Wheelchair Dynamometer

Final Presentation: 05/03/20

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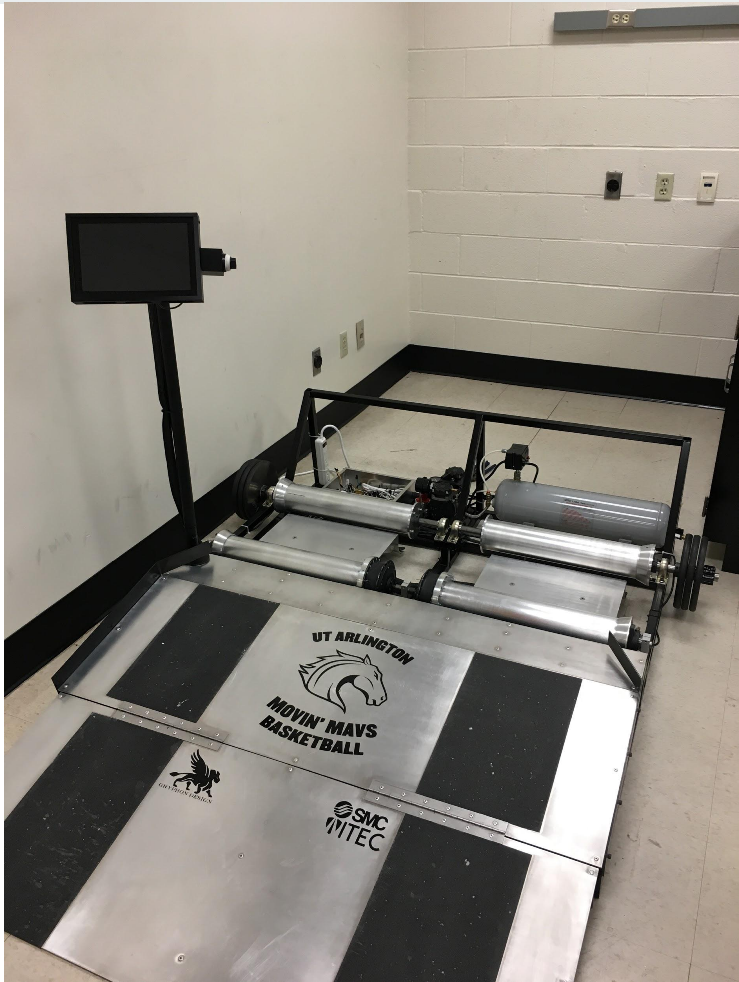
Project Summary

Description & Requirements

- Dyno must use an electrical device to vary mechanical resistance of the rollers and record speed & torque
- Display information (calories, speed, etc..) to the user via a GUI and set difficulty level
- Save & export data of the recorded workout session for performance tracking
- Must function with any browser-supported device such as a smartphone or tablet



Preliminary Products

Invictus Active Trainer ($1300)

Pros:

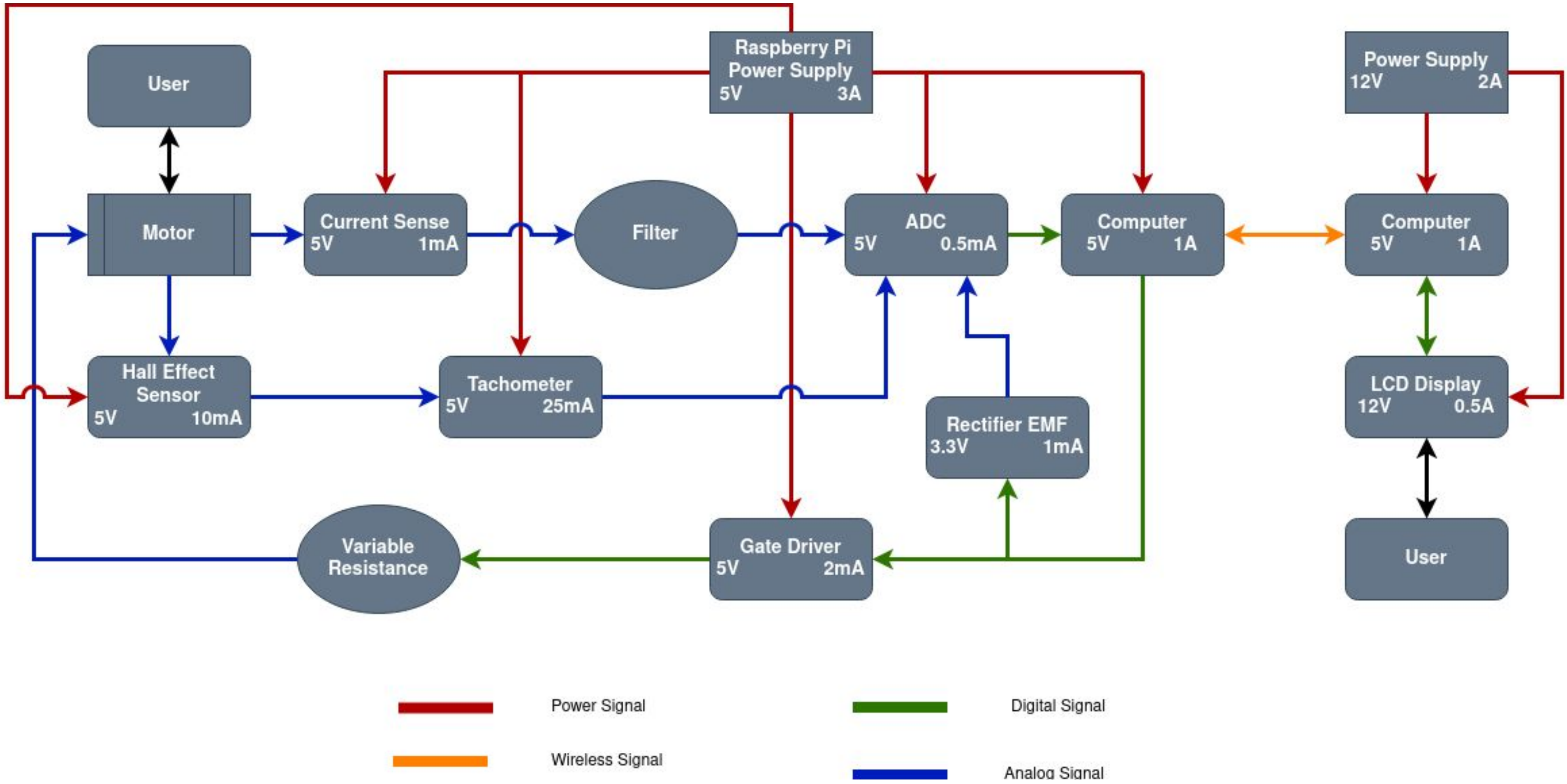
- Measure distance, caloric expenditure, heart rate, and speed
- Portable workout machine

Cons:

- Must own smartphone device
- One resistance setting
- High friction between wheels and rollers
- No torque or power information

https://www.invictusactive.com/product/invictus-active-trainer/

Block Diagram



Dyno Power (Elec./Mech.)

Electrical Calculations

---------------------- Max. Expected Voltage -------------------------

Kt = 0.1085 Nm/A, Ke=0.1090 V/rad/s, R = 2Ω

---------------------- Max. Expected Voltage -------------------------

18MPH record [1]. Assume 20MPH → 1609RPM

$\omega^{*}\tau$ = P = 186 W [2] (M.E. team) → τ = 1.1 Nm

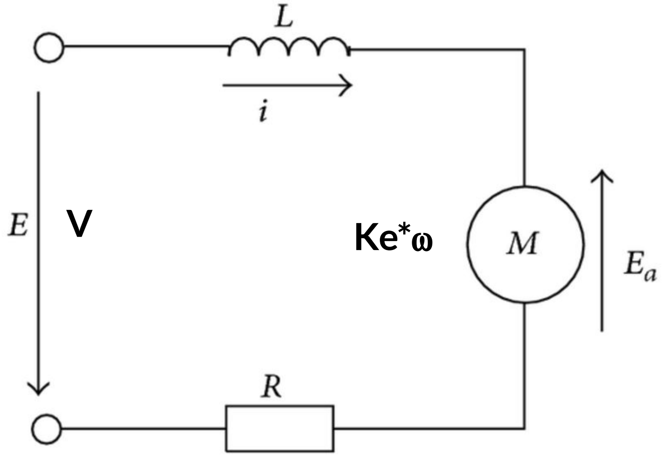
τ = Kt*I

V = I*R + Ke*ω → V = 38.6V ≅ **40V**

-------------------- Max. Expected Current ---------------------------

Max. Force = 6.25 lb [3] (M.E. team) → τ =1.5Nm → I ≅**15A**

V_ind = 0 (Constant current)



https://www.researchgate.net/publication/288918031_Energy_Conservation_Analysis_and_Control_of_Hybrid_Active_Semiactive_Suspension_with_Three_Regulating_Damping_Levels

[1] Veeger, H. E., R. H. Rozendal, and F. Rooth. "Wheelchair racing: effects of rim diameter and speed on physiology and technique." *Medicine and science in sports and exercise* 20.5 (1988): 492-500.

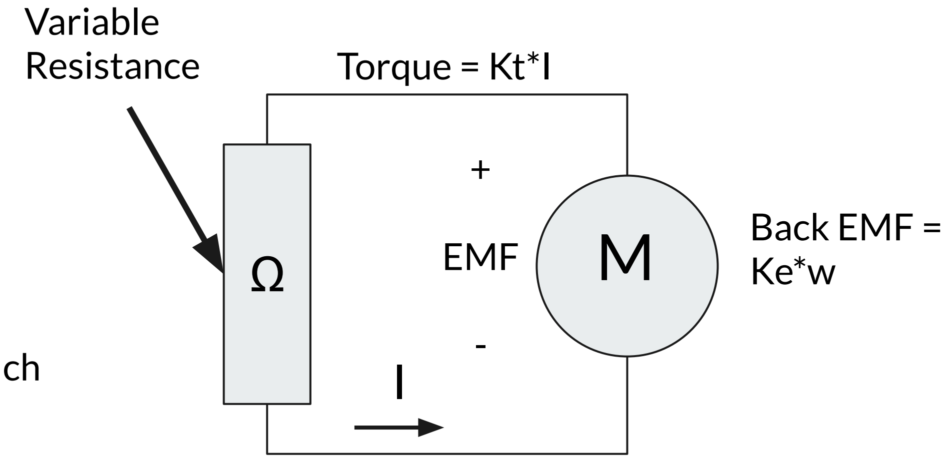
[2] Walker R, Powers S, Stuart MK. Peak oxygen uptake in arm ergometry: effects of testing protocol. *Br J Sports Med*. 1986;20(1):25–26. doi:10.1136/bjsm.20.1.25

[3] Koontz, Alicia M., et al. "A kinetic analysis of manual wheelchair propulsion during start-up on select indoor and outdoor surfaces." (2005).

Design Choices

Variable Resistance

- Potentiometer & step motors
  - Requires separate motors to vary resistance
  - Subject to mechanical wear
  - Expensive
- BJT
  - Most ideal as an amplifier
  - Current controlled
  - High resistance → high power dissipation
- FET's ← **Solution Chosen!**
  - Inexpensive
  - JFET Ideal for low noise applications
  - MOSFET ideal for high noise applications such as switching
  - MOSFET effective for motor control applications
- Digital Potentiometer (Digipot)
  - Only available for high resistance values
  - Low-power applications only so high current not allowed

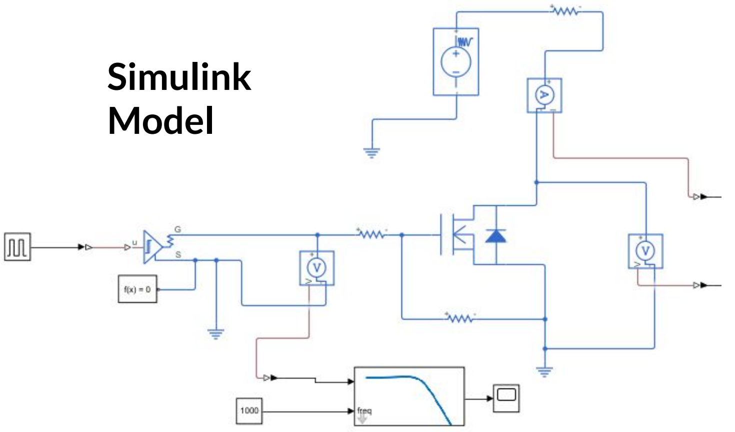


Variable Resistance Pt. 1

Selected Design: Power Mosfet

- Power Requirements
  - 1.5 Nm limit → max load current: 15A
  - 20 mph limit → max load voltage: 40V
- PWM Duty Cycle
  - Resistance settings determined by experimentation
  - Duty cycle simulation discrepancy caused by simplified motor model
- PWM Frequency
  - 25 kHz to prevent audible whine in human hearing range
  - Going higher → greater transition times → more power dissipation

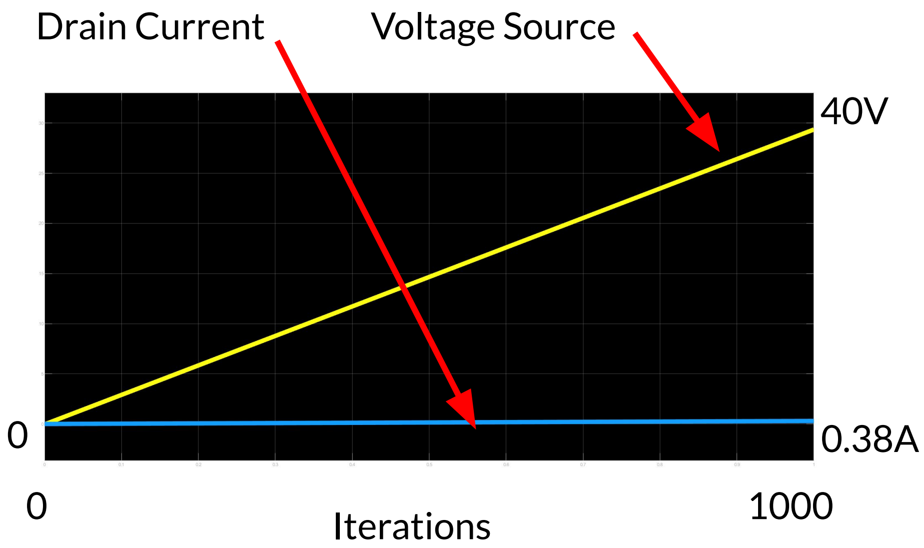
Simulink Model

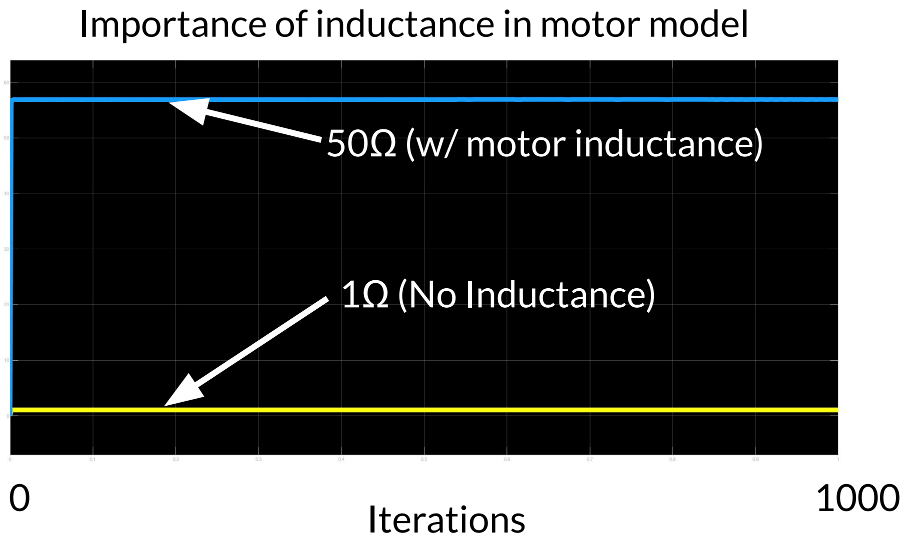


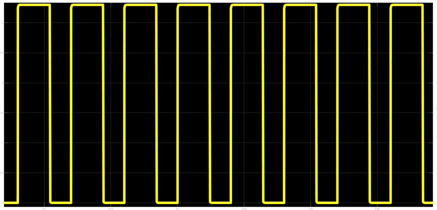
Simulation Results		
Shunt Resistance	**Workout Difficulty**	**PWM Duty Cycle**
1 Ω	Mountain Climbing	66%
100 Ω	Easy Stroll	4.5%

Variable Resistance Pt. 2

Simulation Results





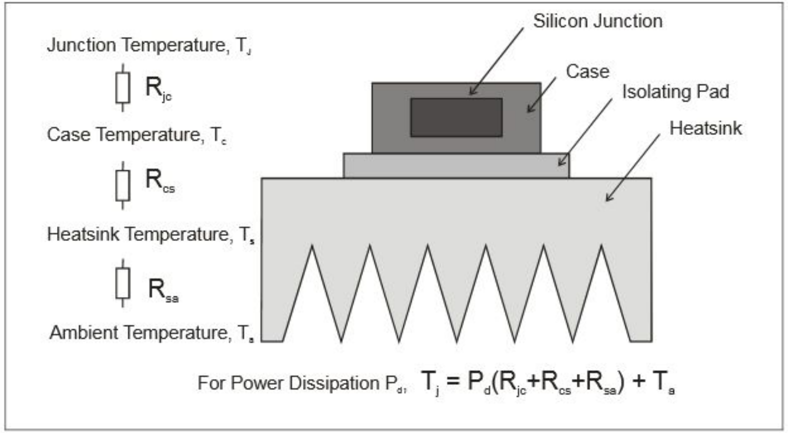


Gate Driver Output → MOSFET Gate Input

Variable Resistance Pt. 3

Power Mosfet

- Power Dissipation
    - Based on switching speeds, load power, and mosfet datasheet parameters
    - Calculated dissipation: 10W
    - Mosfet Temperature: 105℃ < 135℃ (75% max) ✓
- Gate Driver
    - Power Mosfet contains higher input capacitance than normal mosfets
    - Microcontrollers do not provide enough current to have fast transition times and low power dissipation
    - Gate drivers provides enough current to charge the input capacitor



https://www.re-innovation.co.uk/docs/heatsink-calculations/

https://www.sparkfun.com/products/9576

Variable Resistance Experiment

- Experiment to figure out what shunt resistances work well for the user and what is the related PWM cycle
- Relate shunt resistance seen by the motors to a workout difficulty level and PWM duty cycle
- Subjective testing via wheelchair on dyno to determine noticable differences
- PWM duty cycle calculated by Simulink Simulations after figuring out shunt resistance

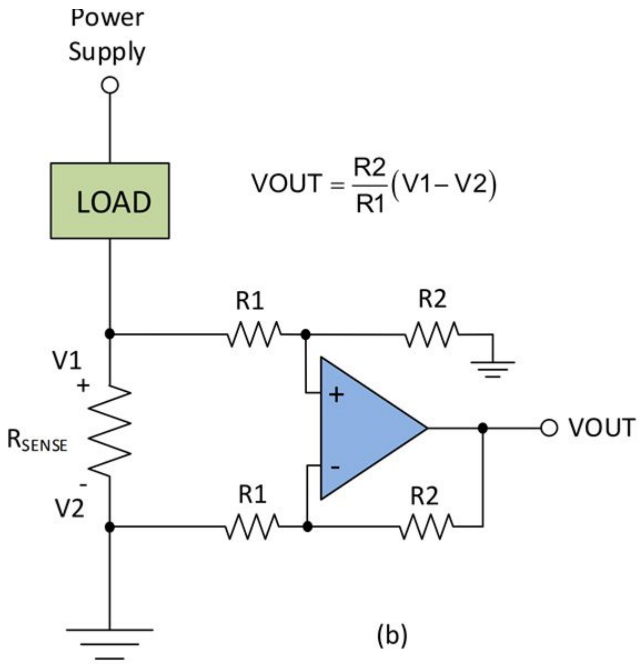
Simulation Results			
Difficulty Setting	**Shunt Resistance**	**Workout Difficulty**	**PWM Duty Cycle**
6	0 Ω	Hardest	100%
5	5 Ω	Hard	30%
4	25 Ω	Medium	7.5%
3	40 Ω	Normal	4.75%
2	100 Ω	Easy	2%
1	Inf. Ω	Easiest	0%

Design Choices

Torque Measurement Pt. 1

Torque = Motor Constant * Current

- Direct current sensing ← **Solution Chosen**!
    - Shunt resistor across motor terminals gives a small voltage that can be amplified
    - Typical when current < 100 A
    - Low cost
    - High & low side implementations
- Indirect current sensing
    - Coil around a conductor causes voltage to be induced, voltage proportional to the system current
    - Used for systems with currents >100 A
    - Requires high cost sensors



http://www.ti.com/lit/an/sboa190/sboa190.pdf

Design Choices

Torque Measurement Pt. 2

- Different implementations
  - Low-side ← **Solution Chosen!**
    - Lower cost & only requires a differential amplifier
  - High-side
    - More expensive and short-circuit detection not important for our applications
    - Other additional features over low-side not required for dyno project

High-Side

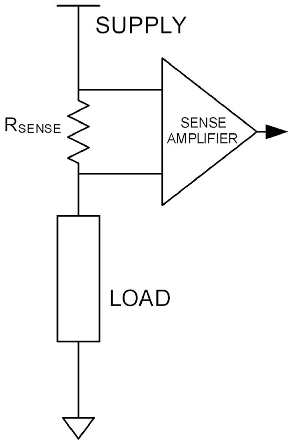


FIGURE 1A

Low-Side

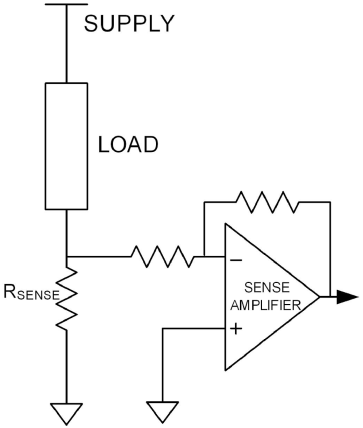


FIGURE 1B

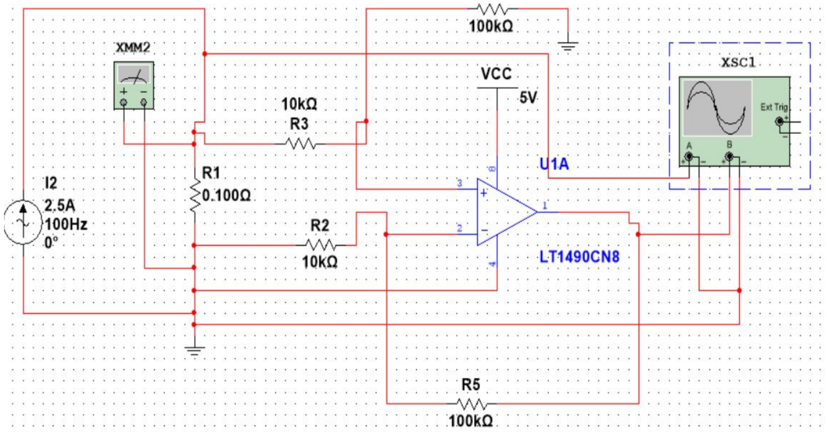
Image Courtesy: Texas Instruments, Inc.

- Low-side implementation used in project with correct gain to map full range to 0-5V

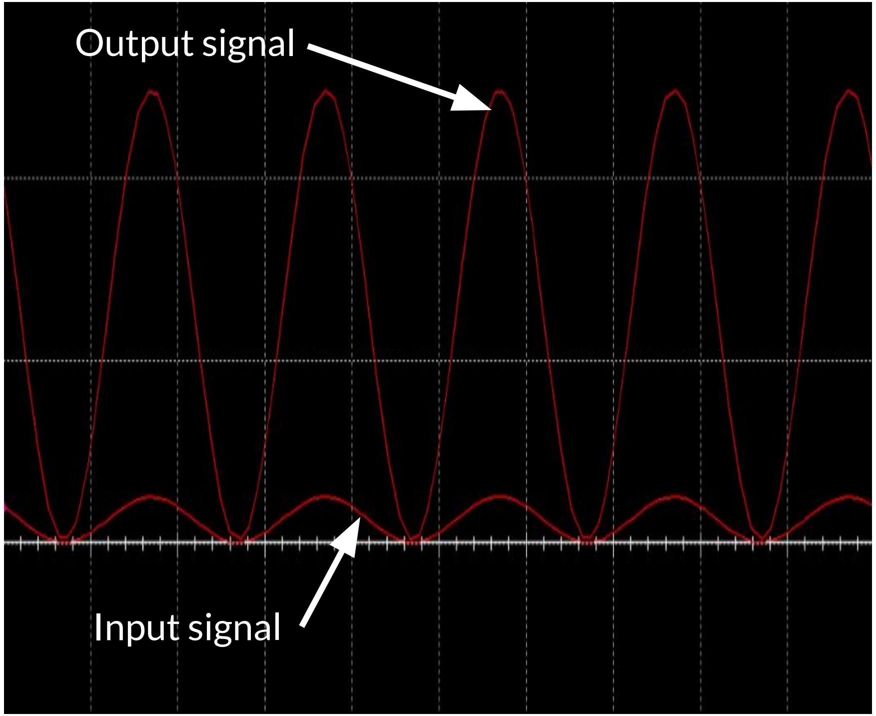
Torque Measurement

Current Sense Simulation

- Input voltage range: 0 V - 0.5 V
- Output voltage range: 0V - 5V
- Gain: 10 V/V



Low side differential implementation in multisim

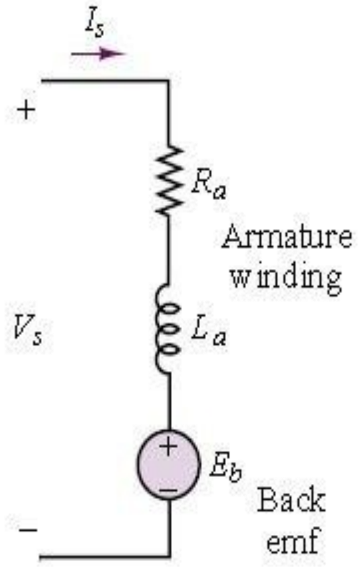


Oscilloscope simulation result

Previous Design Choice

Speed Measurement

- Hall Effect Sensors ← **Solution attempted**
  - Sensor detects a change in the magnetic field of a motor pole while rotating
  - Frequency of the signal contains the speed of the motor so a frequency to voltage mapper is necessary for the single-board computer to read
  - Issues with PWM switching noise leaking to Frequency/Voltage mapper thus giving unreliable data
- Back EMF ← **Solution Chosen!**
  - Estimate speed based on rectifier voltage, current, and change of current
  - Already tracking torque (current) so solution works in theory



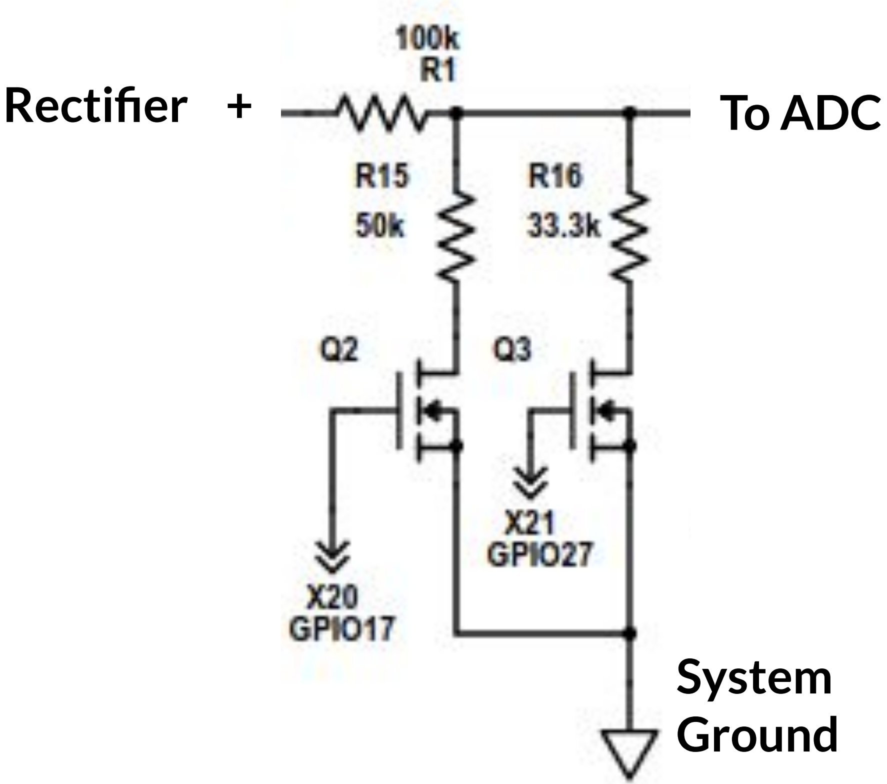
Circuit model for PM motor

https://www.completepowerelectronics.com/permanent-magnet-dc-pmdc-motor/

Updated Design Choice

Rectifier EMF Method

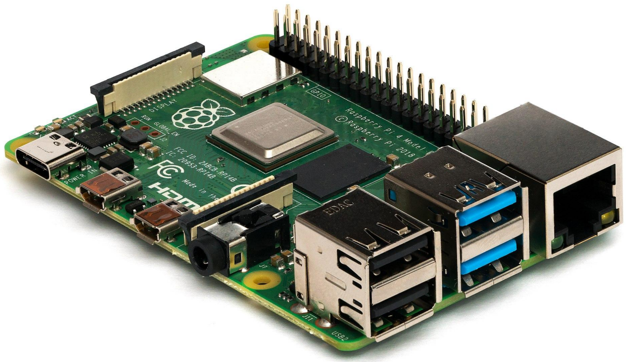
- ADC can only handle 5V max without causing damage to the chip
- Multi-stage voltage divider can accommodate all workout levels and the expected rectifier voltages
- Design tested on Multisim and on a breadboard to ensure success
- Basic voltage divider configuration implemented on past PCB and results look good



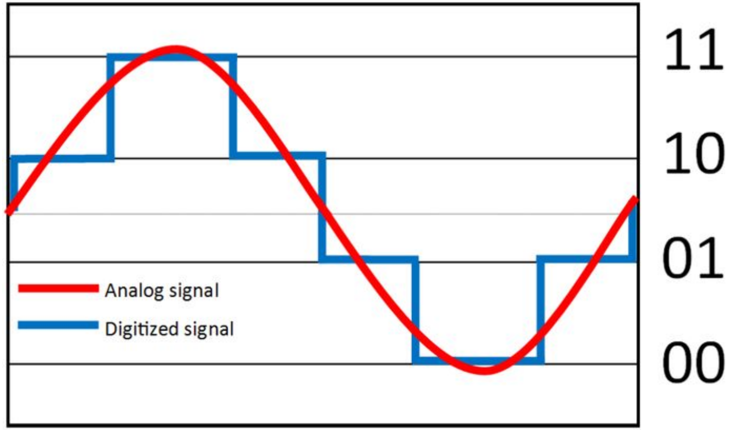
Single-Board Computer

Raspberry Pi & ADC

- Electronic Device
  - Single-board computer needed over microcontrollers since web server hosting is required
  - Requirements: Analog pins and wireless capabilities
  - Cheapest solution is to use a Raspberry Pi + ADC instead of an all-in-one solution
- Analog Digital Converter (ADC)
  - Required since Raspberry Pi has no built-in ADC
  - Sampling rate: Only a few samples needed per second
  - Resolution: 10-bit ends up cheaper than 8-bit ADC and 10-bit leads to noise level under 5% error



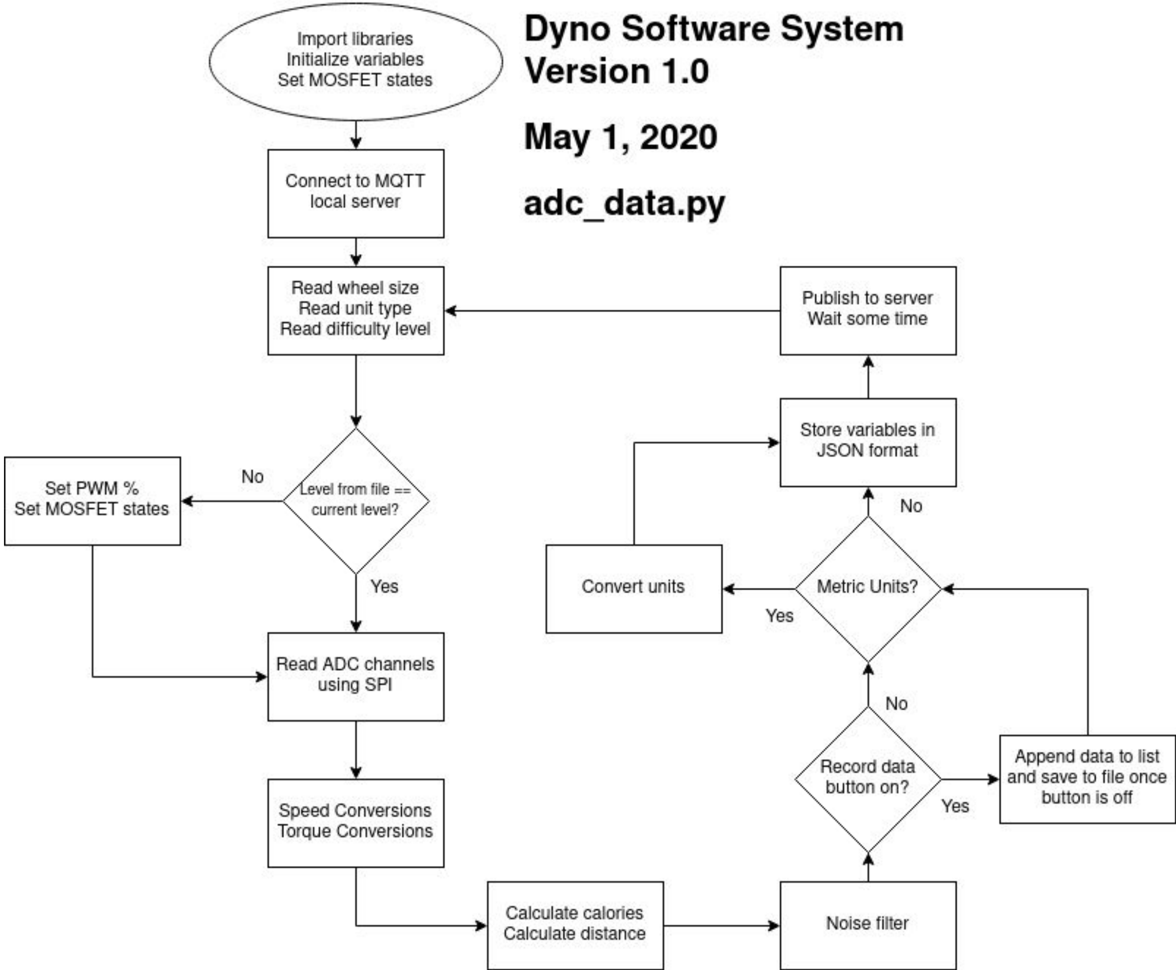
https://en.wikipedia.org/wiki/Raspberry_Pi



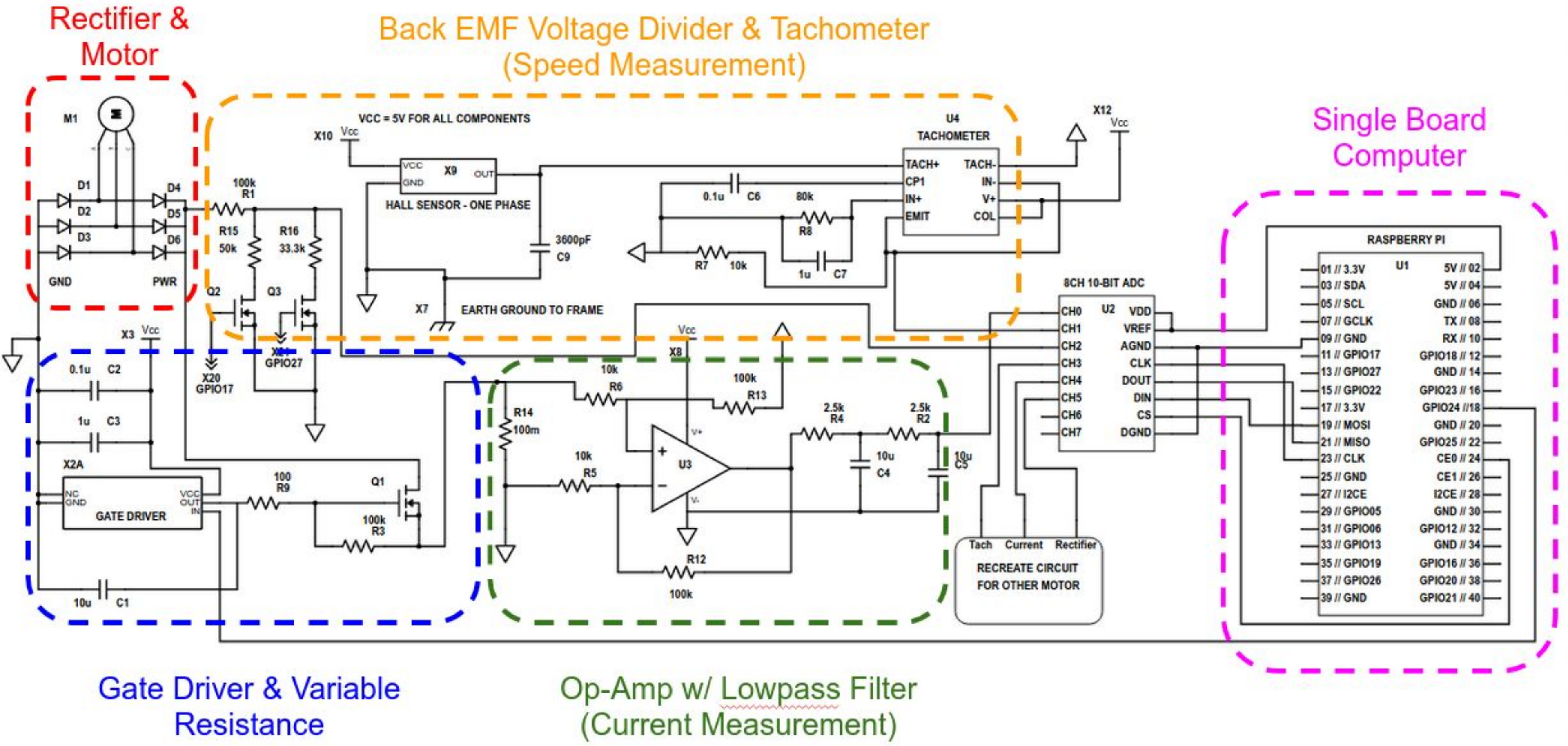
https://community.keysight.com/community/keysight-blogs/oscilloscopes/blog/2016/08/22/this-quick-trick-makes-your-oscilloscope-measurement-1000-times-better

Software System

- Software flowchart for main code file responsible for processing inputs and setting workout levels
- Python file broken into chunks as shown to make it easier to understand overall picture
- Text files store unit type, difficulty level, and wheel size
- Javascript files change file state for control knob and data record button
- PHP script changes text files based on user selection of unit type or wheel size



Detailed Circuit Diagram



Part Selection Pt. 1

- MOSFET
  - Drain-Source voltage should support 40V
  - Drain current should support 15A
  - Low Rds means lower power dissipation
  - Lower gate charge means quicker transition times
- Rectifier
  - Reverse voltage should support 40V as this is the theoretical max value for 20 MPH limit
  - Max surge current should support 15A as this is the torque limit supported by theory
  - Lower diode resistance is better as the motor can get closer to stalling conditions

Mosfet Comparison

Component Name	Breakdown Voltage Vds	Maximum Drain Current Id	Mosfet On Resistance Rds	Gate Charge	Price
IRFZ24NPBF	55 V	17 A	70 mOhms	13.3 nC	$0.63
CSD18537NKCS	60 V	56 A	14 mOhms	14 nC	$1.29
IPP12CN10L G	100 V	69 A	9.9 mOhms	58 nC	$1.67
IRFB3806PBF	60 V	43 A	12.6 mOhms	22 nC	$0.83

Rectifier Comparison

Component Name	Peak Reverse Voltage	Maximum Surge Current	Maximum Operating Temperature	Diode Resistance	Price
FUO22-12N	1200 V	22 A	150 C	120mΩ	$6.88
GUO40-12NO1	1200 V	40 A	150 C	80mΩ	$9.02
FUE30-12N1	1200 V	30 A	175 C	140mΩ	$11.23
FUS45-0045B	45 V	45 A	150 C	36mΩ	$6.83

Part Selection Pt. 2

- Gate Driver
  - Supply voltage is 5V so this should be supported
  - Higher output current means mosfet can switch faster thus less heat dissipation
  - Lower rise/fall times can support higher PWM frequencies
- Single-Board Computer
  - Wireless capabilities are necessary to connect external display
  - GPIO that allows for analog and digital pins is ideal but ADC can be utilized
  - Pi 3 + ADC is cheapest combination and meets requirements so this option is selected

Gate Driver Comparison

Component Name	Supply Voltage	Output Current	Rise / Fall Times	Maximum Operating Temperature	Price
IX4424G	4.5-30 V	2 A	60 nS / 60 nS	125 C	$1.58
MCP14E10	4.5-18 V	3 A	14 nS / 17 nS	125 C	$1.86
MIC4423ZN	4.5-18 V	3 A	28 nS / 32 nS	70 C	$2.20
MIC4424YN	4.5-18 V	1 A	35 nS / 35 nS	85 C	$1.77

Single-Board Computer Comparison

Computers	Wireless Capabilities	Processor	RAM Size	GPIO	Price
ODROID-C2	None	2 Ghz ARM-A53	2 GB	Analog + Digital	$40
Libre AML-S905X	None	1.4 Ghz ARM-A53	2 GB	Only Digital	$45
Orange Pi 4G-IOT	Wifi + Bluetooth	1 Ghz ARM-A53	1 GB	Only Digital	$45
Raspberry Pi 4	Wifi + Bluetooth	1.5 GHz ARM-A72	1-4 GB	Only Digital	$35
BeagleBone Black	None	1 GHz ARM-A8	512 MB	Analog + Digital	$55

Part Selection Pt. 3

- Op-Amps
  - Lower input offset voltage means more accurate results at low currents (--> low torque)
  - Higher CMRR means better resistance against noise
- ADC
  - Sample rate works for any value as we are sampling a few times a second
  - Due to updated design, 8 channels is necessary
  - 8-bit and 10-bit work well since we only go to one decimal place
- Tachometer
  - Input voltage is from -5 to 5V so only half of components work
  - Frequency should support 0 to 100 Hz so all components work

Operational Amplifiers Comparison

Component	Input Offset Voltage	Channels	CMRR	Price
LT1490	110 uV	2	98 dB	$5.09
OPA2227PA	75 uV	2	130 dB	$5.48
OPA2336P	125 uV	2	80 dB	$6.07

Analog Digital Converter

Component	Resolution	Sampling Rate	Channels	Price
MPC3004	10	200 kS/s	4	$2.14
MCP3008	10	200 kS/s	8	$2.25
MCP3204	12	100 kS/s	4	$3.26
TLC0838	8	20 kS/s	8	$5.06

Tachometer

	LM2907N-8	LM2917N-8	LM2917N-14	LM2907N-14
Frequency (kHz)	10	10	10	10
Input Voltage (V)	(-28) - 28	(-28) - 28	0 - 28	0 - 28
Cost	$2.33	$2.13	$2.13	$2.33

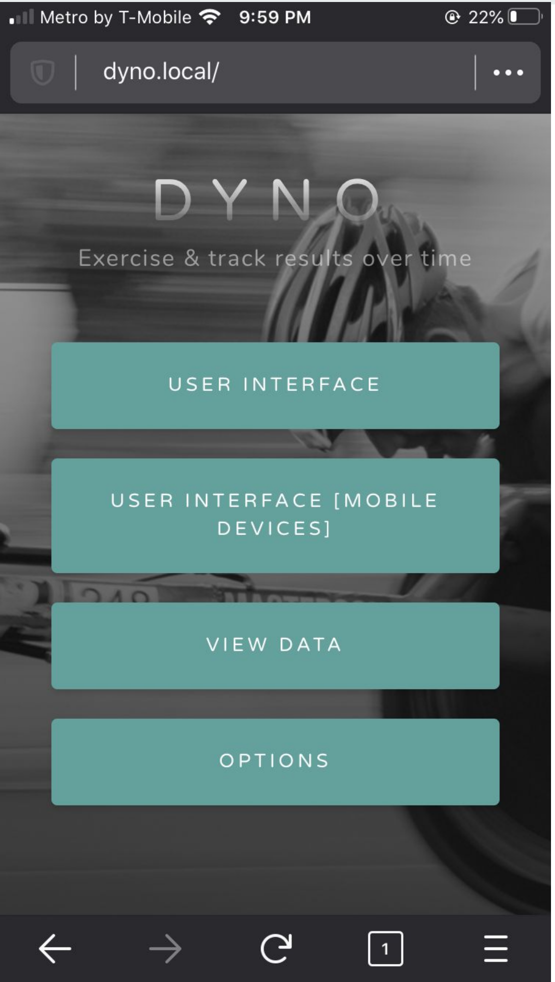
Power Consumption

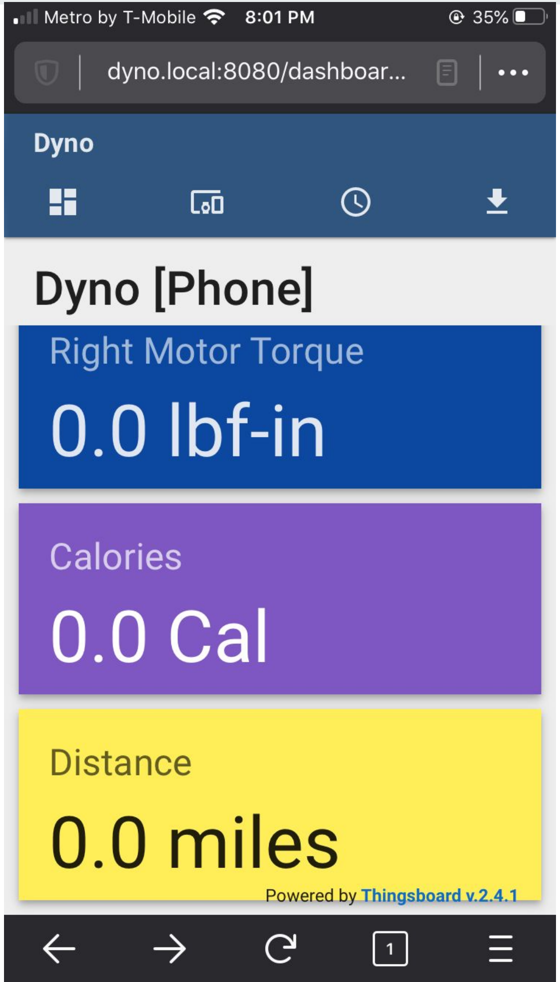
Power Consumption			
Component	Voltage	Current	Power
Tachometer (x2)	5V	0.28A	1.4W
Gate Driver (x2)	5V	0.1A	1W
Amplifiers (x2)	5V	0.02A	0.2W
ADC (x1)	5V	0.01A	0.1W
Total:	5V	0.42A	2.7W

Therefore, 5V 2.5A power supply works well!

User Interface

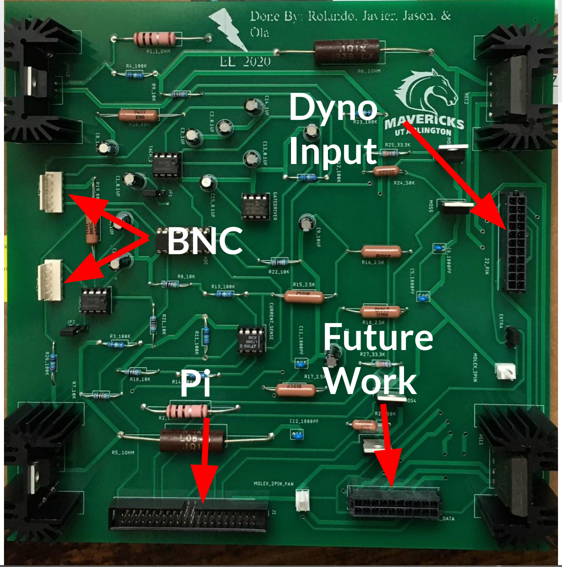
Mobile User Interface

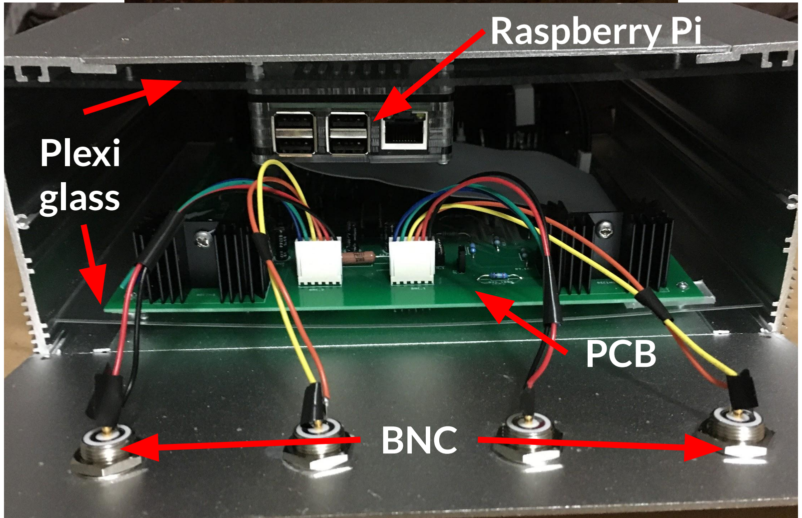




Etched PCB & Enclosure

- Double-layer 2 oz copper FR4 board professionally etched by PCBWay
- Easy connectors for Raspberry Pi, dyno wires (Molex), and BNC connections
- Heatsink on board for proper cooling and adequate trace widths for current capacity
- Future work connector to possibly integrate motor controllers to main system
- PCB and Pi mounted on plexiglass that fits into grooves of aluminum enclosure



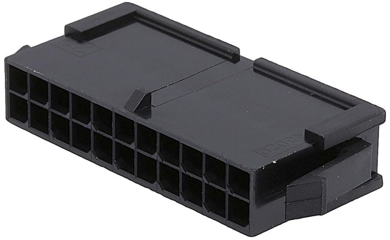


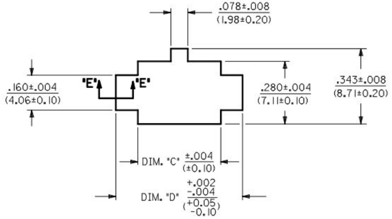
Enclosure Pt. 2

- Aluminum enclosure with internal groves to slide PCB and Pi by using plexiglass
- 22-Pin Molex connector attached at the front to connect dyno wires to the box
- Back panel has four BNC connectors for data acquisition
- Securing enclosure to frame remains to be done

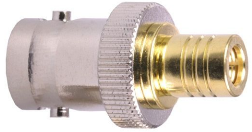
Inside Enclosure

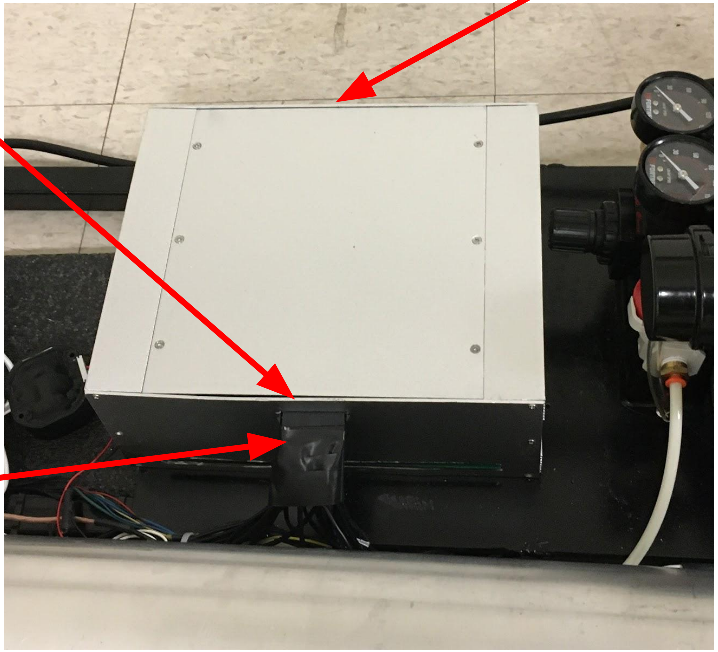
https://www.molex.com/molex/products/part-detail/crimp_housings/0430252200





https://www.aliexpress.com/store/product/1PC-Electronic-Connector-BNC-Female



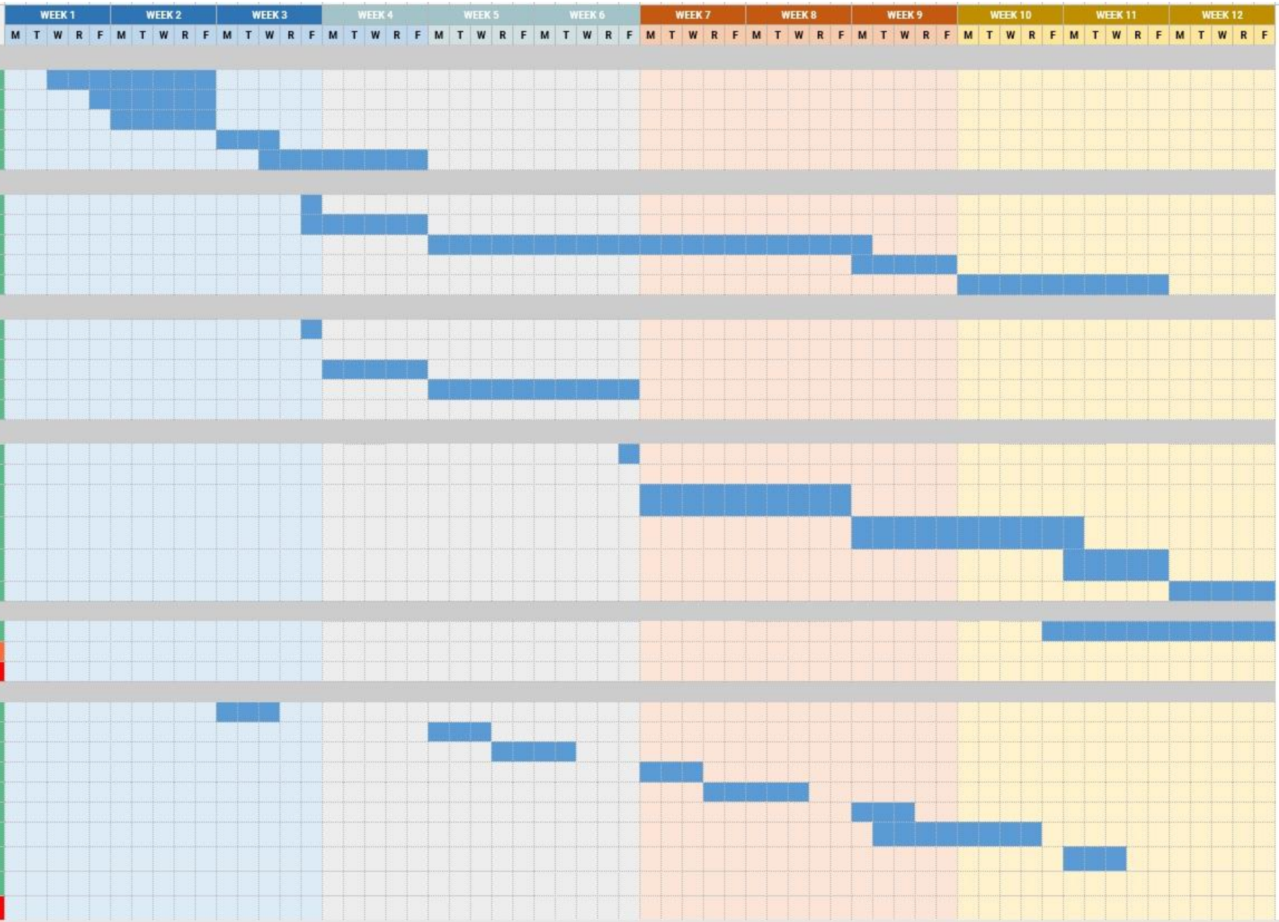


Budget List

Part Name	Part Number	Quantity	Cost
Mosfets	CSD18537NKCS	6	$10.02
Pin Headers (x20)	855-M20-9993045	1	$1.04
Gate Driver	579-MCP14E10-E/P	1	$4.23
Frequency Voltage Converter	926-LM2917N-8/NOPB	2	$4.26
Operational Amplifier	584-LT1490ACN8#PBF	1	$5.48
Current Sense Resistor	66-LOB5R100FLF	2	$3.08
DIP Socket (16P)	571-1-2199298-4	1	$0.23
DIP Socket (8P)	571-1-2199298-2	4	$0.88
Heat Sink	588-RA-T2X-25E	4	$7.96
Thermal Paste	532-249	1	$9.38
Heat Shrink Tubing	650-829131P019	25	$2.60
0.1uF Capacitor	647-UKL1H0R1KDDANA	4	$1.44
1uF Capacitor	647-UKL1H010KDDANA	4	$0.40
10uF Capacitor	647-UKL1C100KDD1TD	4	$1.20
1800pF Capacitor	810-FG28C0G1H182JNT0	4	$0.46
100K Resistor	660-MF1/4LCT52R104G	6	$0.60
10K Resistor	660-MF1/4LCT52R103G	8	$0.80
80K Resistor	71-RN65C8002B	2	$1.35
2.5K Resistor	71-RN60D2501F	4	$1.44
0.1K Resistor	603-FMP300FRF73-1R	2	$1.18
3-Phase Rectifier	747-FUS45-0045B	2	$13.66
Ring-Tongue Connector	571-696424-7	2	$2.64
Analog/Digital Converter	579-MCP3008-I/P	1	$2.19
Raspberry Pi 3 Model B+	B07BC6WH7V	1	$64.99
Raspberry Case w/ fan	B07BTHNW9W	1	$15.99
Molex 2-Pin PCB	538-22-23-2021	2	$0.34
Jumpers	474-PRT-09044	3	$1.05
Pi Ribbon Cable	474-CAB-13028	1	$2.50
Pi PCB Header	474-PRT-13054	1	$0.95
Molex 22-pin Male	538-43025-2200	2	$2.74
Molex 22-pin Female	538-43020-2200	1	$2.50
Molex PCB Header 22-Pin	538-43045-2212	1	$4.42
Female Crimp Terminals	538-43030-0007	65	$9.50
Male Crimp Terminals	538-43031-0007	50	$8.45
Molex 6-Pin Assembly	474-PRT-09922	2	$3.90
50K Resistor	71-RN60C5002D	2	$0.82
33.3K Resistor	660-MF1/4CCT52R3322F	2	$0.38
20-pin PCB Header	538-43045-2012	1	$3.55
20AWG Wire	510-CT2879-0-10	1	$13.65
Molex 2-pin Housing	538-22-01-3027	2	$0.24
Molex 2-pin Crimps	538-08-50-0114	4	$0.68
Enclosure	B07VRKD183 [Amazon]	1	$29.99
32GB MicroSD	B073JWXGNT [Amazon]	1	$7.99
Final PCB	NA [PCBWay]	5 Minimum	$120.00

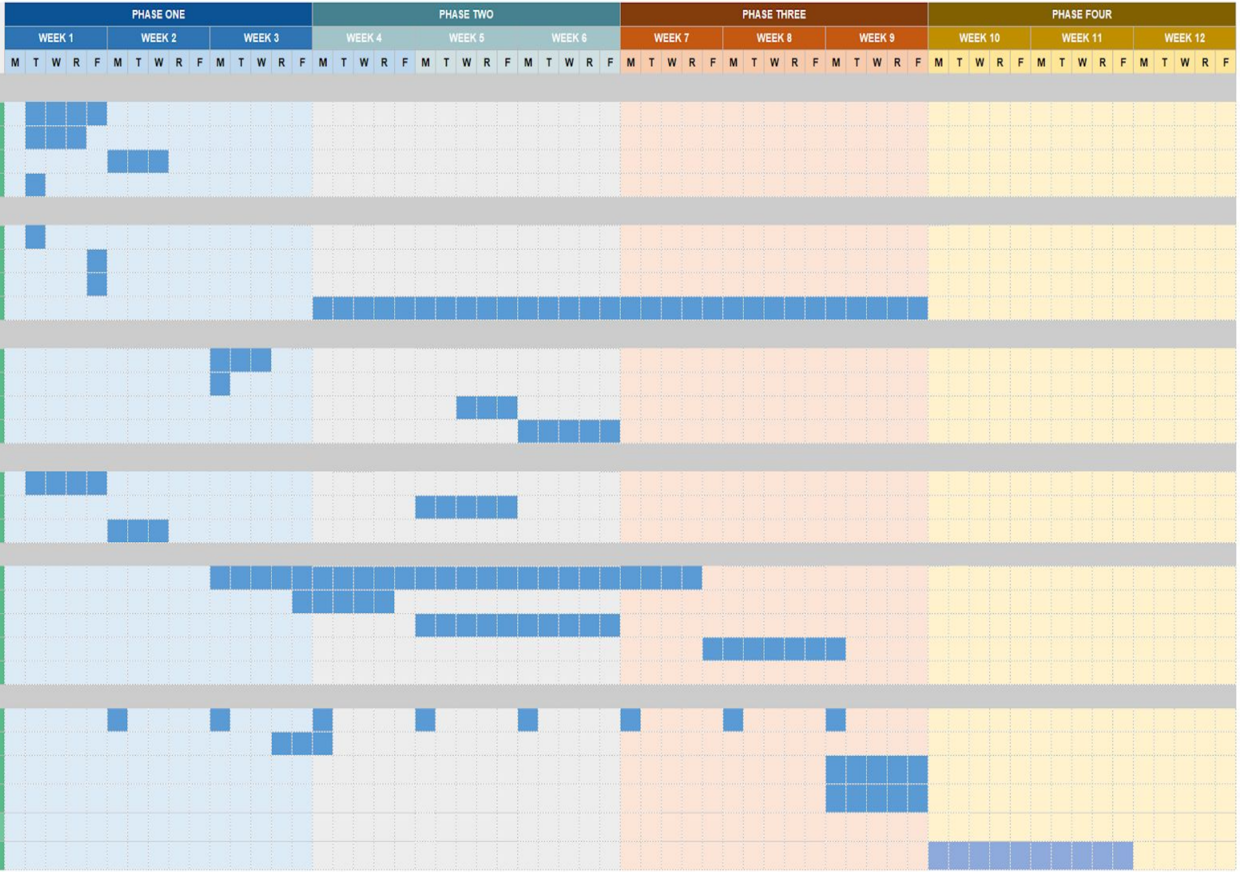
Fall 2019 Schedule

WBS NUMBER	TASK TITLE	TASK OWNER	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
1	**Project Comprehension and Initiation**					
1.1	Project Familiarization	All	8/28/19	9/8/19	10	100%
1.2	Overall General Research	All	8/30/19	9/8/19	8	100%
1.3	Presentation Compilation	All	9/4/19	9/8/19	4	100%
1.4	Project Initial Presentation	All	9/9/19	9/11/19	2	100%
1.5	Analysis of Previous Teams' Work	All	9/11/19	9/20/19	9	100%
2	**Passive Electronics**					
2.1	Scope and Goal Setting	All	9/13/19	9/13/19	0	100%
2.2	Research	All	9/13/19	9/20/19	7	100%
2.3	Circuit Design	Javier	9/22/19	10/21/19	29	100%
2.4	Simulation	Jason; Javier	10/21/19	10/25/19	4	100%
2.5	Testing	Jason; Javier	10/28/19	11/8/19	10	100%
3	**Wireless Data Transmission**					
3.1	Scope and Goal Setting	All	9/13/19	9/13/19	0	100%
3.2	Communication Plan	All	9/14/19	9/15/19	1	100%
3.3	Research	Javier; Jason	9/16/19	9/20/19	4	100%
3.4	Coding	Javier; Jason	9/23/19	10/4/19	11	100%
3.5	Troubleshooting	Javier; Jason	11/25/19	11/29/19	4	100%
4	**Raspberry Pi Coding**					
4.1	Scope and Goal Setting	All	10/4/19	10/4/19	0	100%
4.2	Communication Plan	All	10/5/19	10/6/19	1	100%
4.3	Dynamometer Research	Olateju; Rolando	10/7/19	10/20/19	13	100%
4.4	Coding	Olateju; Rolando	10/21/19	11/4/19	13	100%
4.5	Troubleshooting	Olateju; Rolando	11/4/19	11/8/19	4	100%
4.6	Testing	Javier; Jason	11/10/19	11/14/19	4	100%
5	**Circuit Manufacturing**					
5.1	Eagle Circuit Design	Rolando	11/1/19	11/15/19	14	100%
5.2	PCB Board Milling	Rolando	11/16/19	11/18/19	2	50%
5.3	Testing	All	11/18/19	12/3/19	15	0%
6	**Presentations and Reports**					
6.01	Project Initial Presentation	All	9/9/19	9/11/19	2	100%
6.02	Presentation 2	All	9/23/19	9/25/19	2	100%
6.03	Design-of-Experiment Abstract	All	9/26/19	9/30/19	4	100%
6.04	Presentation 3	All	10/7/19	10/9/19	2	100%
6.05	Two-Page Product Proposal	All	10/10/19	10/15/19	5	100%
6.06	Presentation 4	All	10/21/19	10/23/19	2	100%
6.07	Interim Written Report	All	10/22/19	10/31/19	9	100%
6.08	Presentation 5	All	11/4/19	11/6/19	2	100%
6.09	Final Presentation	All	11/18/19	11/25/19	7	100%
6.1	Final Written Report	All	11/22/19	12/11/19	19	0%



Spring 2020 Schedule

WBS NUMBER	TASK TITLE	TASK OWNER	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
1	**Project and Goals**					
1.1	Familiarization with expectation	All	1/21/20	1/25/20	4	100%
1.2	Recap on research	All	1/21/20	1/24/20	3	100%
1.3	Goal Setting for the semester	All	1/27/20	1/29/20	2	100%
1.4	Refresher on last semester's progess	All	1/21/20	1/21/20	0	100%
2	**Mechanical Integration**					
2.1	Scope and goal setting	All	1/22/20	1/22/20	0	100%
2.2	Air Pressure	Olateju	1/27/20	1/29/20	2	100%
2.3	Circuit clean-up	Olateju	1/27/20	1/29/20	2	100%
2.4	Enclosure	Jason	2/10/20	3/21/20	41	100%
3	**Design Update**					
3.1	Scope	All	2/3/20	2/5/20	2	100%
3.2	Communication Plan	All	2/3/20	2/3/20	0	100%
3.3	Circuit Testing	Javier; Rolando	2/19/20	2/21/20	2	100%
3.4	Troubleshooting	Javier; Olateju	2/24/20	2/28/20	4	100%
4	**Software Improvement**					
4.1	GUI Display Improvement	Javier;Jason	1/21/20	1/24/20	3	100%
4.2	Coding	Javier	2/15/20	2/28/20	13	100%
4.3	Troubleshooting	Javier	1/27/20	1/29/20	2	100%
5	**Circuit Manufacturing**					
5.1	Eagle Circuit Design Adjustment	Rolando;Javier	2/3/20	3/5/20	32	100%
5.2	PCB Board Milling	All	2/1/20	2/13/20	12	100%
5.3	Board Population	All	2/17/20	2/28/20	11	100%
5.4	Professional PCB milling	NA	3/6/20	3/23/20		100%
5.5	Testing	All	3/24/20	4/4/20	10	100%
6	**Presentations and Reports**					
6.1	Weekly Slides	All	1/26/20	5/8/20	102	100%
6.2	Innovation Day Poster	Javier	2/7/20	2/10/20	3	100%
6.3	Interim Presentation	All	3/16/20	3/20/20	4	100%
6.4	Interim Written Report	All	3/16/20	3/27/20	11	100%
6.5	Final Presentation	All	4/10/20	5/1/20	21	N/A
6.6	Final Written Report	All	5/1/20	5/11/20	10	100%



Video Evidence

- PCB Experiments
  - Experiments conducted using the final PCB before connecting things to the actual dyno
  - Components tested include the following: gate driver, ADC, Pi connectivity, Tachometer, Multi-stage voltage divider, and current sensor
  - Power supply, function generator, oscilloscope, and multimeter used to verify components
  - Results look good so testing moved to using the actual dyno machine
  - https://web.microsoftstream.com/video/fa23dd65-769f-4800-a2ae-d4a5f3a12bb8
- Dyno Demo:
  - Demo video recorded to show that project requirements are satisfied
  - Video shows startup, using the dyno display to control resistance, changing settings, viewing past workout data, and showing real-time torque and speed information
  - The mechanical system is also utilized to show complete integration
  - https://youtu.be/Yah3G0mNRrM

Conclusion

- Summary
  - Dyno can display speed, torque, calories burned, distance traveled, maximum value information
  - The user is able to vary the mechanical resistance of the rollers to have different workout levels based on their athletic ability
  - Data can be recorded and accessed with any browser-enabled device or the included display to track progress
  - Electrical system starts automatically and is packaged in a professional aluminum enclosure
- Possible future work
  - Remove friction between wheels and rollers for life-like rolling by utilizing some kind of motor controllers