energy savings in small battery-powered robotic systems. In applications such as autonomous warehouse robots, mobile service robots, delivery robots, and planetary exploration vehicles, even modest improvements in energy efficiency can extend operational runtime and reduce the frequency

of battery charging or replacement. The consistent recovery observed across all operating conditions suggests that regenerative braking represents a practical strategy for improving the energy efficiency of mobile robotic platforms, particularly during repeated braking and downhill operation. These applications are illustrative rather than directly tested, as the present study was conducted on a small-scale laboratory prototype; larger robotic platforms or commercial systems may achieve different recovery efficiencies depending on their specific hardware and operating conditions.

4.2 Experimental Limitations

Although the experimental methodology successfully isolated the effects of motor speed, payload mass, and incline angle on regenerative braking performance, several limitations should be considered when interpreting the results. First, only one independent variable was varied at a time while the remaining two variables were maintained at fixed baseline values. This approach allowed the influence of each variable to be evaluated individually and simplified comparison across experimental conditions. However, real-world mobile robotic systems frequently experience simultaneous changes in speed, payload, and terrain. Consequently, potential interactions among these variables were not examined and may influence regenerative braking performance differently than observed under the controlled laboratory conditions.

The study was also conducted over a limited operating range consisting of three motor speeds, three payload masses, and three incline angles, with three repeated trials performed for each condition. While this experimental design was sufficient to establish consistent trends and demonstrate repeatability, additional operating conditions and a greater number of trials would improve statistical confidence and provide a more comprehensive understanding of system behavior. Expanding the range of tested conditions may also reveal nonlinear effects that were not observed within the operating range investigated.

Finally, the experimental platform represented a small-scale laboratory prototype built using commercially available components, including TT DC gear motors, an Arduino-based control system, and a supercapacitor energy storage circuit. Although these components were appropriate for demonstrating the feasibility of regenerative braking, their efficiency and performance characteristics differ from those of larger robotic platforms or commercial electric drive systems. As a result, the measured energy recovery values should be interpreted as representative of the prototype investigated rather than universally applicable to all mobile robotic systems.

4.3 Future Work

This study demonstrates that regenerative braking is a practical approach for small mobile robotic platforms, and it also identifies several opportunities for future investigation. A factorial design, where motor speed, payload mass, and incline angle all vary together rather than one at a time, would show how these factors interact under realistic operating conditions - interactions that a single-variable approach like this one can't reveal on its own.

Hardware improvements also present opportunities to increase performance. Higher-efficiency motor drivers, brushless DC motors, or larger supercapacitors could all increase the amount of mechanical energy recovered during braking. Additionally, implementing a closed-loop regenerative braking controller would allow the system to adjust braking torque dynamically based on operating conditions, which would likely improve recovery further.

Finally, evaluating the proposed system on larger and more complex mobile robotic platforms would provide a better understanding of its long-term benefits. Autonomous mobile robots used in warehouses, delivery, or outdoor settings would provide a more realistic assessment of the long-term benefits of regenerative braking - particularly whether the small per-event gains seen here add up to something meaningful across long operating periods, where braking happens repeatedly and any efficiency improvement compounds.

CONCLUSION

Motor speed, payload mass, and incline angle all increased the amount of recovered electrical energy in this robotic platform's regenerative braking system, with incline angle producing the greatest effect due to the additional gravitational potential energy available during steeper descents. Although the regenerative configuration recovered only approximately 12% of the theoretical gravitational potential energy available, it consistently outperformed the non-regenerative control, and results remained consistent across all conditions tested. That consistency is the central takeaway of this study: regenerative braking represents a practical approach to improving the energy efficiency of small battery-powered robotic systems. While there is clear potential to further increase recovery through improved hardware and more advanced control strategies, the findings presented here establish a strong foundation for continued research and development of regenerative braking technologies for autonomous mobile robotics.

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