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HKUST-HARVARD 2017 SUMMER ENGINEERING DESIGN PROJECT

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ABSTRACT

This technical documentation elaborates on choices made by Team Cardi during the development and manufacture of the Personal Electric Vehicles (PEVs) that resolves the request for proposal issued by Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS) and Hong Kong University of Science and Technology. The request is to construct a personal electric vehicle (PEV) within the budget $1500.00 that satisfies all the following requirements: have the energy consumption * time product (Wh * hrs) as low as possible; meet the minimum safety requirements and measure power efficiency; every team member should be able to drive the PEV. Considering desired functions, it is critical that the PEV should be safe, stable and energy efficient that can be manufactured within the seven weeks' time constraint.

There are some major changes implemented in the PEV's design if juxtaposed to the PEVs produced by the same program in previous years. Instances of those major changes are the adding suspension system and the implementation of bike gears in the transmission. These changes will be justified and illustrated through the process of how Team Cardi conceptualized the design of the PEV, and how a series of decisions was executed such that the concept was able to be realized. During the course of the PEV's development, there were challenges faced, but there were also valuable lessons learned. All in all, these changes and challenges were faced and overcame in order to make the PEV the best means of completing the requirements.

Figure 1 People joined the 2017 summer design project

Top row (left to right): Jessica Han, Harshal Singh, Tony Turner, Yawer Saad, Liao Kun Jian, Bryant Huggins, Billy Koech, Mang Tik Chiu, Pok Man Chow, Cheng-Hsin WUU ;Bottom row (left to right):yun-ru WUU, Ashlyn Frahm

DESIGN

1. Chassis

The chassis was the structure that supported the rest of the components of the PEV. The final chassis design was an aluminum rectangular chassis with crossing support beams that was divided into a section for the transmission and a section for sitting and steering with a shock dampening system situated in between the sections.

Figure 2 First assembly of the chassis

This section will outline the evolution of the chassis design over the weeks, detailing our considerations during the creation and decision on the form and material of the chassis.

In the beginning of our design it was necessary to establish constraints for our vehicle design. The first constraint discussed was the number of wheels that our PEV would have. The design challenge necessitated that our vehicle has no less than three wheels, so, eliminating designs with five wheels and higher because of their lack of predicted functionality in providing any extra stability and their complication of the design, our decision narrowed between the choice of having three or four wheels. A four-wheel vehicle would have the advantages of greater stability, but it requires differential for transmission system which complicates the design of transmission. Therefore, a three-wheel design, with two front wheels for steering and one rear wheel for transmission was chosen. The second constraint is dimension, the dimension of the vehicle should be enough for a person to sit, but cannot be too large otherwise it will increase the weight greatly. The third constraint will be the material type, aluminum and steel will be two materials for choosing due to availability. Steel and aluminum both provides good strength but steel was heavier. Therefore, aluminum was chosen for the main chassis frame to minimize the weight of the frame.

The frame has go through an iterative design process: First, a general shape (rectangle plate) was made for the frame and the load was applied to find where load is sustained in such frame in Autodesk fusion 360 simulation. Then the shape of the frame was changed according to the simulation results to remove redundant materials. Using such results as a reference, with other considerations (consideration for installation of the seats, ease of manufacturing), the final shape of the frame was produced. The frame was made by 1.5 in* 1.5 in hollow square cross-section aluminum bars, connected by L and T brackets made from steel plates.

2. Suspension

To prevent the vertical force from the uneven ground, we decided to have suspension system and two main advantages can then be gained. One is protecting the structures of our vehicle, another is increasing the traction between the tire and the ground. The first iteration of the suspension system was built by a chassis that allowed rotation in the middle back of the vehicle with two shock absorbers on it. Due to the ease of manufacturing, we used L brackets to attach the shock absorbers on the chassis.

However, this design neglected the effect of the arm and the fact that a higher original position for suspension components is necessary. The result of this design was therefore failed. Under this scenario, we had three possible solutions, using stronger shock absorbers, shortening the length of the car (both front and back will be fine) and raising the original position for suspension components, and we picked up the first and the third. It took lots of time for cutting the aluminum bar and drilling new holes, so we discarded the second choice as it was unrealistic to us. To handle this challenge, we asked one person having the average weight (154 pounds) of our team sit on the vehicle and then measured the compression under this load. Then we used Fusion 360 to find a geometric solution such that when the spring compressed under this specific load (from 10 to 9 inches), the whole chassis is exactly at the horizontal position. After these process, we designed and customized longer L brackets to attach the shock absorber that helps raise the position of suspension components.

3. Steering

Two main steering mechanisms have been proposed and considered, namely Bell-crank and rack-and-pinion. In considering the ease of manufacture and maintenance, bell-crank steering was chosen to be implemented due to its simplistic mechanism and minimal requirement for purchased parts.

A major change to the design of the steering system was made to the steering shaft support. Originally using a ball joint rod end screwed to a steel plate as the shaft support, the idea was abnegated due to later discovery of having too much degree of freedom and the late arrival of the purchased rod end. Instead, the final design used a bent steel plate drilled with a ⅝” hole for holding the steering shaft was screwed on a aluminum stock diagonally cut, which was fixed on the chassis with 2 T-brackets on the sides. This method, although sacrificing smoothness of control due to friction between the steering shaft and the plate hole, gave satisfactory performance.

4. Transmission

The main objective of this part is to design a mechanical transmission that transmits power from the motor to the powering wheels, such that the whole vehicles can move forward and backward. The basic design idea of this part is the implementation of bike gear shifting mechanism (used in bikes) into the transmission system, since a real vehicle often have gear shifting functions. The reason that the gear shifting function is we would like to see the actual performance of gear shifting in PEVs and investigate the methods of implementation of gear shifting in PEVs.

The main components of bike gears consist of a cassette, a chain wheel and a derailleur. Power is transmitted from the chain wheel to the cassette by the bicycle chains. As the cassette consists of concentric gears with different teeth number. By shifting the chains to different planes (where the gears of cassette are on) using derailleur, the chains can be shifted to gears with different teeth number on the derailleur, such that the gear ratio is changed in this process. Instead of using both rear and front derailleur, only rear derailleur is used to simplify the design in the transmission system.

After the main design direction was chosen, some estimation about transmission is carried out. The first question is whether the torque is enough to start the vehicle and accelerate the vehicle. To achieving the desired acceleration, the following equation (eq. #1) must be satisfied (derived from F=ma, note that this equation is only an approximation):

$$\mathrm{a}_{net} = \frac{T_{input} - T_{friction}}{mR} \qquad (1)$$

Where m is the mass of the vehicle, R is the radius of the wheel, T_input is the input torque, T_friction is the frictional torque produced by bearings and is the resultant acceleration. Assuming T_friction = 0, the calculated result requires an overall gear ratio from 2.28 to 9.13 for required acceleration range (shown in presentation). The actual gear ratio should be higher due to frictional term, the reason that is not included in the calculation in presentation will be explained in part 5D.

The second question is about the gear ratio required for continuous running of motor. With respect to the prescribed linear speed range (mentioned in presentation), the motor should be geared down in a way such that when the vehicle is running at the continuous speed range (after accelerated to the speed range), the motor RPM falls in its continuous RPM range also. Having the radius of the wheel and the linear speed range, RPM range of the wheel can be found; knowing the continuous RPM range of motor from its datasheet, the required gear ratio range (7.26-11.2) can be obtained. From the bicycle gear, the maximum gear ratio that can be obtained is only 1.45 (cassette 34 teeth; chainring 22 teeth) due to a limited choice of chainrings. As a result, the gear ratio needs to be further increased.

To get the desired results, different designed was considered. The first design option is using a pair of gears to gear up the torque, the second design option involves multiple pair of gears, the third design option involves worm gears (and worm gear boxes) and the fourth design option involves having an ordinary gearbox (with gear pairs inside). The second option is rejected as it is essentially equivalent with having an ordinary gearbox, however more gear set means more misalignments of each gear axis and more space being used by the gears. Although The third design option can provide a very high gear ratio, it is rejected because of two reasons: the worm gearbox is very expensive, it can be as high as around 300 USD from McMaster Carr, buying a separate worm gear set is possible in terms of budget, but accurate alignment of gears is difficult (different input and output axis direction). For the first option, a very large gear is needed for this high gear ratio, which is difficult to be found in the market (the large one is 120 teeth, paired up with a small gear of 16 teeth). The large size of the gears increases the weight greatly, also the misalignment issues persists when it is compared with ordinary gearboxes. Therefore, a gearbox from Vex robotics (two stage reduction, 9.52 gear ratio) is chosen.

The major change of the transmission system in terms of design is the addition of gearbox. Before the motor was changed, we did not realize that at continuous operation of motor, the speed of motor needs to gear down greatly. Also, the starting torque was inaccurately estimated. As a result, option one was chosen before we came to the final design: since finding a gear pair to attain a gear ratio of 3 is not difficult (teeth 16 & 48).

To connect the rear powering wheel to the shaft, a shaft with keyway was chosen such that the shaft rotates with the wheel. The shaft is mounted on the chassis by two shaft housings, as shown in Fig. 2. A disk brake is also mounted on the shaft.

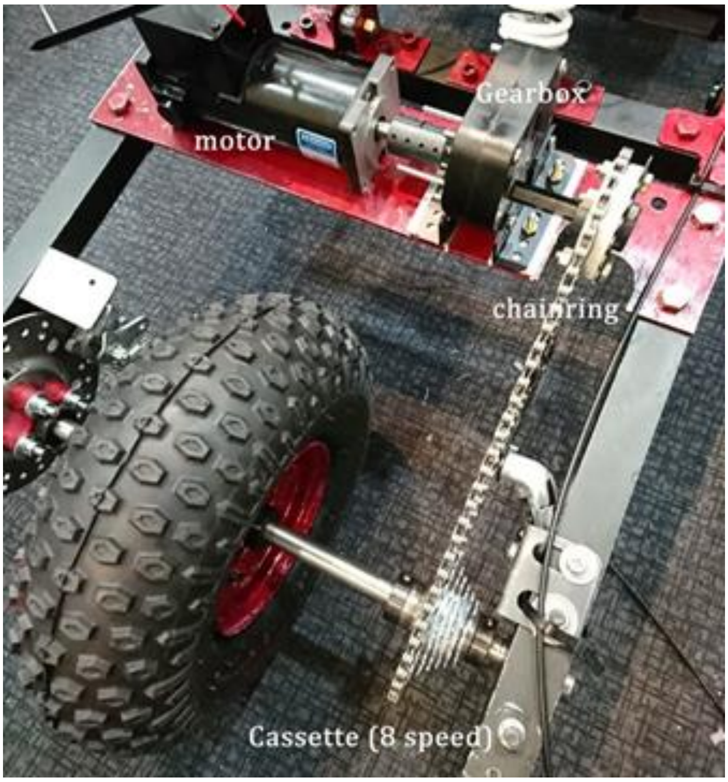


Figure 3 The final transmission system

The resultant schematic is: the motor is directly connected to the input of the gearbox, and the output shaft of gearbox is directly connected to the chainring of the bike gear.

There are still many challenges after the gearbox was chosen. As the input shaft diameter of the gearbox is 8mm, but the shaft diameter of the motor is 1/2-inch, it cannot be directly connected. The solution is finding a machinable shaft coupling, and the hole on one side was machined to 8mm. Another challenge is the mounting of chainring on the 1/2-inch hex output shaft of the gearbox. Using the existing hole on the chainring, it was mounted on a custom aluminum part, and the part is mounted on the hex shaft. Furthermore, the mounting of cassette body on the rear shaft is another challenge. The inner diameter of cassette hub is far larger than the rear shaft, and the inner surface is not a smooth cylindrical surface. A custom steel part is made such that it is wielded to the inner surface of the hub, and the steel part is mounted on the shaft. Details of manufacture and assembly of transmission will be discussed in **part 4D**.

5. Braking

The original design for the braking system involves the use a hydraulic braking system for efficient transmission of the braking force. However, the parts needed to build the hydraulic system are too expensive and beyond the budget for the braking system thus we sought an inexpensive but efficient design. The result of this iteration was the disc brake and brake callipers braking system that involved transfer of mechanical force via a metallic braking cable that resembles a string in a pipe. This design proved convenient because it was easy to calibrate the brake in order to arrive at an optimum setting for the transmission of the braking force to the drivetrain.

Besides, the disc brake that we purchased online could not fit directly onto the shaft thus we designed a mount for the shaft as shown in the figure below. The mount was designed with four holes for bolts which would be attached onto the disc brake. At the center of the mount was a keyed hole for mounting onto the drivetrain shaft.

Possible improvements: we made the disc brake mount out of aluminum, but steel would have been the better choice because steel is stronger than aluminum when it comes to resistance of deformation due to the forces from the motion of the drivetrain.

6. Pedals and user input

To receive input from the driver of the PEV, pedals were designed with key slots for attachment to potentiometers. Turning the pedals would then turn the potentiometers and send a signal to the Arduino for processing. We initially designed the pedals to have a L shaped mount made of steel L bar, and mounted the potentiometers on the chassis using hot glue, but that was not ideal because hot glue was easily detachable from the surface of the chassis. We thus redesigned the pedal mount and used an aluminum U channel. the U channel had two holes on either side of the wall through which we inserted the shaft of the pedal and the shaft of the potentiometer.

7. Electrical System

The main drivetrain was driven by a ½ HP DC electric motor, which was controlled by a DRV8703 H-Bridge Motor Controller. This motor controller is able to interface with both SPI commands and PWM signals, but our controller was driven through PWM. The PWM signals controlled both the speed and direction of the motor, and these signals were produced by an Adafruit Feather M0. The DRV8703 has two pins for motor control, an enable and phase pin. Depending on the input to these two pins, the motor is set into one of four modes: forward, reverse, coast, or brake.

Both the speed and the direction of the motor are determined by user inputs, as is true in a commercial car. Two potentiometers are mounted to the physical brake and accelerator so that when they are pressed the potentiometer resistance will be read by the Feather M0, and an increasing or decreasing PWM signal will be sent to the motor controller.

As an additional safety component, the motor cannot be driven unless the motor enable switch is flipped to the on position, which is located on the driver's left side.

8. Software

The software control system is implemented on the Arduino Feather m0. The main objective is to take inputs from the 2 pedals and output motor PWM, hence controlling the speed of the motor. In addition, a monitoring system is also designed for recording the vehicle speed, motor temperature, and finally displaying all the information through an FeatherWing OLED screen.

The usage of potentiometers for measuring pedal angles instead of encoders facilitates the overall software system design since each potentiometer only requires 1 analog input into the Arduino rather than having to use SPI if encoders were used instead which requires complicated control and timing over all the SPI peripherals. The angle value obtained from the potentiometers would then be transformed into a motor PWM value to be sent to the motor controller, which ultimately controls the motor speed.

The monitoring system takes in a temperature value from the DS18B20 temperature sensor mounted on the motor, the RPM from the AS5048A magnetic rotary encoder mounted on the rear drive shaft and outputs the values to the FeatherWing OLED screen. Both the temperature sensor and the OLED screen provide external libraries, DS18D20 uses the 1-wire protocol and provides its own calculation library "Dallas Temperature", while the FeatherWing OLED uses "Adafruit_SSD1306" provided by the production company Adafruit. The AS5048A does not have any exclusive libraries but uses SPI for communication, thus, calculation of the RPM is done by concatenating 2 raw input values followed by mapping to obtain the expected degree of rotation. The angle is then used to calculate the revolution per second by counting the number of sudden degree jumps from above 200° to below 100° indicating a full revolution plus the partial revolution through current angle of rotation. Scaling the value by a factor of 60 yields the RPM of the drive shaft.

PROJECT IMPLEMENTATION

1. Critical Components

Components	*Quantity*	*Notes*
Motor	1	Provided
Gearbox set	1	
8mm diameter shaft	1	
Shaft coupling	1	
Chainring	1	
Chainring mount	1	Custom part made from Aluminum
Bicycle Chain	1	
Derailleur	1	
Derailleur mount	1	Custom part made from Steel plate
Cassette	1	
Cassette hub body	1	Lathed then wielded to its mount
Cassette hub mount	1	Custom part made from Steel
Rear shaft	1	

Rear wheel	1	
Shaft Housing	2	
Motor mounting plate	1	
Aluminum spacers	2	Custom part made from Aluminum

Table 1: List of major components in transmission

Name of Components	***Function***	***Category***
Clevis pin, shock absorber, customized L brackets	Suspension	Mechanical
Spindles, tie rods, steering shaft, steering plate, steering wheel, customized U brackets	Steering	Mechanical

Table 2: List of major components in Suspension and Steering

2. Assembly Process

a. Chassis

The stock aluminum bars were first cut to suitable dimensions by horizontal band saw, then screw holes was drilled after measurement using drill press. L brackets and T brackets were cut by water jet and band saw. Afterwards, the frame was assembled by putting this all together using ½ in bolts and nuts. Finally, seats and other system was installed.

b. Steering

All steering components except steering rods, spindles and steering wheel were custom manufactured using stock materials, parts scraped from last year and the tools available in Autodesk BUILD Space and Harvard. First, the steel steering shaft used by a team in the previous year was cut in the bottom part to remove the unnecessary component. The steering shaft was then welded to a custom made steering plate which was water-jetted, 2 3/16” holes were then drilled on the steering plate for connection to the rods ends of the steering rods. The steering wheel was bolted on the steering shaft by a circular mount.

Manufacture of the spindle mount was done by cutting of 2 rectangular steel plates followed by manual hammering of the plates. The steel plates were bent into a u-bracket shape. 4 holes were drilled in total on each plate to connect the spindles and chassis bar. After finishing the 2 components, the end rods were bolted onto the steering plate and the spindles, connecting the entire steering system. Finally, wheels were attached and screwed in place.

c. Suspension

Two shock absorbers are attached through eight customized brackets. To make it easier to assemble, all the brackets needed to mount on the aluminum bar first but don't need to lock them tightly. Raise the whole chassis and put the shock absorbers in between of any two pairs of brackets, and check if they are aligned with each other. Finally, lock all the bolts and nuts tightly.

d. Transmission

For the chainring mount, it is first cut from an Aluminum plate using water jet, then the center hole was made to hex shape by a hex broach. The reason using water cut is to minimize the concentricity errors between the 4 screw holes and the center hex hole, which will be an issue if the concentricity errors of the center hex hole with respect to screw holes is too large. Afterwards, the chainring is screwed on the mounting.

To mount the cassette, cassette hub cannot be directed mounted on the rear shaft: the shaft hole on the cassette hub is not large enough, and it can only transmit torque in one rotational direction. For the cassette hub mount, it is made from a cylindrical steel stock. The inner surface of hub body was first lathed to cylindrical, then the outer surface of the steel stock is lathed to same diameter with the inner surface of the hub body. A rear shaft hole was made on the steel piece using lathe and the keyway was made by a broach. Finally, the hub body and the steel mount are wielded together. For the derailleur mounting, a plate was cut first using water jet, then it is bended to 90 degrees. Finally, it is attached on the rear part of chassis and the derailleur is attached on the plate.

For the mounting plate, there is a challenge regarding the screw holes. To minimize the friction in the transmission axis, the tolerance of the location of screw holes is very small. Otherwise, there may have large geometric errors of screw locations, causing the misalignments between the gearbox axis and the motor axis. The best solution is water jet, however drill press with digital reading was used for drilling of these screw holes since the dimension was not fixed initially.

In terms of the assembly process, the gearbox was first assembled. Note that the input 8mm shaft was also installed into the gearbox in this process. In the actual assembly process, a bearing was missing from our orders since we forgot to order it. The bearing is designed especially for this gearbox, and the bearing replacement (due to time constraints we must order that from McMaster), but the dimension cannot fit the gearbox exactly. As a result, an impromptu 3d printed part was made just before the original racing day to mount the bearing.

The components are mounted on rear axial and the motor mounting plate in parallel. For the rear axial, disk brake, disk brake mount, rear wheel, cassette and cassette mount are mounted first, with collars in between them to prevent sliding, then the housings are installed, thus the whole rear shaft and the components attached are installed on the chassis. For the motor mounting plates, the gearbox is installed first, then the motor, finally the chainring and its mount is mounted on the hex output shaft of the gearbox with hex collars. The derailleur mount is installed directly onto the chassis. Finally, the bicycle is installed on the chainring, derailleur and the cassette. Brake and derailleur wires are installed afterwards. A part of the mounting plate was sawed away to prevent the collision between the chains and the plates.

e. Braking

The disc brake is attached to the disc brake mount using four bolts and nuts. The assembly of the disc and mount is then mounted onto the shaft and a key is inserted between the shaft and the mount. Two lock rings are then inserted on either side of the disc assembly in the axis of the shaft to keep the disc from sliding along the shaft.

The callipers are then attached to the callipers' mount using two bolts nuts. The callipers' mount is then attached to the chassis through two bolts and nuts. The brake cable is then installed from the top of the callipers' mount by inserting the cable through the hole at the top. The cable then travels underneath the chassis before resurfacing at the front of chassis at about 3 inches from the brake pedal.

Figure 4 The finished PEVs

1. **Challenges**

a. **Steering**

While a lot of components such as the wheel spindles and tie rods were purchased and reused from last year's program, some major components were self-manufactured to fit the specific dimension requirements. One of the parts that were self-manufactured were the spindle mounts.

From the original PEV assembly CAD, 2 U-brackets with inner diameter of 1.5" and depth of at least 1" were required to connect the spindles to the chassis which were unavailable for purchase. As a result, custom manufacturing was resorted through hammering 2 steel sheets into a U shape, holes were then drilled to connect the steel sheet bracket to the spindle and their openings to the chassis aluminum bar.

b. **Suspension**

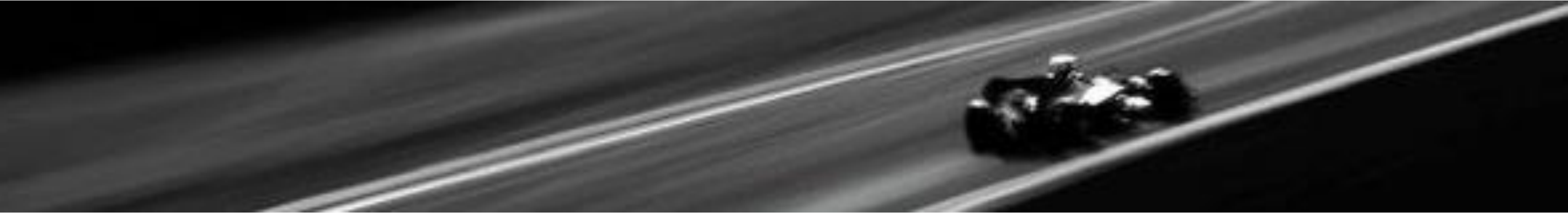
Suspension worked perfectly during the driving time, and it could successfully help the vehicle pass the speed bump smoothly. However, we still met a difficulty, the spring on the shock absorbers didn't have enough restoring force. This means we need to raise the chassis manually every time before the next drive start.

c. **Transmission**

The performance of the transmission system is not satisfactory, since the vehicle cannot start when there is a driver on the seat. This shows that the initial torque was not enough. There may be several reasons of not enough torque. The first reason is obviously not enough gear ratio from calculation. The current highest gear ratio is 13.8, when considering the friction between within the bearings the current gear ratio still falls within the desired range. However, the calculation we used cannot account for the additional friction produced by geometric misalignments of the rear shaft, and such value can be only estimated from actual drive test. It is expected that if more time is provided, the drive test can provide valuable feedback about the gear ratios and we can do it accordingly.

Another issue is the falling of chains, especially at going reverse. This could due to the plane of derailleur is not parallel to the plane of the chainring. As a result, it may continuously derail the chain when go reverse. The solution of this could be using both front and back derailleurs, and carefully adjust the position of the derailleur.

Another improvement can be made on the motor we used. The motor we used have an output power of around 300W, which is lower than expected. The output power of a bicycle rider is around 250W for just cruising along with the pack, and our vehicle weighs around 1.5 times than that of the bicycle (driver weight considered). Thus, a motor with output power around 400 to 500 W will be a better choice. Insufficient output power of motors could be another reason of failed starts of the vehicle.



OUTLOOK AND IMPROVEMENTS FOR THE FUTURE

1. Power steering and autonomous driving

A personal electric vehicle perfectly sets up a platform for research in assistive or autonomous driving. Originally planned to implement some degree of computer vision for road tracking and power steering which leads to autonomous driving, it was soon suspended due to the time and scope constraint of the program. Therefore, given more time and fund, the above two areas are definitely possible areas of research.

2. Transmission

There are some design improvements and planning can be carried out. For the design of the hex shaft mounting, the output shaft of the gearbox should be supported by both sides at both ends of the shaft, in actual cases it is only supported by the gearbox solely, which is bad for the gearbox since the dragging force from the rear wheel will increase the wearing of the gearbox. The decision of size of the wheels is not being well thought of. For example, the traction issue is not considered. (But in fact, the traction is enough, since without the driver the vehicle can start moving by itself, with the driver seating it can only increase the traction due to increase in weight.).

3. General project planning

The design should be reviewed frequently to search for bugs, especially for mechanical design. Another issue is about budget managing which can be done much better by well organizing all parts we need to order, to prevent unwanted parts being ordered.

APPENDIX

1. DRV8703 library file: https://github.com/arfrahm/DRV8703
2. Final Presentation of Team Cardi: https://drive.google.com/open?id=0B56y9d-dKK48cEtuQTVLOE04ckE

DISCLAIMER

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