Watt Balance

Design Document

ECE 445

Team 76

Justin Ansell

Julian O'Hern

John Howard

TA: Abhisheka Sekar

Introduction

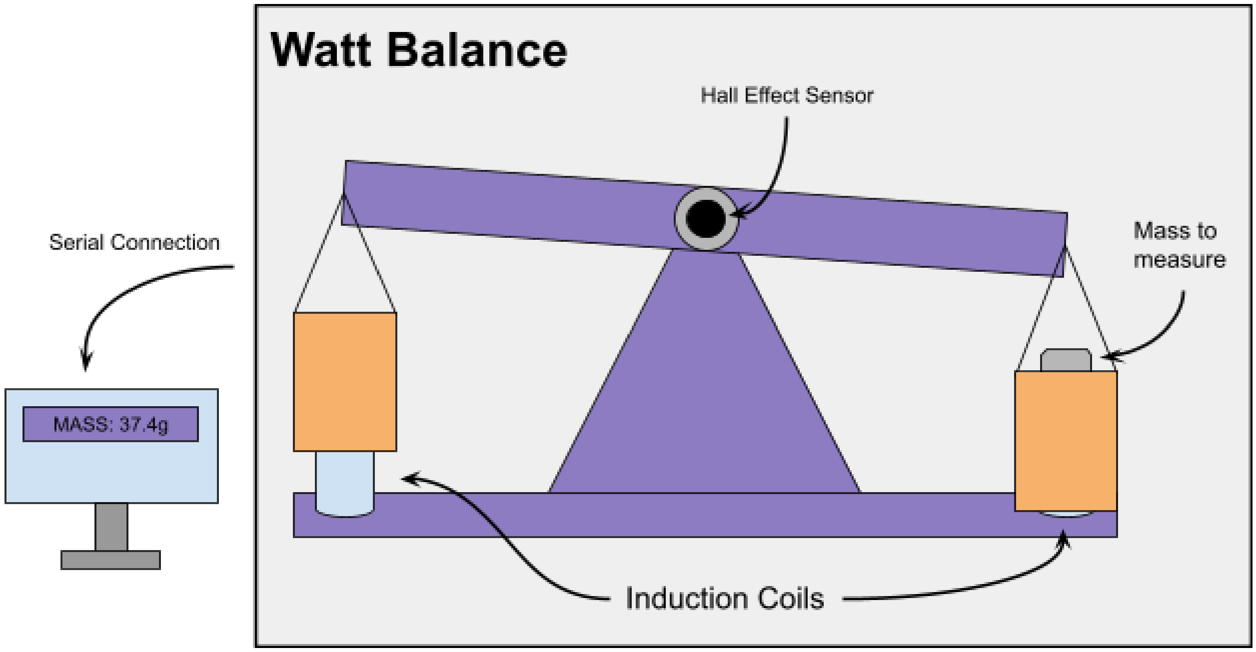
Problem

Since 1879, the universal standard of a kilogram was derived from a physical mass made of a platinum-iridium alloy stored away in a vault. However, even with careful preservation in optimal conditions, over time the mass of the object drifted slightly, which is problematic for use as a constant standard. In 2019, as part of a sweeping change to the SI system, the kilogram was redefined to depend on Planck's constant rather than the mass of a physical object. Researchers at the National Institute of Standards and Technology (NIST) developed a device called a Watt Balance (or Kibble Balance) that uses induced magnetic fields to precisely determine the mass of a given object by measuring the rotational velocity and force generated by the balance. A group of graduate researchers in the ABE department of UIUC created a simple replica of this balance using LEGOs, but it is imprecise, often off by 20-30% or more on measurements. This is problematic for a device whose goal is to create very precise measurements.

Solution

Our solution for this problem involves iterating on the design created by the UIUC graduate researchers and creating a more precise and easier to use Watt Balance. We plan to improve the sensing capabilities of the device and make mechanical improvements to help support those changes. By replacing the 3d printed fulcrum of the balance with a smooth axle and bearing, we can not only reduce friction in the balance, but also use a more accurate sensor on the axle than the ultrasonic sensor the previous design used. We plan to improve the sensing of the induced current in the coil using a discrete current sensor rather than the arduino ports as it was previously measured to further increase the accuracy of the mass calculation. We also plan to update their current MATLAB-based software implementation to a more powerful language to allow for more efficient processing of the data, and create an easier to use user interface to match.

Visual Aid



The Watt Balance works much like a regular balance scale, except instead of comparing against a known mass, the watt balance uses the current induced in the coils and the rotational velocity to compute the mass of the object. The Watt balance uses two modes, “Force” mode and “Velocity” mode. In force mode, the unknown mass is placed on one of the scales, and a current is applied to the coil such that the force applied cancels out the weight of the mass. In velocity mode, we apply a varying current to one coil, while measuring the resulting voltage in the other coil and measuring the velocity of the rotation. Using these measurements, we can solve the two equations $ma = BLI$ and $V = BLv$ for the mass of the object.

High-level requirements

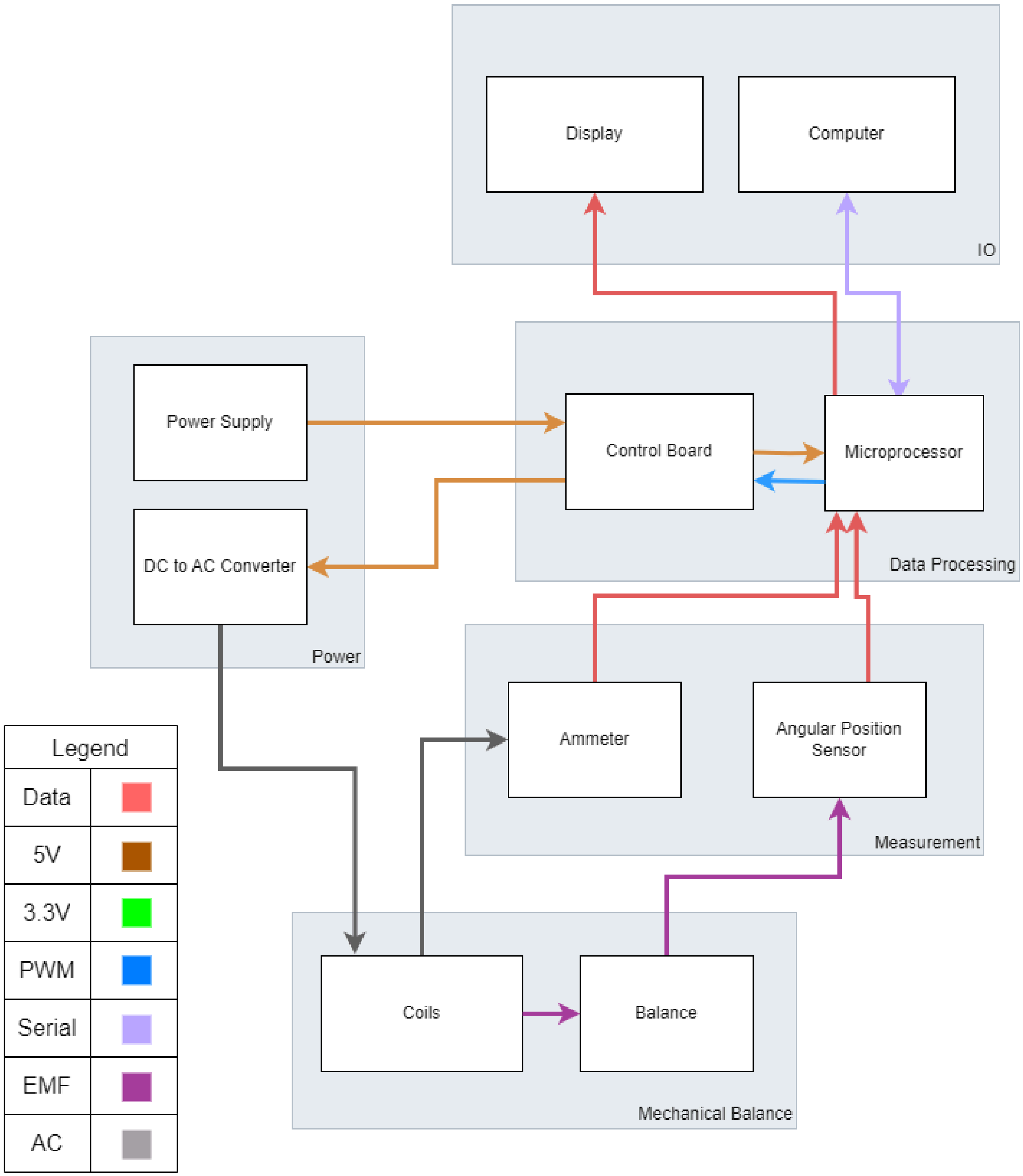
- The device must be able to accurately measure the rotational velocity of the balance. Given that the error when using a known mass in the original ABE device was between 20-30%, we are targeting ~5% error for our measurements to be considered accurate, and ~1% error as a stretch goal.

- The device must be able to accurately measure the force generated by induction in the coil. Similar to the rotational velocity, we are targeting ~5% error for our measurements to be considered accurate, and ~1% error as a stretch goal.

- The device must be able to communicate with the control software and accept input calibration parameters given by the user of the device.

Design

Block Diagram



Physical Design

As of right now there are no physical modeling / designs with accurate measurements.

Device Subsystems

Power Subsystem

The power subsystem is the main source of power for all of the electronics, delivering DC power that is propagated throughout the entire device. The power subsystem also delivers a consistent and expected AC power to the coils to drive the balance force, and can be adjusted by the control board. This is important as precision in the input voltage is directly necessary to getting an accurate current reading from the ammeter.

Requirement	Verification
DC to AC converter (inverter) to the power coils.	Use an oscilloscope on the waveform sent to the coils to make sure they are consistent, and the desired waveform.
5v to the control board from the power supply.	Prob the voltage out of the power supply to make sure the voltage is correct and will not damage the components.

Measurement Subsystem

The measurement subsystems should both be able to measure the current induced in the coils, along with the movement and velocity of the balance as power is applied. The data from these measurements will be sent to the control board for both feedback and tuning purposes, and for calculating the mass of the object.

Requirement	Verification
Accurate sensing of angular position to within 5% error.	Begin with the balance at 0 degrees, then place a heavy object in the measurement area to ensure that it rotates as far as it can go. Compare the difference between the two measured values of the position sensor to the known maximum travel distance and see whether it is within 5% error.
Accurate sensing of current to within 5% error.	To verify, place the leads of an oscilloscope across the current sensor, then run the measurement program. Measure the current using the oscilloscope and make sure it matches with the measured value to within 5% error.

Mechanical Subsystem

The mechanical subsystem allows manipulation of the balance through the electromagnetic force generated by the coils. It also encapsulates the changes to the fulcrum of the balance to allow its angular position to be read by the angular position sensor

Requirement	Verification
Ability to move the balance using the force from an induced magnetic field in the coil	To verify, apply varying currents to one coil, and observe whether the balance moves as a result. Repeat with the other coil to make sure both coils are capable of moving the balance.
Minimal interference with other	To verify, use a gaussmeter to measure the

electronic components (shielding if necessary)	emf at the coils and an ammeter to measure the induced current. When each electrical system is activated (apart from the inverter) measure the EMF and the induced current to be sure that no interference exists.
The device must have minimal friction in the pivot such that a 10 gram weight is measurable to within the 5% accuracy tolerance.	To verify, place a known 10 gram object on the measurement side of the balance. Then, run the force and velocity measurements on the balance using the control software and see if the calculated mass value displayed is within 5% of the known mass.

Data Processing Subsystem

The data processing system should be able to take in input's from the IO, sensors, and voltage readings, and correctly allow for adjusting parameters along with calculate and output measurements.

Requirement	**Verification**
Read in measurements from position and current sensors	To verify, run the measurement program and check that the measurements from both the position and current sensors are displayed in the control program.
Convert position and current data into angular velocity and force data	To verify, run the measurement program and check that the calculated values displayed in the control program match up with those calculated by hand given the measurements from the sensors.

Calculate the mass of the object based off the angular velocity and force data	To verify, run the measurement program and check that the calculated mass displayed in the control program matches with the value calculated by hand given the measurements from the sensors.

IO Subsystem

The IO subsystem will be the primary way for interacting with the control board, there will be some sort of display to give out reading from the sensors, and the mass, along with input methods to tune the inputs to the balance, such as voltage, and tune how the sensors are read.

Requirement	**Verification**
User interface software to input control parameters for the balance	To verify user input of parameters, run the measurement program once using the control program. Then, edit the configuration values in the control program. Finally, run the measurement program again and see if the resulting measurements have changed from their original values based on the new tuning parameters.
Display to read out the mass of the object on the balance	To verify the display of data, run the measurement program using the control program, then check both the control software and the LED screen to confirm that they both display the same measured mass

Tolerance Analysis

One critical component of the device is the rotational position measurement. Looking at Hall effect sensors, which are our current frontrunners for a positional sensor, many seem to be accurate to about 0.3%. Converting the position to velocity is a derivative relationship, meaning that the error in the measurement should remain as 0.3%, which satisfies our target threshold for the velocity measurement. We also will be averaging the slope across many points to further increase the accuracy of the measurement.

Cost Analysis

Physical Part	Unit Cost	Quantity	Subtotal Cost
Hall Effect Sensor	$35.00	1	$35.00
Current Sensor	$1.57	1	$1.57
LED Screen	$3.50	1	$3.50
PLA filament	$20.00	1	$20.00

Subtotal: $60.07

Labor Type	Number of Workers	Hourly Cost	Total Hours	Subtotal Cost
ECE Students	3	$50	8hr* x 15 weeks	$18,000

Subtotal: $18,000

The total cost after combining the cost of the physical parts and labor is $18,060.07

Schedule

Week	Goals	Team Members
2/19	Fix and submit Proposal for Regrade	Everyone

	Complete and Submit Design Document	Everyone
2/26	Design Review Make revisions to design document Design PCB PCB Review	Everyone Everyone Everyone Everyone
3/4	Teamwork Evaluation PCB revisions	Individual Everyone
3/11	Spring Break	
3/18	Start to design software to work with new PCB and sensors Start to construct and iterate designs of balance	Julian John, Justin
3/25	Test to make sure balance fits within expected tolerances Revisions to Software Revisions to Balance	John, Justin Julian John, Justin
4/1	Make sure the balance and software interact correctly Revisions to Software Revisions to Balance	Everyone Julian John, Justin
4/8	Small refinements and tuning to the final version of the balance. Make sure software is stable and accurate.	John, Justin Julian
4/15	Mock Demo	Everyone
4/22	Final Demo	Everyone

	Mock Presentation	Everyone
4/29	Final Presentation	Everyone

Ethics and Safety

Safety and Ethical Concerns

During the design and production of our balance there are a few safety considerations that we have to take into consideration. One of the safety concerns that arose is as with any electrical system making sure that we use safe and proper power equipment to make sure that we are always operating within a safe voltage. We also consider accurate measurements an important safety factor, as inaccurate measurements can lead to accidents and failures when needed for a critical system. Because of this, we will have an indicator for whether the balance has been calibrated recently. This will let the user know that either the balance has been calibrated and is accurate, or if it needs to be recalibrated.

Safety Review

Taking into consideration the safety risks we found while designing our balance, we believe that the user of the scale should have an understanding of the accuracy of the scale, from knowing when it was previously calibrated, along with an expectation of safety from the low wattage required for the operation of the scale. These factors will allow for our scale to be used in various conditions while the user can be assured they are safe.

Citations

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