SPS Chapter Research Award Interim Report

Project Title	Construction of a Watt Balance to Redefine the Kilogram
Name of School	University of Maryland, College Park
SPS Chapter Number	4155
Total Amount Awarded	1,999.66
Project Leader	John Evans

Abstract

Physicists are working towards redefining the kilogram in terms of a natural physical constant through a watt balance, which measures mass by counteracting gravitational and electromagnetic forces. Here, we propose the construction of a high-precision watt balance using low-cost and open-source hardware, in collaboration with UMD Physics Makers. We are implementing an asymmetric balance-wheel design modeled after the NIST-4 watt balance. Our watt balance was designed so that it could reasonably be constructed by students at the undergraduate level, and will help student acquire skills in computer-aided design (CAD), electronics, 3D printing, machining, programming, data analysis, and optics.

Statement of Activity

Interim Assessment

- **Research question:** Can we improve on the watt balance design presented in NIST's DIY LEGO Watt Balance paper, and to what precision can we make measurements of mass with respect to Planck's constant rather than to the way the unit of mass is currently standardized?
- **Brief description of project:** The construction of this watt balance has been dependant on CAD design, programming and coding in Python, and woodworking. Despite some changes to the design of the watt balance, the overall aim of the project has not changed.
- **Progress on research goals:** – Our progress has been focused and significant. In an effort to expedite the construction process we have purchased all necessary components, finalized our design, produced custom printed circuit boards (PCBs), and 3D printed over 40 parts. We are currently considering the use of an interferometer to measure velocity, our most sensitive and critical measurement. However, we must overcome the problem of finding a microcontroller with a sufficiently high sampling rate and laser with a coherence length of at least 10 cm. Prior to the completion of the interferometer, we will be using a computer vision Python library and a camera.
- **Any changes in the scope of project:** Due to scheduling constraints, construction and development have taken longer than previously expected. Progress has also slowed due to complications that arose with the implementation of the interferometer based measurement and the NIDAQ code, but we are confident that this will enhance the quality of the final product. We also saw a drop in personnel from our initial estimate to group roughly half of the expected size. This has not impacted the schedule of the project as much as we thought because of the dedication of the personnel that we retained.
- **Personnel:**
    - Leadership/Construction: John Evans, Brady Easterday, Paul Neves
    - Leadership/Electronics: Brandon Grinkemeyer
    - Construction: Matt Marks, Matthew Spooner, Jacob Prinz
    - Electronics: Peter Zhou, Brendan Van Hook, David Long
    - All personnel are SPS members
- **SPS connection:** Our project helps the local SPS chapter by creating opportunities for SPS students to gain experience in many areas: designing and milling printed circuit boards (PCBs), soldering, 3D computer-aided design (CAD), woodworking (which carries with it many similarities to machining), optics, electrodynamics, and software development. For the national organization, our project will result in a plan to build a cost-effective watt balance to use for outreach and skill-building. We will release the plans to be used by other chapters in the organization.

Updated Background for Proposed Project

Our goal is to create an inexpensive high-precision watt balance that can feasibly be constructed by students at the undergraduate level with access to a workshop. After meeting with the scientists and engineers working on the NIST-4 watt balance, we settled on building an asymmetric balance-wheel design modeled after the NIST tabletop watt balance.

The watt balance has two measuring modes, the velocity mode and the force mode. The force mode measures the current through a coil of wire in an external magnetic field required to apply a force that balances the force of gravity due to the mass of the object being weighed. The velocity mode allows the characterization of the coil and magnets. For this measurement, we must precisely measure the velocity and the induced voltage in the coil as it passes over the magnets. To perform a precise velocity measurement we intend to measure the change in position over a well known time. We are limited by the error in the position measurement because we can much more accurately measure the time.

A do-it-yourself (DIY) watt balance was previously designed by NIST in 2015 [1]. Our design incorporates the following novel improvements:

- We plan on using an interferometer for the velocity mode measurement instead of the shadow sensor used by the DIY watt balance. This yields accuracy in the position that is magnitudes larger than parts per million, which is considerably better than the 1% relative uncertainty of the NIST DIY watt balance. While the interferometer is being built, we will begin by using a high-resolution camera and a computer vision Python library to track the position of the watt balance arm.
- By using a wooden body (figure 6) and 3D printing many of the parts, constructing the body of the watt balance will be cheaper and offer better precision than the LEGO components of the NIST DIY watt balance.
- We are implementing a balance-wheel design similar to the NIST-4 watt balance rather than the equal-arm beam design used in the NIST DIY watt balance. This is more challenging to construct and is less aesthetically pleasing, but results in lower uncertainty. (figures
- The NIST DIY watt balance requires the use of a National Instruments data acquisition device (NIDAQ) [1]. One of our eventual goals is to replace the NIDAQ with an open source and less expensive alternative, e.g. an Arduino-like microcontroller board. However, if we plan on using the interferometer, we will need a board with a sufficiently large sampling rate and bit depth.

Description of Research - Methods, Design, and Procedures

Based on skill level and area of interest, students were separated into groups responsible for certain areas of watt balance development. Each team separately met weekly to develop their ideas and designs. The number of teams and their scopes ended up changing significantly from our initial assessment due to a lack of students with available time to take on leadership roles and the responsibilities involved. These teams and their responsibilities are listed below:

Project Management:

- Consists of team leaders from all teams.
- Made final purchasing decisions
- Coordinates teams and manages project schedule
- Holds weekly meetings to evaluate project progress
- Will write paper/poster upon completion along with other interested team members

Optics, Software, and Electronics Hardware:

- Studied electronics designs and code provided by NIST watt balance team
- Researched the viability and build an interferometer
- Designed and fabricated PCB for photodiode circuit (Figure 3)
- Measure velocity using a camera and a computer vision library while waiting for completion of interferometer
- Will research replacing the NIDAQ with an Arduino or similar microcontroller once calibration of the initial prototype has been completed
- Write new software in Python using the NIDAQ library as well as for possible Arduino integration
- Will write documentation for all software and electronics hardware for public access and improvement

Design, Theory, and Construction:

- Designed a complete 3D CAD model of the watt balance, and all of its structural components
- Made design decisions to make the project as inexpensive and simple to build as possible to maximize accessibility and encourage replication
- 3D printed required components on campus (interferometer optics mounts, solenoid housing, nylon rod guides, mass cradle, camera mount)

- Ensured maximum efficiency of product design through computer simulations of the magnets and coils
- Will research possible improvements to the design, and calibrate and tweak initial prototype
- Will evaluate precision of data measurements, and record findings
- Will write a build guide to instruct others on the procedure for designing and building for public access and improvement

Upon completion of the project, the CAD team will produce design files and documentation, with build notes provided by the construction team. The software team will produce Arduino code and supplemental Python code with documentation. The optics and electronics team will produce design files for the PCBs they design, along with build notes. They will also produce documentation for design improvements and a build guide for the interferometer, as well as provide data and analysis of our accuracy and precision. All of this information will be posted on GitHub where anyone can access our work to replicate or improve on it. Once all of this is complete, the project management team, along with any other interested students, will write a paper or poster (depending on advice from faculty members) to finalize the project.

Initial Results

In order to approximate the voltage we should expect across the coil in velocity mode, we first simulated the magnetic field from our two ring magnets in Mathematica (Figure 1). We then decided we would use about 3000 turns for the coil, and that we would use 36 AWG copper wire. In order to calculate the EMF, we approximated that the wire is square-packed in a 55x55 grid and calculated the total EMF from a sum over each turn of BvL. For a constant velocity of 10mm/s, we found that the EMF would be 0.877V at the moment the coil is centered between the magnets. We then performed this calculation for many other positions through the coil's range of motion (Figure 2).

Using this same square-packing approximation, we were also able to approximate the maximum force that can be generated from a current in the coil. In force mode, we will attempt to hold the coil stationary with its position directly between the magnets, and the current required will be directly related to the mass of the object being tested. With 3000 turns of wire, the wire will be about 2000 feet long and have a resistance of 1.36 Ω/ft, we find that the resistance in the coil will be 2.73kΩ. We can apply 10V with our DAQ, so our maximum current will be about 3.7mA. The force can then be approximated using a sum of BLI over the turns, and we find a force of 0.345 N. This force would be capable of supporting a total mass of 30g against the force of gravity. This mass is achievable, especially since we will be able to make modifications to the balance in order to remove or offset any excess weight on either side of the balance.

It was decided that the most accurate way to measure the velocity of the coil (with the current budget) was to use an interferometer consisting of mirrors, a beam splitter, and a photodiode sensor. To save on costs, the mirror mounts were 3D printed (Figure 4) and the photodiode PCB (Figure 3) were designed using EAGLE and assembled on campus. One issue encountered was that the NIDAQ cannot measure the voltage across the photodiode. Our solution is to use an Arduino-like microcontroller board with a sufficiently high sampling rate. While Arduino is less accurate in measuring voltage, this is not an issue because we only need to find the peaks in the voltage. The last step was to implement the laser. After some calculation, we learned that we need a laser with a coherence length of at least 10 cm. Most commercially available stabilized lasers are outside our price range, but we are considering obtaining a HeNe laser. In addition, the use of an interferometer would require a data acquisition device with a sampling rate that scales as the velocity of the watt balance arm. Given the velocities that we require to induce a measurable voltage in the coil, we would require a sampling rate on the order of megasamples per second. Data acquisition devices with this sampling rate are outside our price range. Efforts to reduce the cost of the interferometer are ongoing, and in the interim, we have implemented a temporary solution by measuring the velocity using a camera and a Python computer vision library. This stop-gap measure allows further development and calibration of the Watt-balance before the interferometer is completed.

Statement of Next Steps

Plan for Carrying Out Remainder of Project (including Timeline)

- Key milestones and project timeline:
  - July 10th: Finish design and assembly of electronics and optics needed for the interferometer
  - July 17th: Update prototype skeleton based on challenges and improvements found during initial construction
  - July 31st: Replace the NIDAQ with an Arduino-like microcontroller to increase accessibility and ease of use
  - August 10th: Complete poster and presentation summarizing process, findings, and functionality of final product
  - August 26th: Have intermediate draft of journal paper submitted for review by professors
  - September 30th: Submit paper to American Journal of Physics for peer review
  - November 9-11th: Present poster at the 2018 Annual Meeting of the APS Mid-Atlantic Section
  - December 1st: Begin writing final report
  - December 20th: Submit final report
- Future personnel:
  - All current members of the project will continue their involvement until the project has been completed.
  - Bruce Rowley (machinist): Will assist with design improvements and possible CNC machining
  - Jack Touart (engineer): Will assist with electronics testing and production
  - Dr. Daniel Lathrop (professor; expert in experiment design and lab safety): Will assist with safety training of new team members and calculating precision of our watt balance
  - New team members: Stephanie Williams (SPS member). Anuraj Talati (SPS member)
- Other experts that we consulted:
  - Frank Seifert, Diana Haddad, Leon Chao: Researchers working on the NIST-4 watt balance.

Bibliography

[1] L. S. Chao *et al.*, "A LEGO Watt balance: An apparatus to determine a mass based on the new SI," *American Journal of Physics*, vol. 83, no. 11, pp. 913–922, Oct. 2015.

[2] D. Haddad, L. S. Chao, F. Seifert, D. B. Newell, J. R. Pratt, and S. Schlamminger, "First mass measurements with the NIST-4 watt balance," in *2016 Conference on Precision Electromagnetic Measurements (CPEM 2016)*, 2016, pp. 1–2.

[3] T. Quinn, L. Quinn and R. Davis, "A simple watt balance for the absolute determination of mass," *Physics Education*, vol. 48, no. 5, pp. 601–606, 2013.

Appendix

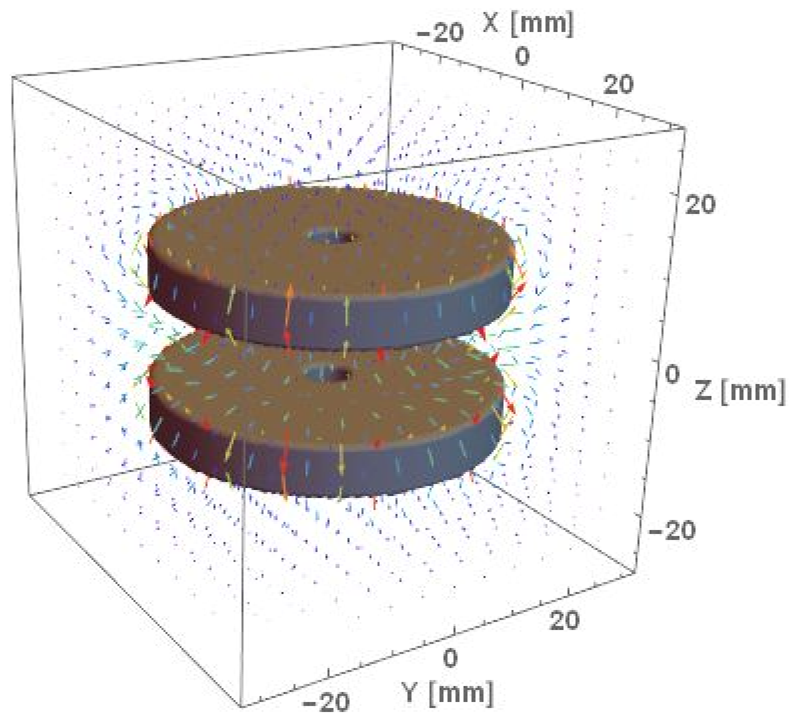

Figure 1: Visualization of computationally simulated magnetic fields produced by our permanent magnets.

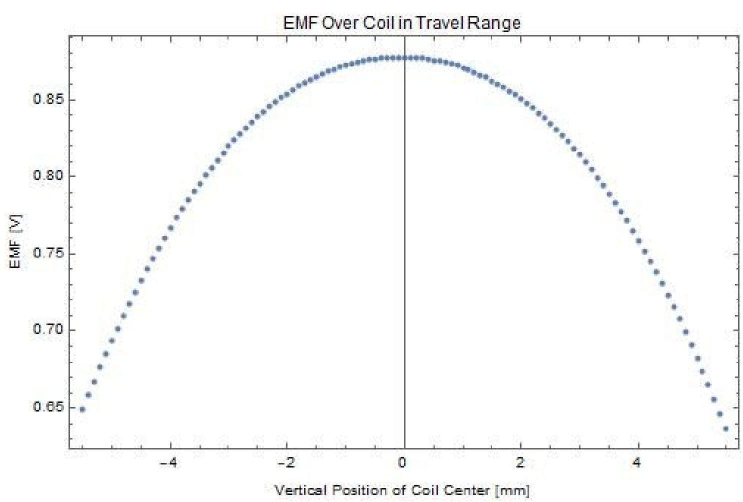

Figure 2: EMF in coil assuming 3000 turns at a constant velocity of 10mm/s.

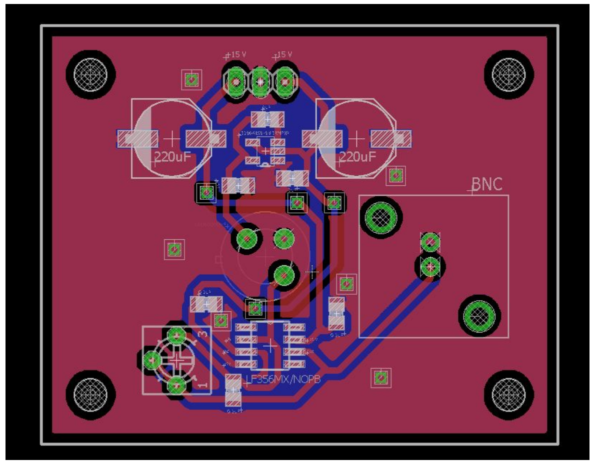

Figure 3: Board layout of the photodiode circuit to be used in the interferometer setup

Figure 4: Mirrors and 3D printed optical mounts

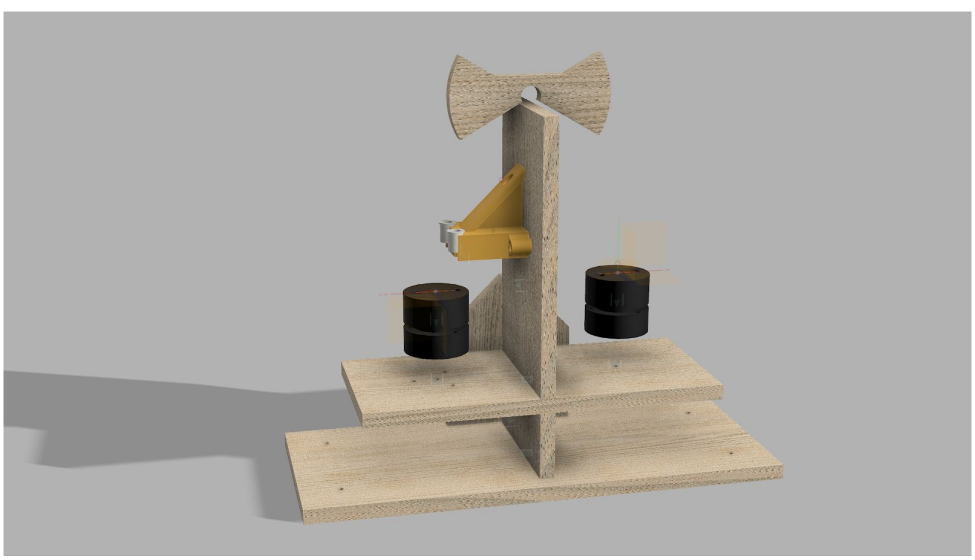

Figure 5: Preliminary CAD model of wooden components with some 3D printed components for reference

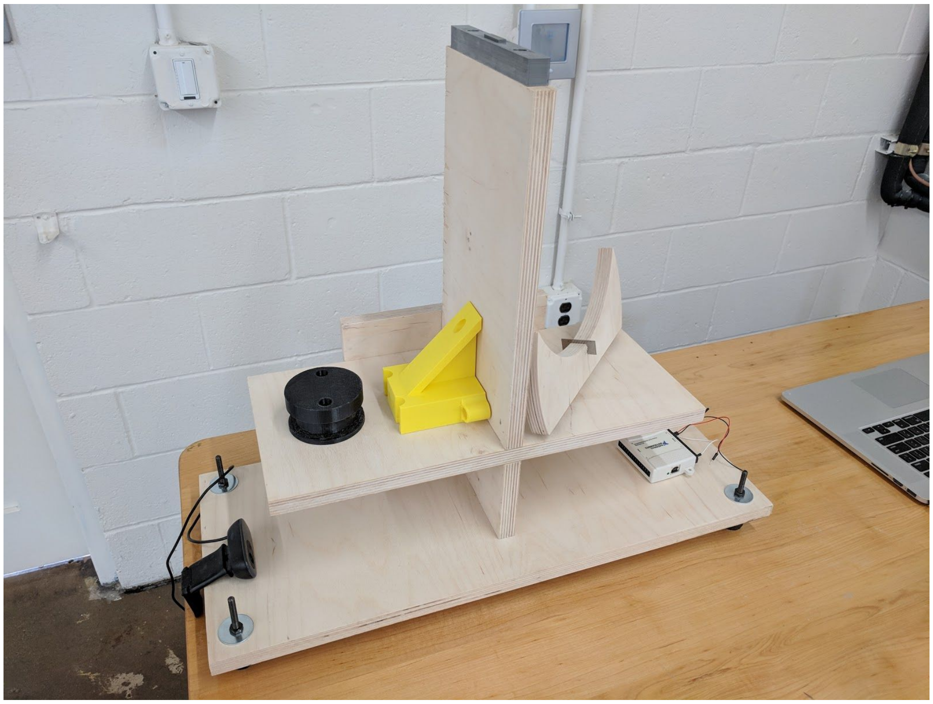

Figure 6: Wooden components for prototype assembled. 3D printed mount for pivot in grey, support for nylon guide rods in yellow, and coil housing in black. Webcam for velocity measurement and NIDAQ roughly placed.