Electronic Automatic Transmission for Bicycle

Design Document

Tianqi Liu, Ruijie Qi, and Xingkai Zhou

Team 4

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TA: Hershel Rege

1 Introduction

1.1 Objective

Nowadays, an increasing number of people commute by bicycles in US. With the development of technology, bicycles that equipped with the transmission system including chain rings, front derailleur, cassettes, and rear derailleur, are more and more widespread. However, it is a challenging thing for most bikers to decide which is the optimal gear under various circumstances and when to change gear. Thus, electronic automatic transmission for bicycle can satisfy the need of most inexperienced bikers.

There are three main advantages to use with automatic transmission system. Firstly, it can make your journey more comfortably. Except for expert bikers, many people cannot select the right gear unconsciously. Moreover, with so many traffic signals and stop signs in the city, bikers have to change gears very frequently to stop and restart. However, with this system equipped in the bicycle, bikers can only think about pedalling. Secondly, electronic automatic gear shifting system can guarantee bikers a safer journey. It is dangerous for a rider to shift gears manually under some specific conditions such as braking, accelerating. Thirdly, bikers can ride more efficiently. With the optimal gear ready, the riders could always paddle at an efficient range of cadence. For those inexperienced riders who choose the wrong gears, they will either paddle too slow which could exhaust themselves quickly or paddle too fast which makes the power delivery inefficiently.

Bicycle changes gears by pulling or releasing a metal cable connected to the derailleurs. Our goal is using sensors and microcontroller to electronically determine and shift to the optimal gear under specific conditions, by pulling or releasing the rear-derailleur’s steel shift cable in the bike with a gear motor. Besides shifting automatically, we add a manual mode to our device as well. Manual mode offers the user an option to take control of the transmission if he or she enjoys the fun of manually switching gears. This feature could also be useful for our testing process.In addition, in order to improve the end user's experience, we add a LCD screen to display data and gear status.

1.2 Background

Another group did electronic bicycle shifting in Spring 2016, but they didn't have an automatic gear shifting function and didn't have the sensor set-up like ours. In the commercial market, both SRAM and SHIMANO have electronic shifting products. However, their products integrate the servo motor inside the derailleurs, and their price is over $1000. Thus, only professionals or rich enthusiasts can afford the electronic automatic bicycles. The transmission system we design could potentially serve as an add-on device at acceptable price to all bicyclists. To use our product, the user only need to detach the cable linking to the rear derailleur from the shift levers on the bike handle, then attach it to our device. The low price and easy installation could attract more bikers to our product. Our design won't necessarily compete with the current commercial products, but it could let more people have a taste of electronically controlled bicycle shifting with low price.

1.3 High-Level Requirements

- Our system must be able to determine the optimal gear from 7 gears[4], based on the conditions described by sensors. Qualitatively speaking, our system should select a lower gear when the cadence/speed goes down, and select a higher gear when the cadence/speed goes up.
- Our system must be able to pull or release the steel shift cable for 2.9±0.1mm[4] in order to shift up or down one gear.
- Our system could have a manual mode, which could allow bikers to change gears manually.
- Our system could be installed on a bicycle easily.

2 Design

Our design mainly contains 5 modules: power supply, control unit, sensing unit, motor module, and user-interface module. The power supply regulates and provides stable electrical power to every component of our device. The sensing unit measures the rider's cadence, and the bicycle's speed. The control unit gathers data from the sensing unit, processes user inputs and sends downshift/upshift signal to the motor module. The motor module pulls or releases the shift cable to actuate the rear derailleur and shift gears. The user-interface module contains a LCD screen to display the current gear, current speed, current cadence, and the status of manual mode.

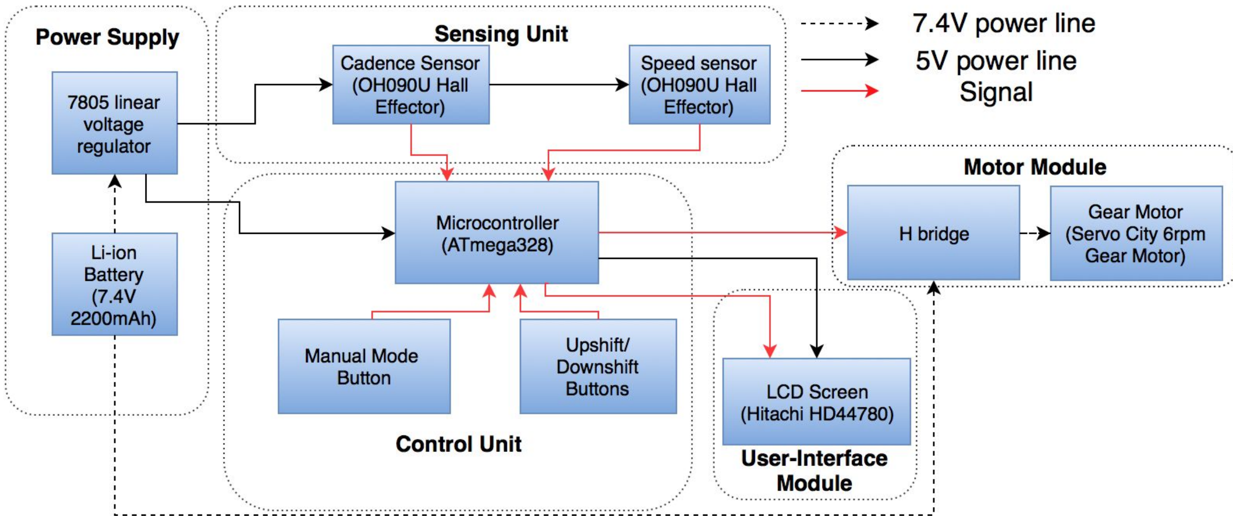

Figure 1. Block Diagram

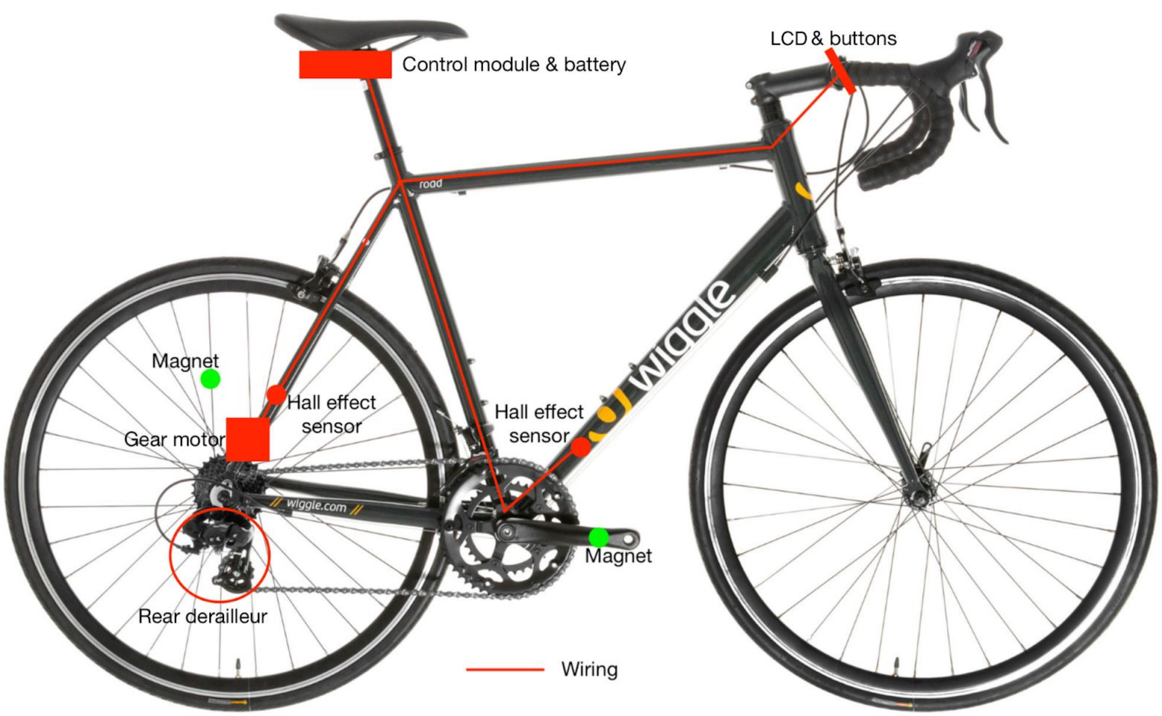

Figure 2. Physical Layouts

Figure 2 represents the positions of each components on the bicycle as we design. The gear motor is placed very close to the rear derailleur to guarantee motor efficiency. Both hall effectors are placed on non-moving frame to make sure the wiring for them is tight and secure. Control module and battery are placed in a case under the saddle which could protect them against dust and water. The LCD screen and buttons are attached to the handlebar so that the user could easily see and operate them while riding. As we design, wiring will not hinder the riders.

2.1 Power supply

The power supply module contains a Li-ion battery and a voltage regulator. This part provides electricity to all components. When the motor is on, the theoretical maximum output current is around 550 mA (500 mA for motor and 50 mA for microcontroller, LCD screen and sensors). When motor is off, the current is around 50 mA (for microcontroller, LCD and sensors only).

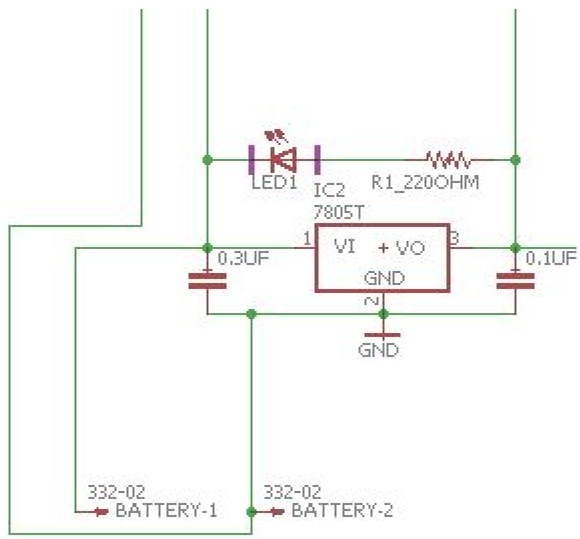

Figure 3. Schematic for Power Supply

2.1.1 Li-ion battery

We plan to use a 7.4 V Li-ion battery. The 7.4 V battery we use is a pack of two 18650 Li battery. The nominal capacity is 2200 mAh.

Since we are using a 6 RPM 12 V gear motor, according to datasheet[7], the maximum current is 500 mA when the motor is stalling. Thus, the maximum theoretical power of this motor is:

$$12\ V * 0.5\ A = 6\ W$$

Based on personal biking experience, we assume that the bike rider changes gear once per 10 second on average. And the target re-charging cycle of our battery is 10 hours. For each gear shifting, we assume the gear motor takes 200 ms to finish the action. Since the motor only operates during gear shifting, the power consumption during this 10 hour period is:

$$6\ W\ *\ 0.2\ s\ *\ \frac{10\ hours}{10\ s}\ =\ 1.2\ W \cdot h$$

The microcontroller and the LCD screen have constant power consumption. The actual value may vary depend on the working condition. For simplicity, in the design document we assume the average current is 50 mA. The power consumption for this part is:

$$5\ V * 0.05\ A * 10\ hours = 2.5\ W \cdot h$$

Thus, our battery should have a capacity of at least 1.2 + 2.5 = 3.7 Wh.

As we choose to have a 7.4 V battery and a 5 V linear voltage regulator, the capacity in mAh is 3.7 Wh/5 V = 740 mAh. Considering that energy capacity of Li batteries might dramatically decrease during winter time, we choose a 2200 mAh, 7.4 V Li battery pack.

Requirement	Validation
Can power the motor to pull the cable to each gear, which means the current through the motor > 500 mA.	(1) Connect the motor with microcontroller. Link the cable to motor output (2) Use the manual mode and upshift/downshift button to switch gears from lowest gear to highest gear. (3) Repeat it from highest to lowest gear. (4) In this process, the battery should power the motor to conduct all these actions within 0.2 second.
Can continuously power the whole system up to 10 hours	In the 10 hour road test, the battery should be able to support the system without recharging
Output voltage is 7.4 V (steady state error within 0.3 V)	The voltage output measured by multimeter should be between 7.1 V to 7.7 V in any

	working conditions.

2.1.2 Voltage regulator

In order to obtain stable battery voltage even when the battery is discharging, we need a voltage regulator. The 7805 linear voltage regulator we choose can convert 7 to 35 V battery to a 5 V power source and sustain maximum current of 1.5 A.

Requirement	Validation
Sustain 550 mA - 600 mA current without overheating (<120 degree celsius)	(1) Connect the output with a 80 Ohm resistor. (2) Connect the input to 7.4 V voltage source for 0.5 second, then disconnect it for 5 seconds. (3) Repeat for 1 min, measure the temperature of the voltage regulator surface
Output voltage is 5 V (steady state error within 0.3 V) when a continuous 7.1 V - 7.7 V input voltage is applied	(1) Use the voltage source to generate 7.1 V to 7.7 V input (2) The output connects a 100 Ohm resistor (3) The voltage output measured by multimeter should be between 4.7 V to 5.3 V.

2.2 Sensing unit

In order to choose the optimal gear to keep the rider paddle at an efficient range of cadence, we should monitor the cadence to check if the rider is paddling within the efficient range and also monitor the speed to calculate which is the optimal gear for the observed speed. Thus, we use one cadence sensor, and one speed sensor. All the data should be received and processed by the microcontroller.

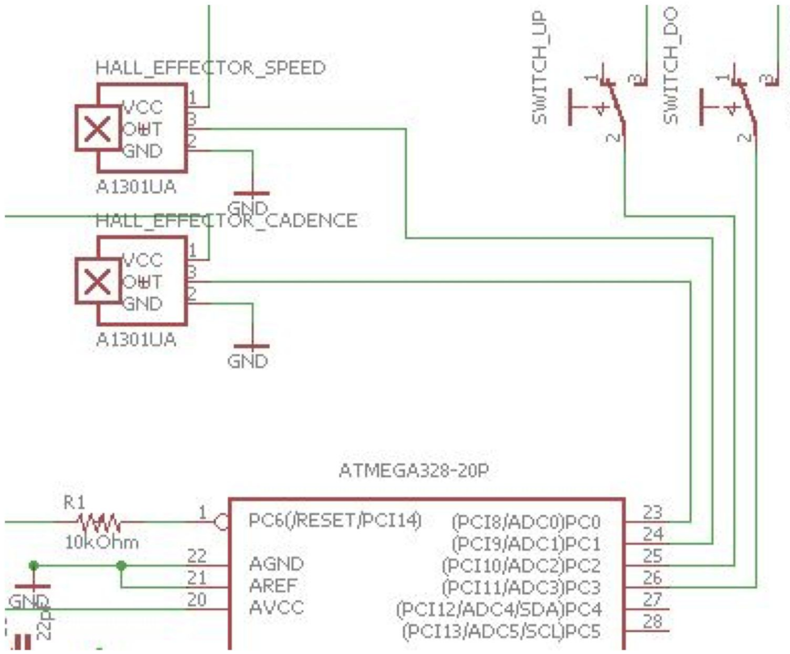

Figure 4. Schematic for Sensing Unit

2.2.1 Cadence sensor

We use oh090u 5V Hall Effector as the cadence sensor. This hall effector is chosen due to its low price. It is also very common and easy to use a hall effector to measure the rpm of a spinning object. This sensor should be placed at the bike's downtube and a small piece of magnet attached to the crankset as *Figure 2* so that it can measure the real cadence and send it to the microcontroller.

Requirement	Validation
Achieve accuracy of 3 rpm	(1) Mount the cadence sensor on bike paddle. Connect it with microcontroller and LCD screen. Put the bike on a test shelf with back wheel free to move. (2) Write a test program that print out the continuous reading of cadence sensor on the LCD. Load it to microcontroller. (3) Rotate the bike paddle for 1 minute. Count the rounds the paddle rotates. (4) Compare the counted number with the displayed number on LCD.

2.2.2 Speed sensor

Speed sensor would use the same hardware as the cadence sensor(oh090u 5 V Hall Effector), and the locations of the hall effector and the small magnet are shown in *Figure 2.* Since the diameter of bicycle wheel is known, the microcontroller could convert the frequency and get the speed.

Requirement	Validation
Achieve accuracy of 1 m/s	(1) The control unit and LCD screen shall be installed first. The LCD should display the speed with less than 0.2 second delay (2) One tester ride the bike at a certain speed and read a steady speed value on LCD. Two signs are places with 10 meters distance. (3) When the bike pass those two signs, another tester measure the time interval. (4) Repeat the test 3 times. (5) Compare the manually measured speed with the speed displayed on LCD. In average, the difference shall be less than 1 m/s

2.3 Motor module

Motor module receives signals from the control unit and mechanically actuates the shift cable. According to our measurements, it requires at least 10 kgf force to pull the cable.

Generally, there are three types of motors that we can choose: gear motor, servo motor and stepper motor. Based on the ECE machine shop staff's experience on Spring 2016's electronic bicycle shifting project, our motor should have more than 20 kg-cm rated torque. To generate the same torque, stepper motors are much more expensive than servo and gear motor. The gear motor with 44.1 kg-cm only cost $25, while a much inferior 19.9 kg-cm stepper motor would cost $51. Also, stepper motor requireds much higher current(2.8 A) compared to gear motor(0.5 A), which means we need to choose larger battery, thus increase the total cost and design difficulty even further[6].

The previous group uses the servo motor to pull the cable. However, the servo motor need to consume electricity all the time. Otherwise, the cable will be loose. But the 6rpm gear motor equipped with worm gear, according to machine shop staff, should be able to hold the cable steady even after the electricity is cut off. Thus, the power consumption could be greatly reduced.

2.3.1 Gear motor

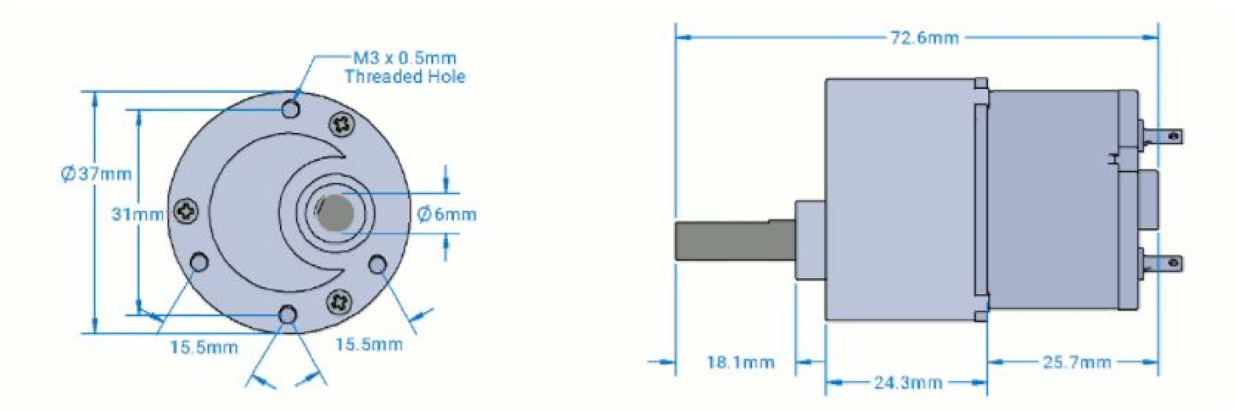

Figure 5. Gear Motor Dimensions

Requirement	Validation
Have enough torque (20 kg-cm) to pull the cable of rear derailleur. Can be powered by 7.4 V voltage source.	(1) Power the motor with 7.4 V voltage source. Connect gear motor with control unit. (2) Rotate the paddle by hand (3) Switch the gear from lowest to highest (4) Switch the gear from highest to lowest (5) Each time the system should switch to the desired gear within 1 second (6) The process shall be smooth (7) The motor should hold cable after switched to proper gear
Rotating at desired rpm with error less than 30 degrees / minute	(1) Power the motor with 7.4 V voltage source, mark the start position (2) Operate for 60 seconds, count the rounds (3) When stopped, the gear motor should have less than 30 degrees difference with the theoretical ending position

2.3.2 Motor Driver

Since the microcontroller can only generate 80 mA[9] while the motor requires at most 500 mA, it is impossible to connect the motor with microcontroller output pin directly. Here we will use a L298N Motor driver, which can supply 7 V, 2 A for the motor[8]. Since the maximum current of the gear motor is 0.5 A, and the input voltage is 5 to 12 V[7], the motor driver should be able to safely control our gear motor. Also, the switching delay time is $0.2\ \mu s$ for turning on and $0.7\ \mu s$ for turning off, which are trivial compared the $200\ ms$ motor operating time.

Requirement	Validation
(1) Power the motor for 0.2 seconds at 7.4 V. (2) The motor should switch up or down a gear based on control signal.	(1) Set bike to lowest gear. Use hand to rotate the paddle. (2) Arduino send 01 signal for 200 ms. (3) The gear motor should rotate and pull the rear derailleur to next gear. (4) Send 10 signal for 200 ms. (5) The gear motor should return to the starting point and the rear derailleur should go back to original gear.

2.4 Control Unit

This unit combines data from sensing unit and user input, runs software to determine the optimal gear or controls the manual mode function. This unit also sends upshift/downshift signals to the motor module and makes LCD screen display current gear, current speed, current cadence, and if manual mode is activated.

2.4.1 Microcontroller

For the microcontroller we will use ATmega328 28-pin PIPD version. We chose this microcontroller because it is the one being used on arduino[11], so that we could use existing library for the communication among this unit, the sensors and the LCD screen. Thereby, we could focus more on refining our algorithm to make sure our device can choose the optimal gear. This 8 bit microcontroller chip contains 32 KB ISP flash memory and 23 general purpose I/O lines. To power the microcontroller, we need one 10k Ohm resistor, two 10 uF capacitors, two 22 pF capacitors, and a 16 MHz clock crystal[11].

We can use the arduino board with its microcontroller removed to load the program into our microcontroller. The circuit is like:

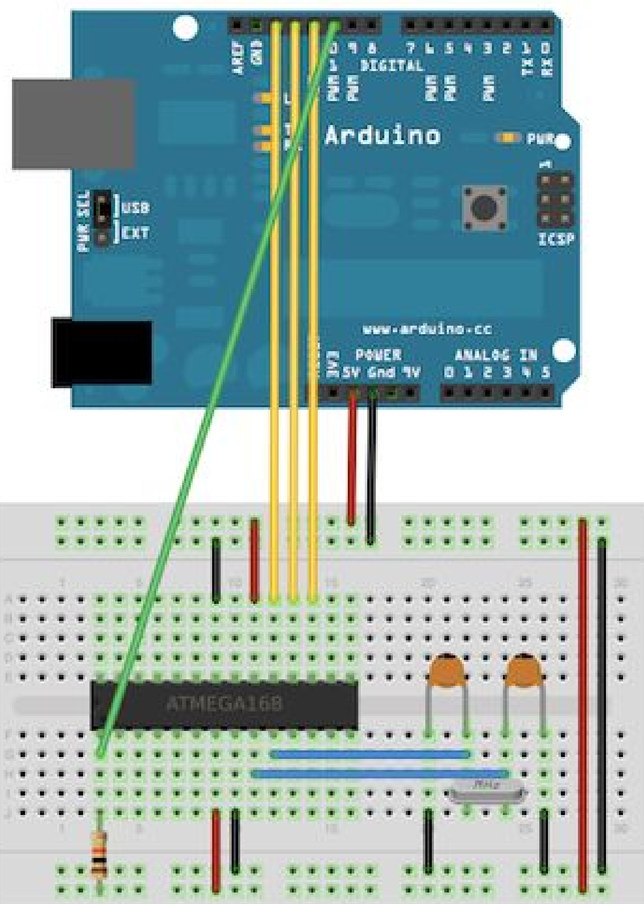

Figure 6. Circuit for loading program into the microcontroller

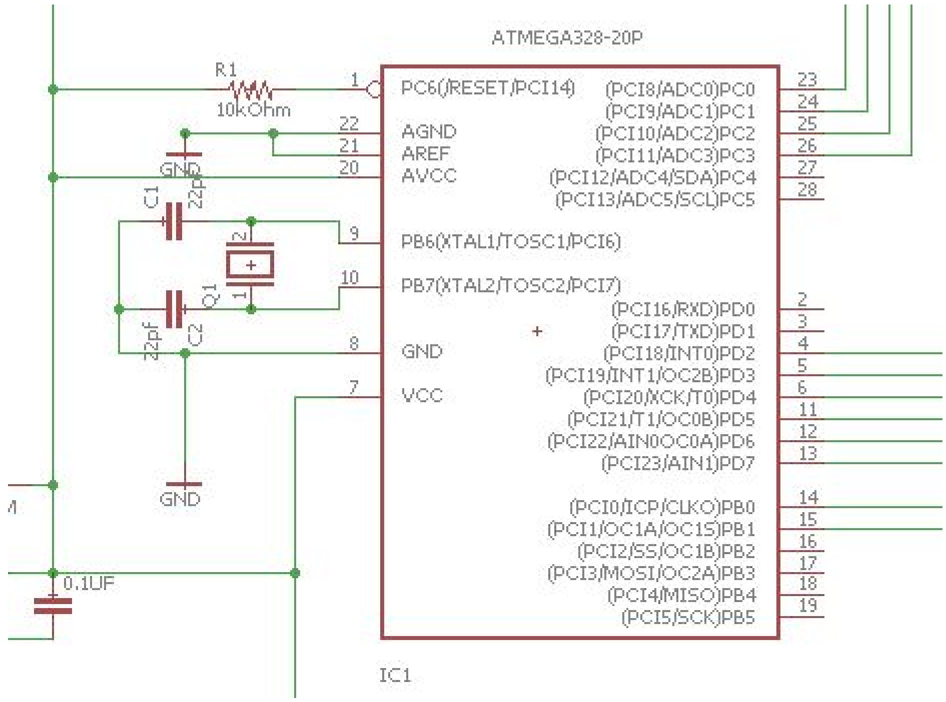

Figure 7. Schematic for Microcontroller

Requirement	Verification
Operate reliably for 2 digital input, 3 analog input and 1 digital output with 5 V power source. Digital outputs sent out with no observable delay	(1) Connect all the digital output pin to leds (2) Load a test program that send 100 pulses to all digital outputs with 1 second interval (3) By human observation, all LEDs should light up and turned off simultaneously for 100 times
Receive digital input without missing	(1) Connect all the digital input pin to push button. (2) Load a test program that print out the count number of digital input pulses on terminal (3) Press one push button for 100 times with 1 second interval (4) The number displayed on terminal should be exactly 100 (5) Repeat for all digital input pins

2.4.2 Buttons

We have three push buttons: activating/deactivating manual mode, upshifting, and downshifting. These buttons are essential for the manual mode described before. The maximum current for these buttons are 50 mA.[12]

Requirement	Verification
The button is functional when connect with 5V microcontroller with error rate less than 3%	(1) Connect the button with 5V voltage source and arduino digital pin. Write a test program that print the count of button pressed on LCD screen. (2) press button for 100 times (3) The result displayed on LCD should be within 97 and 103

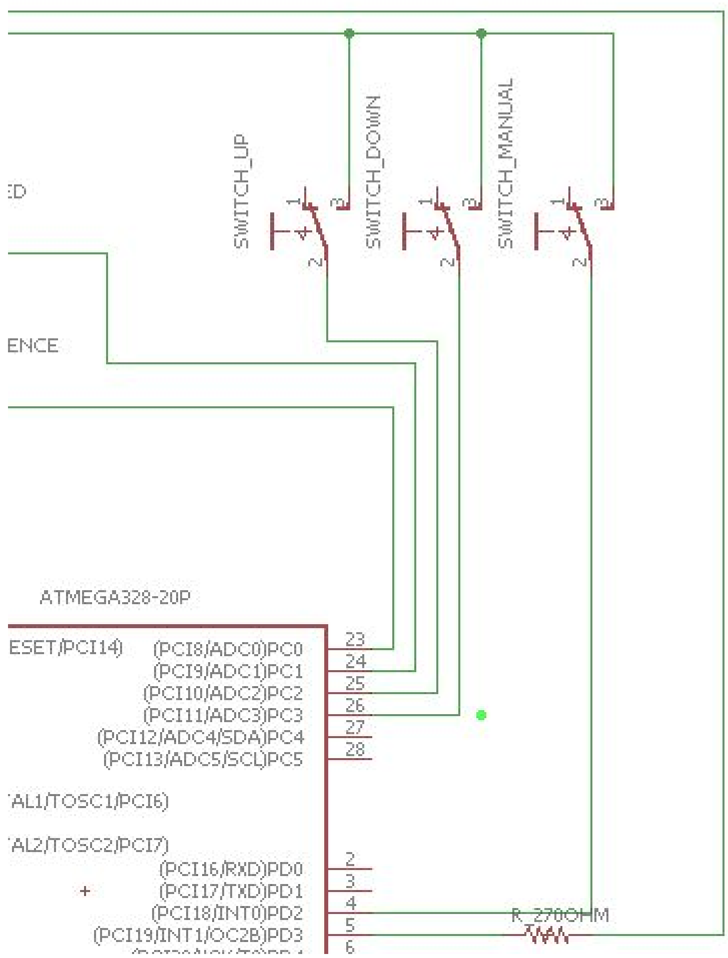

Figure 8. Schematic for Buttons

2.5 User-interface module

This module has a LCD screen displaying the current speed, cadence, gear, and manual mode status. It gets all the information from the microcontroller. This part of device is needed for better user experience. Providing the rider with the current speed, cadence, and gear could help the user to quantize how to paddle efficiently. Knowing if the manual mode is on could avoid user getting unexpected behavior from our device.

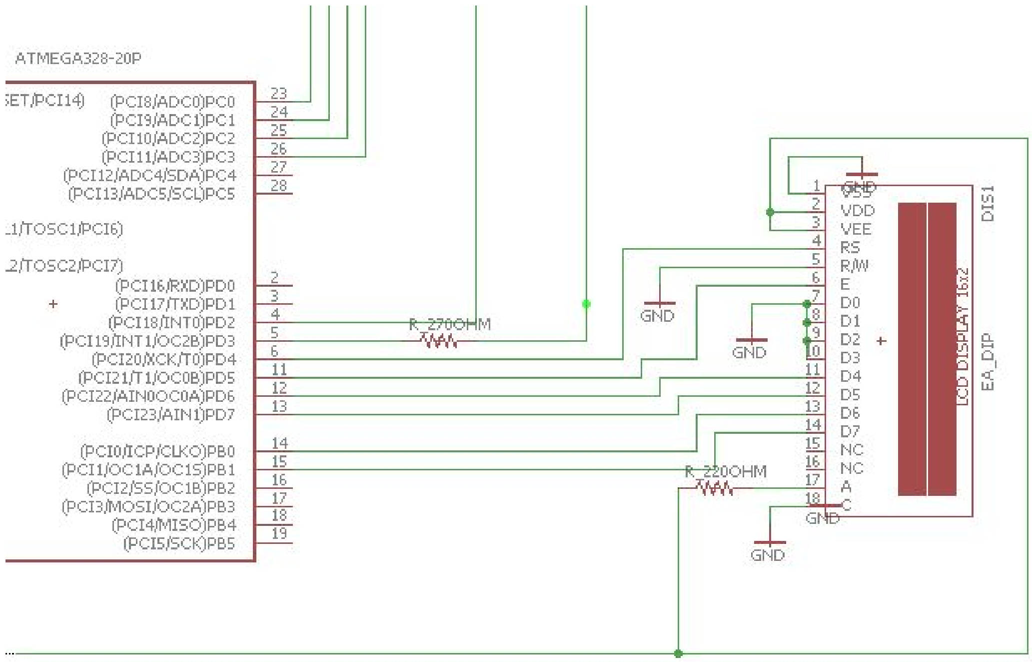

Figure 9. Schematic for UI Module

2.5.1 LCD screen

A HD44780 LCD screen is chosen by us because it could operate under 5 V voltage. Besides, it can display up to 2 16-character lines so it has enough space to display current speed, cadence, gear, and if manual mode is on. It is also of reasonable size(80 mm x 35 mm x 11 mm) to be mounted on the handlebar[14].

Requirement	Verification
Display content correctly and refresh the content every 100 ms	(1) Connect the LCD with microcontroller (2) Write a test program that display 32 consecutive "A"s on the LCD screen for 1 second (3) Display from "A" to "Z", "a" to "z", then "0" to "9" (4) All the letters and numbers should show

	up simultaneously (5) The delay should be less than 100 ms

2.6 Case

In order to avoid short circuit caused by moisture or any damage from dust, we will manufacture a case that protect the PCB, microcontroller and battery.

Requirement	Verification [3]
Pass IP52 Standard Requirement	(1) Vertically dripping water shall have no harmful effect when the enclosure is tilted at an angle of 15° from its normal position. A total of four positions are tested within two axes. (2) Test duration: 2.5 minutes for every direction of tilt (10 minutes total) (3) Water equivalent to 3 mm rainfall per minute

2.7 Schematics and PCB

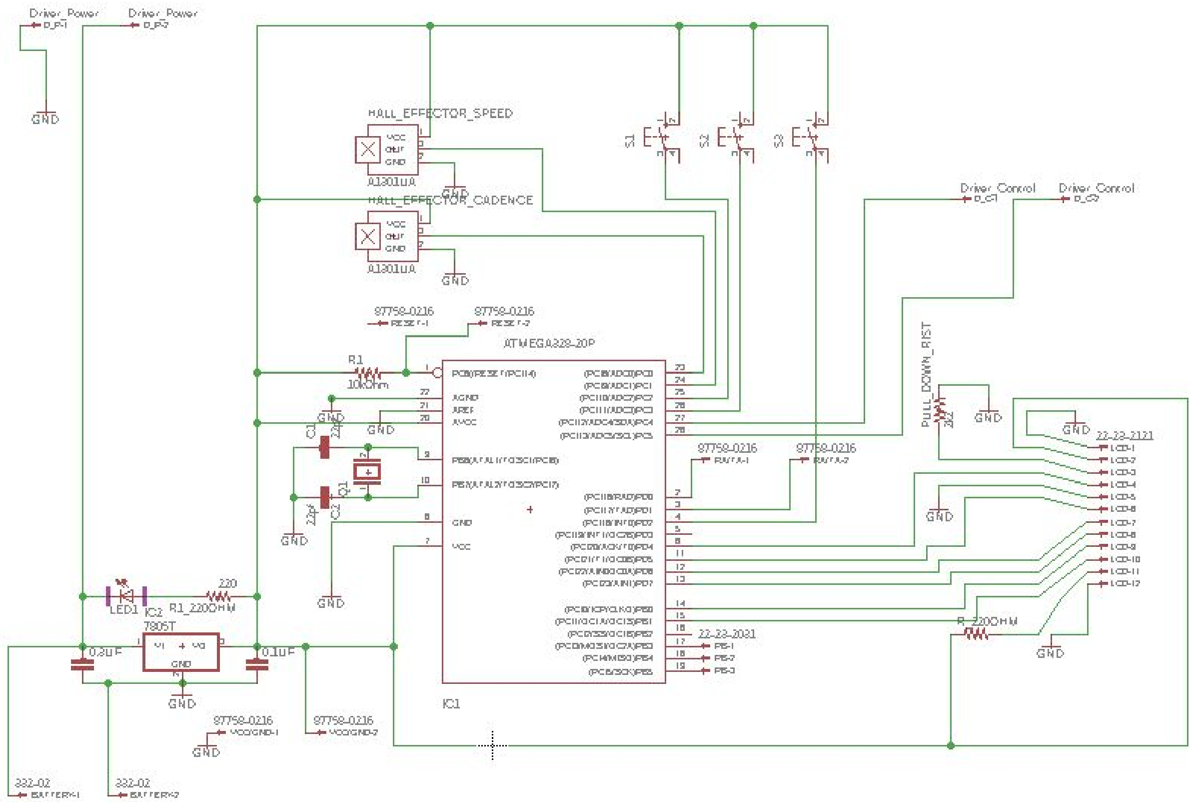

Figure 10a. Circuit Schematics

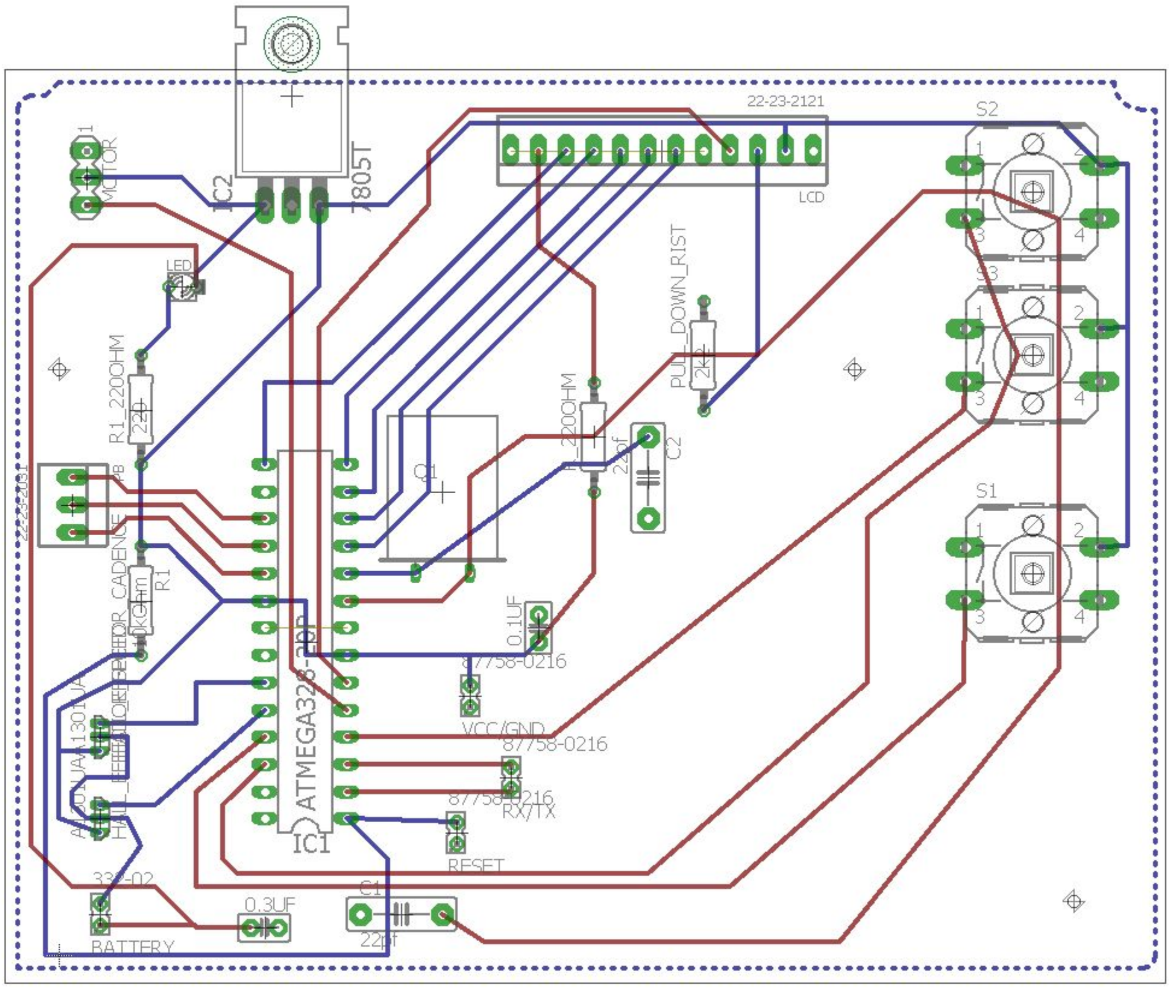

Figure 10b. PCB design

2.8 Software

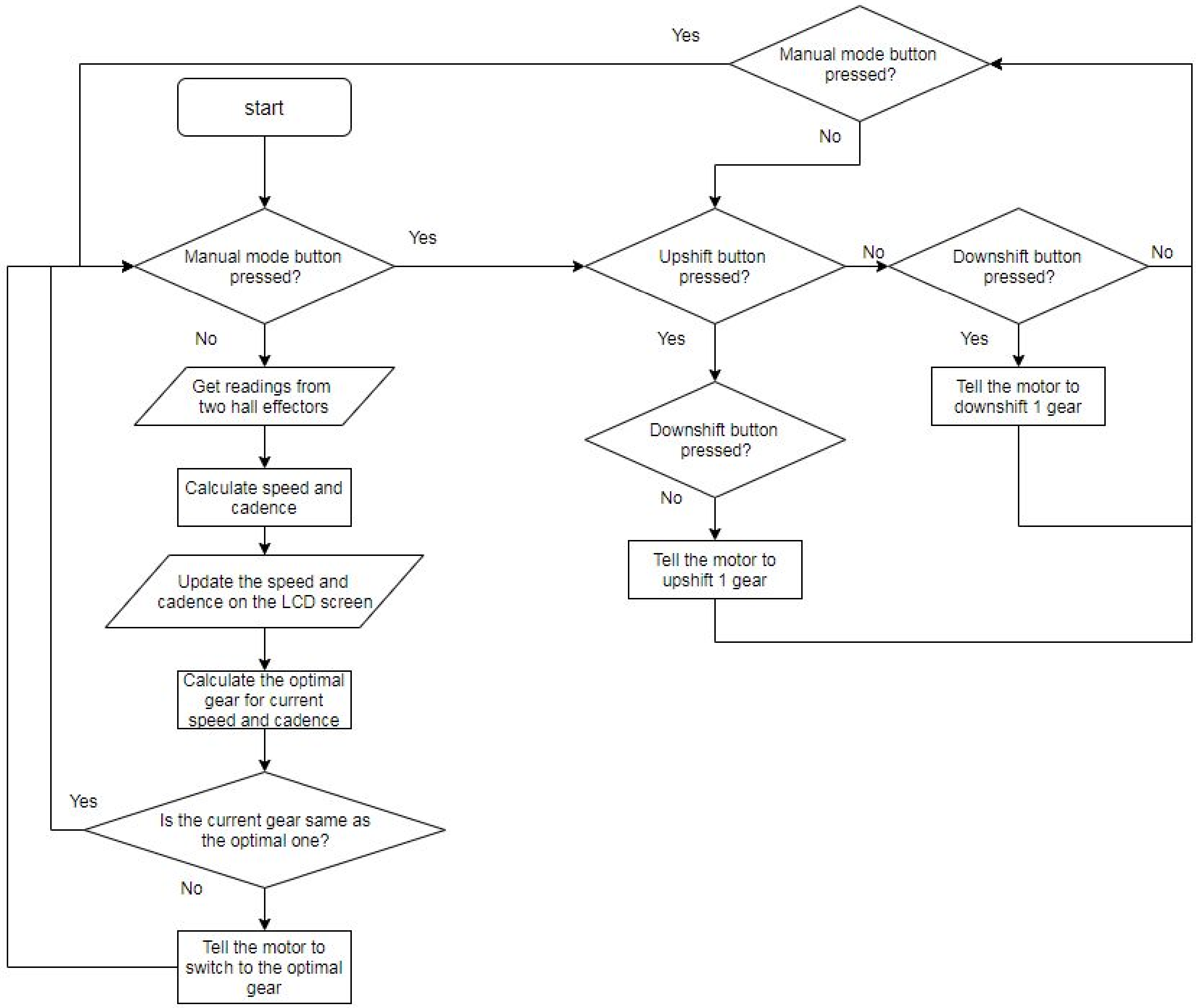

Figure 11. software flowchart

Figure 11 represents how our software flow. How to choose the optimal gear based on speed and current will be further discussed below.

Cadence(rpm) Rear Cog (# of teeth)	30	40	50	60	70	80	90	100	110	120	130
14	8.43	11.24	14.05	16.86	19.67	22.48	25.29	28.10	30.91	33.72	36.53
16	7.39	9.85	12.32	14.78	17.25	19.71	22.17	24.64	27.10	29.56	32.03
18	6.56	8.75	10.94	13.13	15.32	17.50	19.69	21.88	24.07	26.26	28.45
20	5.90	7.87	9.84	11.81	13.77	15.74	17.71	19.68	21.64	23.61	25.58
22	5.36	7.15	8.93	10.72	12.51	14.29	16.08	17.87	19.65	21.44	23.23
24	4.91	6.55	8.19	9.82	11.46	13.10	14.73	16.37	18.01	19.65	21.28
28	4.23	5.64	7.04	8.45	9.86	11.27	12.68	14.09	15.50	16.91	18.32

Table 1. Bicycle's Speed(in mph), with front ring fixed at 50 teeth, 700c x 25mm wheels[13]

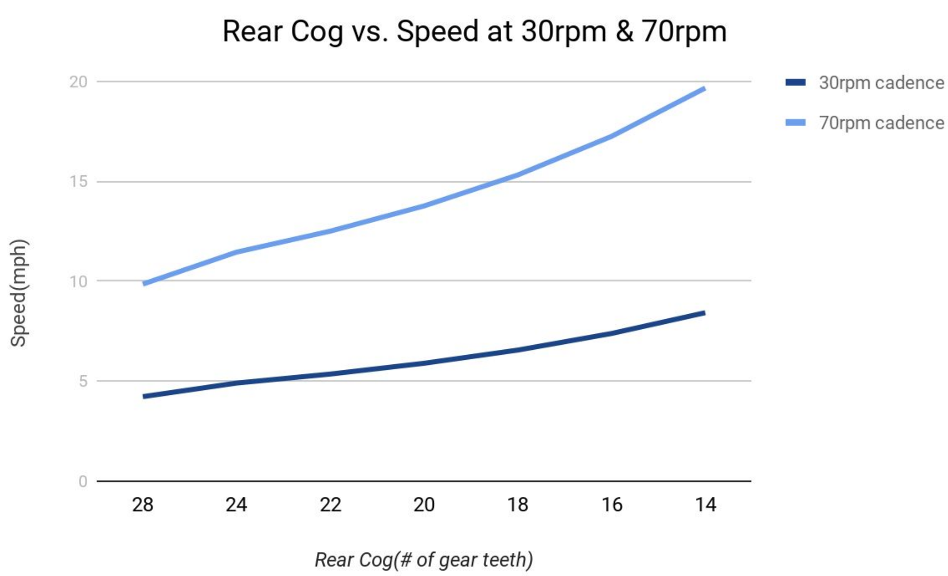

Figure 12. Speed range for cadence between 30 and 70 rpm for different rear cogs

In *Table 1*, a higher number of teeth in the rear cog means a lower gear. In short, lower gears are suitable for lower speed range. To be more specific, a rider could only deliver power efficiently and comfortably when paddling at a certain range of cadence. The optimal gear at a certain speed should put the rider to paddle within this range at that speed. Assume this range to be between 30 and 70 rpm, *Figure 12* represents upper and lower speed limits of this range for each gear. For a gear, if the speed goes above the upper limit, it means it's time to upshift. While the speed goes below the lower limits means it's time to downshift.

In order to make this model more robust, we can take acceleration into consideration as well. We could get both the acceleration of bike speed and cadence based on historical data, and with acceleration data, we could know more about the bicycle's status like if it is slowing down, or if the rider is paddling hard.

2.9 Tolerance Analysis

The motor module in our system is a critical component, since it should not only output enough torque to hold and actuate the bicycle's rear shift cable, but also actuate the cable quickly and accurately.

ECE machine shop staff told us the motor should have more than 20 kg-cm rated torque. The 6rpm gear motor chosen by use could output 44.1 kg-cm of torque[7]. The motor does have enough torque based on the staff's experience. We will do more math to check if this motor indeed outputs enough torque later in this section.

A traditional bicycle shift gears instantly through pure mechanical connections. As a result, our system shouldn't have a long shifting time. We target our shifting time to be 200 ms. Also, the length of cable pull required by each shift for our shimano 7-speed rear derailleur is 2.9 mm[4], and the motor's speed is 6 rpm. With these specifications, we can calculate the diameter of the gear that connects the shift cable to the motor:

$$\frac{2.9\ mm}{\pi * d} = 6\ round/minutes * 200\ ms,\ d = 46.15\ mm$$

46.15 mm is a reasonable size for this gear, since the outer diameter of the gear motor is 37mm, which is comparable to 46.15mm. Thus, with such a gear, the motor control would be quick and accurate enough, as we have the control of time in unit of milliseconds in arduino C library[10].

Lastly, we should confirm that the chosen motor outputs enough torque not just based on machine shop staff's experience. According to our measurement on our own bicycles, it requires at least 10 kgf force to pull the shift cable. Since we now know the diameter of the output gear, 46.15mm, the measured output torque needed from the motor is then:

$$10\ kgf * 46.15\ mm/2 = 23.08\ kg * cm$$

This result verifies that the machine shop staff's experience is fairly accurate. This number is also well below the rated torque of the chosen motor.

3 Cost

Estimated Cost of Labor			
Name	**Hour Rate($/hour)**	**Hours(hours)**	**Subtotal($)**
Tianqi Liu	40	100	4000
Ruijie Qi	40	100	4000
Xingkai Zhou	40	100	4000
Total	40	300	12000

Estimated Cost of Parts			
Part name	**Quantity**	**Unit Price($)**	**Subtotal($)**
18650 2200mAh Li-ion battery pack	1	7.75	7.75
7805 linear voltage regulator	1	0.95	0.95
oh090u hall effector	2	1.74	3.48
ATmega328 28-pin PIPD	1	4.3	4.3
HD44780 LCD screen	1	4.99	4.99
Servocity 6rpm gear motor	1	24.99	24.99
Push buttons	3	0.35	1.05
Total($)			47.51

Total estimated cost = Labor cost+Parts cost = $12000 + $49.26 = $12049.26

4 Schedule

Week	Xingkai	Ruijie	Tianqi
2/19	Prepare design document	Prepare design document and order parts	Prepare design document, choose the specific components
2/26	Temporarily install cadence and speed sensor on the test bicycle	Verify cadence and speed sensor are working on the test bicycle and refine the design of screen and button mount	Talk with machine shop again to design, manufacture and install worm gear and holder for motor.
3/5	Design circuit schematics and verify circuit design on breadboard	Draw PCB using Eagle and verify with ECE workshop	Manufacture and install the holders for sensors , LCD and buttons.
3/12	Verify the functionality of control unit and UI unit.	Verify the functionality of sensing unit and power unit.	Verify the functionality of motor module and mechanical components.
3/19	Spring break	Spring break	Spring break
3/26	Test the system under manual mode on bike shelf	Develop software	Verify the mechanical part on bike shelf
4/2	Solder the components to PCB and test it	Connect each part to microcontroller	Manufacture the case. Install control unit and battery on the bike
4/9	Collect test data and use it to modify the circuit	Collect test data and use it to modify the control algorithm	Conduct road test and modify mechanical part and motor
4/16	Redesign and remanufacture any problematic part of control unit and UI unit	Redesign and remanufacture any problematic part of sensing unit and power unit.	Redesign and remanufacture any problematic part of motor module and mechanical components
4/23	Collect data during the road test and fix any emerging issue.	Collect data during the road test and fix any emerging issue.	Conduct 10 hour road test and fix any emerging issue.
4/30	Prepare for final demo	Prepare for final demo	Prepare for final demo

5 Ethics and Safety

5.1 Ethnics

Our project should follow the IEEE Code of Ethics, and there are some points worth to be addressed.

According to the IEEE Code of Ethics #5 [2], our product should not injure any people nor their property. We must make sure we think thoroughly about the potential hazard that can be caused by our project. Since our project involves battery and a bicycle, we should follow certain safety procedures when we are operating these two parts, and should also inform our user of any potential hazard.

According to Ethics #6 [2], we have to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations. We are a group of ECE major students, so working on such a project involving certain degree of mechanical engineering can help us expand our knowledge, but we should also ask for help from people with expertise in mechanical engineering when we encounter any problem in mechanics. With this in mind, I believe we could learn a lot through this project.

5.2 Safety

We should handle battery with certain rules to avoid dangers. To be more specific, we should follow the ECE445 battery safety document when we are using battery[15], which includes but not limited to not over charge a battery, not over discharge a battery, not mechanically abuse a battery, not leave a battery to excessive heat or moisture, and etc.

Besides handling battery with great caution, we should also watch out for our safety when we are using a bicycle:

First, changing bike gear at unexpected time might cause injury to the bike rider's knees and feet ankle. When the bike rider is riding in full speed, he or she might put all the body weight on the paddle. If the gear is changed in that situation, the sudden glitch will apply a counter force on one leg and might cause pain on that knee and ankle. To avoid or eliminate such danger, we would implement and test our design on an indoor bike stand whenever possible to minimize this danger, and we would suggest our user not to ride too harsh.

Second, a bike should have the ability to function under unfavorable weather conditions, including raining. Moisture in the environment could potentially cause a shortcut and result in battery burning or even explosion. Thus, we will follow the IP52 standard in design and manufacture process [3], which means the device exclosure should provide protection against dust and water spray. To further ensure our safety, we would still try to develop our project either indoor or under dry outdoor conditions.

Another harmful situation is bike crushing. The physical impact on battery could cause a short circuit inside the battery cell, overheat the neighboring part of the battery and propagate to a fire or even explosion. One of the possible solution is to put the battery inside a container to avoid puncture. Also, we would try to ride the bicycle mildly when we are developing the project and wear all necessary protections like helmet, long sleeve shirts and long pants.

References

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