UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Watt Balance

Electrical & Computer Engineering

Team 76

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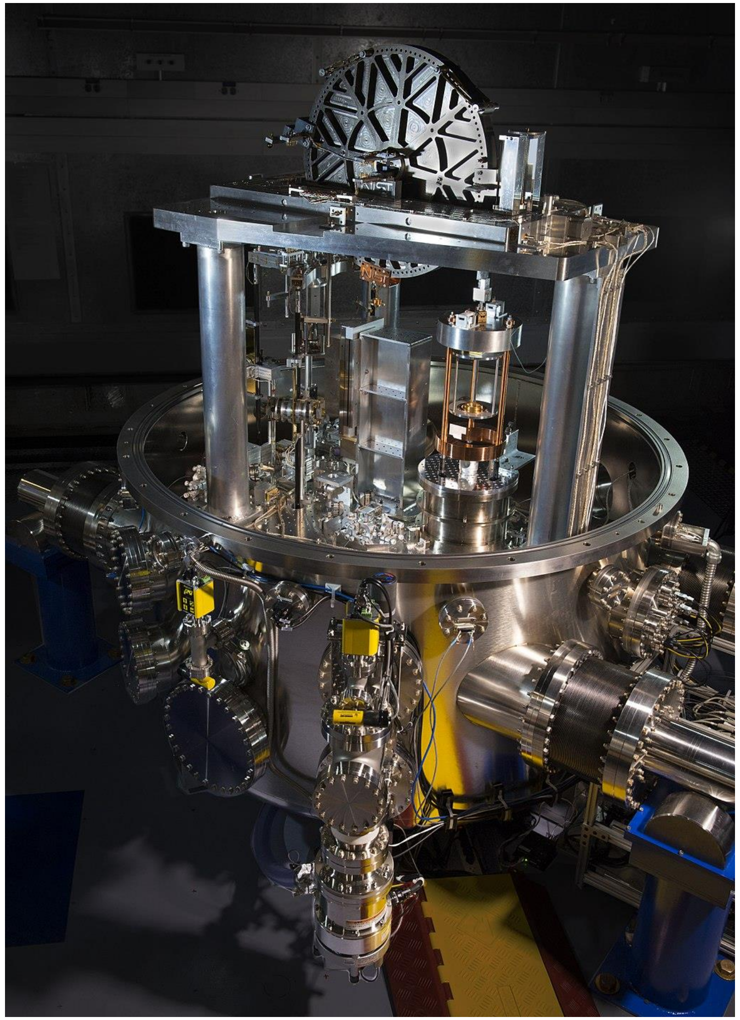
April 29, 2024



The NIST-4 Kibble Balance [1]

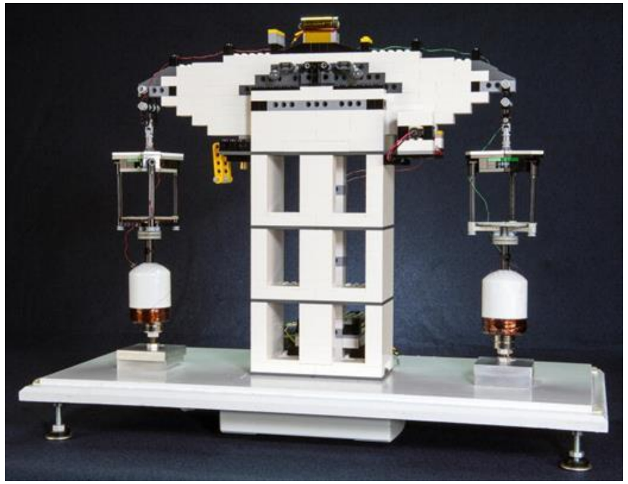
The Watt Balance

The Watt balance, also known as a Kibble balance was invented by Dr. Bryan Kibble. It is an instrument that finds the mass of an object through electromagnetic force and gravity. Additionally, it can be used to measure Planck's constant.

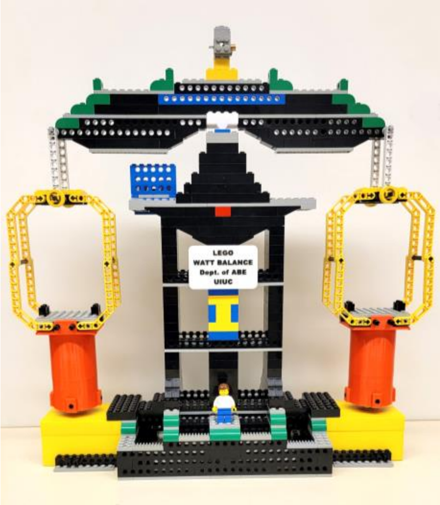
Our Balance

Our goal was to replicate one of these balances in a cost effective and accurate manner.

Background



The NIST LEGO® Watt Balance [2]



The UIUC ABE Graduate LEGO® Watt Balance

A LEGO® Balance

Researchers at the National Institute of Standards and Technology (NIST) wrote a paper detailing the process of how to create a DIY LEGO Watt balance.

A Second Balance

A group of graduate students from the UIUC ABE department used the NIST paper to create their own version of the LEGO Watt balance. They pitched a project to create a more refined version.

Balance Operation Modes

Velocity Mode

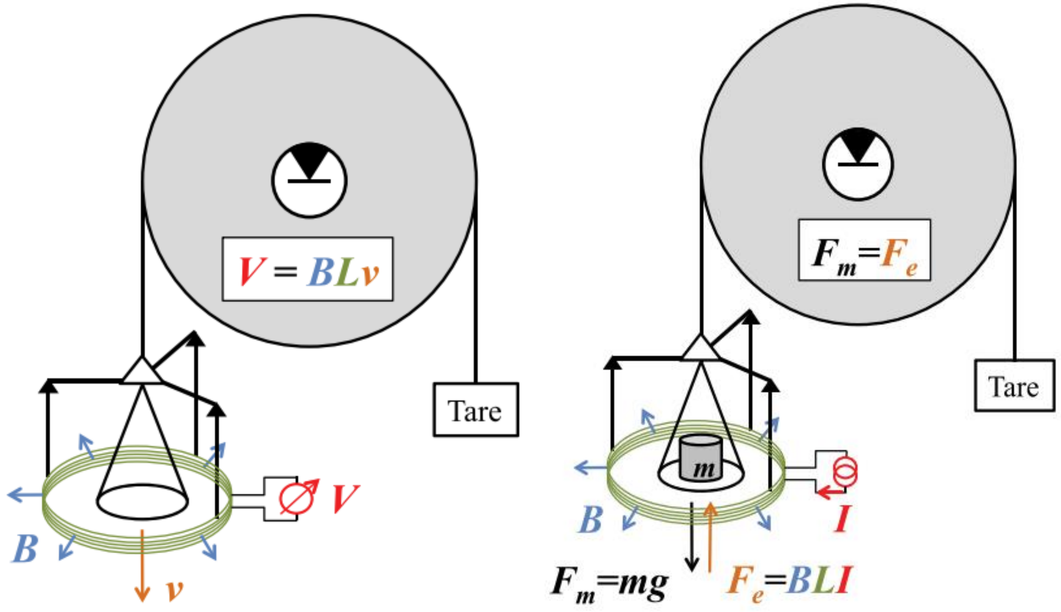
Drives coil B and measures the velocity of the basket and the induced voltage in coil A.

Force Mode

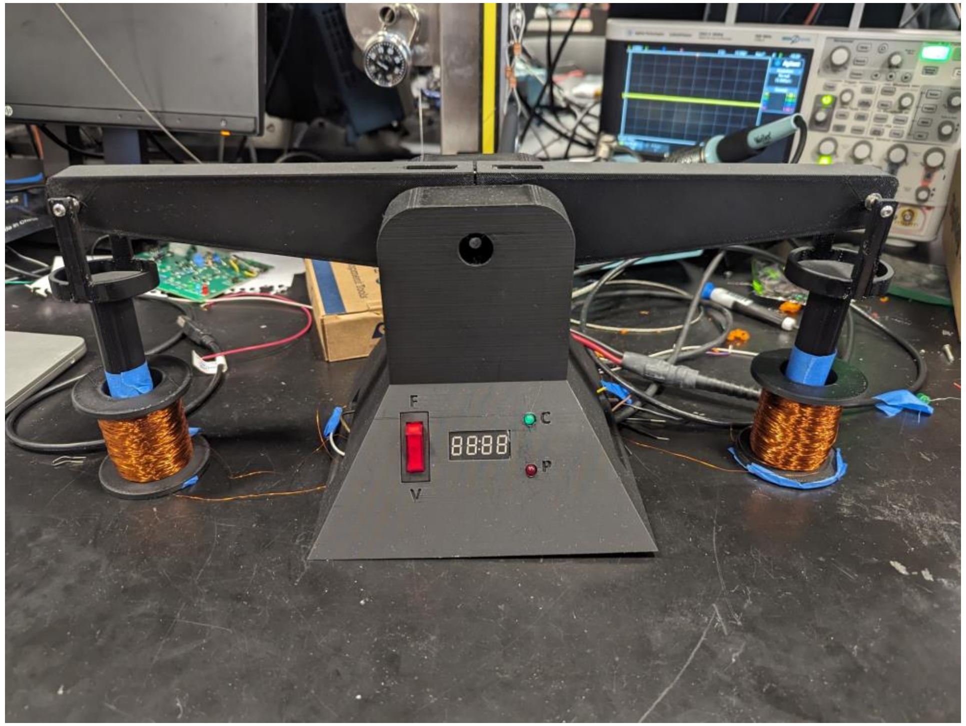
Drives coil A and measures the current required to cancel out the gravitational force.

Combining the Results

In velocity mode: $V = BLv$
In force mode: $F = BLI = mg$
Solving for mass: $m = \frac{VI}{gv}$



Velocity Mode Force Mode



Our Final Balance Design

Design Goals

Improve upon the accuracy of the ABE graduate team's LEGO® version.

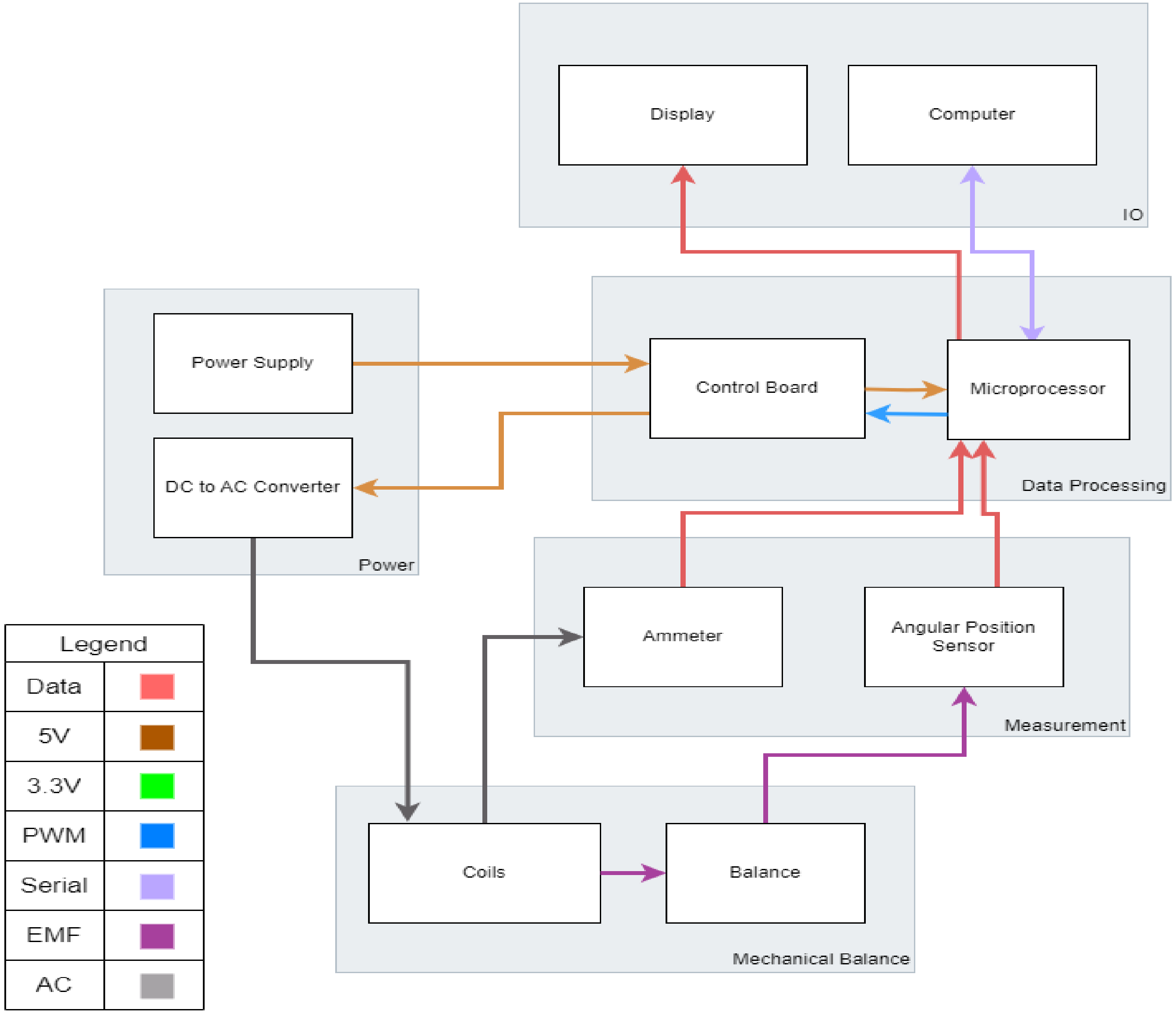
Hall Effect Potentiometer

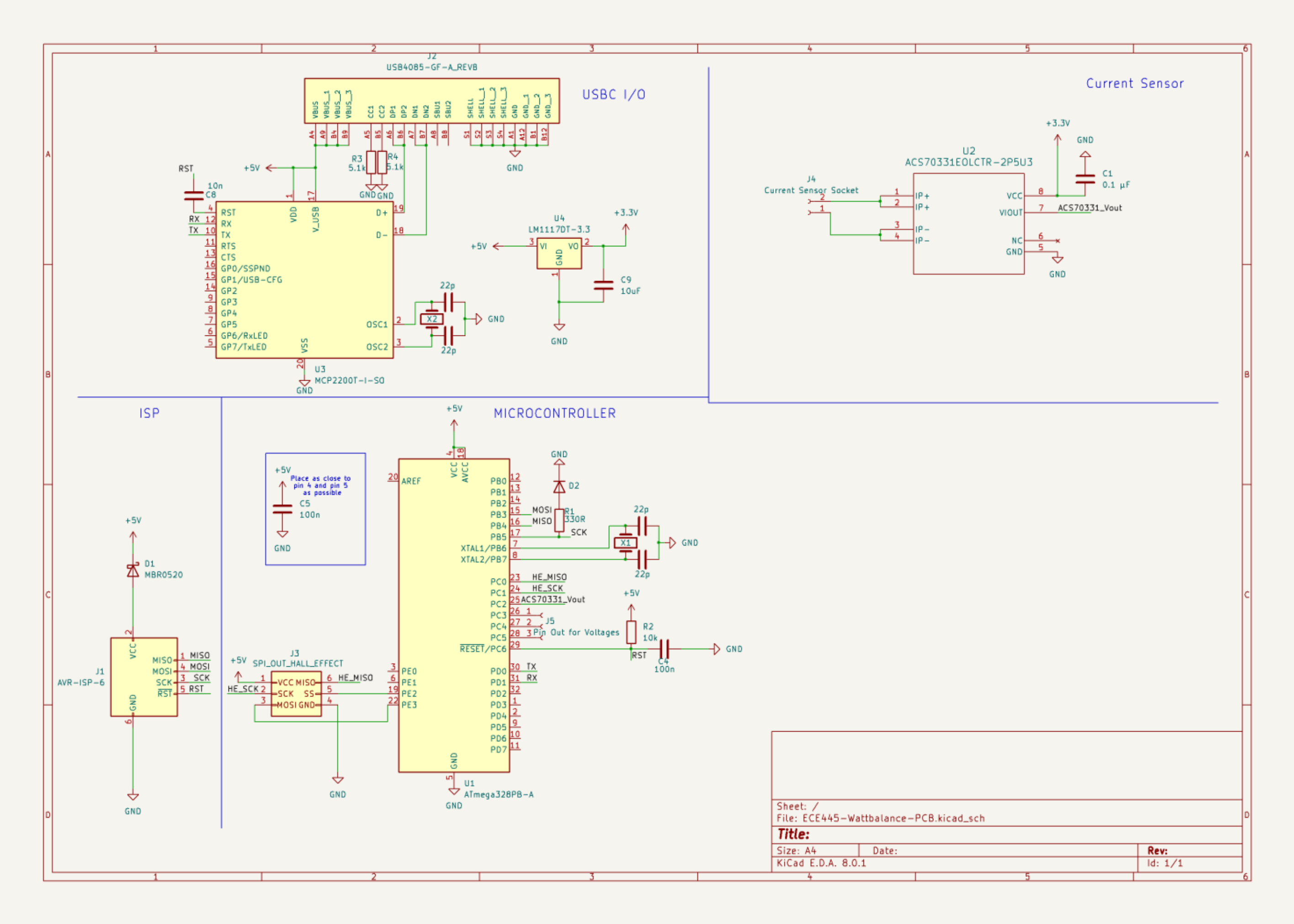
The ABE team used an ultrasonic sensor, which we changed for a Hall effect potentiometer.

Mechanical Improvements

Our balance is fully 3d printed and uses a bearing around an axle as the fulcrum.

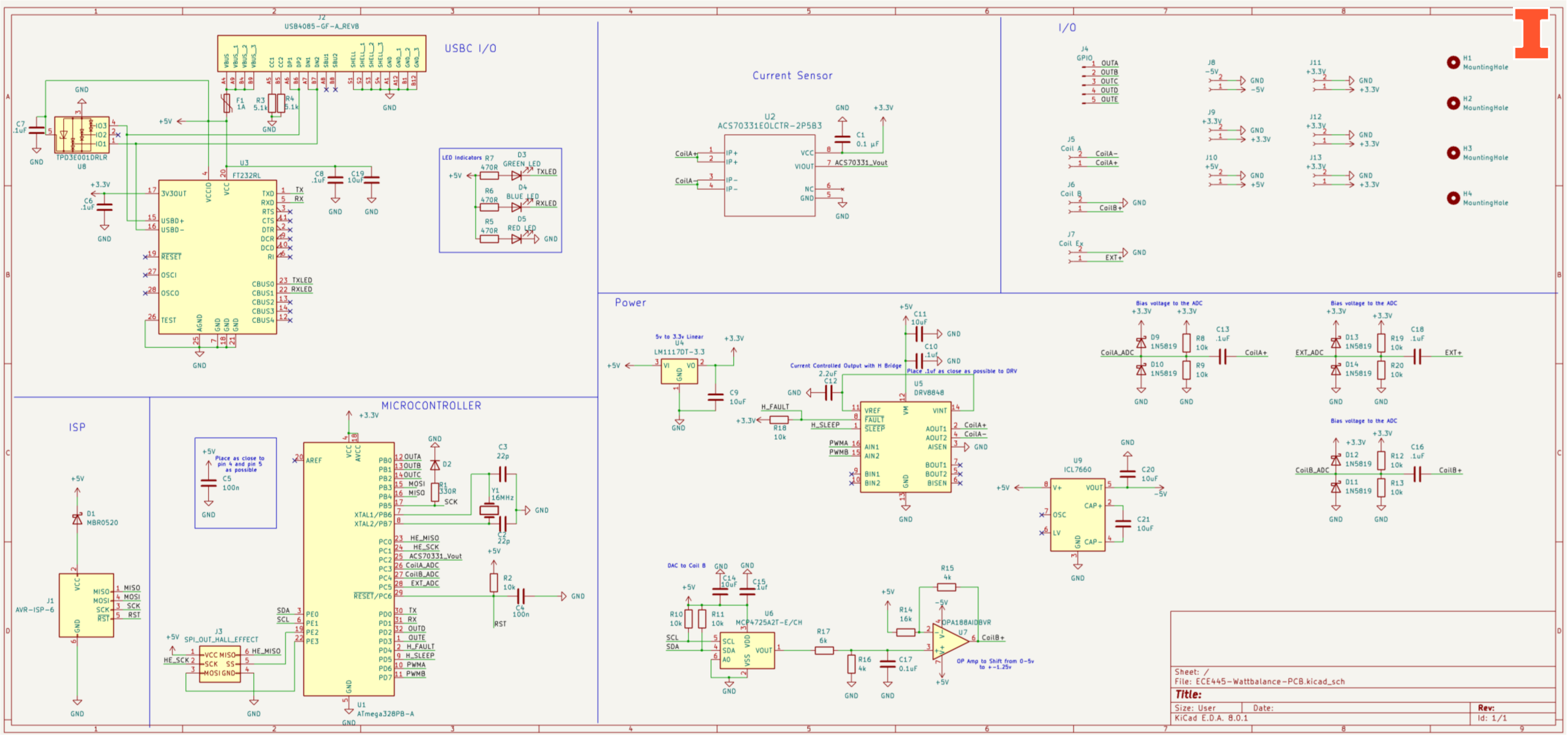
Block Diagram





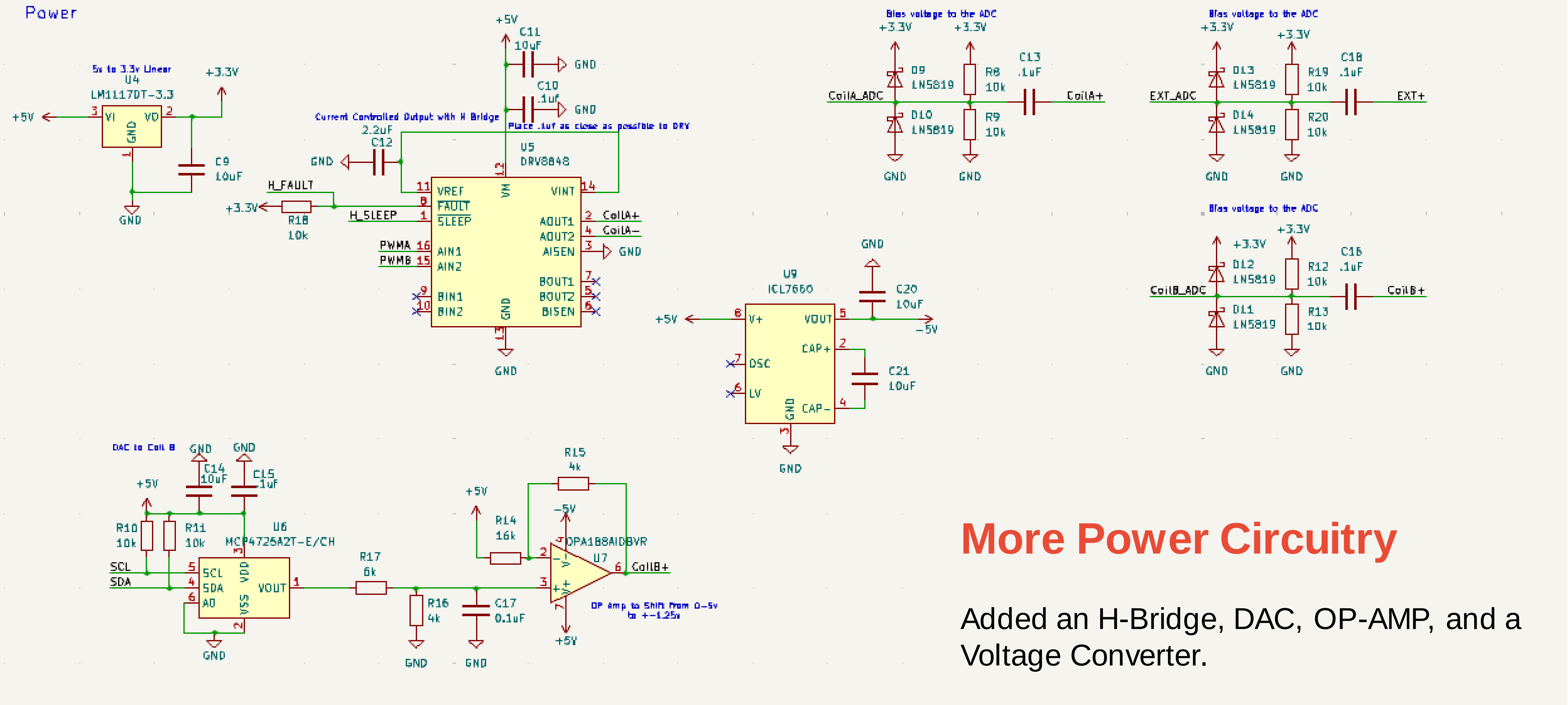
First PCB Iteration

Our first PCB had circuitry for our ATmega microcontroller, connections to a current sensor, pins outs to the Hall effect sensor, and a USB-C port.



Updated PCB Schematic

New Power Components



More Power Circuitry

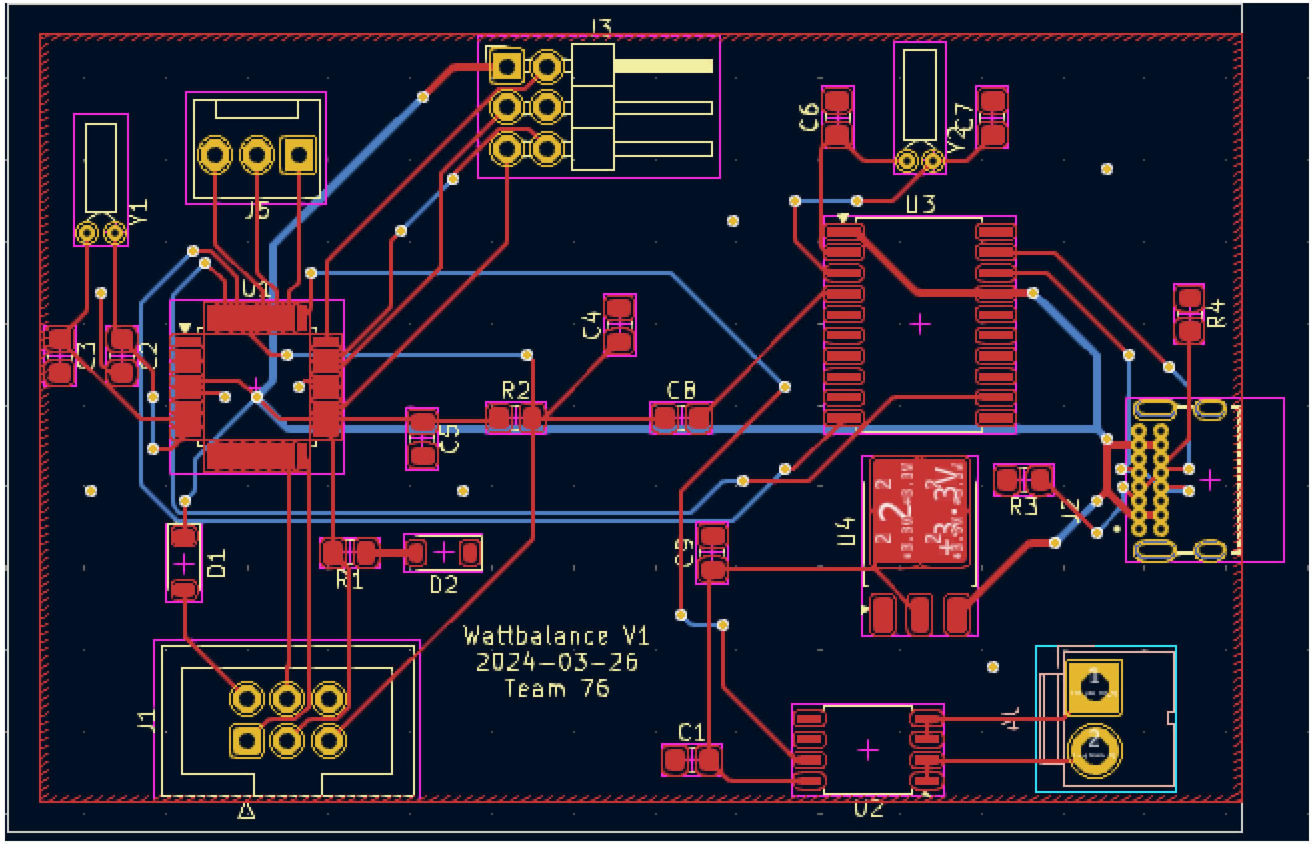
Added an H-Bridge, DAC, OP-AMP, and a Voltage Converter.

The First PCB

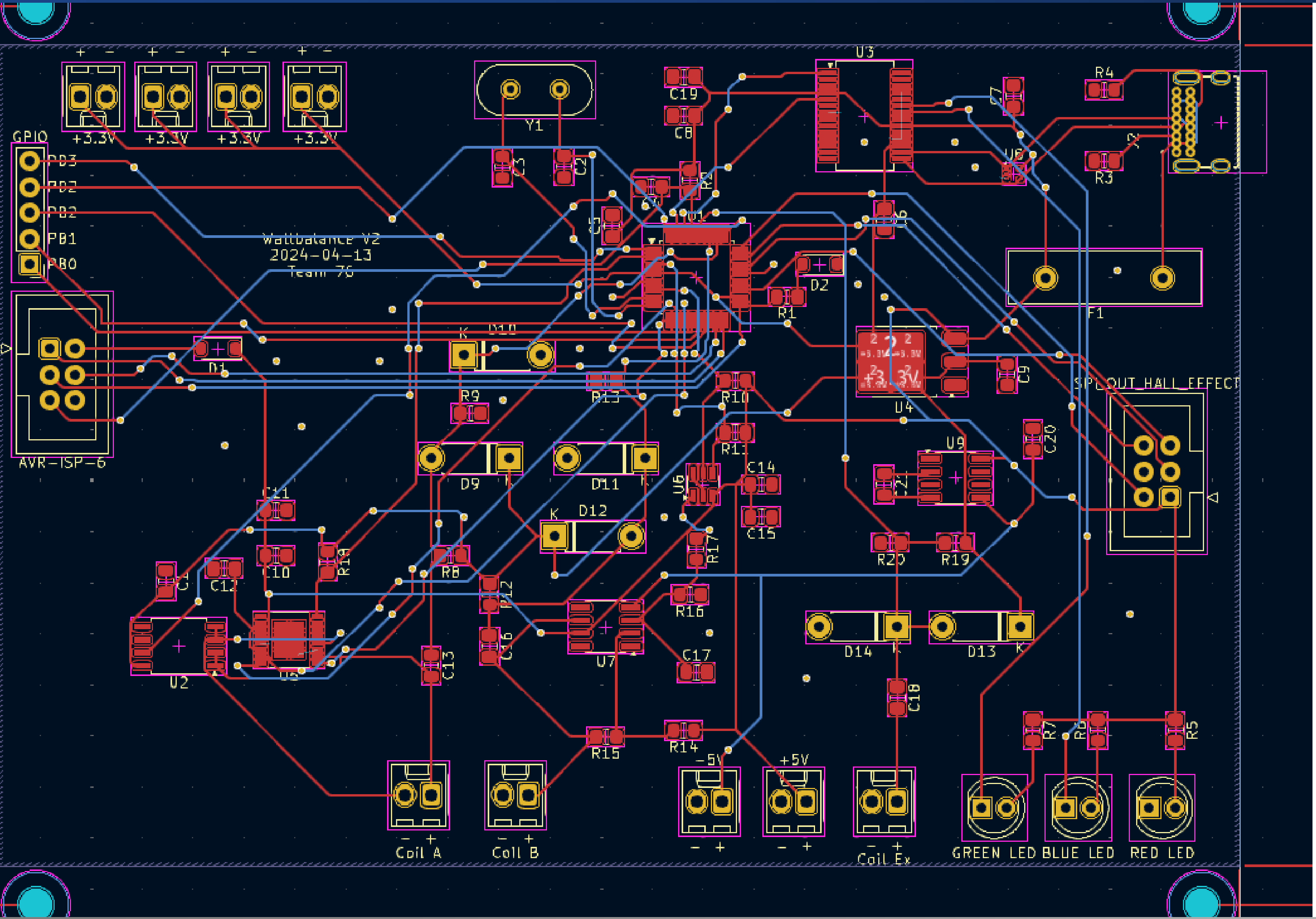
The first iteration of the PCB layout used placeholder footprints for the Hall effect sensor and voltage measurements.

Mistakes

The footprint for the crystal oscillators was wrong, and a few components were on the back of the board.



PCB Layout V2



Way bigger

The old PCB was 75x50mm, V2 ended up being 120x95mm.

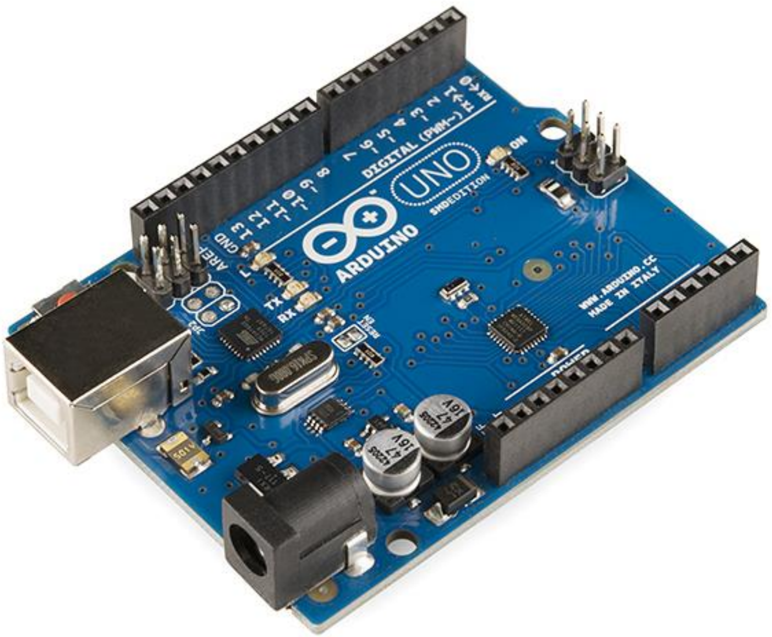
Changed Footprints

Updated footprint for the oscillator, switched the Hall effect footprint to match the ISP footprint, changed voltage I/O to use Molex connectors.

New Mistakes

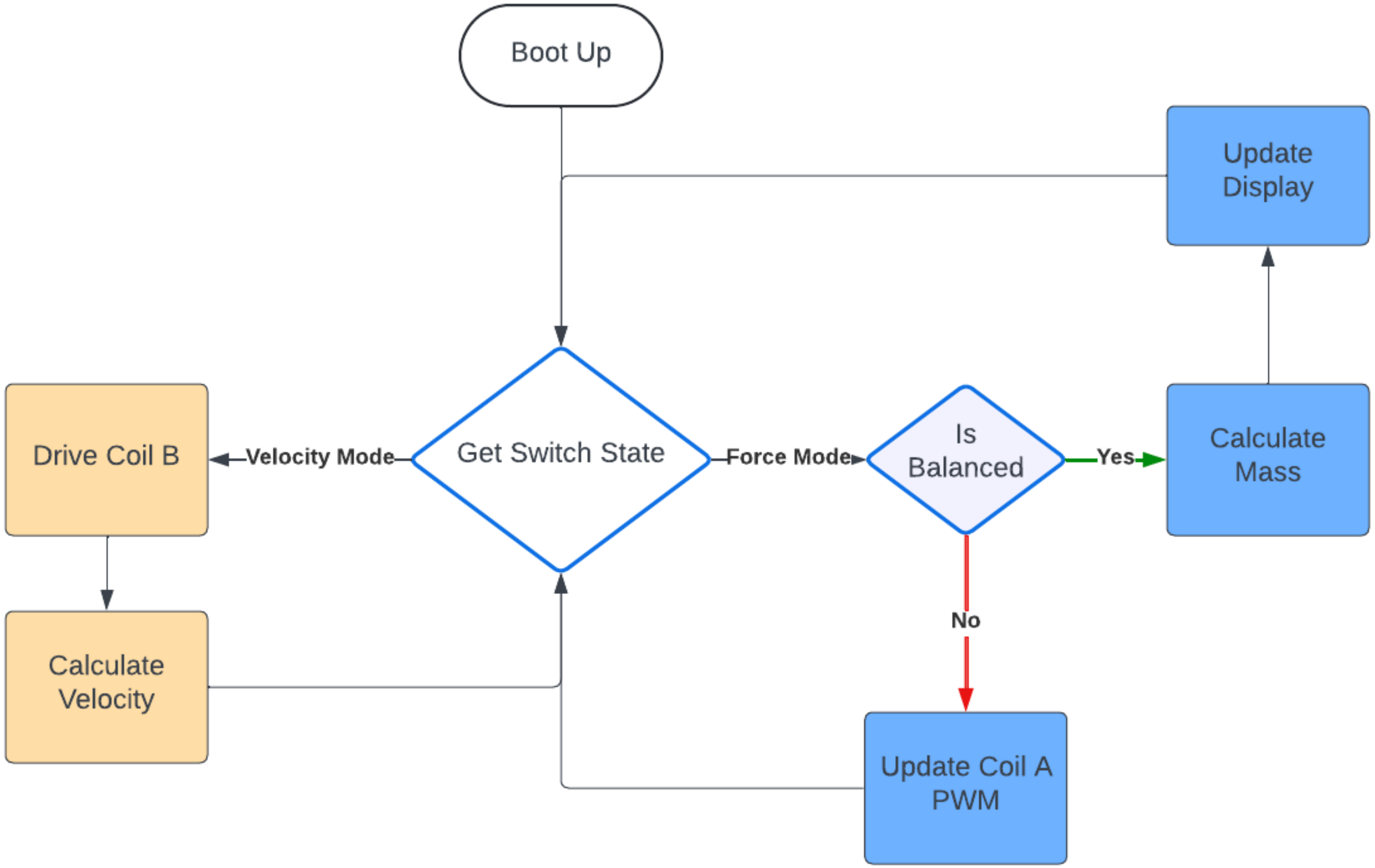
Grounding was missing on H-Bridge and USB-UART, OP-AMP Footprint was wrong.

Switch to Arduino



Problems getting the ATMega to program forced a change in hardware.

Software



The Differences

Original ATMega Software

Lots of HAL.

Custom Serial Program.

New Arduino Software

Followed same general design.

More high level.

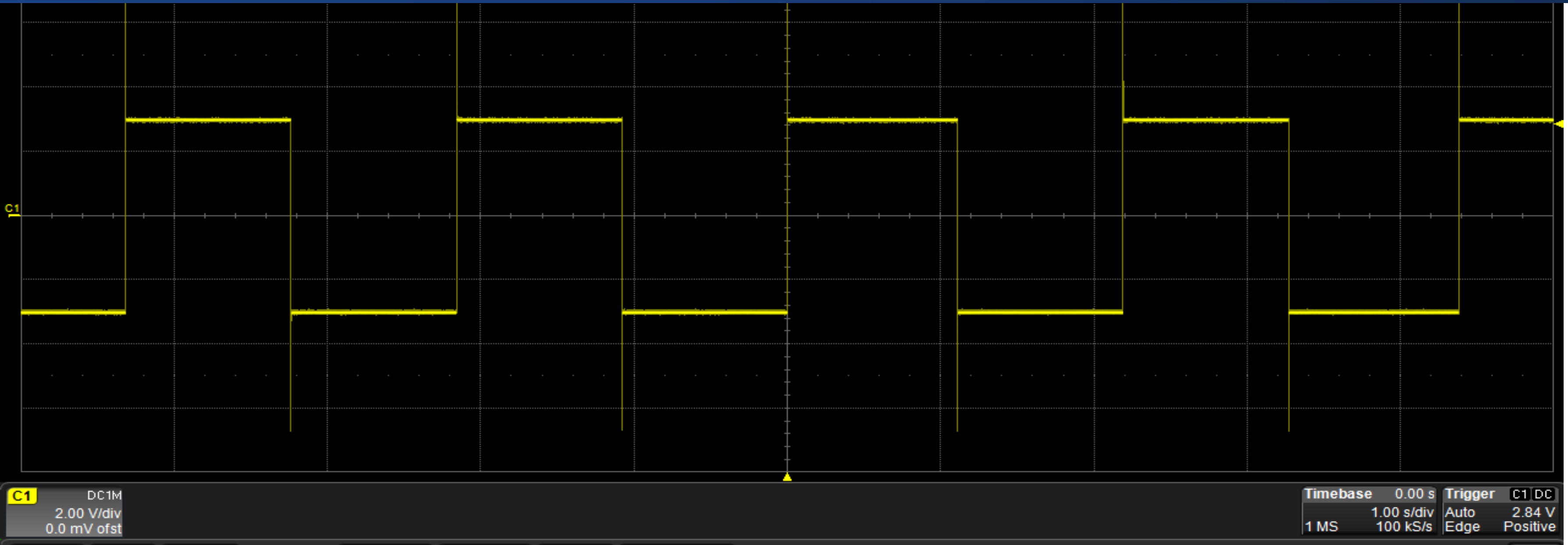
Helpful Libraries.

Power Subsystem Requirements

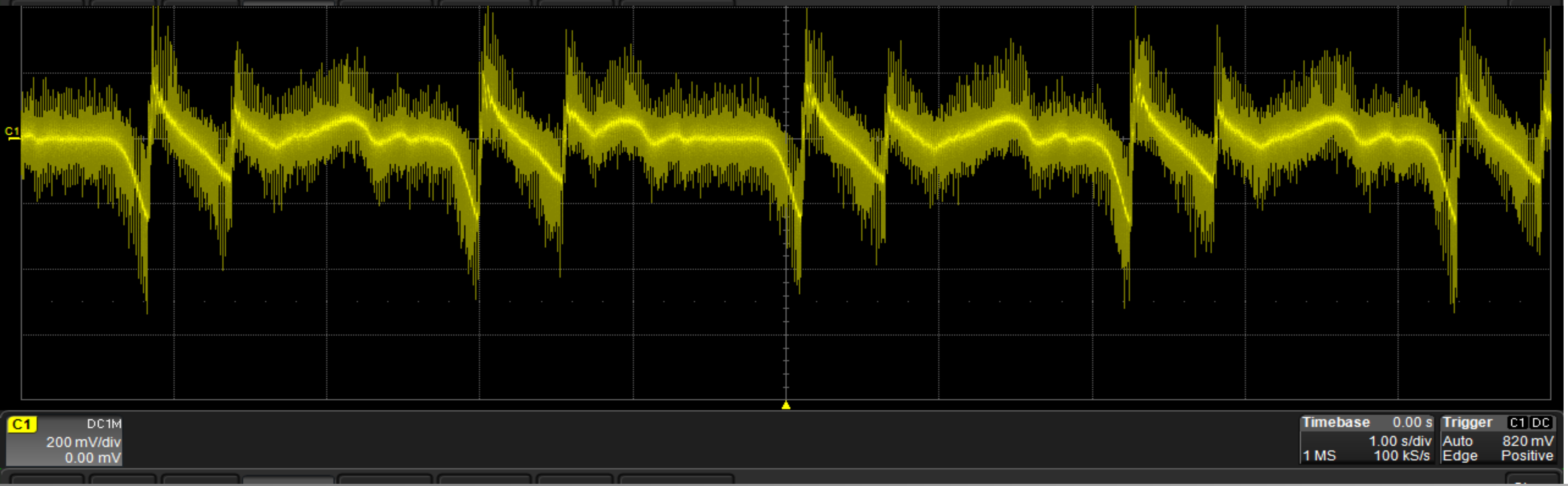
DC to AC converter to the power coils.

5 volts to the control board from the power supply.

Velocity Mode – Power Subsystem

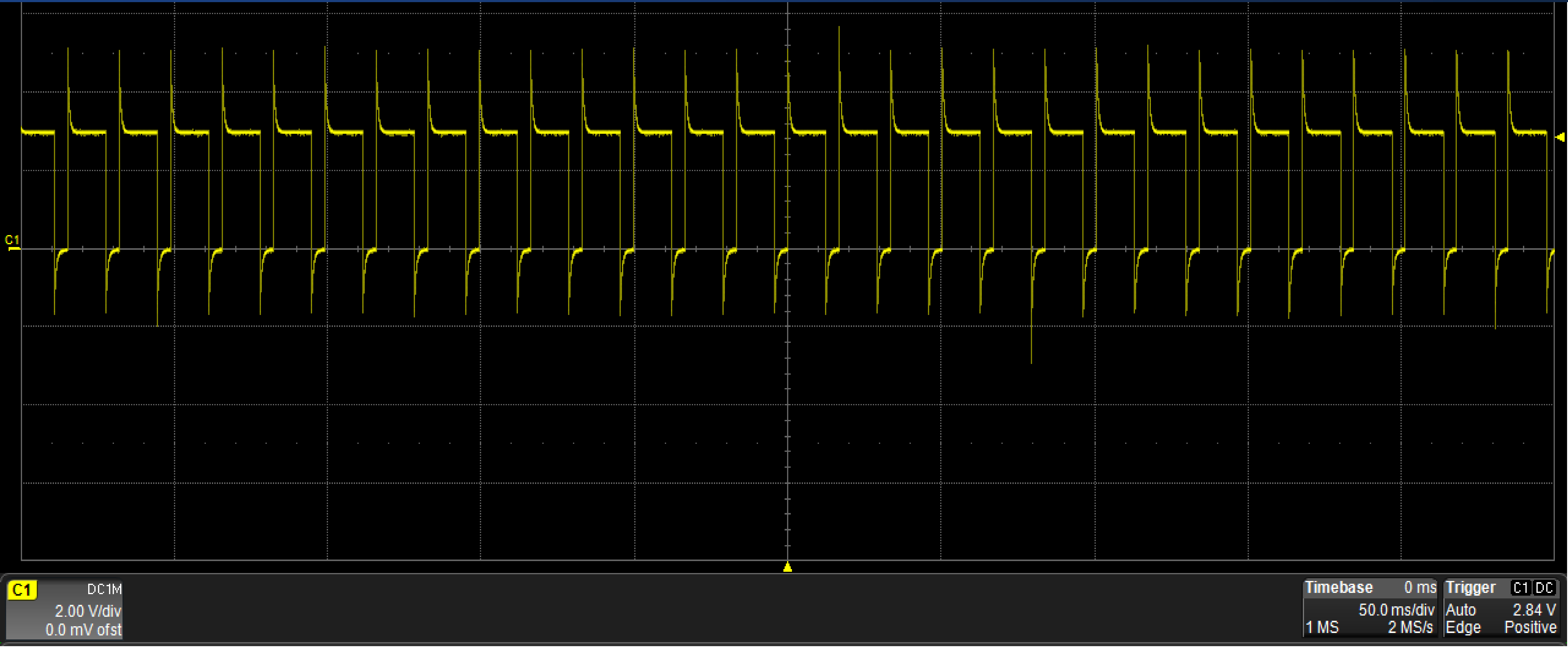


Coil B (Bipolar Wave) – Velocity Mode



Coil A (Induced) – Velocity Mode

Force Mode – Power Subsystem



Coil A (PWM) – Force Mode

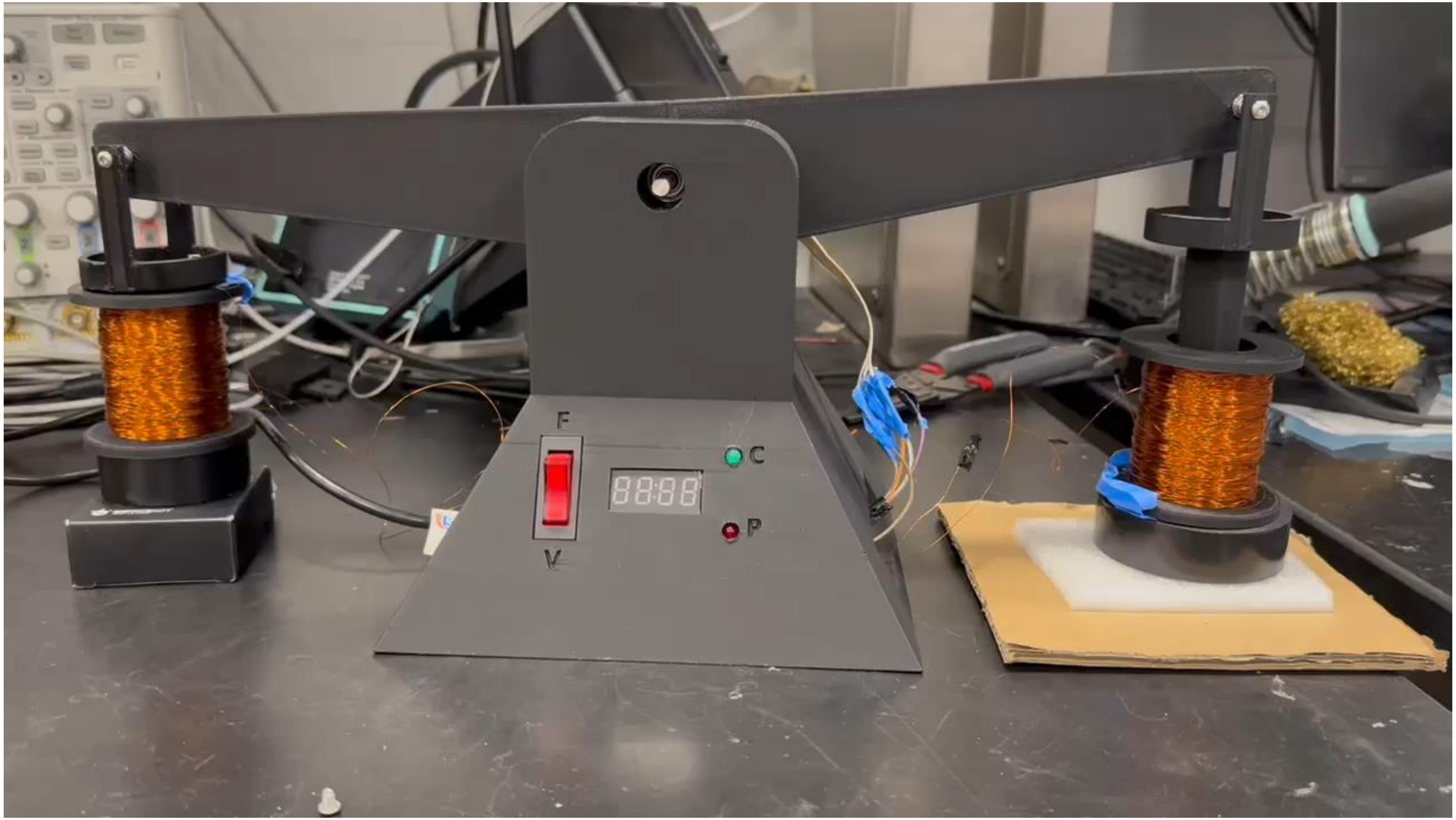
Mechanical Subsystem Requirements

The ability to move the magnets from the current driving the coil.

Minimal interference between electrical components.

Minimal friction in the pivot, such that the device can measure 10 grams within 5% accuracy.

Mechanical Subsystem



Movement of balance from Coil A in force mode

Measurement and Data Processing Subsystems

Measurement Subsystem Requirements

Accurate sensing of position to within 5% error.

Accurate sensing of current to within 5% error.

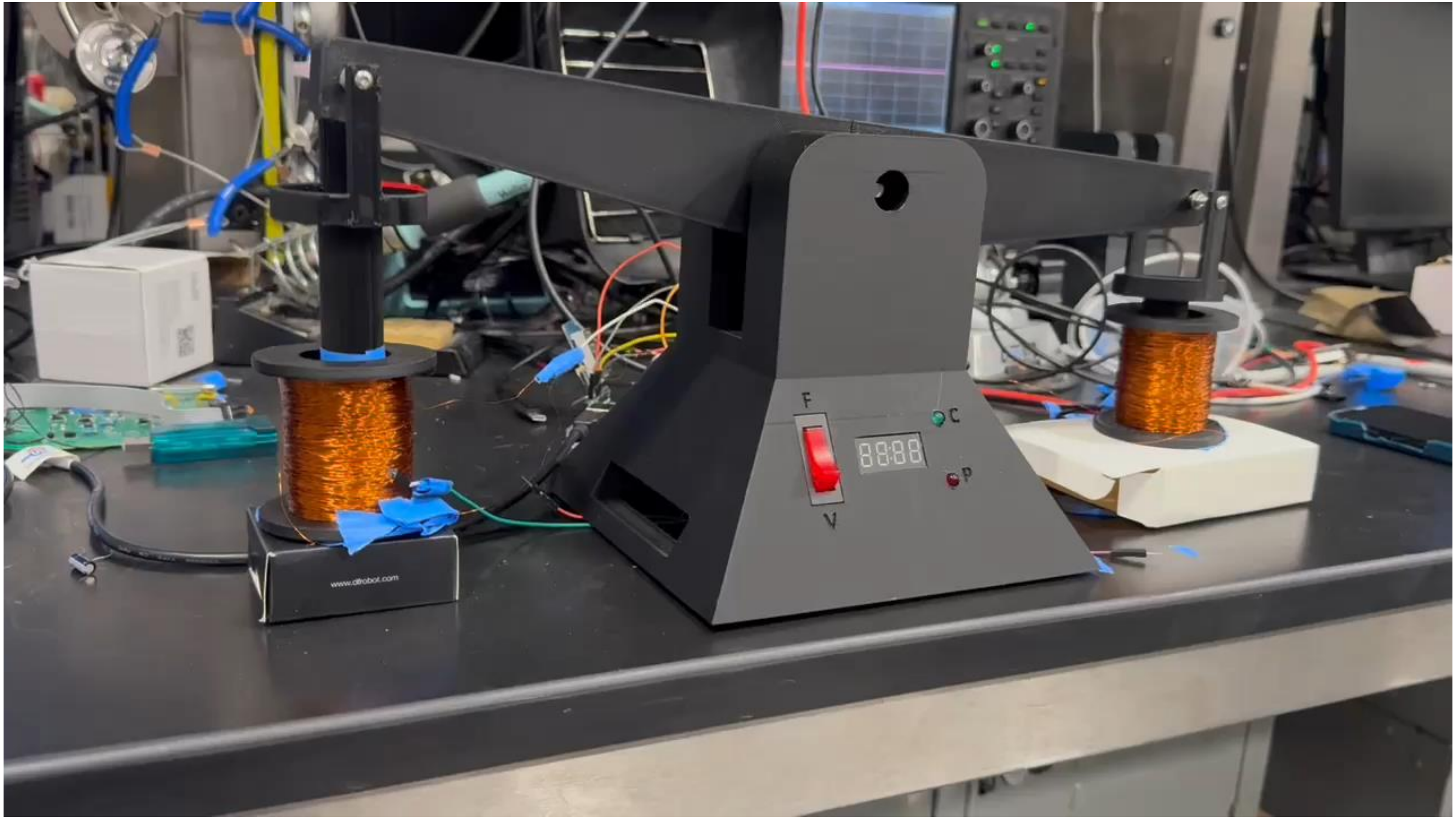
Data Processing Subsystem Requirements

The ability to read in measurements from the position and current sensors.

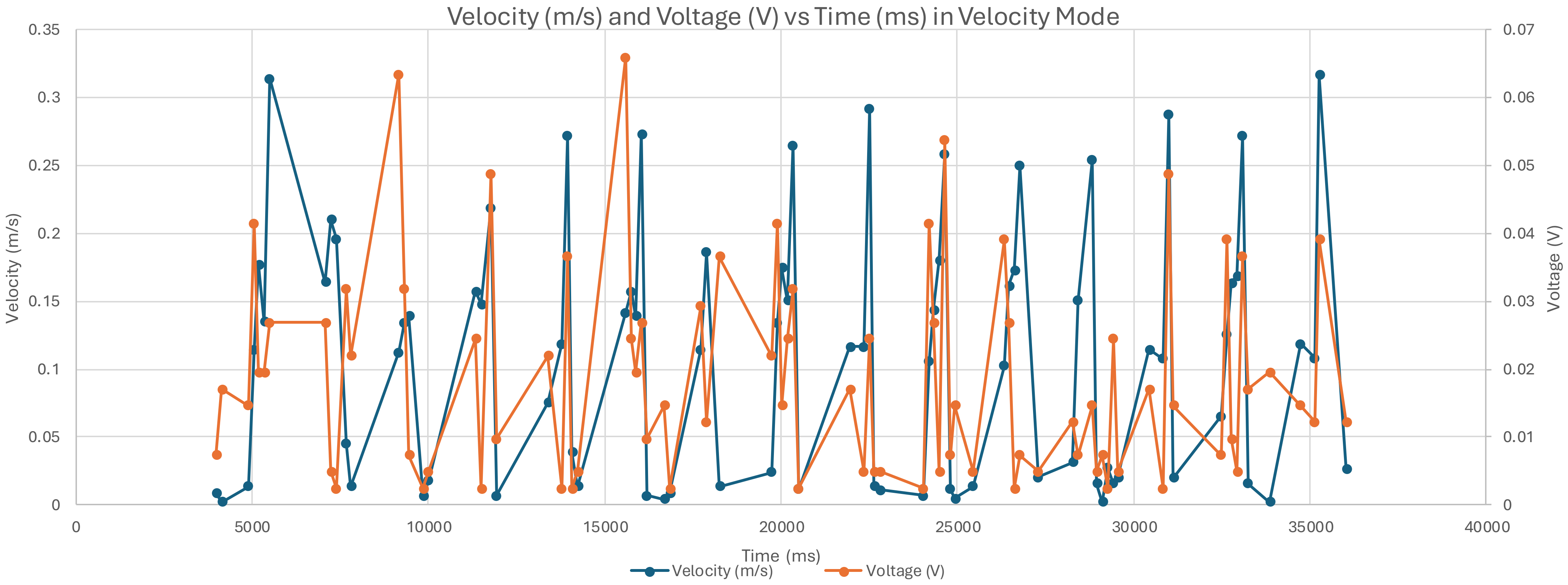
Convert position and current data into velocities and forces.

Calculate the mass of an object based on the data.

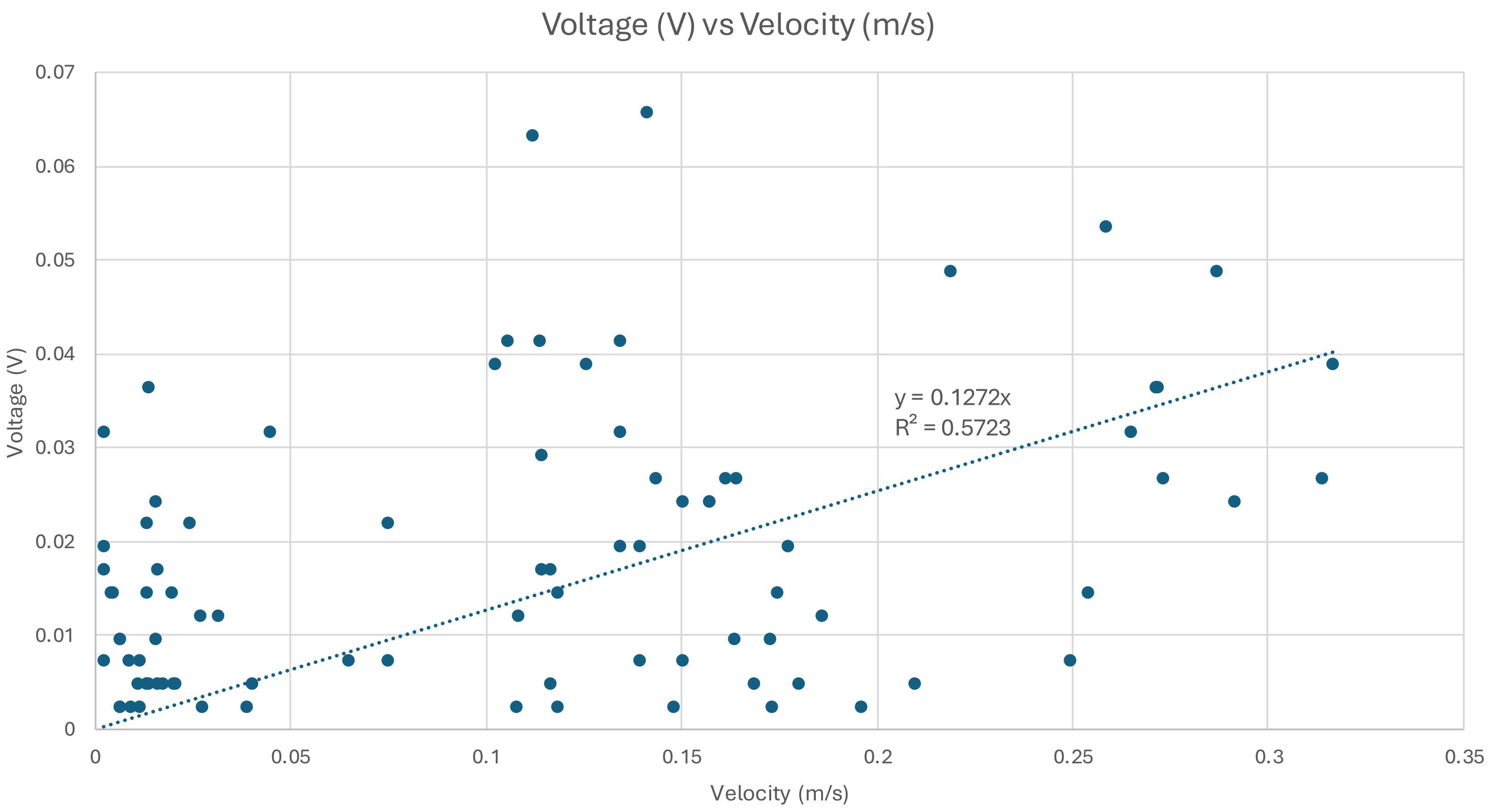
Velocity Mode Demonstration



Velocity Mode Operation – Measurement Subsystem

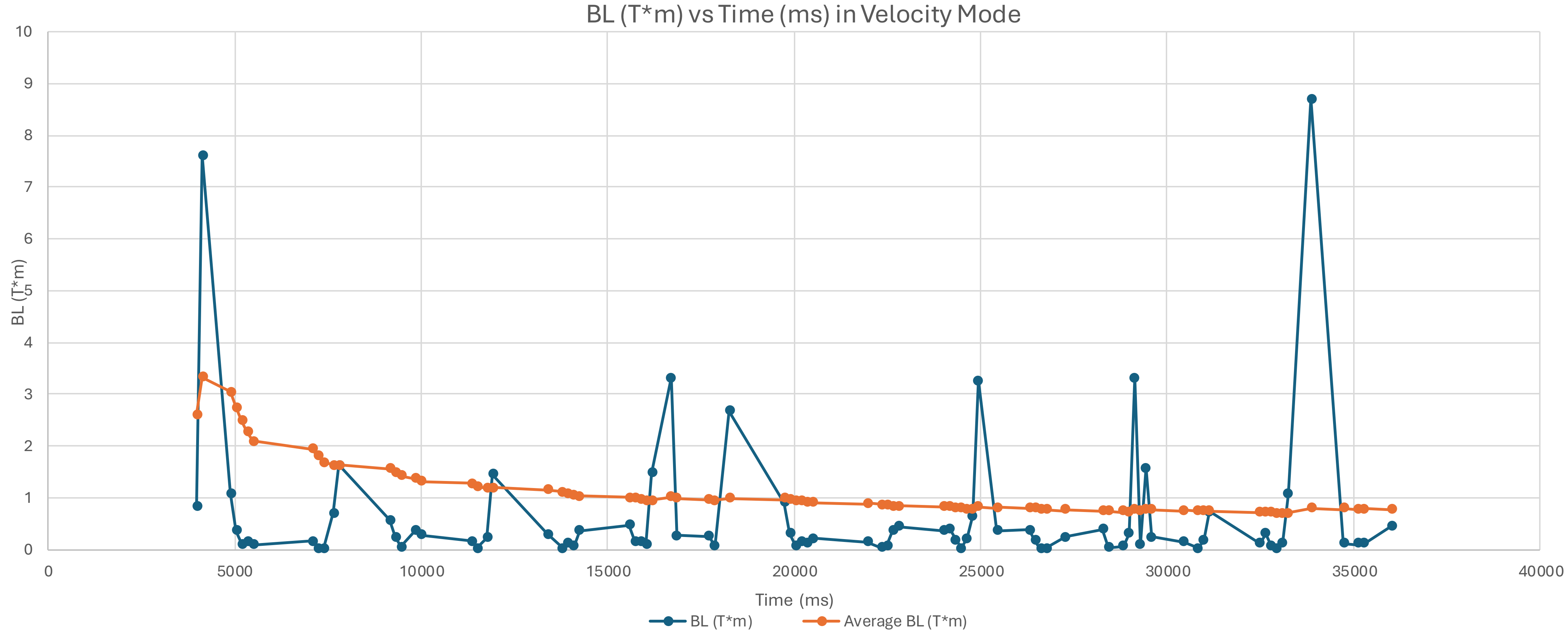


Velocity Mode Inaccuracy – Measurement Subsystem

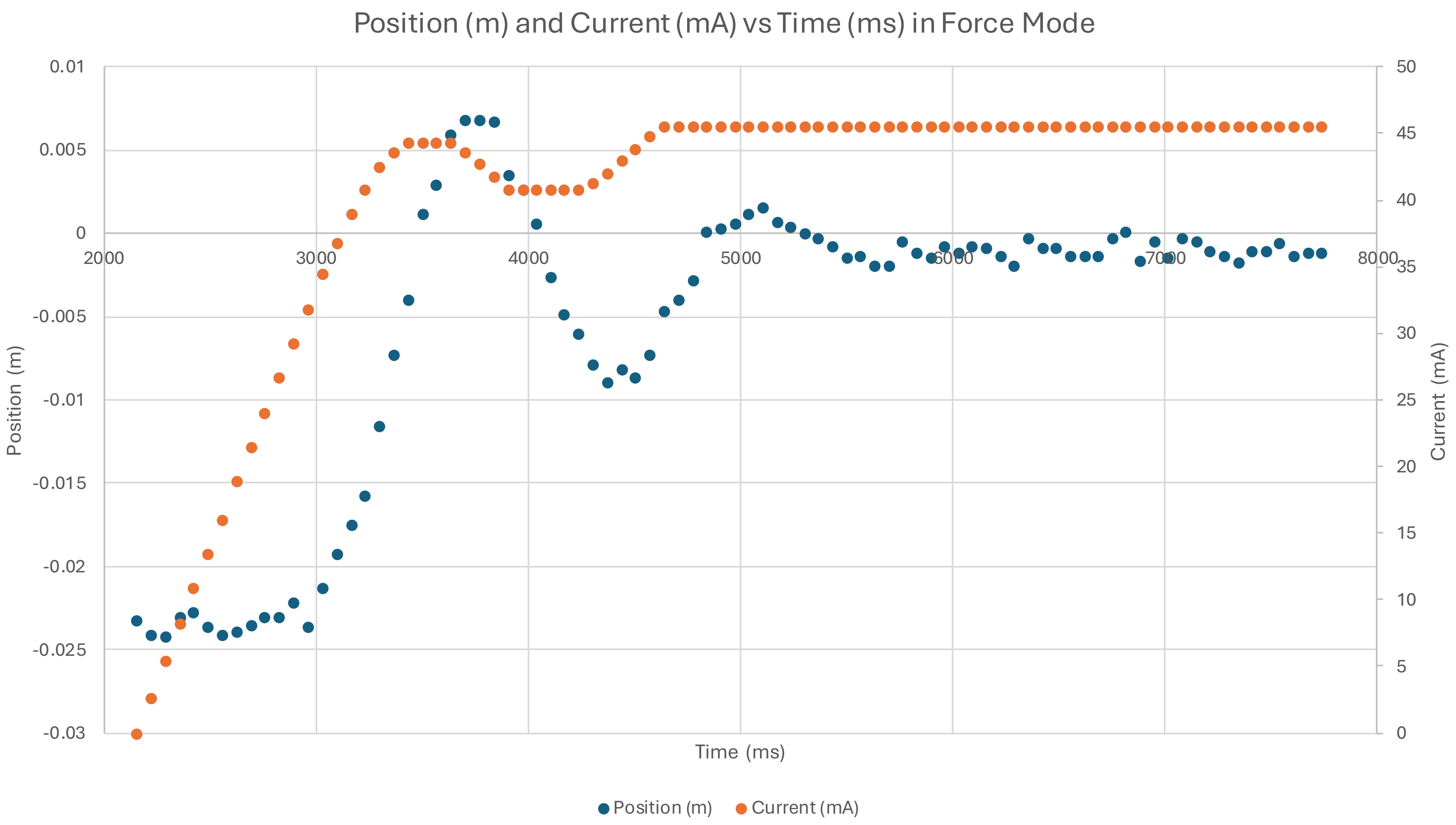


Measured Average BL = 0.0665 T * m

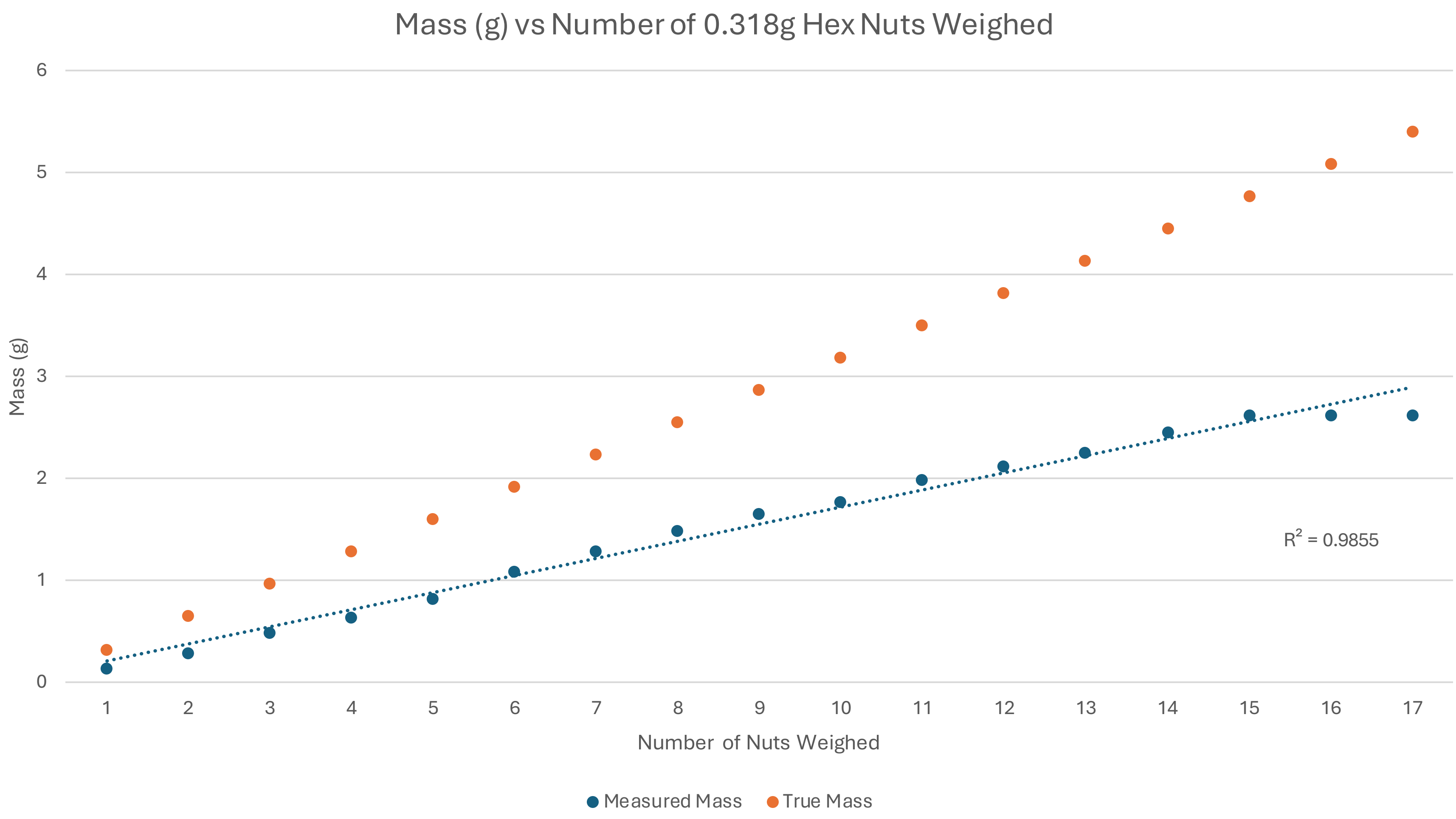
BL Calculation in Velocity Mode – Data Processing Subsystem



Force Mode Operation – Measurement Subsystem



Mass Calculation In Force Mode – Data Processing Subsystem



IO Subsystem Requirements

Software that allows for the user to input control parameters into the balance.

Display to read out the mass and the state of the balance.

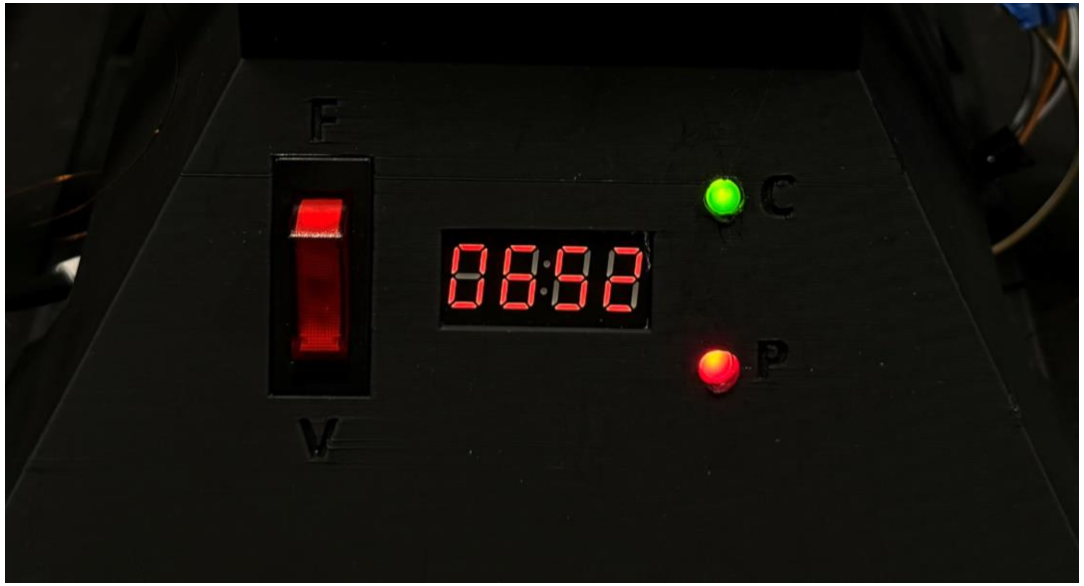
IO Subsystem

```
//Position
#define PI 3.14159265358979323846
#define ARM_LENGTH .19017          // 190.17 mm
#define VELOCITY_SAMPLE_DELAY 10  // Velocity sampling delay
#define MIN_VEL          0        // Minimum Velocity to sample
#define MIDDLE_POSITION 4730      // Position when instrument is balanced
#define POSITION_ERROR   0.005    // Error allowed for balanced position

#define BL_ARRAY_SIZE 100       // Size of array to hold measured bl
#define MIN_CALIBRATE_SAMPLE 20 // How many samples until calibrated

#define KP 500                  // The feedback coefficient for force mode
#define FORCE_START_DELAY 100 // Delay before starting force mode
#define GRAVITY 9.81
```

Computer Parameter Control



Front IO

Conclusions

What We Learned

Making a schematic and picking parts.

PCB design.

Designing for accuracy.

What to do Differently

More quantitative analysis.

More thorough PCB testing / simulation.

Develop code early

Areas for Improvement

Hall Effect Sensor

Power Button

Physical Design

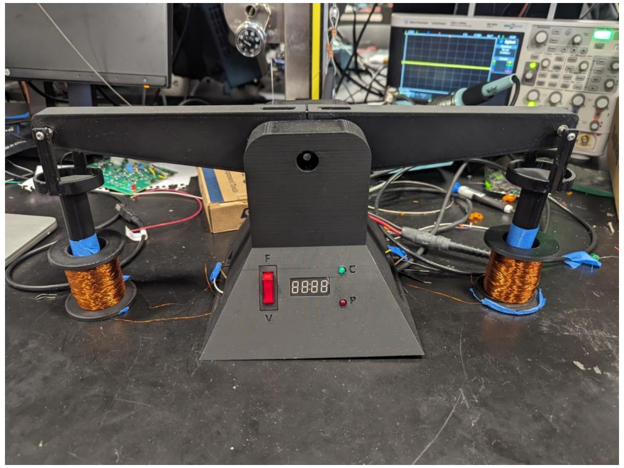
Ease of Programming

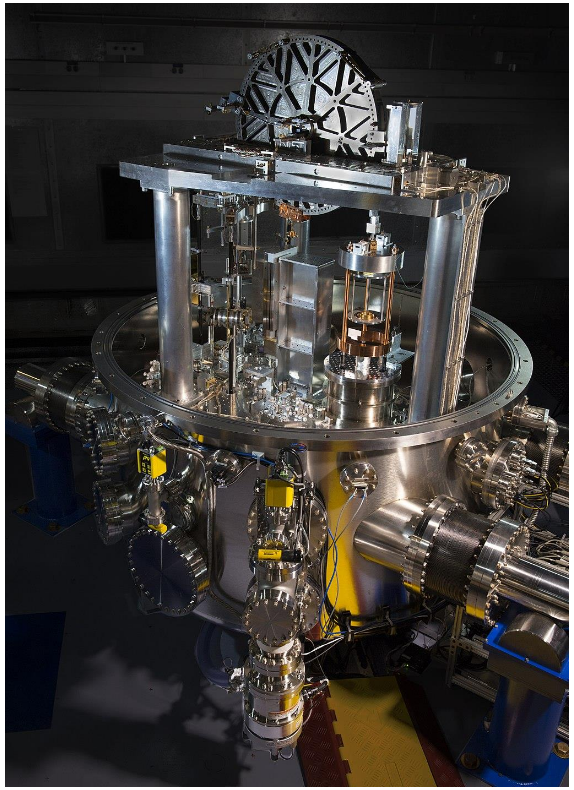
Improved IO Feedback

Balanced Level Detection

Measuring Planck's Constant

More Condensed PCB





Citations

[1] *Kilogram: The Kibble Balance*. NIST. 2 June 2021. https://www.nist.gov/si-redefinition/kilogram-kibble-balance

[2] L. S. Chao, S. Schlamminger, D. B. Newell, J. R. Pratt, F. Seifert, X. Zhang, G. Sineriz, M. Liu, D. Haddad; A LEGO Watt balance: An apparatus to determine a mass based on the new SI. *Am. J. Phys.* 1 November 2015; 83 (11): 913–922. https://doi.org/10.1119/1.4929898