Title
Design and Performance Assessment of a Novel Electric Scooter

Author
Ringer, Kurt D

Publication Date
2019

UNIVERSITY OF CALIFORNIA
SANTA CRUZ

DESIGN AND PERFORMANCE ASSESSMENT OF A NOVEL ELECTRIC SCOOTER

A thesis submitted in partial satisfaction of the
requirements for the degree of

MASTER OF SCIENCE

in

COMPUTER ENGINEERING

by

Kurt Ringer

June 2019

The Thesis of Kurt Ringer
is approved:

Professor Patrick Mantey, Chair

Professor Gabriel Elkaim

Dr. Ali Adabi

Lori Kletzer
Vice Provost and Dean of Graduate Studies

Table of Contents

List of Figures

List of Tables

Abstract

Design and Performance Assessment of a Novel Electric Scooter

by

Kurt Ringer

Electric based propulsion has been rapidly growing across all forms of transit; providing a clear path to reduced emissions, especially within urban areas where people will most notably benefit. Most recently, personal light electric vehicles have shown great promise in both reducing emissions and downsizing to meet the needs of urbanites. This paper presents the design of a two-wheeled electric scooter for adult transit. The distinct features of the design are: dual motor parallel drive, greatly improved torque, and reliable electric braking. Analysis of the market needs, current product shortcomings, and the goal to improve overall performance all contribute to a more effective scooter design. The design is assessed through real-world tests which show promising performance, exceeding the metrics of existing electric scooters in nearly every category. Compared to the prevalent Bird electric scooter, this design improves velocity by 37.5%, climb velocity by 66.7%, and range by 131.6%.

Ken Brown, a technical mentor in life, passions, and profession.

Acknowledgments

Thank you: Formula Slug for providing the experience and connections necessary to tackle this project, TR Engineering for enabling and supporting my love of manufacturing while supporting my education, Jason for giving me access to your shop and staying up late into the night to help me, Ali for helping ignite an idea which was meaningful and interesting to me, Pat and Jose for allowing and assisting my remote study against the odds, my parents for their love and support, and Michaela for supporting me in the hectic life of being a full time student and professional.

Chapter 1

Introduction

Personal Light Electric Vehicles (LEVs) have rapidly grown in popularity in urban areas due to their convenience and emission reductions. The recent success and aggressive growth of scooter-share companies [1, 2] has demonstrated the existence of large market for expeditious short range urban transport. Flooding of the market and rapid adoption of electric scooters has helped highlight the shortcomings of current scooter designs. Scooter-related accidents have skyrocketed, some accidents ending in fatalities [3]. Major causes have been inadequate brakes or complete failure of braking mechanisms [4, 5].

This research aims for developing a simple and effective electric scooter design that addresses the shortcoming of current popular designs. The performance metrics of an effective electric scooter are high power density, high torque, high efficiency, high cruising speed, reliability, ease of control, and low maintenance. In producing an electric scooter which meets these goals, while remaining economically viable, adoption and applications will be increased, and the electrification of transportation will be furthered [6].

1.1 Overview

When developing a new vehicle design, it is important to prototype and test the vehicle in real world conditions, as well as understand the need which the vehicle will fill. The text begins with a market analysis to understand current scooter usages, and how their designs influence their failures. From this analysis, the desired metrics to address these shortcomings are defined. The consequent design is presented, and examined on how its characteristics address these metrics. Verification and testing of the design yield its real world performance and effectiveness relative to the desired metrics. Finally, potential improvements and emerging technologies are explored for implementations in future designs.

Chapter 2

Industry Analysis

2.1 Users

Looking at the existing industry one can identify customer needs and the electric scooter's fundamental functions. Currently they are used for short distance transport within urban cities. While their adoption has been rapid, the problems with them have become more apparent. Existing scooters suffer from ineffective brakes, low power, and the number injuries has greatly increased.

Many accidents have occurred due to ineffective brakes. Some designs mechanically brake with the rear tire only, limiting braking potential due to the innate transfer of weight towards the front wheel during braking. Additionally, forward weight transfers resulting reduction of grip in the rear makes locking up the rear wheel more likely, greatly decreasing stability in such a scenario. Common designs do not inspire confidence for the user. Users have cited these "sketchy" brakes as making them feel safer walking rather than riding downhill [7]. Another issue: these mechanical brakes often do not receive the maintenance they require by the companies who provide them, sometimes causing complete braking failure. Some brakes are found to be so poor that users find themselves rolling past stop signs.

[7].

In addition to being ill suited for downhill travel, these common scooters perform poorly going up hills. Lack of torque in these scooters is evident upon first start-up. To get moving, users must first kick off before pulling the throttle as the scooters' stall torque is too low to start from a standstill. Consequently, uphill performance, to no surprise, is poor. On slight hills users report major slowdowns [8, 9]; even for low-weight users, scooters slow to a crawl. In trying to tackle some steeper hills, the scooters stop entirely, going into a safe mode.

Not only are users experiencing adverse performance due to hardware, but also a software bug in Lime electric scooters has been causing severe injuries to riders [4]. Randomly rebooting scooters are causing unexpected and excessive braking, throwing users off scooters. Injuries have included broken bones and head injuries.

Current scooters are unstable, with narrow handlebars and short decks. Users describe not having confidence to perform evasive maneuvers [7]. Because scooters require constant throttle input, users also do not feel stable taking a hand off the handlebars to signal before they turn [8]. Reports show users have found a wider deck provides a more stable ride [9].

Lack of maintenance also has led to the chances of finding a shared scooter in good condition to be low. Therefore, users have sometimes no choice, but to take a scooter with a loose head tube or touchy brakes.

In cities where scooter share companies operate there has been a large rise in injuries. Consumer Reports cites 1,500 injuries in late 2017 after these products gained popularity [3]. There have been three reported deaths due to shared scooters; in one case, inadequate brakes prevented a rider from stopping in time to avoid collision with a car [5].

There are conditions where users are finding the range of current electric scooters is inadequate. Ridding up and down hills in San Francisco limits range to only 25 minutes for the SPIN e-scooter [9]. Due to the poor power of scooters, going uphill greatly taxes their battery, and greatly limits their range. By necessitating running the scooter at peak power 100% of the time, the motor is pushed into a far lower efficiency.

Conclusively, existing electric scooters have been plagued with problems. There have been growing injuries and failures to meet user needs under common conditions in urban areas. Brakes do not inspire confidence and have failed, power is inadequate for hills, and an unstable control discourages riders. These issues can and will be addressed with a more capable and robust design.

2.2 Suppliers

The growing number of suppliers have helped provide diversity and lower costs for electric scooter technology. While in North America, where electric scooters were recently seen more as a lifestyle choice rather than as a valid commuting option, in Asia and Europe their popularity and viability is not a new concept. In these external markets both legislation and popularity have contributed to supplier growth.

Asian suppliers and startups have been venturing into scooter sharing for many years; their expansions in financing and technology have greatly lowered costs. In Europe, EU legislation has mandated and encouraged electrification of transportation. Current battery technology is high in performance and low in cost. Brushless motor technology has allowed high power density and more durable products, penetrating countless industries. Readily available technology, and the demonstrated need for convenient electric transport in North America, makes the light electric vehicle market attractive. A more competent design would be readily adopted and would further encourage the electrification of transport.

Chapter 3

Performance Metrics

The performance metrics of an effective electric scooter which should be maximized are: power density, torque, efficiency, cruising speed, reliability, ease of control, and low maintenance. After analyzing the failures of existing electric scooters in chapter 2, it was established that the primary goal, which all other metrics should be based on, is ease of control. The control and performance of the scooter should make users confident and thus safer. Additionally, the subsystems must be reliable such that they do not generate an unsafe condition.

3.1 Requirements

To begin, some hard requirements based on the target user will be defined. The proposed scooter is intended to target adults, and therefore we will aim to proportion the design accordingly. The scooter must be able to support a 135kg rider. It must be able to start from a dead stop on level ground under its own power. Additionally, a reliable controls and braking system for such an adult is required.

For all the rest of the metrics there will be a threshold, median, and objective.

In general, the existing electric scooters performance will be used as the threshold. All performance metrics can be found in Table 3.1.

3.1.1 Velocity

Speed is the first metric which to look at. The absolute maximum speed of popular electric scooters is 24km/h [10]. The legal maximum speed for a motorized scooter in the United States is 32km/h [11], which will be used as a median. An additional important speed is uphill speed. Many factors go into uphill speed: gradient, rider weight, and a motor's power at the given speed. For simplicity, only a threshold will be provided of 9km/h, exceeding the walking speed of most humans.

3.1.2 Torque

Torque will be rated by the vehicles gradeability, which is the grade at which a vehicle can maintain a speed. The United States maximum grade for a federally funded highway of 6% in urban areas is the threshold. For the objective the steepest gradient in San Francisco Filbert Street, 31.5%, will be used.

3.1.3 Efficiency

For efficiency a range on level ground will be measured. The range of a Bird scooter is 24km, which will be the threshold. The objective will be the newest and longest-range scooter on the market, a Lime-s with a 59.5km range [10].

Metric	Threshold	Median	Objective
Load Capacity (kg)	135		
Velocity (km/h)	24	32	35
Climb Velocity (km/h)	9		
Gradeability (%)	7	14	31.5
Range (km)	24	42	59.5

Table 3.1: Performance Metrics

Chapter 4

Design

The design of this electric scooter will follow the goals set by the performance metrics in chapter 3. It is essential that from the ground up all aspects of the design build into these metrics, and therefore meet the overall goal of filling the identified market need in chapter 2. Additionally, as this design serves more the role of a prototype, there is a demand to ensure a low cost build. This is achieved by basing the design on off-the-shelf components and keeping it easily reproducible. The system will be broken down into three major components: powertrain, vehicle, and controls.

4.1 Powertrain

The powertrain is the starting point of the overall electric scooter system. It most directly effects the performance metrics of the system. The major components of the powertrain are the motor(s), electronic speed controller(s) (ESC), and electrical accumulator (battery). A parallel dual motor design is selected as the basis of the powertrain, which is the key innovation of the system. With a parallel motor system key metrics are addressed, torque output is doubled, regenerative braking capacity is doubled, and power is spread evenly across the two motors, reducing heating and increasing efficiency.

4.1.1 Motors

A Permanent Magnet Brush-less DC (PMBLDC) motor is selected because of its high power density, high efficiency, and containing no maintenance parts [12]. Additionally, a PMBLDC enables the motor to be in the wheel hub due to its external rotor design. A hub motor reduces the drive mechanism to a single unit, eliminating any chains, sprockets, or extra bearings [6]. The result is a reduced parts count, and an increase in ease of assembly, both helping to keep the electric scooter low cost. A supplementary asset is the sealed mechanism, reducing pinch points and adding the benefit of being able to operate in water, which increases the system's safety.

Due to the scope of this research it is preferred to use existing technology from a supplier, as opposed to pursuing a custom motor design. To achieve the objective max velocity of 35km/h an eight inch nominal wheel Figure 4.1 was necessary based on the available options. This appears appropriate as most existing electric scooters use approximately eight inch wheels [13]. Additionally, too large a wheel would have potential packaging and stability issues based on its effect on deck height. A low deck height helps increase stability. Despite a larger wheel's gyroscopic effect on stability increasing with speed, due to the intended speed of the scooter an exceedingly large wheel would be required for this gyroscopic effect to take meaningful impact.

To maintain simplicity, it was decided to use the same motor for both wheels, front and back. The motor selected is rated for 350W at 36V with a top speed of 35km/h, meeting the velocity objective. The higher voltage is beneficial in

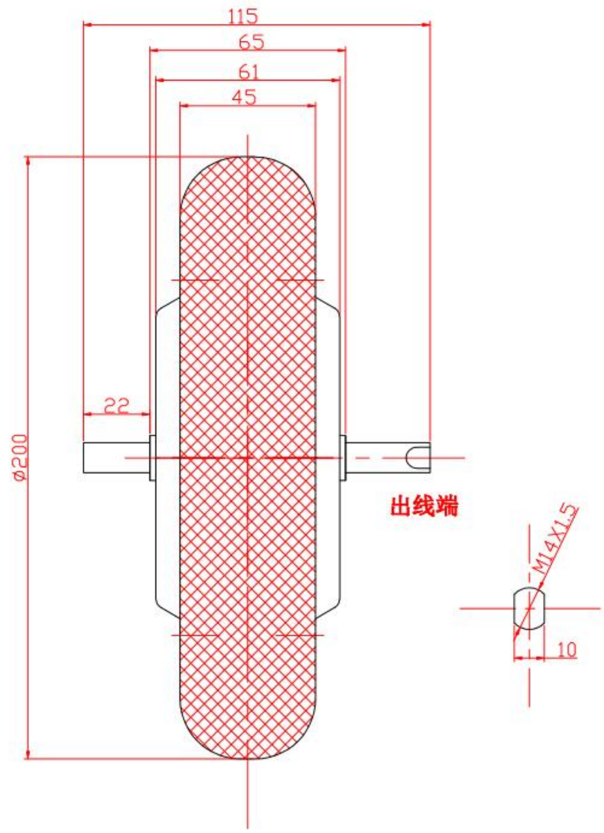

Figure 4.1: Motor Drawing

reducing the current required, decreasing I^2R losses and increasing efficiency. Additionally, higher voltage reduced the weight by allowing a smaller diameter conductor for the motor windings and other power leads.

Addressing load capacity, the motors are rated for a 100kg load, the two axles give a 200kg total load rating, which will easily accommodate the desired load capacity of a 135kg rider.

Next, is ensuring the motor will meet the torque objectives. To calculate the velocity for a given grade Equation 4.1 was used. To ensure the design has margin, the system is assumed to have a worst case efficiency of 75%[1]. The specifications

[1]Approximation based upon the motors rated efficiency of 90% and aerodynamic losses of a bicyclist at 30km/h of 14%. Precisely calculating losses at various speeds and loads is beyond the scope of this prototype; real world results in chapter 5 are more valuable.

Power (W)	Grade (%)	Angle (^{0})	Velocity (m/s)	Velocity (km/h)
700	7	4	5.12	18.43
700	14	7.97	2.58	9.27
700	31.5	14.48	1.19	4.28
1000	7	4	7.31	26.33
1400	14	7.97	5.15	18.55
1400	31.5	14.48	2.38	8.56

Table 4.1: Climb Velocity

from Table 3.1 are substantiated using Equation 4.1 for Table 4.1 assuming a 150kg total load (rider and scooter). Additionally, cases are presented exceeding the motors rated power. It is reasonable to run the motors at 200% as they are intentionally and often underrated [14]. The calculations show these motors should be able to meet the minimum climb velocity for all but the objective grade of 31.5%.

$$V = \frac{Efficiency \times P}{m \times g \times \sin\theta} \tag{4.1}$$

4.1.2 ESC

An Electric Speed Controller (ESC) is necessary for a PMBLDC motor control due to stator timing, which must be maintained between the positive and negative current pulses of the three phases [15]. Due to utilizing two motors two ESCs are required. The ESC selected is produced by the same company which produces the motors. This commonality was necessary because ESC had the correct Hall Effect sensor circuitry and conectorization to interface with the specific PMBLDC motor used. Rated for 20A and 36V each ESC will support up 720W to each motor.

Although information provided from the manufacture on the ESC was sparse, they were successfully bench-tested upon receipt. The ESC was proven to operate with an input range of 42V-28V. Additionally, the ESC did not have a hard current limit and was tested drawing 20A at 42V for 5 minutes with a 25C ambient temperature. The highest measured temperature recorded during this test was 40C at the motor connectors, which indicates the ESC itself had sufficient thermal mass to sustain the load as tested.

Figure 4.2: Electronic Speed Controller

4.1.3 Battery

The significant improvements in energy storage systems which the world has witnessed in recent years have enabled electric transport to grow to its current success [12]. Specifically, Lithium-Ion (Li-Ion) batteries have been the technology of choice. For this design a Li-Ion Polymer (LiPo) pouch cell battery was selected. These were selected as they are one of the more mechanically stable and energy dense batteries available. The Xiaomi Mi electric scooter [13], which the Bird Spin, and Lime-S scooter are based on, utilizes a 10 series and 3 parallel configuration of 18650 Cells. At a minimum these cells take up a volume of $65mm \times 270mm \times 36mm$ 0.6318L, which is the volume of the 30 cells for a 10S3P configuration. The Xiaomi Mi battery is 216Wh giving it an energy density of 341.88Wh/L. Comparatively the LiPo battery selected is 0.8168L and 296Wh giving it an energy density of 362.39Wh/L. All though only a 6% improvement, the bus bars and casing which cylindrical cells require were not considered, unlike the LiPo pouch cells. Additionally, new graphene blend LiPo cells that are commercially available now have energy densities up to 672Wh/L [16].

4.2 Vehicle

For the vehicle it was decided to stick with a traditional two-wheel inline layout. This layout provides a balance between stability and maneuverability while keeping cost/complexity down. Compared to a three-wheeled scooter the design has higher maneuverability and lower cost, at the trade of less stability, especially at low speed. Another alternative is a Segway type vehicle; although these are highly maneuverable and stable, once the rider is familiar with them, the cost and complexity of the extra control outweighs the benefits. A traditional two-wheeled scooter will provide a familiar platform which most people have ridden previously and will feel at home with.

For the vehicle chassis a Razor electric scooter was modified. This platform provided an existing compartment to house the battery and ESCs. Additionally, the Razor scooter has proper clearances and fork width to accommodate the hub motors selected. This was beneficial as it was an accessible platform for prototyping, saving time which would have been otherwise spent pursuing a custom design.

Initial testing determined the scooter lacked the stability desired. To correct this two changes were made: increased wheelbase, and lowered deck height. The wheelbase was increased by 178mm to 838mm total. The primary benefit of this change is increased longitudinal stability, easing transitions from acceleration to deceleration, as well as improved stability on hills. Additionally, a longer wheelbase decreases the scooters response to steering angle [17]. In requiring more input from the rider for a turn, stability at speed is increased due to bumps and

Figure 4.3: Razor Electric Scooter

weight shifting having less impact. Furthermore a longer wheelbase decreases the likelihood of the scooter transitioning to countersteer Figure 4.4, which is when steering input in one direction results in the vehicle turning the opposite direction. Countersteer, especially a sudden transition, is undesirable. This condition would surprise most users, as they expect to control turns with steering, not shifting weight to lean.

The deck height was decreased by 38mm which lowers the center of gravity, creating a lesser moment causing increased lateral stability. Additionally, a lower center of gravity eases the rider's ability to kick-propel the scooter if necessary, and gives the rider more confidence to touch their foot down, if necessary, to increase stability.

Figure 4.4: Countersteer on a Motorcycle

4.3 Controls

The primary goal of the vehicle is ease of control, which greatly influenced the design. The physical controls are the most important factor in that they are the interface between the rider and the scooter. Easily understandable controls give the rider confidence, resulting in them being safer. The scooter uses a traditional handlebar layout to steer, which provides familiarity to the user. On the handle bars the controls are an accelerator throttle/kill switch, electronic-brake throttle, and cruise switch shown in Figure 4.5.

Figure 4.5: Electric Scooter Controls

4.3.1 Accelerator

The accelerator is a thumb throttle with an integrated kill switch as well as battery life indicator. This all in one unit is helpful in making sure any throttle is deliberate, with the kill switch a flick of a thumb away. The battery indicator also acts as a visual indicator for whenever the scooter's throttle is in an enabled state. Thanks to the indicator being on top of the throttle lever the user can easily see the throttle is armed whenever touching it, hopefully helping avoid inadvertent throttle application. A thumb throttle increases safety over a twist throttle due to reduced likeliness of being inadvertently actuated when picking up the scooter by the handlebars or steering.

4.3.2 Brake

The e-brake throttle allows the rider to control the amount of regenerative braking which the motors apply. Regenerative braking is a great benefit to electric vehicles, extending range by an average of 8% to as much as 25% [18]. A thumb throttle is an intuitive and familiar interface for many people. By giving the user the fine control of a throttle to their regenerative braking force a smooth transition into deceleration is granted. Sudden regenerative braking has been attributed to cause accidents on other electric scooters. Additionally, the thumb throttle gives the user the control to choose if they want to cruise or instantly transition to regenerative braking when off throttle. Regenerative braking has an additional benefit of inherently built in ABS in its control [19]. If the braking torque were to be too high such that the wheel would begin to lock-up, the reduced motor velocity would lower the braking torque. This effect helps balance the braking force between the rear and front wheels on our electric scooter, where both brake in parallel.

4.3.3 Cruise

The cruise switch enables the rider to maintain a speed without constantly having to control throttle input. Cruise control helps the rider, once they've found a speed they're comfortable with, have the scooter automatically maintain speed. Control can be taken back over by the rider by applying either the brake or throttle. Unlike a typical cruise control found in a car, the ESCs also help maintain a speed when going downhill by applying regenerative braking when needed. This benefit allows the rider to give their full attention to where they are going. The cruise control should help the rider maintain a smooth consistent ride.

Chapter 5

Results

In this section validation against the goals in chapter 3 using real-world test results is described. The scooter has been tested for many months and taken on over twenty rides. Although this testing is dwarfed in comparison with the number of rides scooter-share companies' scooters go through, it's a sign of initial quality. Zero failures which would put the rider or others in an unsafe condition have been observed.

All the hard requirements on the scooter were proven to be met in the real world. A load over 135kg was supported without issue. Starting from a dead stop with a load of over 135kg was achieved, and there was no indication of the powertrain struggling. The controls, motor controllers, and brakes have proven reliable, without any observed failures or issues.

5.1 Controls

Controls, the main interface between the rider and scooter, were intuitive and easy to use from the start. The throttle was not too sensitive and allowed low speed control. The cruise button worked as intended and was canceled immediately upon an input from the accelerator or brake. The cruise control demonstrated smooth control both uphill and downhill, adjusting motor torque as needed. It responded well, without any sudden jerks, and maintained speed from the perspective of the rider. Though, when reviewing measured velocity, overshoots were common when transitioning from level travel to uphill. The electronic-brake throttle was smooth and linear; however, the initial transition to braking was slightly abrupt. This abruptness may be more apparent due to the control defaulting to coasting when off throttle versus immediately transitioning to low regenerative braking. Overall the physical controls clearly met their goal of being easily comprehensible with responses comparable to any motorized vehicle.

5.2 Vehicle

Regarding controllability and stability, the physical vehicle was well balanced for the target user. The vehicle is rigid and feels stable as a platform. At speed, the vehicle felt under control and tracked smoothly without extraneous vibrations. In terms of maneuverability the vehicle was easy to control at low speed. The low deck height allowed the rider to drag a foot to give a third contact point for added stability if desired. As this design is not a sporting scooter, but intended for commuting, it is recommended riders slow down before performing any major turns. The lower deck height does limit the amount of lean possible, but wasn't an issue going over any bumps in the road.

5.3 Verified Metrics

The electric scooter metrics which were tested are shown in Table 5.1. The test conditions were with a full weight of 170kg. The tests were performed on asphalt

Metric	Result
Load Capacity (kg)	150
Velocity (km/h)	33
Climb Velocity (km/h)	15
Gradeability (%)	10.5
Range (km)	55.6

Table 5.1: Tested Performance Metrics

streets and bike paths. Range data is projected by measuring the capacity used during a 4.7 km ride with a 6 m climb and 60 m descent. The results shown are the maximum that the scooter was tested to, but are not necessarily hard limits and the scooter may be capable of more.

Chapter 6

Potential Improvements

In working through this design process and performing thorough testing on the novel electric scooter design, some potential areas for improvement were identified. These improvements are singular, each with its own identified strengths and weaknesses.

6.1 Three-Wheels

A three wheeled scooter would provide great improvements in stability. By providing a triangulated, three-point contact patch, both longitudinal and lateral stability would be improved. We would recommend that this be implemented with two wheels in the front, to be steered. Both front wheels should be driven wheels, such that torque is equal. By having both driven wheels upfront the electronic-braking potential would be increased, as there is significantly more grip at the front due to load transfer. The rear wheel would be undriven.

The negative aspects of a three wheeled scooter would be: increased costs, weight, and lower maneuverability. By adding a third wheel to the scooter additional parts are required increasing cost and weight. Additionally, the front fork would become more complex requiring additional structure to accommodate two wheels. Maneuverability would be decreased as slipping of the inner wheel during a turn is required due to the due to non-Ackerman parallel steering Figure 6.1, which especially limits high speed maneuverability [20].

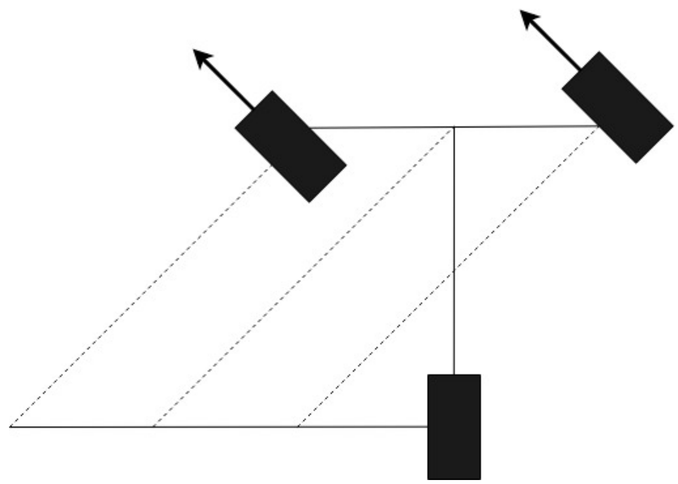

Figure 6.1: Parallel Steering Geometry

6.2 Seat-Post

The addition of a seat-post to the scooter would increase stability and rider comfort. Stability would be increased by lowering the center of gravity decreasing the moment. Rider comfort would be increased by a seated posture, which is likely most beneficial on longer trips or for older/physically impaired users. The cons of this addition would be increased cost and weight due to the additional components.

6.3 Graphene Blend Battery

A graphene blend LiPo battery pack with an energy density of 672Wh/L, would net an 85% improvement in energy density over the current battery pack's 362Wh/L. Additionally, owing to its far lower internal resistance it would benefit from lower cell heating, increasing cycle life. Although cost differences are negligible over the current battery, these cells are new to market and potentially unproven.

6.4 Staged Braking

Although the initial transition to braking was more abrupt than desired. Employing a progressive, staged braking control where one motor would begin electric-braking before the other, would lower initial braking torque. This change would require additional communication between the ESCs.

Chapter 7

Conclusion

Research on the rapidly expanding market of electric scooters has shown critical discrepancies between performance and users' needs. Results have proven that the design presented in this thesis achieves all desired performance metrics of an effective electric scooter in the real world, filling the gaps in users' needs. In comparison to the prevalent Bird electric scooter, this design improves velocity by 37.5%, climb velocity by 66.7%, and range by 131.6%.

The two-wheel parallel-drive electric scooter is a novel idea; paramount is its greatly improved torque, and reliable electronic braking. This design has great potential to improve the effectiveness of electric scooters for daily travel, by allowing performance in more diverse urban environments, and awarding greater safety for both riders and everyone around them. Electric scooter adoption can be further accelerated by utilizing similar design cues, thus helping improve our cities by reducing car usage, traffic, and emissions. The design presented in this thesis shows great promise, and does not have any technically challenging barriers to implement. It should be further explored and its features Incorporated in commercial scooter products.

Appendix A

Build Guide

Note: Use caution when handling any wiring or batteries as there may be voltage present.

A.1 Vehicle Components

A.1.1 Parts List

- Razor E100 Electric Scooter
- Thunder Power TP8000-10SPX25 battery
- 2x FLD-01 36V 350W hub motor
- 2x Brainpower 48V motor controller
- Wuxing thumb accelerator 36V
- Wuxing brake thumb throttle
- Handlebar mount latching push button switch, normally open
- 65mm scooter front fork
- 6mm diameter steel rod, 150mm
- 22AWG wire

- 12AWG wire
- 2x Deans connector, socket
- Deans connector, plug
- Velcro straps

A.1.2 Tools

- 10mm box end wrench
- 10mm socket and ratchet
- 12mm box end wrench
- #2 Philips screwdriver
- Hex key set
- 2x 17mm wrench
- 250mm adjustable wrench
- Wire cutters
- Precision knife or hot tweezers
- Soldering iron
- Zip ties
- Heat shrink
- Angle grinder
- Welder
- Permanent marker
- Wire brush, steel
- Pick set

A.2 Chassis

A.2.1 Razor E100 Disassembly

One should begin by disassembling the Razor E100 entirely to its component level. Disassembly will require the 10mm box end wrench, 10mm ratchet, #2 Philips screwdriver, Hex key set, 17mm wrenches, and adjustable wrench. Remove the deck of the scooter using the screwdriver, which will allow access the batteries and motor controller. Disconnecting the connectors, these components can be discarded.

Remove the rubber grips from the handlebars, using water as a lubricant may help with the process, keep these grips to reinstall at a later point. The existing scooter controls should all be removed with the required hex keys, the controls can be discarded. Remove and discard the brake mechanism from the front fork using the 12mm wrench.

The front and rear wheels can now be removed, then discarded, using two 17mm wrenches. Retain the rear wheels 6mm axle for use later. Next, uninstall the chain tensioner using a 10mm wrench and 10mm ratchet. Remove the motor with the necessary hex key. The rest of the drive components can be discarded.

Finally, to remove the front fork, first remove the steering stop using the 10mm wrench and necessary hex key. The scooters head tube bearing assembly may need to be loosened using the adjustable wrench. The clamp must be loosened between the handlebars and fork using the necessary hex key. The fork can now slide out, retain all components for later reassembly.

A.2.2 Chassis Modifications

The front fork must be slotted vertically to allow installation of the new hub motor. Using the angle grinder with a cut-off wheel, make an 11mm wide slot tangential with the existing 11mm hole. This modification must be done on both ends of the fork, care must be taken to ensure each sides slot is parallel along the forks steering axis. Utilize the hub motor to test fit and adjust the slots as necessary to allow the motor to sit coincident with the existing 11mm holes. This should ensure the motor axis is perpendicular with the steering axis and parallel with either end of the fork. When finalized, repaint where ground to avoid corrosion. This entire process must be repeated on the additional 65mm fork before it's added to the rear of the scooter.

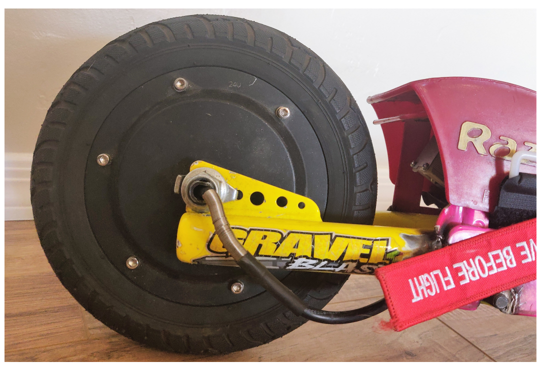

Figure A.1: Rear Fork Position, Side View

The additional 65mm front fork is to be added to the rear of the scooter to accommodate the hub motor and lengthen the wheelbase. First, use the angle grinder with cut-off wheel to remove the old motor mounts from the scooter frame. Next, position the front fork in the rear between the existing frame as shown in Figure A.1 and Figure A.2. Finally, place the 6mm steel rod in the rear axle holes to support the fork. Take care that the fork is oriented along the scooter such that the offset fork mounts are facing upwards, which ensures the scooters ride height

Figure A.2: Rear Fork Position, Bottom View

is lowered. Additionally, the yoke must be properly spaced such that the rear wheel will not contact the scooter deck or frame. Use a distance of 180mm from the existing rear axle to the added fork's axle. Ensure the fork sits even within the frame and is rotated such that the fork axle is parallel along the scooter frame. Carefully mark all areas where the new fork contacts the scooter frame and 6mm support rod on both the fork and frame.

Once the position is marked, remove the fork and 6mm support rod. Using the angle grinder with a flapper disk remove all paint from the marked areas on the fork and scooter frame. Take off an additional a 12mm minimum margin around the areas marked. Use the wire brush to further clean the ground areas, which ensures the steel is adequately prepared for welding.

Reposition the additional fork and support rod as previously described. Tack weld the support rod and fork into position. Test fit the hub motor onto the tacked fork, ensure it clears the scooter frame. Adjust as necessary such that the wheel is positioned along the length and center of the scooter and the axle is parallel to the bottom of the scooter frame. Once the front fork is properly positioned remove the hub motor and fully weld the fork, support rod, and frame. Repaint all exposed metal to prevent corrosion.

A.3 Wiring

A.3.1 Battery Harness

The ESCs require a "Y" harness, shown in Figure A.4, made to connect the two to the battery in parallel. This harness consists of two Deans socket connectors, one Deans plug connector, and 12AWG wire. First, solder a short length of black and red wire to the plug connector. Make sure to follow the +/- standard for the connector. Insulate the solder joints with heat shrink. Next, create a three-way splice by adding two lengths of black wire to the existing black wire, and two lengths of red wire to the existing red wire. The overall length of each branch should be approximately 150mm. Again, insulate the splices with heat shrink. Next the two socket connectors must be added. Before soldering the connectors on make sure to slip heat shrink over each wire, as it's difficult to add after attaching the connector. Each connector shall receive one red wire and one black wire, again ensuring the +/- standard of the connector is followed. Now the heat shrink previously placed over each wire can be recovered to insulate the solder joints.

Caution: Deans connector housing can be easily melted when soldering, do not apply too much heat and do not exceed 10 second of contact when soldering.

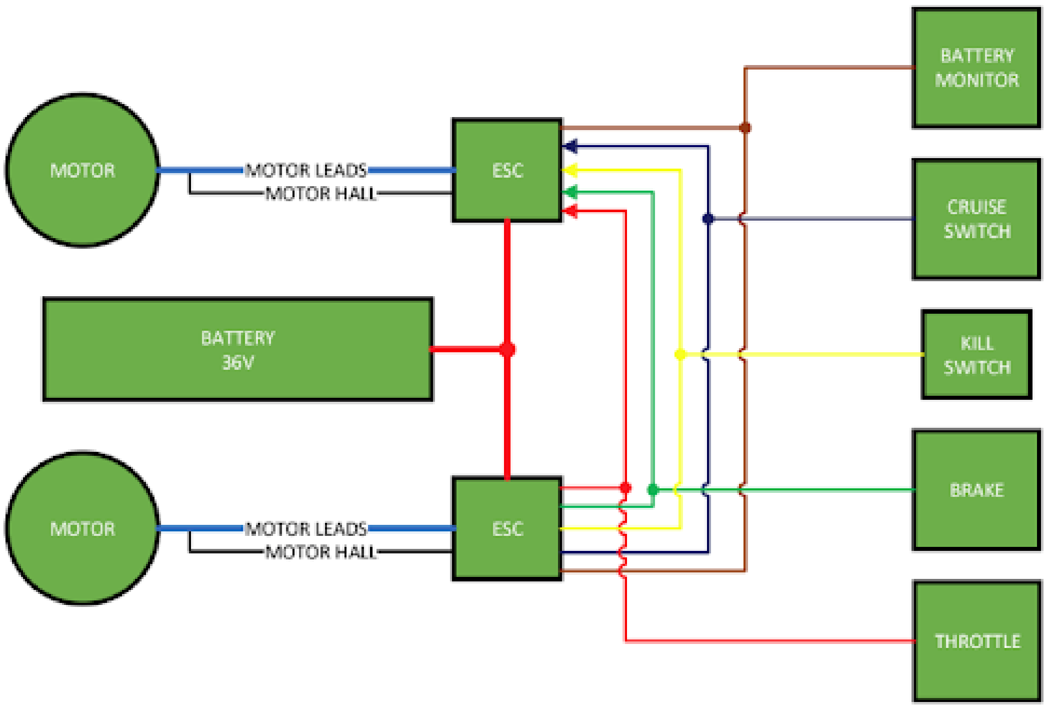

Figure A.3: Electrical Block Diagram

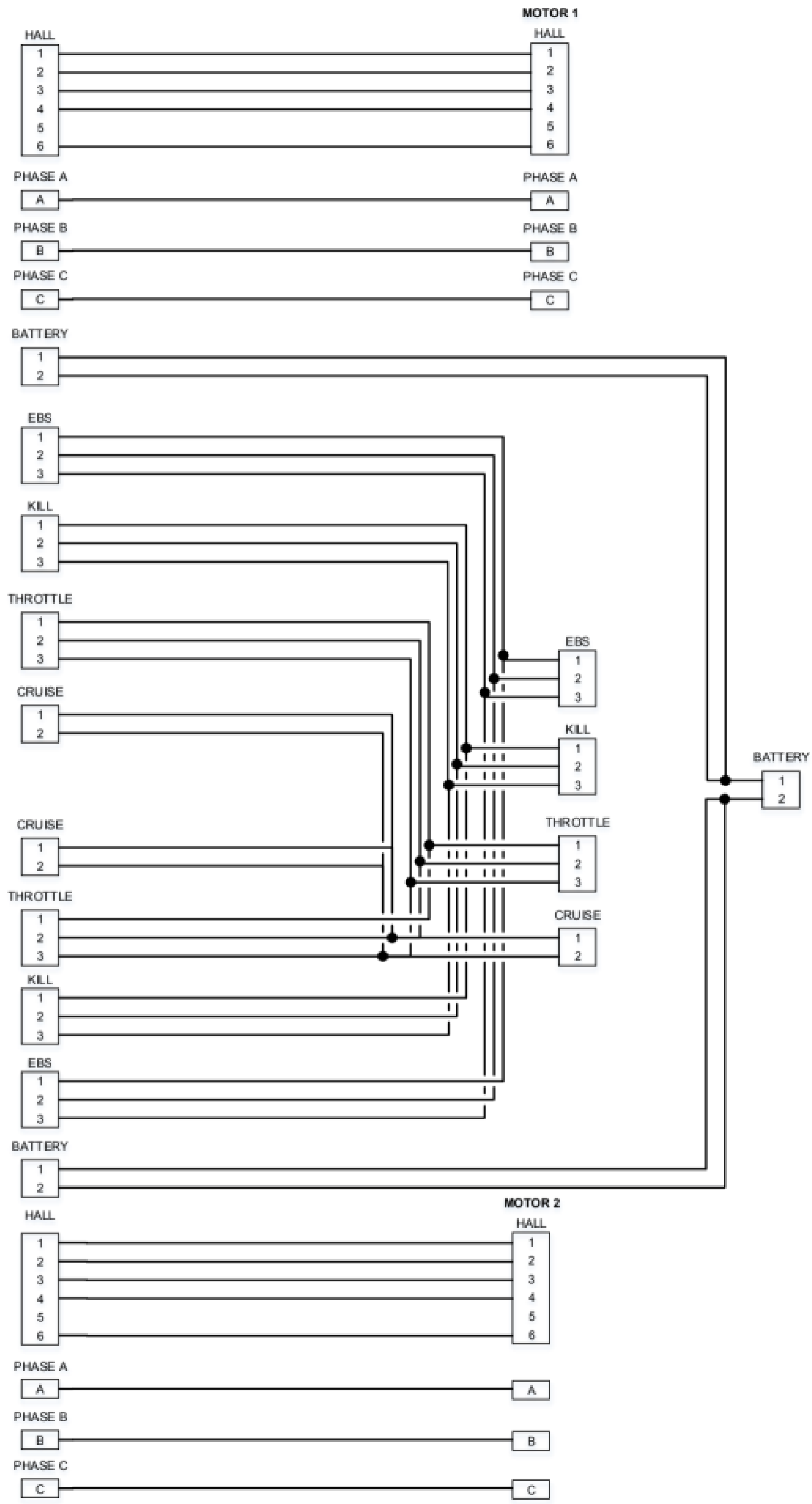

Figure A.4: Electrical Schematic

A.3.2 Control Harnessing

The scooter controls must connect to both ESCs to allow parallel control. Parallelizing is achieved by splicing 22AWG wires between the ESC pigtail connectors. The electric brake, kill switch, throttle, and cruise inputs all need to be paralleled as shown in Figure A.3. To perform the window splices it is easiest to remove the contacts from the connector housings; make sure to note the pin-out based on wire color before performing this step. Methodically go through the system one connector at a time to avoid mistakes. Once a contact is removed from its housing, strip a window in the insulation close to the contact utilizing a precision knife or hot tweezers. Lap splice in approximately 150mm of 22AWG wire and insulate the splice with heat shrink. Next, connect the spliced wire to the other ESCs corresponding wire utilizing the same procedure. Once finished splicing, reinstall the contact into the appropriate connector housing position, ensure proper contact latch orientation relative to the housing. Repeat this process on all wires per the schematic in Figure A.4.

A.4 Assembly

Assembly begins by reinstalling the front fork and handlebar into the head tube. This process requires the hex key set, 10mm wrench, and adjustable wrench. First, insert the front fork and tighten the bearing. Then install the handlebars and tighten the stem clamp while ensuring the handlebars are aligned parallel with the forks. Finally, reinstall the steering stop. Ensure smooth lock-to-lock rotation of the steering assembly, adjust bearing preload as necessary.

Next, the hub motors can be installed. The process is identical for both the front and rear. Position the motor, ensuring proper orientation for the direction of rotation. The trailing edge of the tread points in line with the direction of rotation. Install the motor with the included washers on the inside of the forks and the included locking wedges, with the wedges oriented outward as shown in Figure A.5. Ensuring the locking wedges are aligned inside the slots, tighten both nuts simultaneously utilizing two 17mm wrenches.

Figure A.5: Motor Mounts

The controls are fitted to the handlebars using their built-in clamps. Install the thumb throttle on the right and the cruise button and electronic brake switch on the left. Locate and tighten with the necessary hex keys. Trim to fit and reinstall the grips. Zip ties secure the cables along the steering shaft. Route the cable bundle to the underside of the scooter frame and allow an appropriate service loop for turning.

Position the battery between the scooter's lower frame rails with the wires towards the rear. Secure with Velcro straps. Position the ESCs above the rear fork where the scooter's original motor was mounted. Ensure the wires are facing forwards and secure with Velcro straps. Proceed to connect all the scooter's

Figure A.6: Controls

components as shown in Figure A.3, utilizing zip ties for cable management where necessary. Once finished, reinstall the scooter's deck using the screwdriver and its hardware.

Figure A.7: Final Prototype

Bibliography

[1] A. Griswold, "Bird is the fastest startup ever to reach a $1 billion valuation," Jun 2018. [Online]. Available: https://qz.com/1305719/electric-scooter-company-bird-is-the-fastest-startup-ever-to-become-a-unicorn/

[2] C. Schubarth, "Scooter startups break unicorn speed records to $1 billion valuations," Jun 2018. [Online]. Available: https://www.bizjournals.com/sanjose/news/2018/06/15/scooter-startups-break-unicorn-speed-records-to-1.html

[3] R. Felton, "E-scooter ride-share industry leaves injuries and angered cities in its path," Feb 2019. [Online]. Available: https://www.consumerreports.org/product-safety/e-scooter-ride-share-industry-leaves-injuries-and-angered-cities-in-its-path/

[4] C. Keck and C. Keck, "Lime scooters face suspension in auckland amid reports of unexpected braking and rider injuries," Feb 2019. [Online]. Available: https://gizmodo.com/lime-scooters-face-suspension-in-auckland-amid-reports-1832847558

[5] "Scooter fault leaves lime riders injured," Feb 2019. [Online]. Available: https://www.bbc.com/news/technology-47371925

[6] C. Sachs, S. Burandt, S. Mandelj, and R. Mutter, "Assessing the market of light electric vehicles as a potential application for electric in-wheel drives," *2016 6th International Electric Drives Production Conference (EDPC)*, 2016.

[7] B. Stewart, "48 hours without four wheels: What i learned living the ridesharing scooter life," Jun 2018. [Online]. Available: https://www.popularmechanics.com/cars/hybrid-electric/a21073216/bird-ridesharing-scooter-review/

[8] L. Acker, "I took an electric scooter on a 12.5-mile journey through portland – here's what happened," Jul 2018. [Online]. Available: https://www.oregonlive.com/portland/2018/07/i_took_an_electric_scooter_on.html

[9] R. Yean, “A san franciscan tries the future of mobility - limebike, spin, bird, and jump bike,” Apr 2018. [Online]. Available: https://medium.com/@rickyyean/

[10] S. Hollister, P. Holland, M. Serrels, and M. Little, “The electric scooter war continues. here’s how they work (faq),” May 2018. [Online]. Available: https://www.cnet.com/news/electric-scooters-bikes-dockless-ride-share-bird-lime-jump-spin-scoot/

[11] D. Steinman, “Which electric scooters for adults are street legal?” Nov 2018. [Online]. Available: https://www.ridetwowheels.com/electric-scooters-adults-street-legal/

[12] K. L. Shenoy and M. S. Kumar, “Design topology and electromagnetic field analysis of permanent magnet brushless dc motor for electric scooter application,” *2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*, 2016.

[13] “Mi electric scooter.” [Online]. Available: https://www.mi.com/us/mi-electric-scooter/

[14] “Motor power ratings.” [Online]. Available: https://www.ebikes.ca/learn/power-ratings.html

[15] S.-H. Chang, J.-F. Tsai, B.-T. Sung, and C.-C. Lin, “Design of integrated power module for electric scooter,” *2013 World Electric Vehicle Symposium and Exhibition (EVS27)*, 2013.

[16] [Online]. Available: http://www.store.revolectrix.com/Products/Blend435-PLATINUM-Label-40C-GoPACKS/Revolectrix-5000mAh-5S-LiPO-Blend435-Platinum-Label-40C-GoPACKS

[17] L. Zhang, L. Yu, Z. Wang, L. Zuo, and J. Song, “All-wheel braking force allocation during a braking-in-turn maneuver for vehicles with the brake-by-wire system considering braking efficiency and stability,” *IEEE Transactions on Vehicular Technology*, vol. 65, no. 6, p. 4752âĂŞ4767, Aug 2015.

[18] J. Paterson and M. Ramsay, “Electric vehicle braking by fuzzy logic control,” *Conference Record of the 1993 IEEE Industry Applications Conference Twenty-Eighth IAS Annual Meeting*, Oct 1993.

[19] B. Balasubramanian and A. C. Huzefa, “Development of regeneration braking model for electric vehicle range improvement,” *2017 IEEE Transportation Electrification Conference (ITEC-India)*, 2017.

[20] D. Thompson, “Ackerman? anti-ackerman? or parallel steering?” *Racing Car Technology*, p. 1âĂŞ10, 2015.

[21] M. Corno, M. Tanelli, and S. M. Savaresi, “High performance braking for racing motorcycles,” *2007 European Control Conference (ECC)*, 2007.

[22] Y.-H. Hung, S.-W. Chang, W.-T. Hsiao, S.-T. Huang, L.-J. Wang, and C.-T. Chung, “Mechanical designs, energy management, and performance assessment of a novel hybrid electric scooter,” *2016 International Conference on Advanced Materials for Science and Engineering (ICAMSE)*, Nov 2016.