A Low Cost Power Assist for Active Wheelchair Users

By

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Abstract

Wheelchair power assists are devices that a wheelchair user may retrofit onto their wheelchair to increase their range, speed, and power. Users of these devices may already have the ability to propel themselves manually, but their mobility is further enhanced with these devices. This is particularly true for “active” wheelchair users, who use wheelchairs specially designed for an active, physical lifestyle. However, commercial power assists often cost thousands of dollars, which can be a significant financial barrier for wheelchair users who cannot get insurance to cover the cost. For this reason, I have partnered with a permanent wheelchair user to create and test a low cost power assist, which we call the “Tailwind,” that wheelchair users can build with minimal tools. By enabling more wheelchair users to add a power assist to their wheelchair, we intend to facilitate exercise and independence for wheelchair users who may feel otherwise restricted in range, speed, or power.

Based on the prototype, I estimate the total cost to be less than $450, which is an order of magnitude less than commercially available power assists. I estimate the range to be 11 miles on smooth terrain such as concrete and 4.3 miles on rough terrain such as grass, and I estimate the maximum speed to be 9.7 mph. As for power, I estimate that the Tailwind can climb a slope of 7.4° (13% grade) on its own power and at least 15° (27% grade) when the user is also manually pushing theirself. Additionally, the Tailwind has a lift mechanism that allows the user to lift the Tailwind’s wheel off the ground when not in use. Lifting the Tailwind eliminates its rolling resistance and is a feature that does not appear on any commercial power assists as far as I am aware.

Thesis Supervisor: Amos Winter
Title: Associate Professor of Mechanical Engineering

Acknowledgements

I would like to thank the active wheelchair user Erik Kondo for providing the initial idea for this power assist and for his continuous feedback and suggestions throughout this project. Erik constructed a wheelchair out of PVC pipes that proved invaluable as a testbed for the original prototypes of this power assist and also provided the hoverboard from which much of this power assist was constructed.

I would also like to thank MIT Associate Professor Amos Winter for supervising this project and providing valuable early direction on how to analyze and document the performance of this power assist.

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1 Introduction

1.1 Background

Wheelchair users come from all walks of life [1], and the variety of wheelchairs they use is a reflection of this diversity. A wheelchair user with a lack of arm strength may rely on a caregiver to push them on a transport chair [2], while a very young user may use a pediatric wheelchair that adjusts to their growth [3]. An athletic user may use a basketball wheelchair to play with their friends [4], while a user who enjoys exploring outside may use an all-terrain wheelchair [3]. For this reason, this study cannot focus on all possible wheelchair users since their wheelchairs and their specific needs do not always overlap. Instead, this study will focus on the subset of wheelchair users who enjoy physical activity and have the upper body strength to push themselves manually. These wheelchair users often use a style of wheelchair known as "active" wheelchairs, which are specially designed for a lifestyle of physical activity through their light, compact design [5].

In this study, I have partnered with a permanent active wheelchair user who has identified power assists as a valuable method for encouraging and enhancing the physical activities of active wheelchair users. Power assists are designed to retrofit onto a manual wheelchair and assist but not replace the user's ability to move themselves manually [6]. The user still needs to steer manually, and they are often used in combination with the user manually pushing theirself in order to maximize speed, power, and range. This is in contrast to power wheelchairs, which are specialized wheelchairs with built-in motors that are fully controlled by a joystick or some other form of electrical control [7]. As for the potential benefits of power assists to active wheelchair users, examples include: the extra range encouraging users to explore outside and exercise more, the extra power helping them handle steeper hills, and the higher speed helping them keep up with jogging friends. However, commercial power assists often cost thousands of dollars, and insurance may not cover this cost for users who do not show a strong medical reason for requiring a power assist [8]. For this reason, I have prototyped a power assist called the "Tailwind" that is designed to be inexpensive ($250-$450) and easy to build by wheelchair users with access to common power tools. In addition, at the recommendation of the wheelchair user I have partnered with, I gave this power assist a lift mechanism that allows the user to lift the power assist off the ground when not in use in order to eliminate rolling resistance. As far as the wheelchair user and I are aware, no other power assist has this feature.

1.2 Current Market

Before I discuss the features of the Tailwind power assist, I will briefly summarize the current power assists available on the market in order to motivate the design decisions I made in this project. Broadly speaking, there are three types of power assists [9], which I will call pushers, pullers, and wheeldrives.

Pusher-style power assists attach behind the main axle of the wheelchair and push the wheelchair from behind [8]. They are among the lightest styles of power assist, weighing around 15 pounds [10][11]. Examples of this power assist include the SmartDrive [10] and SMOOV [11], and the cost range is around $5000-$7000 [9].

Wheeldrive power assists replace the main wheels of the wheelchair [8]. Force sensors embedded in these power assists sense when the user pushes on the wheel's pushrim, which activates the hub motor [8]. This option is quite heavy, with each wheel generally weighing between 13 to 22 pounds [12][8]. Examples of wheeldrive power assists include the Twion [12] and NaviONE [13], and the cost range is around $6000-$7000 [9].

Finally, puller-style power assists mount to the front of the wheelchair in such a way that they lift the front caster wheels of the wheelchair off the ground [9]. These power assists resemble scooters not just in appearance but also in their steering, throttle, and brakes. Their large front wheel combined with the fact that the wheelchair's front caster wheels are lifted off the ground allows this style of power assist to move quickly, with top speeds of at least 15 mph [9]. However, they are fairly heavy, with a typical weight of around 30 pounds [14][15]. Examples of this power assist include the Firefly [14] and EZRide [15], and the cost range is around $2000-$4000 [9].

The Tailwind uses a pusher-style configuration primarily because it can be lifted off the ground when not in use and, at the beginning of this project, it appeared to be the most straightforward to build. A wheeldrive power assist, for instance, would have involved finding a way to implement force sensing for the pushrims and install hub motors into the wheels, which seemed expensive and not easy to build in a way that would be straightforward for other people to follow. Additionally, such a project would have required two motors and motor controllers instead of just one of each since a wheelchair has two main wheels. As for puller-style power assists, its high speed and ability to traverse a variety of terrains was attractive, but it would not have provided the same exercise benefits as a pusher-style power assist since the user would need to keep their hands on the power assist to maintain steering control. One option was to implement a handcycle into the power assist, but that would have added extra complexity and cost to the project.

1.3 Overview

For prototyping purposes, the wheelchair user I was working with built a “testbed wheelchair” out of PVC pipes. Even though its exact dimensions will differ from a commercially available active wheelchair, the Tailwind was designed to mount to locations that are consistent across active wheelchairs, such as the main wheel axle and a crossbar near the front of the seat. In future work, I intend to test the Tailwind on a commercially available wheelchair in order to ensure that the design would work with as many active wheelchair geometries as possible. After that, I plan to publish a detailed article on Instructables explaining how to build the Tailwind from scratch.

In the top panel of Figure 1-1, I show the primary mechanical components of the Tailwind. Note that one of the main wheels has been removed to provide a clearer view. The mounting bar provides attachment points for the other components of the Tailwind and is hose clamped to the wheelchair’s main axle and front crossbar underneath the seat. I tested the Tailwind on a PVC wheelchair built by a wheelchair user, but these attachment points appear to be consistent across active wheelchairs. In the future, I intend to test the Tailwind on commercially available wheelchairs. The swivel bar is attached to the mounting bar, and the hub motor is attached to its lower end. As its name suggests, the swivel bar can rotate around its axle on the mounting bar, which helps the hub motor maintain contact with the ground even on rough terrain and enables the motor to be lifted up when not in use. This lift mechanism relies on the lift and lock bars, which will be discussed shortly.

In the bottom panel of Figure 1-1, I show the electrical components and controls of the Tailwind. The battery is attached to the mounting bar with velcro and a buckle strap, and its power is sent to the hub motor via the brushless motor controller. The emergency stop button and throttle are located near where the wheelchair user’s right hand would be, and a voltage monitor displays the battery’s capacity and warns the user if it is running low.

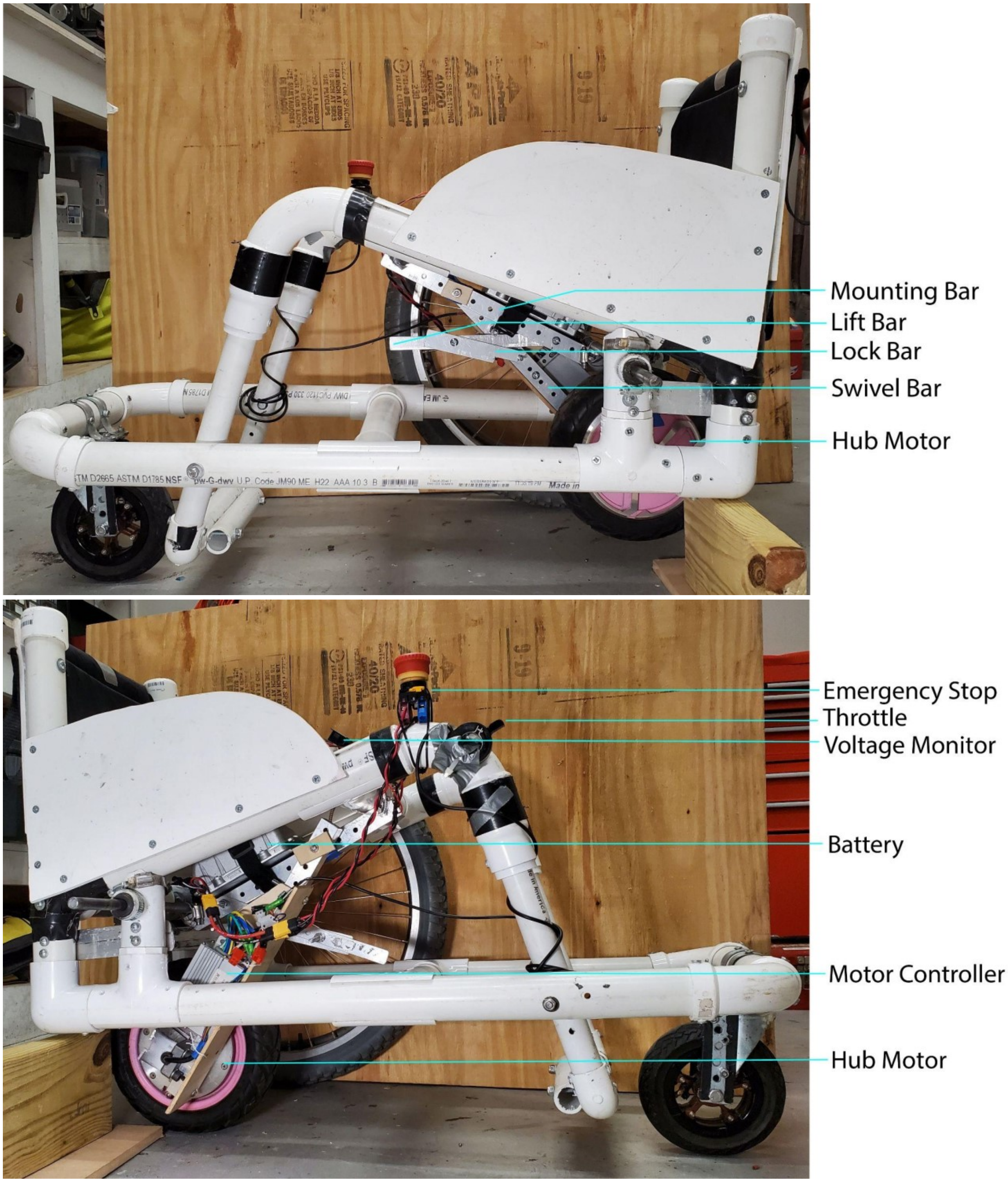

Figure 1-1: Summary of mechanical and electrical components

Like other pusher-style power assists, the Tailwind's steering is manually controlled by the user in the same way as they would on a manual wheelchair: by pushing one of the main wheels at a different speed than the other.

2 Design Features

2.1 Lift Mechanism

One of the defining features of the Tailwind is its lift mechanism. If the Tailwind's battery becomes drained or the wheelchair user decides not to use power assist, they may lift the Tailwind to eliminate any rolling resistance due to the Tailwind's wheel. As seen in panels (a) and (b) of Figure 2-1, pulling up on the lift bar causes it to push up against the lift roller, which causes the swivel bar and hub motor to lift off the ground. The lift roller is designed to roll since this greatly reduces the friction between it and the lift bar as the lift bar is being lifted. As seen in panel (c), once the lift bar has been fully lifted, gravity causes the lock bar to fall onto the lock pin. Once this happens, the user can let go of the lift bar and the Tailwind maintains its lifted position. The Tailwind may be dropped back down by lifting the lift bar slightly, pushing down on the shorter end of the lock bar, and then letting the entire assembly drop. The actions of lifting and dropping the Tailwind may both be performed without leaving the chair. In contrast, commercial power assists are commonly located behind the main axle or on other locations inaccessible from a seated position and contribute to rolling resistance when they are not being used. Lifting the Tailwind also provides a convenient way for a new user to become familiar with the throttle and other controls of the Tailwind without being unintentionally propelled forward. Finally, as seen in panel (d) the lift mechanism also prevents the swivel beam from rotating to a vertical position and potentially locking itself in that position under the wheelchair. Without this safety measure, performing a wheelie or traveling over rough terrain such as a depression in the ground could lock the user in a wheelied position.

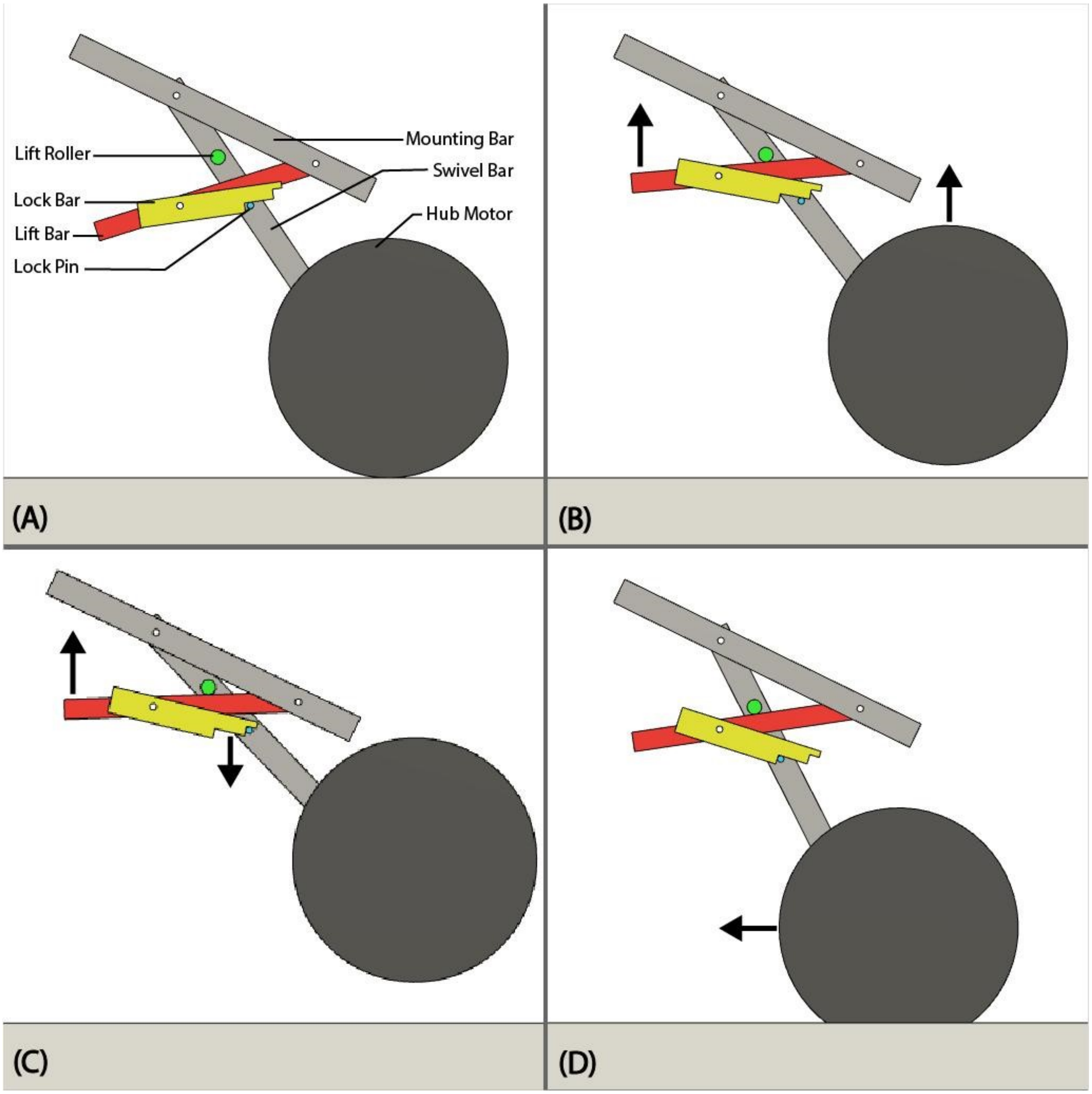

Figure 2-1: Tailwind lifting mechanism

In order to quantify the resistance the Tailwind produces when it is dragged along the ground and unpowered, I experimentally determined a relationship between the wheel's angular velocity and resistance torque. As seen in the left panel of Figure 2-2, I applied fixed amounts of force to the edge of the wheel by wrapping it with rope and hanging a weight from the end of the rope. Once the wheel reached a steady rotational speed, I knew that the resistance torque in the motor was perfectly balancing the torque due to the weight hanging from the edge of the wheel. By measuring how quickly the weight descended, I was able to calculate the speed at the edge of the wheel, which is equivalent to the speed at which the wheelchair would move if the wheel maintained the same rotational speed and was rolling on the ground. As seen in the right panel of Figure 2-2, I observed a positive correlation between the speed and force applied to the edge of the wheel. I use speed and force instead of angular velocity and torque because they will become relevant to my more in-depth discussion on rolling resistance later, and they are just as accurate since the radius of the wheel is fixed. Note that for all non-zero speeds of the wheel (i.e., the wheelchair is moving), there was always some force required to overcome the resistance of the motor. Assuming the user is pushing their wheelchair at a typical speed of 1.1 m/s (2.5 mph) [16], based on the linear fit we see that the hub motor's resistance will be equivalent to around 2.5 N pushing against the user's direction of motion. In my tests, I disconnected the motor from the motor controller and kept its terminals separated in order to prevent additional damping due to the induced current the spinning motor would produce. Note that the true rolling resistance of the motor would likely be higher when it is actually in contact with the ground due to deformations in the rubber, slippage, and other factors. As for the PVC test wheelchair I was using, I found its rolling resistance on concrete without the Tailwind to be approximately equivalent to 5 N pushing against the user's direction of motion. Even though different wheelchairs will have different rolling resistances, the fact that this conservative estimate of the hub motor's rolling resistance was comparable to the rolling resistance of the test wheelchair suggested that the hub motor's rolling resistance was non-negligible. Since I expected the intended users to use a combination of power assist and manual input for their daily travel, the Tailwind's lift mechanism serves to increase overall range by conserving their energy whenever they are not using the power assist.

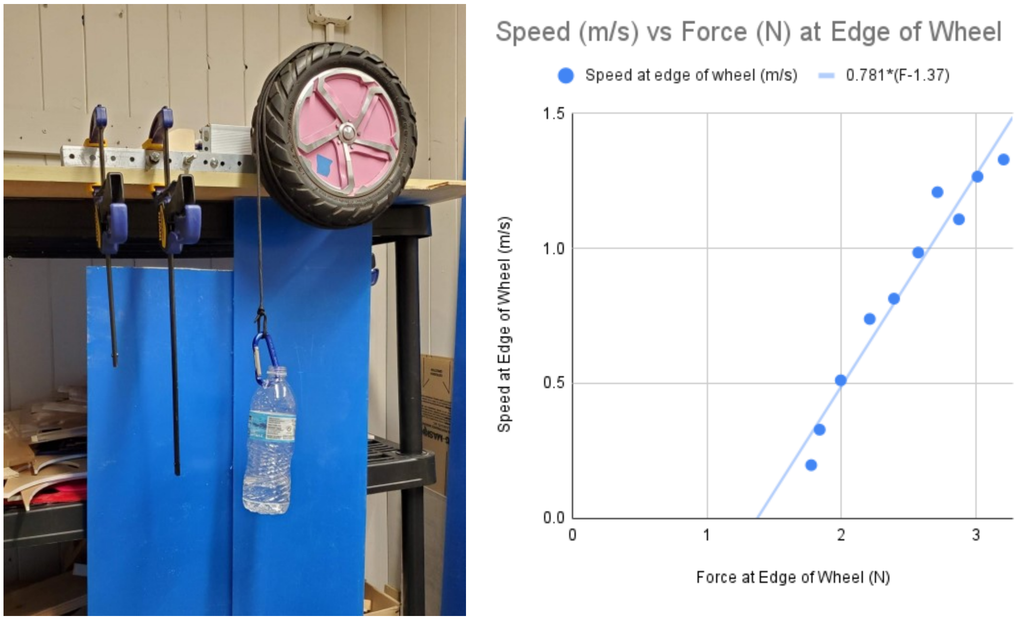

Figure 2-2: Measuring the motor's resistance to turning

2.2 Cost and Construction

I intended for active wheelchair users to be able to construct the Tailwind out of inexpensive commercial components with commonly available construction tools. For this reason, many of the key components for the Tailwind, including the hub motor, motor axle mount, battery, and battery charger, were taken directly from a commercial off-road hoverboard [17]. This had the advantage of ensuring that the battery and motor would have compatible power specifications and would give the Tailwind a similar range, speed, and power as the hoverboard. The use of a hub motor also eliminated the need for a more complex transmission system, which reduced the physical size and complexity of the project.

As for other electrical components, I purchased a 350 W brushless motor controller [18], an electric bicycle thumb throttle [19], emergency stop button [20], and battery voltage monitor [21]. I did not use the hoverboard’s motor controller since it was integrated into its motherboard. For the Tailwind’s hardware, I used 1”x1”x1/16” aluminum square tubing, 1”x1/8” aluminum bar stock, 3/16” thick plywood, hose clamps, and ¼”-20 threaded rod, screws and fasteners, all of which are commonly available at hardware stores across the United States [22][23]. A comprehensive list of materials is later listed in the “Materials” section.

Additionally, I tried to choose commonly available construction methods that do not require extensive technical knowledge. The only powered machines I used while prototyping the Tailwind were a drill press, drill, bandsaw, and soldering iron. However, I believe a drill and hacksaw could have been used in all instances where I used a drill press and bandsaw. All assembly was possible with common hand tools such as screwdrivers and pliers.

One of the greatest hardware challenges of the Tailwind was finding a secure way to attach the hub motor’s axle to the swivel bar without using more complex manufacturing methods such as mills or waterjets. One of my previous attempts is shown in the left panel of Figure 2-3 and involved constraining the axle with wooden panels on either side of the swivel beam and clamping the axle against the swivel beam with an aluminum bar. However, due to the high thrust force of the motor and the clearance between the drilled hole diameters and the axle and screws passing through them, the axle would routinely shift around and occasionally cause the wheel rim to rub against the swivel bar. I eventually settled on the solution seen in the right panel, where I used a hacksaw to saw off the motor axle mount portion of the hoverboard and attached it to the swivel bar. This proved to be much more secure, as the axle mount on the hoverboard was made entirely of aluminum and conformed to the axle almost perfectly.

Figure 2-3: Old and new axle mounting solutions

2.3 Compatibility

I also designed the Tailwind to be compatible with a wide variety of wheelchairs and use cases. For instance, the mounting bar is mounted to the main axle and front crossbar under the seat of the wheelchair, both of which appear to be universal across active wheelchairs. Even though the exact dimensions and spacing between these features varies from wheelchair to wheelchair, the user could compensate for this by using longer or shorter lengths of square tubing and adjusting the axle locations of the Tailwind accordingly. Additionally, the low cost and ease of construction of the Tailwind should give users the ability to customize the Tailwind's features for their specific needs. For instance, wheelchair users who wish to travel long distances could use a higher capacity battery while wheelchair users who live in hilly areas could use a more powerful motor. Another advantage to the use of low cost components is the low cost of replacing components compared to commercial power assists. For instance, if the Tailwind's throttle breaks or the user wishes to try out a different throttle, they could likely purchase a new throttle for under $20 [19]. In contrast, if the throttle of a commercial power assist breaks, it is not uncommon for replacements to cost hundreds of dollars [10][11].

2.4 Design Geometry

The Tailwind's wheel was mounted in line with the wheelchair's main wheels in order to minimize resistance while performing turns. If the wheel was mounted away from the main wheels, it would be forced to slide sideways whenever the user tried to turn. This is likely the reason why power assist devices that are not mounted in line with the wheelchair's main wheels tend to have some method of sliding (such as the Omni wheels in the rear-mounted SmartDrive [10]) or pivoting (such as the scooter-like controls of the Firefly [14]). I did not quantitatively measure the resistance of the Tailwind's wheel to pivoting, as I qualitatively found the resistance of the wheelchair's front caster wheel to pivoting to be far more noticeable. This seems reasonable given the caster wheel's large distance from the main axle of the wheelchair.

In order to increase the traction of the Tailwind's wheel, the swivel beam was mounted at an angle to the ground so that both the Tailwind's weight and the thrust force of the motor contribute to the wheel's normal force. The mounting angle of the swivel beam has a multiplicative effect on the normal force. For instance, in this prototype, the mounting angle is 56°, and this results in a normal force that is

$$tan\ (56°) = 1.48 \qquad \text{Eq. 2-1}$$

times greater than the thrust force. I measured the maximum thrust force of the motor to be 133 N (30 pound-force), which means the normal force due to the motor's maximum thrust force is

$$133\ N * 1.48 = 198\ N \qquad \text{Eq. 2-2}$$

Since the Tailwind weighs 58 N (13 pound-force), the main contribution to the normal force therefore comes from the motor's thrust force, and the most effective way to increase this force would be to increase the mounting angle. With this 56° mounting angle, wheel slippage was never observed on dry concrete but has sometimes been observed on wet grass and snow.

Since the Tailwind is tucked underneath the wheelchair, it does not increase the wheelchair's overall width, length, or height. This keeps the wheelchair compact and does not interfere with its ability to fit through doors and other tight spaces. Additionally, like other pusher-style power assists the Tailwind is lightweight compared to wheeldrive and puller-style power assists, with a mass of only 5.9 kg (13 lb). Most of this mass is due to the battery and hub motor. If a user wishes to ride their wheelchair without the added mass of the Tailwind, they may detach the swivel bar and battery, leaving behind only the mounting bar, lift bar, and lock bar. (Figure 2-4) The process of detaching and reattaching the swivel bar and battery does not require tools.

Figure 2-4: Side view of the wheelchair without the swivel bar and battery

2.5 User Controls

As for user controls, the wheelchair user I was working with helped me determine how to arrange the thumb throttle and emergency stop button to maximize convenience and safety. As seen in Figure 2-5, the thumb throttle is oriented so that pushing the lever away from the user pushes it to the off position, which is intended to match a user's instinctual movement in the event of a surprise. I also installed an optional resistor-capacitor (RC) network between the throttle and motor controller in order to smooth out sudden changes to the throttle, which could result in unintentional wheelies. The emergency stop button is located near the user and may be pushed at any time to cut power to the Tailwind. There is also a battery voltage monitor that warns the user if they are about to overdrain the battery. Finally, the lift bar is located under the seat towards the front of the wheelchair, and allows the user to lift the Tailwind from a seated position.

Figure 2-5: A view of (from left to right) the throttle, emergency stop button, and battery voltage monitor

3 Assessment

3.1 Maximum Range

There were two steps to estimating the maximum range of the Tailwind. The first step was to measure the force required to push the wheelchair with the Tailwind attached over concrete and grass. The concrete and grass were meant to simulate smooth and rough terrains, respectively. The second step was to estimate the Tailwind's electrical efficiency by measuring the battery's power output and the speed at which the hub motor could lift weights that simulated the rolling resistance of concrete and grass.

In order to measure the force required to push the wheelchair with the Tailwind over concrete and grass, I pushed the wheelchair from behind, with a hand dynamometer placed between my hand and the back of the wheelchair. As seen in Figure 3-1, pushing the wheelchair with the Tailwind in its lowered position required 2.5 to 5 N of extra force compared to pushing the wheelchair with the Tailwind in its raised position. With the Tailwind lowered, I observed that the force required to push the wheelchair over grass was much higher than the force required to push it over concrete, at 20 N compared to 7.5 N.

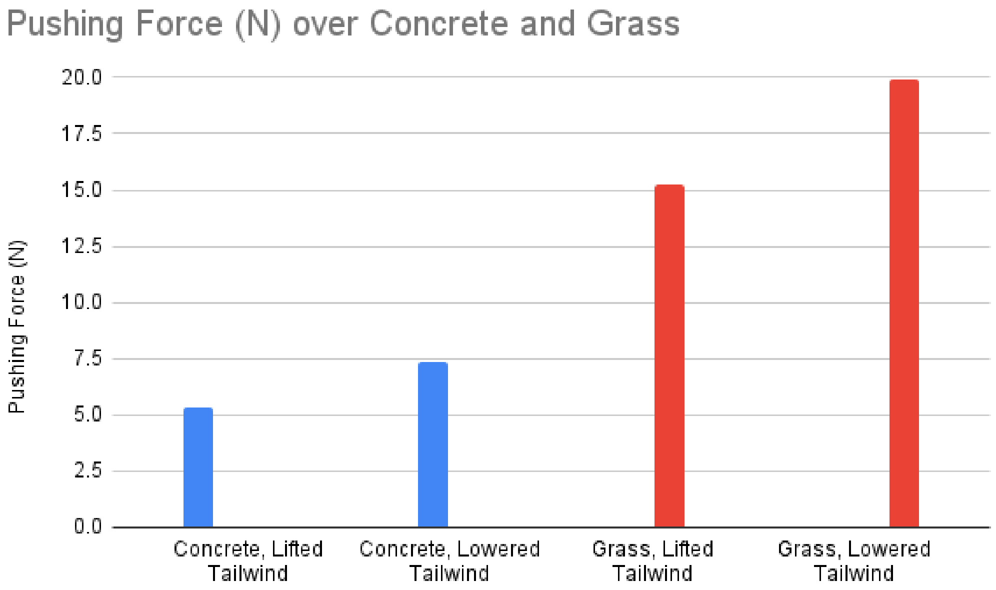

Figure 3-1: The force required to push the wheelchair over concrete and grass

I then calculated electrical efficiency by finding the ratio between the motor's power output and the battery's power output. As seen in Figure 3-2, I measured the motor's power by wrapping a rope around the motor's wheel and suspending a weight from this rope. By measuring the speed at which the motor lifted this weight, I could determine the motor's useful power output. As for the battery, I measured its power output by monitoring its current output using an ammeter and multiplying that by its voltage, which remained around 39.0 V throughout the experiment. For a given weight hanging from the motor, I varied the throttle to obtain different values of current and lift speed, which allowed me to determine the efficiency of the motor at different speeds. To determine the appropriate amount of weight to hang from the motor, I chose weights that simulated the force required to push the wheelchair with the Tailwind lowered over concrete and grass. As determined by my previous experiment, this was around 7.5 and 20 N, respectively. In my experimental setup, I approximated these loads using 7.9 and 20.0 N weights. I specifically chose the force corresponding to the lowered Tailwind instead of the lifted Tailwind because this force included all the non-negligible mechanical energy losses I expected to encounter: the hub motor's resistance to spinning, the rolling resistance of the hub motor's tire over different terrains, and the rolling resistance of the wheelchair's big wheels and caster wheel over different terrains.

Figure 3-2: Experimental setup for measuring the efficiency of the Tailwind

In Figure 3-3, I show the resulting plots of motor efficiency as a function of lift speed. Note that I can equate lift speed with wheelchair speed since the speed at the edge of the spinning motor is the same speed at which the wheelchair would move if the motor was placed on the ground and maintained the same angular velocity. I created two plots in order to show the expected efficiency over both concrete and grass and fit them with a quadratic fit. Despite the large difference in weights used, the quadratic fits appear very similar, with a maximum electrical efficiency of 60% occurring around a speed of 3.5 m/s (7.8 mph) and an efficiency of around 40% occurring at the average wheelchair user's speed of 1.1 m/s (2.5 mph) [16].

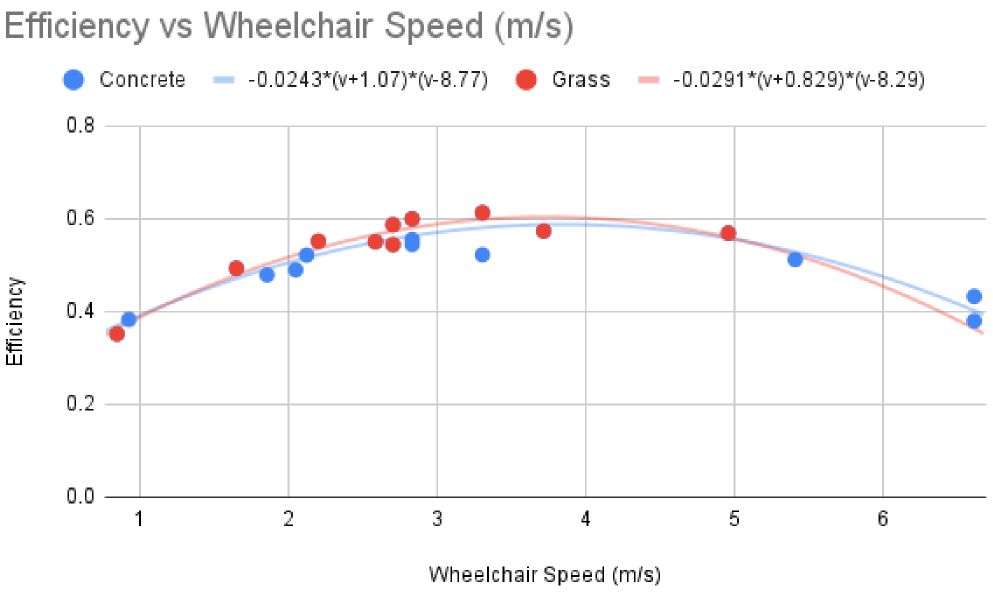

Figure 3-3: Efficiency as a function of wheelchair speed

With these estimates of the Tailwind's efficiency and rolling resistance, I was able to proceed with calculations estimating the Tailwind's maximum range over concrete and grass. Assuming a wheelchair user travels at a typical speed of 1.1 m/s [16], I could estimate the Tailwind's efficiency to be η = 0.4 for both concrete and grass. The Tailwind's battery has a capacity of

$$E_{battery} = 96.2\ Wh = 346\ kJ \qquad \text{Eq. 3-1}$$

This means the energy available to the motor is

$$E_{motor} = \eta * E_{battery} = 0.4 * 346\ kJ \ = \ 139\ kJ \qquad \text{Eq. 3-2}$$

The motor's energy is related to the maximum distance the Tailwind can travel via the equation

$$E_{motor} = F_{resistance} * d_{max} \qquad \text{Eq. 3-3}$$

$F_{resistance}$ is the rolling resistance over a specific terrain and d_{max} is the maximum distance. Using Figure 3-1's result for concrete,

$$F_{resistance} = 7.5\ N \qquad \text{Eq. 3-4}$$

$$d_{max} = E_{motor}/F_{resistance} = 139\ kJ/7.5\ N = 18\ km \qquad \text{Eq. 3-5}$$

Similarly, using Figure 3-1's result for grass,

$$F_{resistance} = 20.\ N \qquad \text{Eq. 3-6}$$

$$d_{max} = E_{motor}/F_{resistance} = 139\ kJ/20.\ N = 6.9\ km \quad \text{Eq. 3-7}$$

If I consider concrete to be representative of a low rolling resistance terrain and grass to be representative of a high rolling resistance terrain, then I may estimate the Tailwind's minimum range to be around 6.9 km (4.3 miles) and its maximum range to be around 18 km (11 miles). However, it is worth noting that actual results would depend not only on the rolling resistance over the terrain but also the overall incline.

3.2 Maximum Speed

I estimate the maximum speed of this prototype to be 4.35 ± 0.03 m/s (9.74 ± 0.08 mph). This was calculated by taking multiple measurements of how long it took to cross a prespecified distance and then averaging the corresponding speeds. This is higher than the average human jogging speed of 1.8 to 2.7 m/s (4-6 mph) [24]. This is not an inherent maximum speed to the Tailwind, but rather the maximum speed set by the motor controller I was using.

3.3 Maximum Incline Angle

According to my calculations and field testing, the Tailwind can handle slopes of at least 7.4° (13% grade) on its own power and slopes of at least 15° (27% grade) if the user is also manually pushing theirself up. These measurements assume a wheelchair user mass of 81.6 kg, a wheelchair mass of 17 kg, and a Tailwind mass of 5.9 kg and sufficient traction between the wheelchair's wheels and the ground to avoid slippage.

I estimated the maximum incline angle the Tailwind could handle on its own power by first wrapping rope around the hub motor and observing the maximum mass the motor could lift without stalling. This turned out to be around 13.5 kg at the perimeter of the wheel. I then modeled this as an inclined plane problem [25] and solved for the incline angle, which involved estimating the total mass of the wheelchair user, wheelchair, and Tailwind. I assumed the average wheelchair user had a mass of 81.6 kg (180 lb), which is the mass of an average adult in the United States [26], and I measured the mass of the wheelchair and Tailwind to be 17 kg (37 lb) and 5.9 kg (13 lb), respectively. This resulted in a total mass of 104.5 kg (230 lb), which was then used to calculate the maximum incline angle using the formula [25]:

$$arcsin\ (F_{parallel}/F_{total}) = arcsin\ (m_{parallel}/m_{total}) \quad \text{Eq. 3-8}$$

Plugging in the mass values, I obtained

$$arcsin\ (13.5\ kg/104.5\ kg) = 7.4° \quad \text{Eq. 3-9}$$

This corresponded to a grade of 13%. Note that this is more than enough to handle the steepest ramps allowed by the American with Disabilities Act of 1990 (ADA), which is 5° (8.3% grade) in public spaces [27].

I then tested the Tailwind on a 7.6 m (25 ft) concrete slope whose incline angle increased from less than 5° to 15° at its steepest section. I measured the maximum incline angle the Tailwind could handle on its own power by going up the ramp until the motor stalled and then measuring the incline angle of the slope at that point using an inclinometer. I had to adjust my theoretical prediction of this angle from 7.4° to 8.5° since I weighed 68 kg (150 lb) instead of the 81.6 kg (180 lb) used in my calculations. In the test, the Tailwind motor stalled once the slope reached around 8°, which was in reasonable agreement with my prediction.

I also observed that if the user was manually pushing their wheelchair while the Tailwind was active, they were able to ascend the entire slope, which was 15° at its steepest section, without much difficulty. As a testament to the assistance the Tailwind provided, when I first attempted to ascend the slope without the Tailwind, I lost control and began rolling backwards down the slope around 10°. When I attempted the slope again with the Tailwind active, I was able to ascend past the 15° point of the slope with only light effort. I also performed this test with the wheelchair user I was working with. He was already able to manually push himself past the 15° point of the slope without the Tailwind, but with the Tailwind he was able to do so in half the time, and, according to his comments, with much less exertion.

3.4 Wheelies

During testing, I observed that suddenly increasing the throttle could result in an unintentional wheelie. Typically, wheelies are used by wheelchair users to go over obstacles such as curbs and are also useful for descending steep ramps in order to avoid falling forward [28]. However, the sudden, unintentional wheelies I observed in some of the tests could cause the wheelchair user to lose control of the chair, and I have looked for ways to address this.

As seen in Figure 3-4, the wheelie occurs due to a large, upwards force F pushing up at the front of the wheelchair. This force is produced when the thrust force F_{thrust} of the wheel is transmitted through the Tailwind's swivel beam, and this force applies a torque τ that can flip the wheelchair backwards. The exact way the wheelie-inducing force at the front of the wheelchair is produced likely depends on the control algorithm in the motor controller. For instance, if a user suddenly steps up the throttle, the motor controller sees a discrepancy in the motor speed commanded by the throttle and the actual motor speed and must then use its control algorithm to determine how much more torque the motor needs in order for it to reach the target speed within a reasonable time. For small discrepancies in speed only a small increase in torque is necessary to reach this target speed, but larger discrepancies in speed would require larger torques if the motor controller is trying to reach the target speed in a similar amount of time. Since the torque in the motor results in a thrust force F_{thrust} at the wheel and this thrust force results in an upwards force F at the front of the wheelchair, this larger motor torque may cause the wheelchair to wheelie while it is attempting to accelerate to the speed commanded by the throttle. For this reason, sudden changes in throttle are more likely to result in the upward force necessary to wheelie the wheelchair than gradual changes. Note that the speed of the wheelchair at the moment the throttle is increased does not affect the wheelchair's tendency to wheelie--rather, it is the sudden change in throttle that creates this wheelie-inducing thrust force.

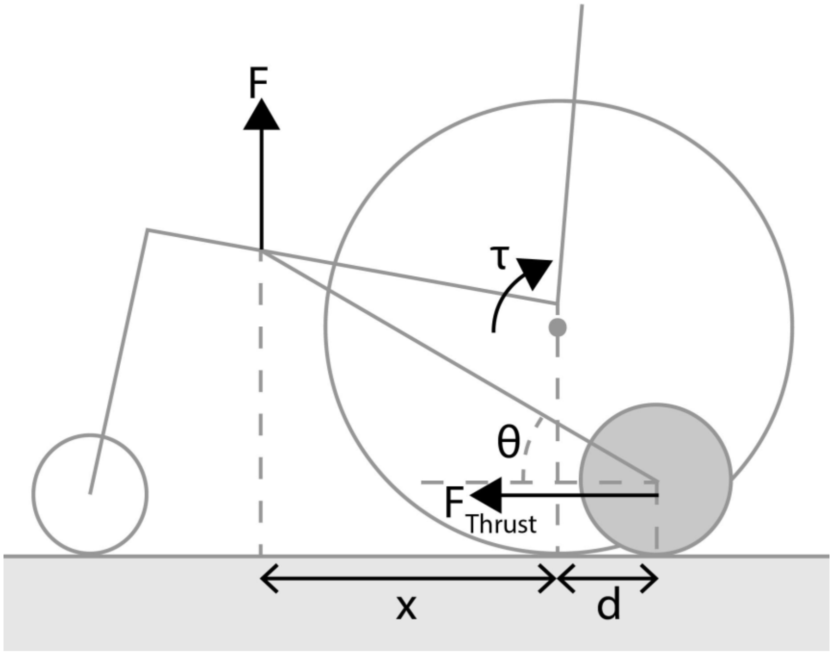

Figure 3-4: Relevant dimensions, forces, and torque acting on the wheelchair in the event of a wheelie

In view of this explanation, I have come up with two primary methods for reducing the wheelchair's tendency to wheelie: modify the mounting geometry and use an RC network to smooth out the throttle voltage.

The first method relies on reducing the torque on the wheelchair via physical means. In order to systematically assess which dimensions should be modified I first derive an equation for the torque τ due to the thrust force F_{thrust}. The torque may be calculated according to the equation

$$\tau = F * x \qquad \text{Eq. 3-10}$$

where x is the horizontal distance between the mounting location of the Tailwind and the center of the main wheel and. Note that I ignore the inertial force arising due to the acceleration of the wheelchair because that is experienced regardless of whether or not the wheelchair has a power assist. The upwards force F is related to F_{thrust} by the equation

$$F = F_{thrust} * tan\ (\theta) \qquad \text{Eq. 3-11}$$

where θ is the angle between the swivel bar and ground. Substituting this into Equation 3-10, I have:

$$\tau = F_{thrust} * tan\ (\theta) * x \qquad \text{Eq. 3-12}$$

From Equation 3-12, we can see that decreasing the mounting angle θ (perhaps by increasing the length of the swivel bar) and decreasing x by moving the Tailwind's mounting point closer to the back of the wheelchair should reduce this wheelie-inducing torque. In the extreme case, the swivel bar could be mounted directly to the main axle or somehow behind it, and this would cause the force F to either result in no torque or a negative torque that acts against the direction of the wheelie. However, note that these changes would increase the parameter d, which represents the horizontal distance between the center of the main wheel and the center of the hub motor. This would make it more difficult to steer the wheelchair since the hub motor would be dragged sideways across the ground.

The second method for reducing the wheelchair's tendency to wheelie is to electronically smooth out changes to the throttle, which should reduce F_{thrust} as discussed previously. This could be implemented by an RC circuit, as shown in Figure 3-5. The thumb throttle used in this prototype produces an analog voltage V_i, where higher voltages correspond to higher throttle. Between V_i and ground, I installed the resistor R_1 and the capacitor C_1 to act as a low pass filter before sending its output voltage V_o to the throttle wire of the motor controller. With a multimeter I observed that there was a built-in 10 kΩ resistor R_2 between the brushless motor's throttle wire and ground, presumably acting as a pulldown resistor. This constrained R_1 to a smaller value since once the capacitor has had time to charge up, the entire circuit acts as a resistor divider where the output voltage may be calculated using

$$V_o = V_i * \frac{R_2}{R_1 + R_2} \qquad \text{Eq. 3-13}$$

If R_1 was set to a large value compared to R_2, V_o would never be able to reach higher voltages and would not have the full throttle range. I set R_1 to 1 kΩ because it was close to the maximum resistor value that would not clip the throttle's range. The capacitance C_1 was determined by choosing a time constant τ that was close to human-scale reaction times on the order of tenths of a second [29] and backsolving for C_1. For this circuit specifically, I found the time constant to be

$$\tau = \frac{C_1 R_1 R_2}{R_1 + R_2} \qquad \text{Eq. 3-14}$$

Setting the capacitance C_1 to 470 µF, R_1 to 1 kΩ, and R_2 to 10 kΩ resulted in a time constant τ of around 0.43 s. While it is possible to use even larger capacitors for even greater throttle smoothing, one drawback to this is that it would increase the time it takes for the motor to accelerate or decelerate due to the it would take to charge a large capacitor. As of the writing of this study, I have not collected enough feedback from wheelchair users to determine the optimal time constant or mounting geometry of the swivel bar, but I intend to continue exploring these options in future work.

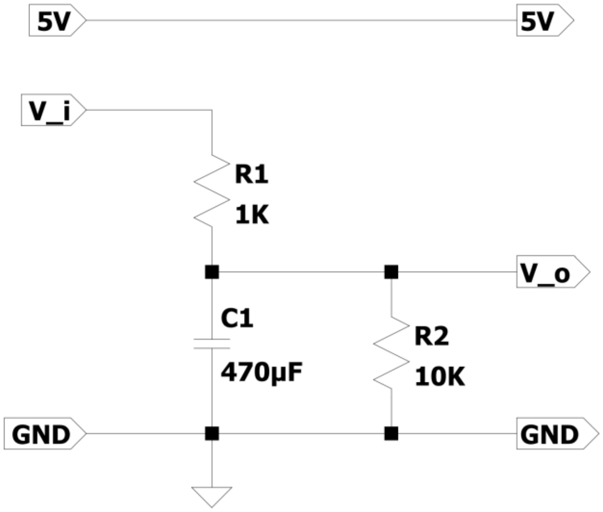

Figure 3-5: Schematic of the RC circuit used for the Tailwind's throttle

3.5 Recommended Usage Strategy

Based on the data collected and tests with the wheelchair user, I recommend the following usage strategy for the Tailwind:

1. Turn the Tailwind off when not in use to avoid leakage current.
2. Ensure the throttle is off before powering on the Tailwind.
3. To avoid wheelies, avoid suddenly increasing the throttle. Only increase the throttle gently, especially when on an incline.
4. To maximize efficiency, keep the Tailwind lifted when not in use in order to eliminate rolling resistance.
5. To increase the maximum range, consider bringing multiple batteries and swap out batteries as needed or connect multiple batteries in parallel at the same time.
6. To service the Tailwind, consider rotating the wheelchair so that its underside is vertically oriented and facing you.

3.6 Further Improvement

Even though the current state of the Tailwind prototype I have shown here is more than adequate for testing its range, speed, and other performance parameters, there are significant improvements I could make to ensure it is suitable for daily use. These include: implementing waterproofing and dust protection, attaching the throttle and emergency stop button to the wheelchair frame more securely, and securing loose wires to reduce the risk of snagging. The geometry and throttle smoothing could also be further optimized to reduce the chance of unintentionally wheelies, as described previously.

4 Materials

As seen in Table 4-1, the total cost of the Tailwind is $448.77, with the bulk of the cost coming from the $349.99 hoverboard. The hoverboard supplies many of the key components, including the battery, battery charger, motor, and motor axle mount. For users who do not need the same power or range as the Tailwind created in this study, there are many lower-cost hoverboards available in the United States.

Item	**Cost ($)**
Swagboard off road hoverboard [17]	$349.99
Opaltool brushless motor controller (48 V, 350 W) [18]	$22.49
Aluminum square tube (28.5”x1”x1/16”) [30]	$16.58
Aluminum bar (15”x1”x1/8”) [31]	$4.14
TWTADE emergency stop button [20]	$10.99
Battery voltage monitor [21]	$11.99
Keenso thumb throttle [19]	$9.59
Plywood (less than 12"x12"x3/16")	$3.00
Screws, threaded rods, nuts, lock nuts, lock washers, hose clamps, electrical connections, wires, velcro, buckle strap	$20.00
	Total: $448.77

Table 4-1: Bill of materials for the prototype Tailwind

5 Conclusion

With the feedback and suggestions of a wheelchair user, I created a power assist for active wheelchair users designed to enhance their range, speed, and power at a fraction of the cost of a commercial power assist. Since wheelchair users are a very diverse group who use a similarly diverse variety of wheelchairs, I designed this power assist to be easy to customize for a user’s specific needs, whether that be through modifying the lengths of the aluminum bars to match the wheelchair’s geometry or selecting a different choice of hoverboard components to modify its performance. In future work, I will begin tests with the Tailwind on commercially available active wheelchairs while continuing to add improvements such as waterproofing and reducing the chance of unintentional wheelies. With the help of user feedback, I will then publish a detailed article on Instructables so that users may make the Tailwind for themselves.

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