Watt Balance

ECE445 Project Proposal

Justin Ansell (jansell2)
Julian O'Hern (johern2)
John Howard (johnlh3)

Introduction

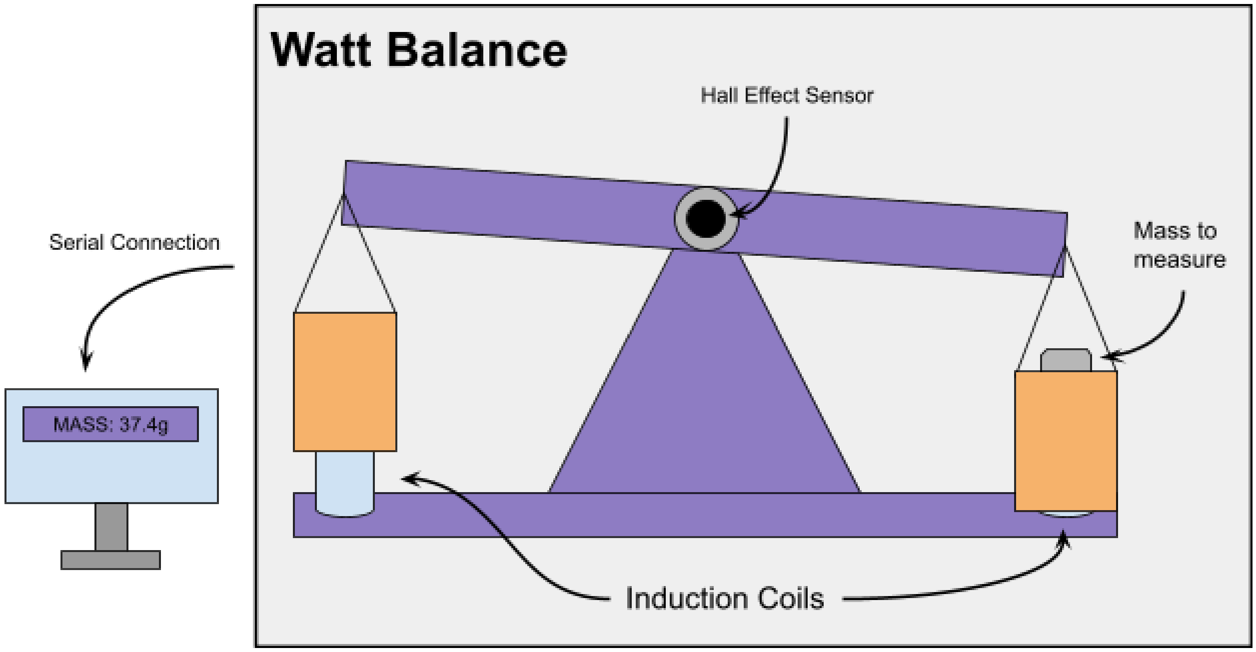
Problem

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 an ammeter 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.

Visual Aid



The Watt Balance works much like a regular 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.

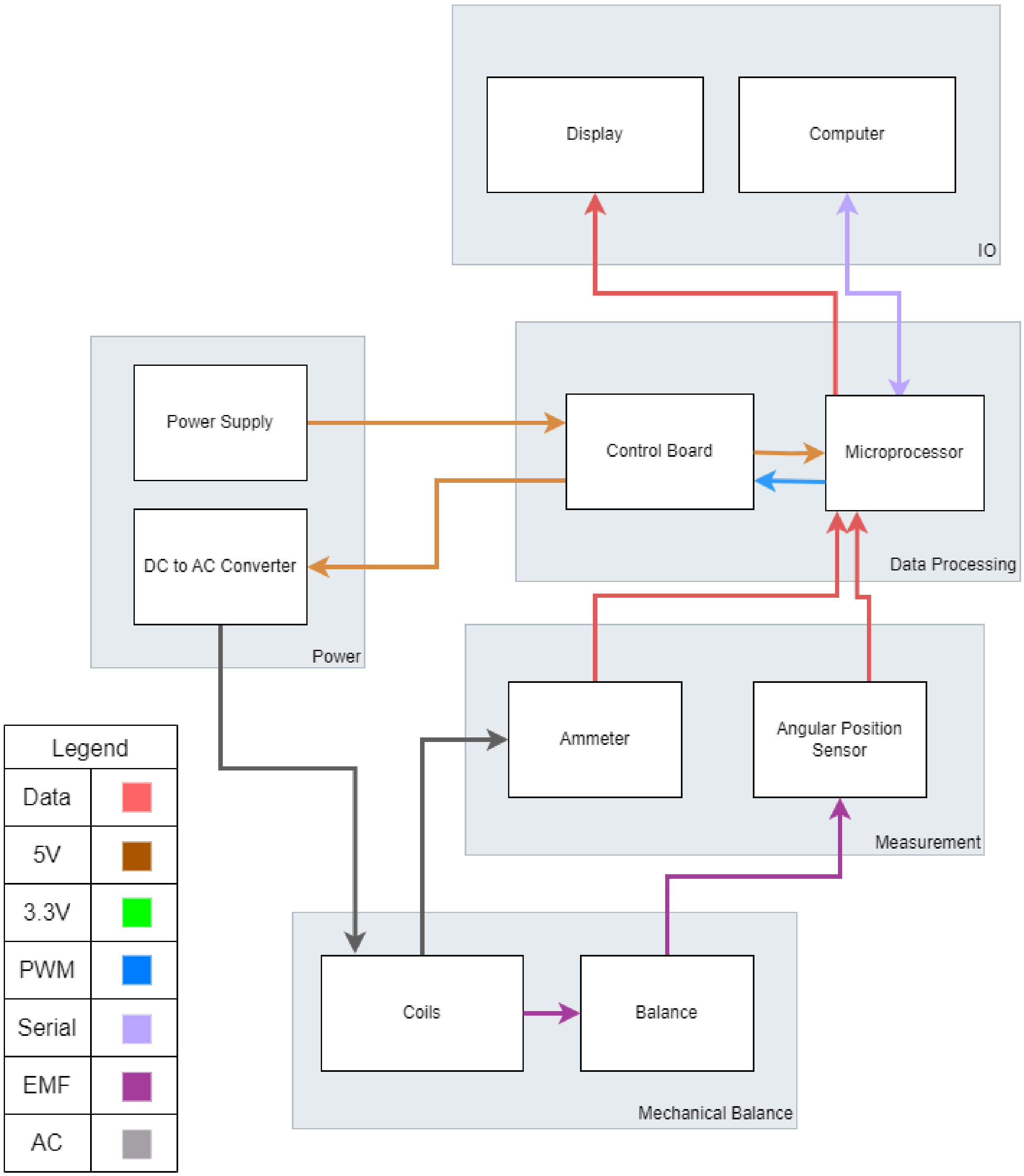
High-level requirements

For our balance to be considered successful the following goals must be met. Having completed these goals on our balance we believe that the instrument will fulfill the expectations of being able to measure masses with the expected accuracy.

- 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.

Design

Block Diagram



Subsystems

Our block diagram demonstrates the connection between subsystems, which are described below. For each subsystem we further explain the function of the subsystem, and then go on to describe our requirements for the subsystem to operate. Also described is stretch goals for that requirement which we would like to additionally meet. Finally, we describe verification methods for each requirement, which are the methods we will use to test if the requirements were met.

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.

Requirements	**Verification**
DC to AC converter to power coils	Use an oscilloscope on the waveform sent to the coils to make sure they are consistent, and the desired waveform
Power to the Control Board	Probe 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.

Requirements	**Stretch Goal**	**Verification**
Accurate sensing of angular position to within 5% error	Accurate sensing of angular position to within 1% 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	Accurate sensing of current to within 1% 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.

Requirements	Verification
Ability to move the balanced 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 electronic components (shielding if necessary)	Use a gaussmeter to measure the 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.
Minimal friction in the fulcrum	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.

Requirements	Verification
Read in measurements from position and current sensors	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	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	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.

Requirements	Stretch Goal	Verification
User interface to input and read data and parameters		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.
Communication of data and parameters between a computer and the microcontroller	Setting of parameters based off automatic calibration	Connect the balance to the computer. Then check the control program for values matching the state of the system. Move the scale arm to make sure the program is updating correctly.
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.

Ethics and Safety

While it may seem that our project is rather straightforward in terms of safety, there are still dangers involved and safety should always be taken into account. As our instrument will work with electricity it is important to take into consideration risk factors inherent to any project which works with electricity.

- avoid shorting (smoke/fire danger)
- make sure to follow regulation for any device plugged into wall
- safe voltages throughout the device, grounding
- let user know about accurate measurements / last calibration
- make sure user knows limits of device / clear labeling
- safety considerations when soldering and working on prototype

References

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