Hanover College Engineering Department
ENGR 409 – Senior Thesis
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Electric Scooter (with Regenerative Braking)

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ABSTRACT

In this project, we designed and built an electric scooter using many tools and materials. The key concept of the design was to study the effect of regenerative braking on the overall electrical system. Is the effect negligible or significant? This design comprises two primary components: mechanical and electrical. Rodolfo oversees all mechanical aspects, while Al-Ameen is tasked with the electrical elements of the design. The project's major objectives are to design and build the scooter's frame, create a work instruction manual for the speed controller, and analyze the efficiency of the regenerative braking. The project is also expected to stay within a specific budget allocated by the project supervisors.

NOMENCLATURE

Symbol	Mathematical Quantity	Unit
T	Temperature	° F
V	Potential difference (V)	V
R	Resistance	Ω
I	Current	A
W	Power	Watts
I_m	Moment of Inertia	Kg*m^2
F	Force	N
M	Mass	kg
G	Gravity	m/s^2
L	Length	m
E	Young's Modulus	Pa
Δx	Displacement	m
H	height	in
W	width	in
T	thickness	in

1. INTRODUCTION

The area moment of inertia (I_m) of a beam is an important property used in the calculation of the beam's displacement (Δx) and the calculation of stress caused by a moment, product of a force and perpendicular distance from the point of action of force, applied to the beam.

To calculate I_m we use the equation below:

$$I_m = \frac{1}{6}h^3 \cdot t\left(1 + 3\frac{b}{h}\right) \tag{1}$$

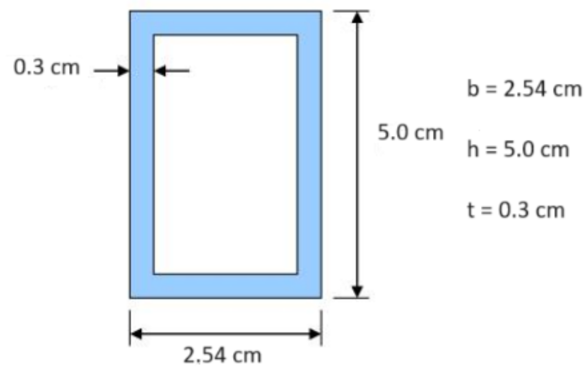

FIGURE 1: Vertical Representation of the beam

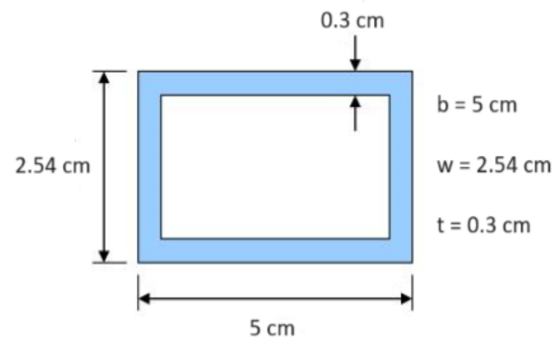

FIGURE 2: Horizontal Representation of the beam

Using Eq. 1 to calculate I in Figures 1 and 2, we get:

$$I_{m2} = 4.70 \cdot 10^{-5}$$

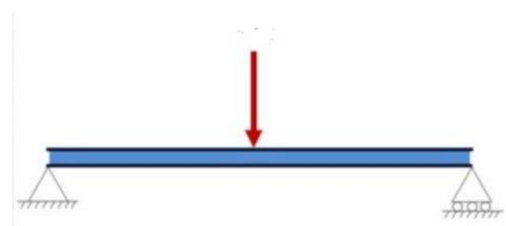

FIGURE 3: Displacement of the beam with fixed ends when force is applied in between

To calculate the displacement in the beam as shown in Figure 3 we use the equations below

$$F = mg \tag{2}$$

$$\Delta x = \frac{1}{48}\left(\frac{FL^3}{EI_m}\right) \tag{3}$$

And so, we get a displacement of:

$$\Delta x_1 = 5.8*10^{-7}\ m$$

$$\Delta x_2 = 1.7*10^{-6}\ m$$

As we can see, displacement in Figure 1 is much smaller due to the beam's orientation.
Also, is important to know that, starting July 2019, a vehicle is considered an "electric foot scooter" if it meets all the following criteria:

- Has handlebars and a floorboard to stand on while riding
- Weighs 100 pounds or less
- Has three or fewer wheels
- Maximum propulsion of 20 mph or less on flat ground

E-scooters that meet these criteria all have the same rights and responsibilities as a bicycle. You can ride them in the street and on bike paths, and you do not need insurance or a license to ride one. They are also not legally considered motor vehicles.[2][3]

2. MATERIALS AND METHODS

2.1 MATERIALS

The materials used for this project are:

- 36 Volts Lithium-Ion Battery (Figure 10)
- 6.5 inches Brushless Hub Motor (350W) (Figure 17)
- Regenerative Braking kit (Thumb throttle accelerator, Thumb throttle brake, Liquid Crystal Display) (Figures 11, 12, 13)
- 14 AWG Wires (Figure 14)
- 2 Screws Toggle Switch (Figure 16)
- 8-inch Solid Replacement Wheels (Figure 23)
- Handlebar Stem (Figure 25)
- Tarp (Figure 26)
- Brainpower Motor Controller (Figure 18)
- (3) 4130 Alloy Rectangular Tube, 1"x 2" x 3"
- PALMGREEN Metal Bandsaw (Figure 4)
- PowerMatic Drill Press (Figure 5)
- DeWalt Miter Saw (Figure 6)
- DeWalt Bench Grinder (Figure 7)
- Grizzly Metal Bandsaw (Figure 8)
- Steiner Industries Welding Station (Figure 9)
- Perf Board (Figure 21)
- Quad Comparator chip (LM339N) (Figure 19)
- 1Ω 10W Power resistor (Figure 15)
- Green and Red-Light Emitting Diode (Figure 20)
- Voltage drop resistors (Figure 22)

FIGURE 4: PALMGREEN Metal Bandsaw


FIGURE 5: PowerMatic Drill Press


FIGURE 6: DeWalt Miter Saw

FIGURE 7: DeWalt Bench Grinder

FIGURE 8: GRIZZLY Metal Bandsaw

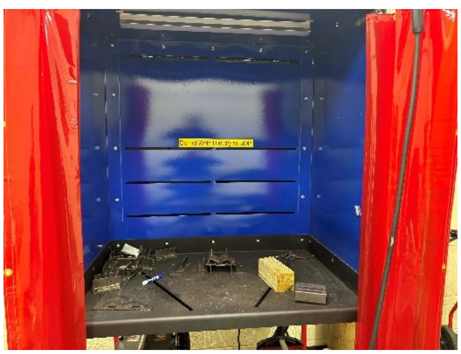

FIGURE 9: Steiner Industries Welding Station

FIGURE 10: Lithium-Ion Battery 36V

Figure 11: Liquid Crystal Display

Figure 12: Thumb throttle accelerator

Figure 13: Thumb throttle accelerator

Figure 14: 4ft AWG 14 wires

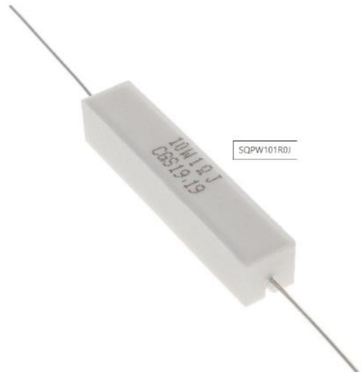

Figure 15: 1ohms 10 Watts through-hole Power resistor

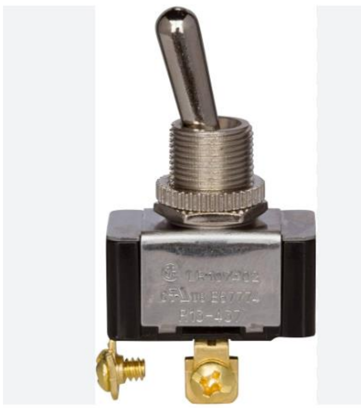

Figure 16: Toggle switch

Figure 17: Brushless Hub Motor

Figure 18: Brainpower Motor Controller

Figure 19: Quad Comparator Chip

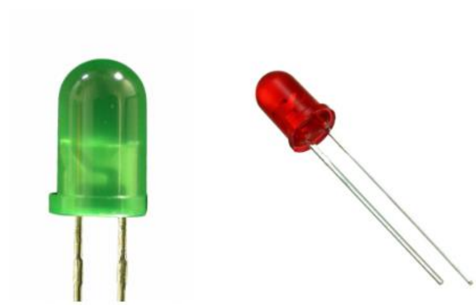

Figure 20: Green and Red LED

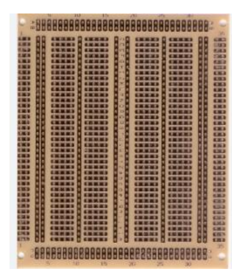

FIGURE 21: Perf Board

FIGURE 22: Voltage Drop Resistors

Figure 23: Tube used to enlarge the Stem

FIGURE 25: 8 inch Back Wheel

Figure 26: Tarp

2.2 METHODS

The construction of the electric scooter can be divided into four parts,

- Wiring the electrical system on a table to test all the components.
- Designing the Regenerative tester circuit and embedding it into the electrical system
- Constructing the scooter frame to accommodate electrical components
- Implementing the wiring in the framework.

2.2.1 Compatibility of Materials (Safety)

During the process of building an electric scooter, it's crucial to ensure compatibility between the controller, motor, and battery to achieve optimal performance, efficiency, and safety. These are guidelines we carried out to guarantee the compatibility between these components:

Voltage Compatibility: We checked the voltage rating of the controller, ensuring it aligned with the battery pack's voltage. In this case, the controller's voltage rating is 36V, so the battery purchased had a 36V rating. We also verified that the motor's voltage rating matched those of both the battery and controller, avoiding any potential damage from mismatched voltages.

Current Compatibility: We scrutinized the current rating (in amperes) of the controller, ensuring it fell within the acceptable limits of both the battery and motor. This was done to prevent drawing more current than the components can handle. Additionally, we ensured the motor's current rating was compatible with the controller to prevent overheating and extend its operational lifespan.

Power Compatibility (W): we calculated the power (in watts) by multiplying voltage by current, verifying that the power ratings of the motor, controller, and battery were compatible. we ensured the controller could effectively manage the power demands of the motor. To account for occasional power spikes and prevent continuous operation at maximum capacity, we included a safety margin in the design.

$$\text{Power (W)} = \text{Current(I)} \times \text{Voltage (V)} \quad (4)$$

Throttle Compatibility: Speed controllers do not work with all throttles. we ensured the controller was compatible with the intended throttle type which is a thumb throttle. Different controllers may necessitate specific throttle inputs.

Motor Type and Controller Compatibility: We distinguished between brushed and brushless motors and ensured that the controller matched the motor type accordingly. Additionally, we confirmed that the controller supported the sensor type of the motor.

Battery Compatibility: We verified that the battery's chemistry matched the requirements of both the controller and motor.

2.2.1.2 Hub Motor Driver Testing: Oscilloscope Analysis and Component Evaluation (No Load)

We connected all the electrical parts of the scooter, including the motor, to an arm mounted on a flat surface. This setup allowed me to conduct various tests, including component checks and current measurements under different conditions. These tests enabled me to understand the behavior of each component which helped to achieve efficient wiring on the frame.

We placed three probes on the three motor drivers while the motor ran at different gears to record the result on the oscilloscope. We also ensured that the three probes connected to each motor driver were grounded to ensure accurate readings on the oscilloscope.

- Channel 1 (yellow signal) is connected to the green motor driver.
- Channel 2 (blue signal) is connected to the blue motor driver.
- Channel 3 (purple signal) is connected to the yellow motor driver.

These tests yielded multiple results, most of which were expected and some that weren't. Each motor driver formed square wave signals with different amplitudes. These amplitudes correspond to the amount of current going through the motor.

At gear 1:

The current going through the electrical system is 0.19A. The amplitudes of each signal of the motor drivers are different. They also form square waves that are out of phase. The blue motor driver, represented by the blue signal (channel 2) is seen to have no amplitude at that point in time, a sweep of the signal does a better job describing the signals generated by each motor driver but unfortunately, that cannot be represented by a picture. The differences in amplitude may indicate variations in the control signals sent to each motor driver, which could result from differences in motor load or other external factors. The fact that the signals are out of phase suggests that the motor drivers are not synchronized and may be operating based on different reference points or timing signals. The observed square waves exhibit the Gibbs phenomenon which is caused by sudden changes in current during acceleration. Despite a nominal maximum current flow of 0.19A within the electrical system at gear 1, instances of overshooting occur upon accelerator engagement. Additionally, the current fluctuates between 0.04A and 0.19A when the accelerator is not fully depressed. Figure 27 below, illustrates the waveform captured on the oscilloscope.

Figure 27: Waveform at gear 1.

At gear 2:

The current going through the electrical system is 0.41A. Each signal forms square waves with different amplitudes. As described earlier the amplitude of the signals generated by the motors vary in time and are out of phase. The square waves formed by the signals in this case also exhibit the Gibbs phenomenon. Figure 28 below shows the signals generated by each motor driver. As repeated in gear 1, the blue motor driver had no amplitude when the data was recorded.

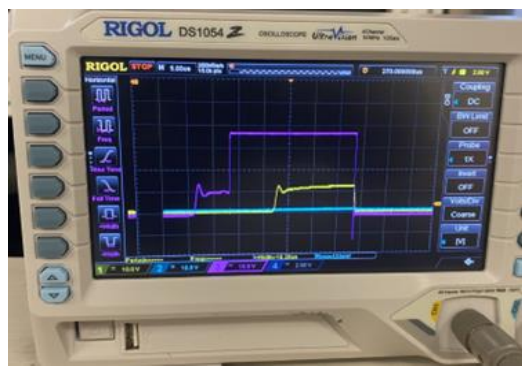

Figure 28: Waveform at gear 2

At gear 3:

The current going through the electrical system is 0.63A. The three motor drivers generate signals that form square waves at different Amplitudes. In this case, the signals are out of phase by a little and the blue motor driver's signal's amplitude is shown in Figure 30. We notice that in Figure 29, the amplitude is 0 and in Figure 30 the amplitude is not 0 proving that it changes with time and a sweep is the best way to record this data. The signals also exhibit the Gibbs phenomenon.

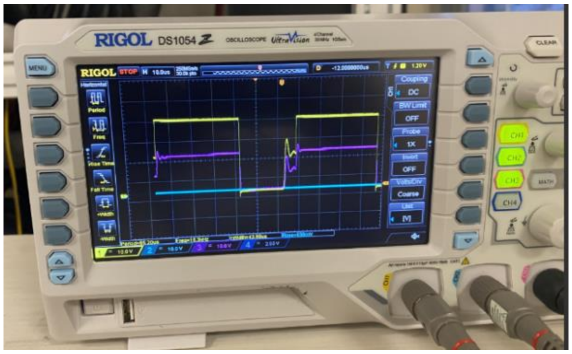

Figure 29: Waveform 1 at gear 3.

Figure 30: Waveform 2 at gear 3.

At gear 4:
The current going through the electrical system is 0.86A. The results obtained at gear 4 are like the previous results. The signals form square waves with different amplitudes in time, they also exhibit the Gibbs phenomenon. The results also prove that the wavelengths of the signals increase when the gear increases. Figures 31, 32 and 33 presented below illustrate the waveform captured on the oscilloscope.

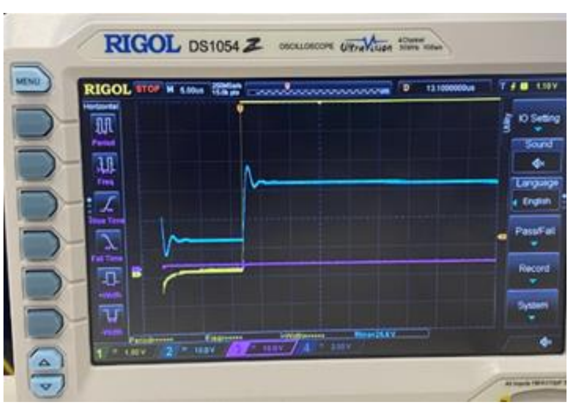

Figure 31: Waveform 1 at gear 4.

Figure 32: Waveform 2 at gear 4.

Figure 33: Waveform 3 at gear 4.

At gear 5:
The current going through the electrical system is 1.16A. In this case, the signals generated by the motor drivers also form square waves that are out of phase. The signals also have different amplitudes. The only difference observed is the length of the wavelength of these signals. The elongation of the square wavelength at the highest gear setting reflects nuanced dynamics within the motor control system, including variations in acceleration profiles and electrical characteristics. After carefully analyzing the wavelengths of the square waves at lower gears, I realized it increases according to the gear level. Figure 34, presented below, illustrates the waveform captured on the oscilloscope.

Figure 34: Waveform at gear 5.

2.2.1.3 Hub motors

The electric scooter motor which can be categorized as the engine of the design is a 36-volt DC brushless hub motor. Hub motors work on the principle of electromagnetism, where the interaction between electromagnets and permanent magnets causes the motor to spin. The hub motor can be divided into 5 major parts.

1. Rotor: The rotor contains permanent magnets which can be arranged in different configurations, radially or axially magnetized. This has a direct effect on the motor's performance.
2. Stator: The stator is an important component that encapsulates the windings responsible for producing the magnetic field essential for inducing rotation in the rotor.
3. Electronic Commutator: Brushless DC motors replace traditional mechanical commutators and brushes with electronic ones. These electronic commutators regulate current flow to the stator windings, relying on rotor position data gathered by sensors such as Hall effect sensors.
4. Magnetic Pole Sensors: Brushless DC motors utilize magnetic pole sensors, such as Hall effect sensors, to detect the position of the rotor. This information is then utilized for electronic commutation, ensuring precise control and efficiency in motor operation.
5. Controller: An electronic driver or controller is required to properly commute the BLDC motor by switching the current to the stator windings based on the rotor position feedback.

2.2.2 Regenerative Braking

Regenerative braking is a technology commonly used in electric vehicles, including electric scooters, to improve energy efficiency and extend battery life. It works by converting kinetic energy (motion) into electrical energy during braking or deceleration, which is then stored back into the battery for later use. Regenerative braking, unlike conventional braking, doesn't dissipate energy as heat into the environment. Instead, it reverses the flow of current in the motor, causing it to function as a generator. The generated electrical energy is then redirected back into the battery, effectively recharging it. This process not only extends the electric scooter's battery life but also enhances its overall energy efficiency.

There are 4 types of regenerative braking[1]. They are:

1. Electromagnetic Regenerative Braking
2. Hydraulic Regenerative Braking
3. Flywheel Regenerative Braking
4. Hybrid Electromagnetic-flywheel Braking

Electromagnetic Regenerative Braking: This is the most common type of regenerative braking found in hybrid and electric vehicles. It uses the electric motor that propels the vehicle in reverse to act as a generator, converting the kinetic energy from braking into electrical energy that is stored in the vehicle's battery pack. This helps recharge the battery and extends the vehicle's driving range.

Hydraulic Regenerative Braking: In this setup, braking kinetic energy compresses hydraulic fluid, stored under pressure. When acceleration is needed, the pressurized fluid powers a hydraulic motor, propelling the vehicle by driving the wheels and effectively utilizing stored energy.

Flywheel Regenerative Braking: This system utilizes braking energy to spin a flywheel, storing it as rotational kinetic energy for future acceleration. Although it is seen in early hybrid prototypes, it's less prevalent in current production vehicles.

Hybrid Electromagnetic-flywheel Braking: This is a combination of electromagnetic and flywheel. They help maximize the amount of energy recovered during braking.

2.2.2.1 Regenerative Braking Tester Circuit

The Brainpower speed controller in the electrical system possesses a regenerative braking feature which is tested by this circuit to prove it exists. The circuit carries this out by monitoring the direction of current in the electrical system. This is applicable because regenerative braking can be defined as the flow of current back to the battery while decelerating.

This circuit is built around the Quad comparator chip (LM339N). The other components in the circuit are the power resistor, voltage drop resistors light-emitting diodes and a switch.

<u>How the Quad Comparator Works</u>

The Quad comparator has two terminals: the inverting terminal (-) and the non-inverting terminal (+). These terminals are labelled as IN- and IN+ respectively. The voltage at the non-inverting terminal (+) is compared to the voltage at the inverting terminal (-). The comparator compares the voltages at its two input terminals and produces a digital output based on the

relationship between these voltages. When the voltage at the non-inverting terminal (+) is greater than the voltage at the inverting terminal (-), the output of the comparator goes high. In this case, there is typically an open collector output. The built-in output transistor is designed to act as a switch, connecting the output to ground, thereby preventing current flow to the load.
When the voltage at the inverting terminal (-) is greater than the voltage at the non-inverting terminal (+), the output of the comparator goes low. Here, there is typically an open drain output. The built-in output transistor connects the output to either the negative supply voltage or ground, depending on the specific configuration, allowing current to flow to the load connected to the output. The output is an open-collector or open-drain output, which means it can sink current but cannot source current. The schematic (Figure) below illustrates the explanation above.

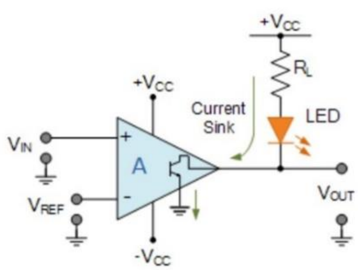

Figure 35: Quad Comparator Schematic

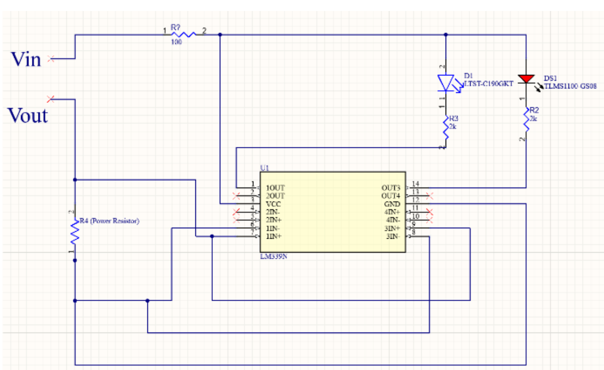

Figure 36: Regenerative tester circuit schematic

The power resistor displayed in the circuit's schematic above (Figure 36) enables the various comparator inputs to be at different polarities when the current moves in both directions. The outputs of both comparators in the circuit are connected to a green and red light-emitting diode (LED) which are also connected to resistors to ensure a safe amount of current is going through the LEDs. The red LED lights up when the current is flowing out of the battery to the system while the green LED lights up when the current is flowing back into the battery hence signifying regenerative braking in the system.

<u>Wiring the Quad Comparator Circuit</u>

We constructed the final prototype and soldered it on a perf board. The negative terminal of the voltage source is connected to the lower side of the power resistor. The higher terminal of the power resistor is connected to the ground of the LM339N chip. The positive terminal of the voltage source is connected to the first terminal of the toggle switch. The second terminal of the toggle switch is connected to the higher terminal of the voltage drop resistor, and the lower terminal of the voltage drop resistor is connected to the supply voltage of the quad comparator chip. The inputs going into quad comparators 1 and 2 have varying polarities. The wire connected to the positive input of comparator 1 is connected to the negative input of comparator 2. The wire connected to the positive input of comparator 2 is connected to the negative input of comparator 1. The output of comparators 1 and 2 are connected to two pull-up resistors and green and red LEDs.

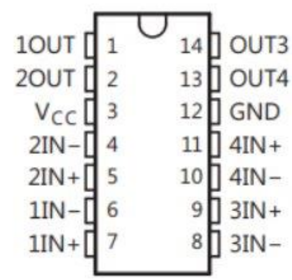

Figure 46

2.2.2.2 Integrating the Regenerative Tester Circuit (Quad Comparator) into the Scooter's Electrical System.

The illustration below (Figure 37) shows what the electrical system looked like before the integration.

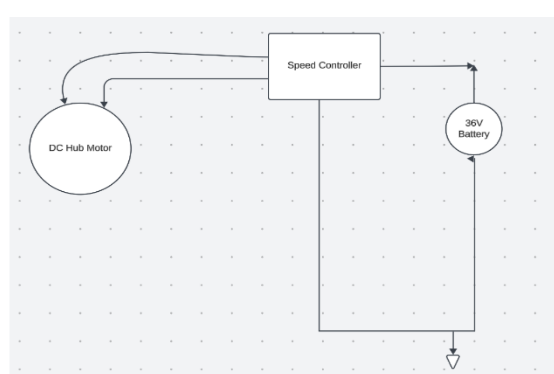

Figure 37: Scooter's electrical system original wiring

The figure above is a summarized drawing of the electrical connection of the system without the Regenerative tester circuit. A more detailed diagram (Figure 38) displays all the components of the speed controller.

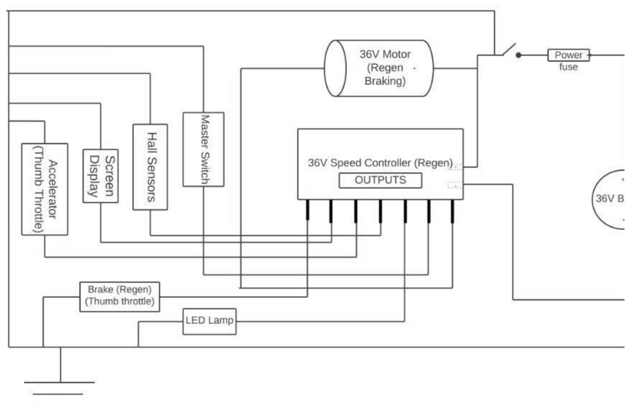

Figure 38: A more detailed schematic of the electrical scooter. (Pre-Regenerative Braking Tester Circuit)

A bunch of factors had to be considered before integrating the Quad Comparator circuit into the electrical system. The most important was safety and reliability.

			MIN	MAX
Supply Voltage, V^+	LM139N, LM239N, LM339N, LM2901N			36
	LM3302N			28
Differential Input Voltage	LM139N, LM239N, LM339N, LM2901N [2]			36
	LM3302N [2]			28
Input Voltage	LM139N, LM239N, LM339N, LM2901N		−0.3	36
	LM3302		−0.3	28
Input Current ($V_{IN}<-0.3\ V_{DC}$) [3]				50
Power Dissipation [4]	PDIP			1050
	Cavity DIP			1190
	SOIC Package			760
Output Short-Circuit to GND [5]				Continuous
Lead Temperature (Soldering, 10 seconds)				260
Soldering Information	PDIP Package (10 seconds)			260
	SOIC Package	Vapor Phase (60 seconds)		215
		Infrared (15 seconds)		220
Storage temperature, T_{stg}			−65	150

Figure 39: Absolute maximum rating of the Quad Comparator Chip (LM339N).

From the table above (Figure 39) we can deduce that the maximum voltage rating of the Quad Comparator (LM339N) is 36V hence it is expected to run at a voltage supply decently lower than 36V to prevent the effects of overvoltage. The voltage rating of the power supply is 36V which means to integrate the quad comparator circuit into the electrical system we need to create a good amount of voltage drop to ensure the voltage going through the comparator is below the maximum voltage hence making it safe and reliable.

We carried out a circuit analysis that gives the best resistor value that causes the perfect voltage drop. While carrying out the component tests we measured the current going into the circuit using a multimeter at each gear level. The minimum current flowing into the system was at gear 1 and the maximum current flowing into the system was measured at gear 5. These results were expected because as the gear increased, the motor's speed increased, resulting from increased current flow in the system. At gear 1 the current rating was 0.2A and at gear 5 the current rating was 1.16A. Since we are trying to get a voltage drop of 6-10V, we know the current rating at the minimum and maximum point, the voltage rating of the voltage supply we resort to Ohm's law. The intended Voltage drop is 6V and we calculated the resistance values at the maximum and minimum cases. The calculation below is for the minimum case 1. $V_{drop} = 6$ V

$$V_{battery} - V_{drop} = I_{min}R \tag{5}$$

$$R = \frac{V_{battery} - V_{drop}}{I_{min}} \tag{6}$$

$$R = \frac{36-6}{0.2}, \quad R = 150\Omega \tag{7}$$

For the maximum, I = 1.16A:

$$V_{battery} - V_{drop} = I_{max}R \tag{8}$$

$$R = \frac{V_{battery} - V_{drop}}{I_{max}} \tag{9}$$

$$R = \frac{36-6}{1.16}, \quad R = 25.9\Omega \tag{10}$$

Case 2, $V_{drop} = 10$V. Using equation (6)

$$R = \frac{36-10}{0.2}, \quad R = 130\Omega \tag{11}$$

Maximum, I = 1.16A

$$R = \frac{36-10}{1.16}, \quad R = 22.4\Omega \tag{12}$$

Note that the current ratings were obtained when there was no load on the motor. It is expected that a spike in current occur when there is enough load which is a form of resistance. It was important to avoid picking a resistor value that would cause a voltage drop that could affect the performance of the quad comparator circuit.

From the analysis, we deduced that the higher the current in the system, the higher the voltage drops. To prevent a voltage, drop that affects the functionality of the circuit we needed to select the best resistor value that would suit high and low current cases. we ran a transient simulation on LTspice. This helped me pick the best resistor value for the Voltage drop resistor. The circuit analysis provided an idea of the range of the resistor value needed while the simulation helped me confirm which value worked best. We ended up using a 100Ω resistor. This resistor did not always give the wanted amount of voltage drop but it always kept the voltage value going into the comparator less than 36V which was the most important thing. Below (Figure 40) is an illustration of the transient analysis on LTspice.

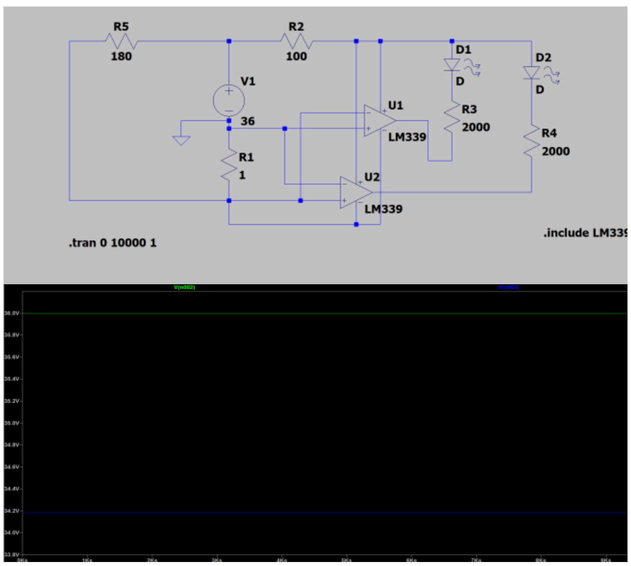

Figure 40: Transient simulation at low current

The simulation above (Figure 40) shows the voltage rating at the node above the battery represented by the green line on the graph (36V). The blue line represents the voltage rating (34.2) at the node after the 100Ω resistor. Resistor 5 represents the speed controller and the hub motor. Its resistance value is 180 because the simulation is carried out when the electrical system is at its lowest gear and the current is 0.02A.

$$R5 = \frac{Voltage}{I_{min}}, \quad R5 = \frac{36}{0.02}, \quad R5 = 180 \quad (13)$$

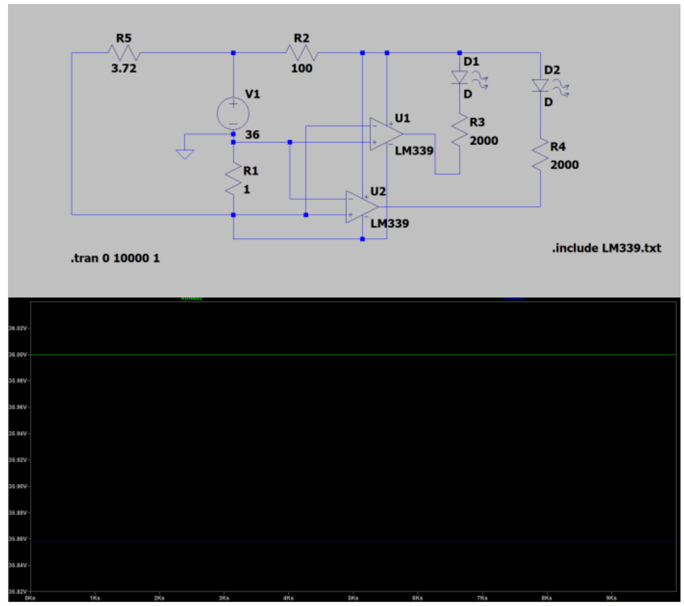

Figure 41: Transient Simulation at high current

In the previous simulation (Figure 41), we accounted for the maximum current flowing through the electrical system, which includes the load of the scooter and frame. Since the hub motor's power rating is 350W and the voltage source's rating is 36V. Using equation(2),

$$I_{max} = \frac{Power}{Voltage}, \quad I_{max} = \frac{350}{36}, \quad I_{max} = 9.72A \ (14)$$

$$R5 = \frac{Voltage}{I_{max}}, \quad R5 = \frac{36}{9.72}, \quad R5 = 3.7\Omega \quad (15)$$

At this peak current condition, denoted by I = 9.72A and R5 = 3.7Ω, the simulation revealed that the voltage rating before the voltage drop resistor was 36V, while after passing through the resistor, it decreased slightly to 35.85V. Although this difference is minimal and very close to the expected 36V, it represents an extreme scenario likely to occur during sudden spikes in current within the system.

Despite the slight decrease in voltage after passing through the voltage drop resistor, which is less than the 36V rating, it's important to note that the comparator remains safe. This indicates that even under maximum current conditions, the voltage level remains within acceptable limits, ensuring the proper functioning and safety of the comparator circuit.

We also carried out a similar analysis for the two LEDs. The maximum current value of the two LEDs in the circuit is 20mA. In this case, we used the maximum voltage rating in the circuit to obtain the best resistor value. Using Ohm's law again, we calculated the resistance for the LEDs that ensured the

current going through the LEDs where always less than 20mA.
$I_{max} = 0.02A$, $V_{max} = 36V$.

$$R = \frac{V_{max}}{I_{max}},\ R = \frac{36}{0.02},\ \ R = 1800\ \Omega \qquad (16)$$

We made use of two pull-up 2kΩ Resistors in the circuit based on this calculation. The simulation below (Figure..) shows the current going through the electrical system at maximum current flow in the circuit. The current going, both LEDs are represented by the blue and green lines on the graph at values smaller than 20mA. The current going through LED (D1) is 34.24pA while the current through LED (D2) is 410.6nA.

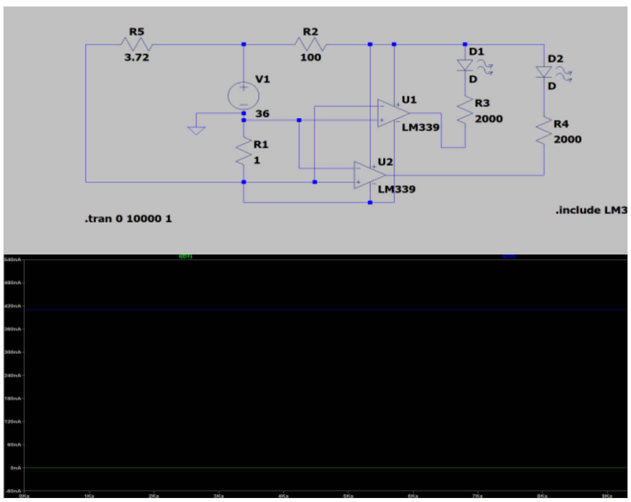

Figure 42: Transient Simulation at low current

When the current going through the electrical system is at its minimum. This is implied by the resistance of R5 in the figure below. The current going through both LED's are lower than 20mA.

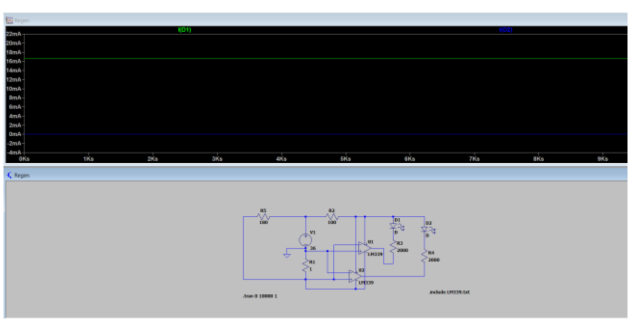
Figure 43: Transient Simulation at high current

These were the precautions taken to ensure the integration process was successful. The illustration shows what the electrical system looks like after the integration.

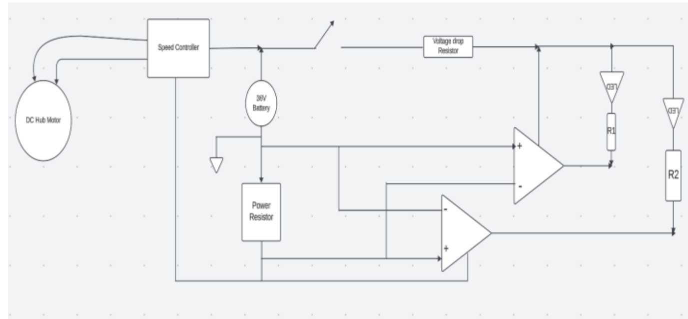

Figure 44: Integrated Electrical System

2.2.3 Construction of Framework

2.2.3.1 Designing of the Frame

The first step in the designing of the framework was the design drawings:

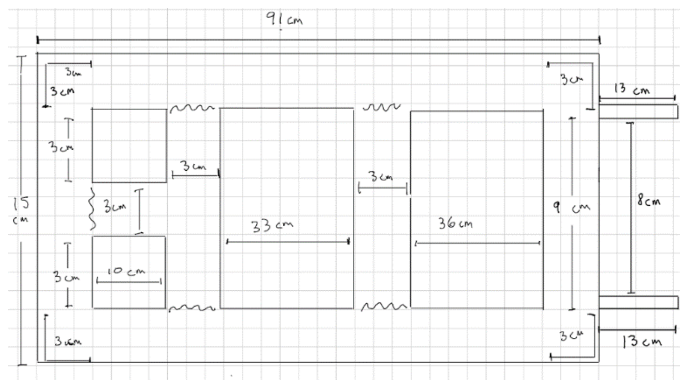

FIGURE 47: Top View of the Deck of the Scooter

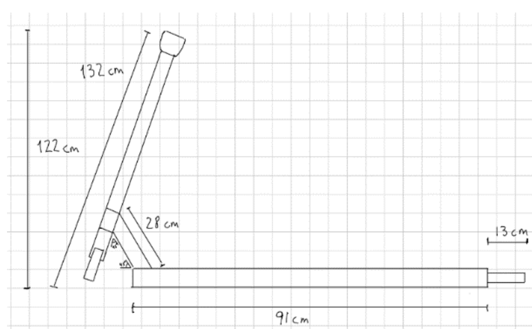

FIGURE 48: Side view of the Frame of the Scooter

As shown in the results of Eq. 3 the beams while be in vertical orientation to minimize bending of the material, 4130 Alloy Steel.

2.2.3.2 Building of the Frame

From the design drawing we begun building, we cut one of the 91-cm 4130 Alloy Steel, in 5 9-cm pieces with 90 degrees on both sides, and the other was cut to 28-cm with 45 degrees cuts in both sides. The 9-cm pieces were used to weld together the other 2 91-cm steel beams, as we can see in Figure 47, 3 of the were welded in a H-shape to be used in the front of the deck and the other 2 are used in the middle and at the back of the deck to connect the 91-cm beams. The back bracket was repurposed from a scooter provided by Professor Brooks, we cut it off using the metal bandsaw (Figure 49) and then used the metal grinder to make it flat, so that the welding to the back of the deck of the scooter would be easier

FIGURE 49: Metal Bandsaw cutting back bracket

The 28-cm piece is used to connect the deck and the stem of the scooter, so it is welded to the front to be used later (Figure 50)

FIGURE 50: Deck of the Scooter

The stem of the scooter was also repurposed from an old scooter provided by Professor Timothy Brooks. This was a sitting scooter, so a tube was bought to enlarge the stem and make it into the 132-cm stem as specified in Figure 48. To do this, we cut the 91-cm circular tube into a smaller piece 70-cm long, as the stem was originally 52 cm long.

Since this was a repurposed stem, the bracket was not compatible with our front wheel, as the axis of the front wheel was too thick and therefore did not fit. So, a new bracket needed to be made, to create the new bracket we used scrap metal, we used the drill press (Figure 5) to create several holes of the right size throughout the metal in the shape of a bracket, then we trimmed the edges of the holes created to create a cleaner path for the axis to fit better (Figure 51) using the metal bandsaw (Figure 4). We did this twice for the other bracket.

FIGURE 51: Self-Made Bracket

Then, we welded the bracket in a 90-degree angle to another piece of scrap metal to create this L-shape bracket (Figure 52), we did this again for the other bracket.

FIGURE 52: L-shape bracket

FIGURE 53: Repurposed Bracket

After, we cut the old ends off the old bracket (Figure 53), then we weld the L-shape brackets (Figure 52) into the recently cut piece to finish the new bracket (Figure 54)

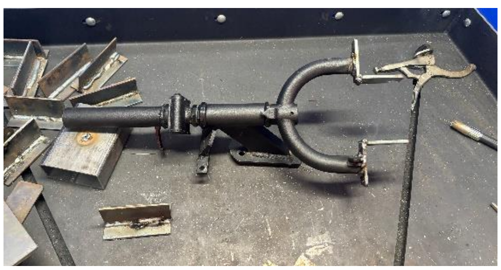

FIGURE 54: New Bracket

After we welded together all both the extension piece, and the upper part of the stem together (Figure 55)

FIGURE 55: New Stem

So, we welded the stem and the deck (Figure 50) together to finish off the frame (Figure 56)

FIGURE 56: Finished Frame

2.2.4 Implementing the wiring into the framework

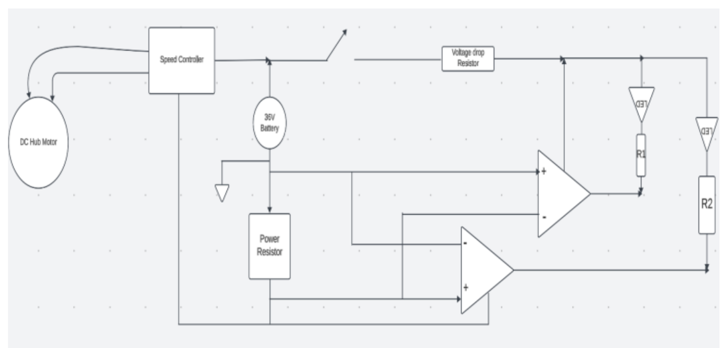

FIGURE 45: Electrical system circuit schematic (block diagram).

To help with the wiring, pockets were made from tarp so the battery and the speed controller could be situated in the gaps in the deck, making the wiring more efficient, also holes were drilled into the metal and the wood to pass the wires through.
We made use of the 14AWG wires to carry out the wiring of the electrical system. The 14AWG wire can carry up to 15-20 amps which is sufficient to handle the typical current draw of a 450W or less electric scooter motor. The power of the DC brushless Hub motor is 350W keeping it in an acceptable position.
We made sure to practice safe wiring guidelines while wiring the electrical system of the scooter on the frame. There were holes created within the layers of the frame to enable efficient connection. The pinout diagram (Figure..) of the Quad Comparator chip (LM339N) helps give a better understanding of the wiring process.

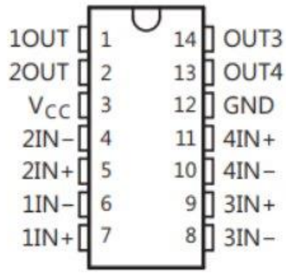

Figure 46: Pinout Diagram of the LM339N chip

We started by connecting the positive terminal of the battery to the positive terminal of the speed controller. We then connected the negative terminal of the speed controller to the positive side of the power resistor of the quad-comparator circuit. The next step was wiring up the switch that creates a connection between the comparator circuit and the voltage source. We connected the first terminal of the switch to the positive terminal of the speed controller and the second terminal to the positive terminal of the voltage drop resistor on the quad comparator circuit. The quad comparator was already built and soldered on a perf board before the wiring process so there was not any wiring to do within itself. We connected pin 3 of the chip to the negative terminal of the voltage drop resistor. We also connected pin 12 to the reference ground of the electrical system which is the negative terminal of the battery. Finally, we connected the negative terminal of the power resistor to the reference ground hence completing the wiring of the electrical system.
Throughout the wiring, we ensured tight connections between wires and ensured there were no naked wires to prevent short connections in the circuit.

2.2.4.1 Brainpower Controller Instruction Manual

Upon purchasing the Brainpower speed controller, it lacked documentation that could help with the wiring set-up. However, after familiarizing ourselves with its various components and how their connections, we took the initiative to develop a comprehensive instruction manual for enhanced user guidance. Please find the attached instruction manual for reference.[5]

3. RESULTS AND DISCUSSION

After the successful completion of the construction, we carried out some tests to prove the functionality of the scooter, as well as to quantify the effects of regenerative braking in the range of the scooter.

Figure 57: Final prototype's top view

Figure 58: Final prototype's side view

The scooter was ridden around campus until the battery died to assess how much distance it could cover, both with and without regenerative braking.

- With Regen. Braking: 19.4 km (about 12.05 mi)
- Without Regen. Braking: 19.3 km (about 11.99 mi)

So, we can see we get a range increase of 0.1 km or about 0.5%. Considering the average scooter gets a range increase of around 1.7% with Regen. Braking [4], our scooter did not benefit from the addition of Regenerative Braking. Regardless, the experience of building a scooter and the knowledge we gained from this has been quite a journey and will surely prove useful in the next step of our lives.

4. CONCLUSION

Some of the things we would do differently would be to use a 48V motor, instead of a 36V motor, this would allow us to get a greater output that would make the electric scooter faster and therefore get better results with the Regenerative Braking. Using a 48V instead of a 36V motor will also enable the overall system to withstand heavier weight during the scooter's operation.

Also, we would change the material as well, we were really limited on what material we could use since the engineering workshop can only work with steel, but if it was up to us, we would have preferred to use either plastic or aluminum, both are lighter than steel and therefore would have allowed the scooter to go faster and in return get more energy back. Also, we did not make a 3-D design of the scooter's frame, after design drawings we jumped straight into production, but it would be fair to say that the building of the frame would have been smoother, as some issues would have been revealed earlier.

4.1 ACKNOWLEDGMENT

We would like to express our gratitude to the Director of the Engineering Program Dr. Jeffrey Phillips and Professor Timothy Brooks for providing us with the opportunity to conduct this experiment and for teaching us the necessary skills to conduct it properly. Special thanks to Mario Bravo for his assistance throughout the project

4.2 REFERENCES

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