SOCIETY OF PHYSICS STUDENTS

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SPS Chapter Research Award Final 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	$1999.66
Total Amount Expended	$2110.38
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 students acquire skills in computer-aided design (CAD), electronics, 3D printing, machining, programming, data analysis, and optics.

Statement of Activity

Overview of Award Activity

- **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 primarily 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:** While we were unable to get to the point where we can press a button and measure a mass, we are very close. We have a structure design that works well, and we have software that completes every aspect of calibration automatically. The final hurdle is with our chosen digital to analog converter (DAC). It has proven to be very difficult to interface with, but with more time, we will get it working. Our design means that not only will the cost to build a duplicate be less than half of the cost of the LEGO watt balance, but it will be able to produce better results, and without the need of an additional computer. This makes our device perfect for outreach events and conferences. In the future, we still intend to use an interferometer as a higher precision position measurement. Older 3 pin laser interfaces with pre-installed photodetectors operate in a way such that light is emitted in both directions, and the light that is emitted in the opposite direction of the main beam can be back-reflected by a remote target, creating an interference pattern that can be used to generate a lower error position measurement. [4]
- **Any changes in the scope of project:** Due to scheduling constraints, and a lack of a suitable workspace, construction and development of the watt balance took longer than previously expected, as the workspace only became fully available to us around late summer. We were still able to begin working on prototyping, but the bulk of our progress towards a fully working prototype occured after we got full use of our workspace. Additionally, we saw a drop in personnel from our initial group to 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. The biggest design related change in our project was the decision to use machine vision for relative position measurements as opposed to interferometry, but as the previous section stated, we plan to go back to this method in the future.
- **Personnel:**
  - Leadership/Construction: John Evans, Brady Easterday, Paul Neves
  - Leadership/Electronics: Brandon Grinkemeyer
  - Construction: Matt Marks, Matthew Spooner, Stephanie Williams
  - 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.

Description of Research - Methods, Design, and Procedures

Determining Ideal Magnet Coil Dimensions

In order to determine the ideal magnet coil size, we first selected the magnets we would use to induce a magnetic field in the wire coil. We determined that two ring magnets would be the most ideal type to use, because the magnetic field between the magnets would be strongly radial. The ring magnets in particular that we decided on using are neodymium N42 magnets with a ¼ inch inner hole and thickness, and a 2 inch outer diameter. Around these magnets, we developed a 3D printed coil housing with a 1/16 inch clearance around the magnets for the inner circumference. In order to determine the ideal coil dimensions, we based our calculations on a 3000 turn coil of 36 AWG magnet wire. We used the Radia simulation tool in Mathematica to simulate the magnetic field strength of the magnets as a function of distance from the center of the ring to determine the ideal thickness of the coil. In order to get more accurate measurements, it was key to ensure that the radial dimension of the coil lay within the range where the magnetic field strength was largely linear, as opposed to a more exponential drop-off. By integrating the force equation $F = q(v \times B)$ and setting that equal to $I(l \times B)$ (where q is the total charge, v is the velocity, B is the magnetic field, I is the current, and l is the length of the wire coil), we were able to determine the weight that our magnet wire coil should be able to counteract with a sufficient current through it. We found that with a coil of that size and given the limitations of the DAC that we are using to provide current, we should be able to handle a mass of 30g. [5]

Obtaining Accurate Velocity Measurements

Initially, we intended to use an encoder with our motor to determine its relative motion, but friction between the eocoder and the motor was too high a source of error to be a viable option. Our second attempt was centered around the use of a Michelson-Morley interferometer, which would provide a much more precise measurement of relative position without the friction concerns described in the previous design. However, this method proved to be too time consuming to pursue within our time constraints, so we were forced to pursue other options for the time being. In the future, we intend to use an interferometry method centered around the self-mixing of a three-pin laser diode to measure relative position. We believe that this will yield a low enough error to be acceptable in our calculations. In the meantime, we agreed that a good and simple method for measuring position of the mass pan would be through machine vision via a Logitech webcam. Our initial plan for the machine vision was to have a white and black alternating stripe pattern attached to the mass pan be interpreted by the webcam to determine velocity based on the speed with which the stripes alternate, and relative position based on how many stripes alternate, but this method failed due to resolution issues with the camera, as well as the image that the camera was interpreting not being "white and black enough". We were able to get a successful position measurement through the detection of a thin black ring of electrical tape wrapped around the white nylon rods holding up the mass pan. The stripe was located via a brightness threshold detected by the webcam, and the precision with which the position was identified with a sufficiently narrow strip was more than precise enough for our calculations. Using this relative position measurement along with the 360 degrees = 3200 steps resolution due to angular motion by the NEMA-17 stepper motor, we were able to obtain a sufficiently low error velocity measurement for our calculations.

Accurately Establishing the Local Acceleration due to Gravity

In order to obtain a highly accurate value of the local acceleration due to gravity (*g*), we use a Wolfram|` widget that generates a location-specific value for the magnitude and direction of *g*. The widget allows precision to 10 ppm in *g* through use of a 12th order spherical harmonic model of the earth's gravitational potential field based on the EGM2008 model. In future, we plan to directly integrate the EGM2008 model into our code to higher harmonic order, allowing direct determination of the value and uncertainty of *g* during operations simply by inputting geospatial coordinates.

Development of Balancing Mechanism

The main goal of the balancing mechanism was to create a low friction contact between the balancing mechanism, and the frame. The first method we evaluated ended up working acceptably, and was a metal razor blade embedded into the balancing wheel mechanism that would balance on a block of tungsten carbide attached to the main frame of the watt balance. The hardness of the tungsten carbide block would ensure that there would be no wear on it over time from the razor blade. The balancing wheel mechanism was developed as two arcs of a circle with grooves on the outer circumference in order to guide the titanium wire connecting the stepper motor to the balancing wheel, and the balancing wheel to the mass pan and wire coil. Bolts on the top of the wheel allowed us to adjust the length of the titanium wire to ensure that the wire was sufficiently taut. Because of the weight of the magnet coil in particular on the mass pan side of the watt balance, a counterbalance bucket was developed and attached on the motor side to make the entire apparatus balanced during operation. Initially, we developed a mount with nylon bushings to make sure that the mass pan side did not swing during operation, but the bushings ended up causing too much friction for the watt balance to be sufficiently sensitive, and had to be removed. However, the swinging of the mass pan and coil mechanism with the bushings removed was relatively minimal, and the low friction due to having only one contact area to the main frame in the razor blade was ideal for having a high-sensitivity balancing mechanism.

Discussion of Results

Ultimately, we were unable to get to the point where we can press a button and measure a mass. However, we are very close to this goal, having a well working physical structure, and software that automatically calibrates the watt balance upon use. The biggest problem that we have encountered is interfacing with our digital to analog converter, which is the last step in getting our force mode to work properly and get a mass measurement. Once this is working properly however, our watt balance design will be able to yield higher accuracy results at half of the cost of NIST's LEGO watt balance that was the inspiration for our project. Additionally, we will be able to operate the device without the use of an additional computer, making our device perfect for outreach events or conferences. In the future, we intend to use an interferometer as a higher precision position measurement. Older 3 pin laser interfaces with pre-installed photodetectors operate in a way such that light is emitted in both directions, and the light that is emitted in the opposite direction of the main beam can be back-reflected by a remote target, creating an interference pattern that can be used to generate a lower error position measurement. The two most significant sources of error in our measurements were inconsistencies in the motion of the stepper motor, and the slight swinging and twisting of the mass pan and coil after we removed our bushing apparatus from the watt balance to reduce friction. The main limitation preventing us from getting a higher accuracy measurement is cost. Higher quality tools such as a CNC mill/lathe, and drill press would have enabled us to machine components like our frame with much higher precision and accuracy. Additionally, superior DAQs and motors would have decreased any vibration due to relatively large step sizes, and given us higher resolution of the data we collected.

Thanks

Dissemination of Results

We plan to present our findings and results in poster and published journal article format. Additionally, we plan to present our research at the APS April Meeting in 2019, as well as using our completed watt balance as a complimentary piece for a talk given by Bill Phillips, a Nobel Laureate professor at the University of Maryland.

Bibliography

[1] L. S. Chao, S. Schlamminger, D. B. Newell, J. R. Pratt, F. Seifert, X. Zhang, G. Sineriz, M. Liu, and D. Haddad, American Journal of Physics **83**, 913 (2015).

[2] T. Quinn, L. Quinn, and R. Davis, Phys. Educ. **48**, 601 (2013).

[3] D. Haddad, L. S. Chao, F. Seifert, D. B. Newell, J. R. Pratt, and S. Schlamminger, in *2016 Conference on Precision Electromagnetic Measurements (CPEM 2016)* (2016), pp. 1–2.

[4] G. Giuliani, M. Norgia, S. Donati, and T. Bosch, J. Opt. A: Pure Appl. Opt. **4**, S283 (2002).

[5] B. Easterday and J. Evans, *Watt Balance Design* (2018), pp. 1-8.

Impact Assessment:

How the Project Influenced your Chapter

Overall, this project was an amazing opportunity to practice and experience the entirety of project development and management from start to finish. Based on various interests and areas of expertise within our development group, we were able to hone invaluable skills in disciplines such as CAD, woodworking, programming, and data analysis. The biggest lessons that we learned over the project is the extreme importance of dedicated, committed individuals we can rely on over the year-long process to ensure project success, and the importance of having the proper resources to conduct the project by the time we submit the proposal. One of the main hindrances that we experienced during development was a lack of a suitable workplace until late summer, which limited our ability to properly develop our prototype on schedule. This project strengthened our SPS chapter by increasing our skills at the aforementioned disciplines, and through our planned attendance at the APS April Meeting and Bill Phillips' talk, our chapter will hopefully receive more publicity and notoriety. For any other SPS chapters applying for research awards, we would recommend an emphasis on recruiting any interested and committed individuals, and to ensure that they have the proper guidance and instruction to hone skills related to their area of interest. Additionally, we cannot recommend enough that you ensure that your project is manageable, and doable in conjunction with a heavy academic workload.

Key Metrics and Reflection

How many students from your SPS chapter were involved in the research, and in what capacity?	10 students from our SPS chapter were heavily involved in various facets of this project's completion.
Was the amount of money you received from SPS sufficient to carry out the activities outlined in your proposal? Could you have used additional funding? If yes, how much would you have liked? How would the additional funding have augmented your activity?	The research grant was sufficient to carry out the activities outlined in our proposal. However, additional funding could have been used to purchase NIST certified masses for calibration, a diode laser with a longer coherence length for interferometry, higher quality bearings to reduce friction, a drill press for more precise holes, a more superior DAQ for data acquisition, and the ability to make our Watt Balance primarily out of (non-magnetic) metals such as aluminum via a CNC lathe and mill.
Do you anticipate continuing or expanding on this research project in the future? If yes, please explain.	In the future, we intend to replace the machine vision method we use for our position measurement with a laser interferometer. As mentioned earlier, we believe that the self-mixing method of a 3-pin laser diode should be sufficient to get a low-error position measurement.
If you were to do your project again, what would you do differently?	If we were to do this project again, we would focus a lot more on frequent recruitment efforts to get more people involved, and ensure that we had the proper tools in our workspace before our project window began.

Expenditures

Expenditure Table

Item	Please explain how this expense relates to your project as outlined in your proposal.	Cost
FDS100 - Si Photodiode	This was intended to be used for the shadow sensor or interferometer	$14.08
12.5mm Diameter, 50R/50T, Plate Beamsplitter	This was intended to be used for the interferometer	$35.00
Steel Extension Spring (12 pack)	This was intended to be used for the mirrors in the interferometer	$7.00
Steel Hex Nut (100 pack)	Used to connect components to each other	$1.32
18-8 Stainless Steel Cap Nut (25 pack)	Used to connect components to each other	$4.04
18-8 Stainless Steel Socket Head Screw (25 pack)	Used to connect components to each other	$7.22
Class 8.8 Steel Hex Head Screw (100 pack)	Used to connect components to each other	$6.13
E52100 Alloy Steel Balls (25 pack)	This was intended to be used for the mirrors in the interferometer	$3.61
36 Gauge Motor Winding Wire	Used for the 300 turn wire coil on the measurement side of the watt balance	$19.20
Off-White Nylon Rod (½ inch dia., $1.05/ft)	This was intended to go through the bushings and connect to our wire coil, but there was too much friction, and a slippery rod was purchased instead	$5.25
Off-White Nylon Rod (¼ inch dia., $0.49/ft)	Used to connect the mass pan to the magnet coil	$2.45
Tungsten Carbide Block	Used to create low friction connection between balancing wheel razor edge and main frame.	$24.99
Dry-Running Sleeve Bearing (length 1 inch, x2)	Used to create a low-friction connection on the measurement side of the watt balance	$2.96
Dry-Running Sleeve Bearing (length ½ inch, x2)	Used to create a low-friction connection on the measurement side of the watt balance	$1.88
18-8 Stainless Steel Socket Head Screw (25 pack)	Used to connect the tungsten carbide block housing to the balancing wheel	$9.85
Glass-Filled Nylon Socket Head Screws (1", 10 pack)	Used to connect components to main frame	$10.02
Glass-Filled Nylon Socket Head Screws (2", 10 pack)	Used to connect components to main frame	$10.51
Swivel Leveling Mount (x4)	Used to level base of watt balance	$33.04
Installation Bit (¼ insert)	Used for component fabrication	$9.26
Brass Hardwood Tapping Inserts (25 pack)	Used to connect components to main frame	$11.97
Titanium Socket Head Screw	Used to hold neodymium magnet stack together	$11.11
Titanium Hex Nut (x2)	Used to hold neodymium magnet stack together	$5.14
Slippery Nylon Rod (¼" dia.) ($0.68/ft, 5ft)	Used to connect magnet wire coil to balancing wheel.	$3.40
Slippery Nylon Rod (½" dia.) ($1.44/ft, 5ft, x2)	Used to connect magnet wire coil to balancing wheel. A second one had to be purchased, as the first one was misplaced	$14.40

Neodymium Rare Earth Magnets (x4)	Placed inside magnet wire coil as part of force and velocity mode operation	$35.96
Irwin Industrial Tools Drill Bit Set, 60-Piece	Used for component fabrication	$83.19
Bosch 18V Jig Saw	Used for component fabrication	$149.00
Bitholding Screwdriver and Pouch Set, 33-Pieces	Used for component assembly	$79.95
Irwin Tools 12' Combination Square,	Used for dimensioning frame and precision outlining	$12.99
Swanson Tool 7-inch Speed Square	Used for dimensioning frame and precision outlining	$8.99
NEMA-17 Stepper Motor Driver	Used to decrease step size and increase smoothness of NEMA-17 motor operation	$14.99
17x 211.1g 10mg-100g Grams Precision Calibration Weight Set	Used to calibrate the watt balance, and to determine accuracy of measurements	$11.99
Logitech C270 Widescreen HD Webcam	Used along with machine vision software to determine relative position of the mass pan	$19.88
100W Hot Glue Gun	Used for component assembly	$29.99
Adafruit NEMA-17 Stepper Motor	Used to generate a constant linear velocity for velocity mode of the watt balance	$18.95
Adafruit Motor Shield for Arduino	To increase functionality of NEMA-17 motor	$18.91
Arduino UNO R3	Was used in initial prototype of motor-pulley system	$19.15
Irwin Tools Carbon Steel Tap 1/4" - 20 NC	Used for component fabrication	$15.90
Vacmaster 5 Gallon Wet/Dry Vacuum	Used to clean up the workspace during construction	$47.06
HeNe Laser + Amplifier	Intended to be used for the interferometer	$162.40
Plywood (25ft^2, ¾ inch, Baltic Birch)	Used to build the main frame and wheel for the balancing mechanism	$59.00
Oil-Embedded Flanged Sleeve Bearing (5 mm shaft dia., x2)	Used as a bearing for the NEMA-17 stepper motor and pulley system	$3.64
12-Bit DAC w/I2C Interface	Used for digital-analog conversion for data interpretation	$4.95
Shipping (various orders)	Shipping costs for various material orders	$70.67
Prusa i3 MK3 3D Printer	Used for component fabrication	$999.99
DRV8825 Stepper Motor Driver Carrier (x2)	Used to control stepper motor	$17.90
Total		$2134.37

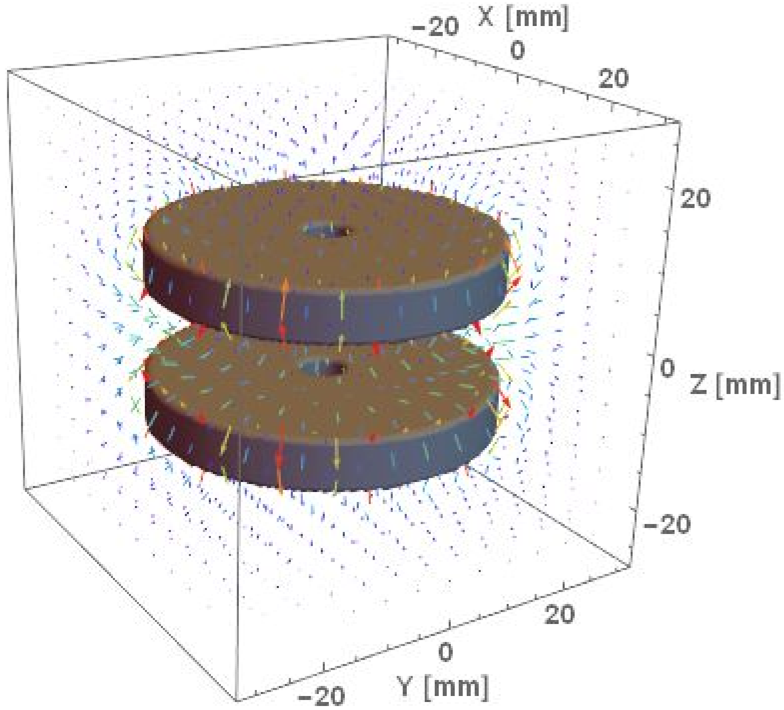

Figure 1: Visualization of computationally simulated magnetic fields produced by our permanent magnets.

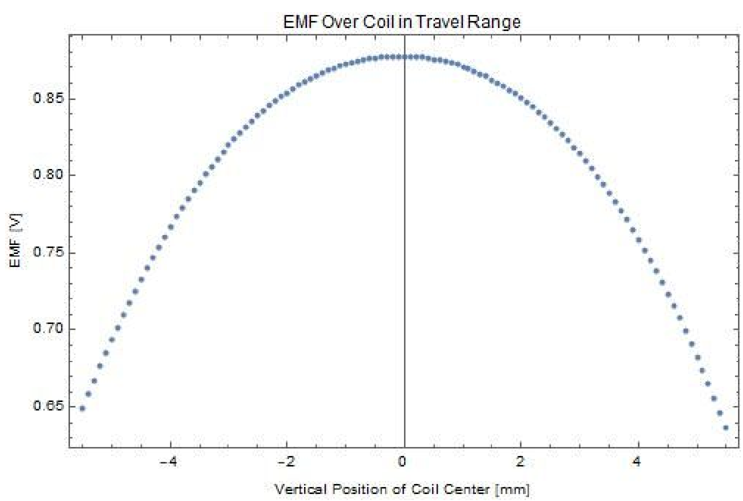

Figure 2: EMF in coil assuming 3000 turns at a constant velocity of 10mm/s.

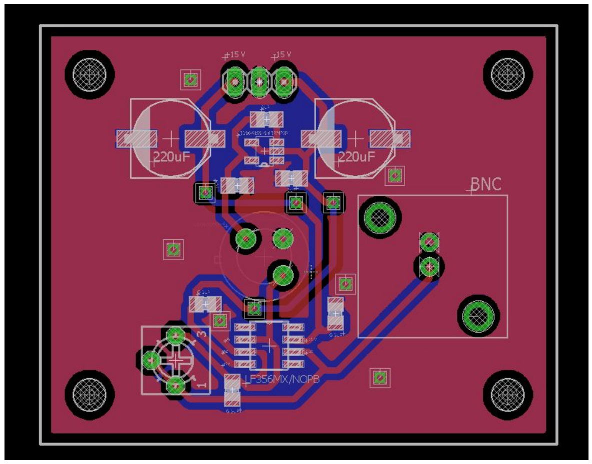

Figure 3: Board layout of the photodiode circuit to be used in the interferometer setup

Figure 4: Mirrors and 3D printed optical mounts
Taken By: John Evans

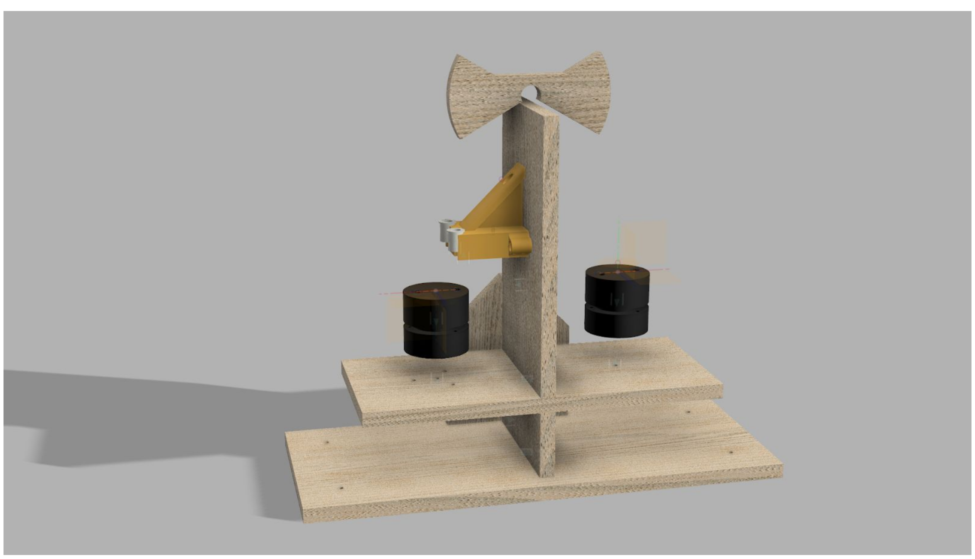

Figure 5: Preliminary CAD model of wooden components with some 3D printed components for reference
Taken By: John Evans

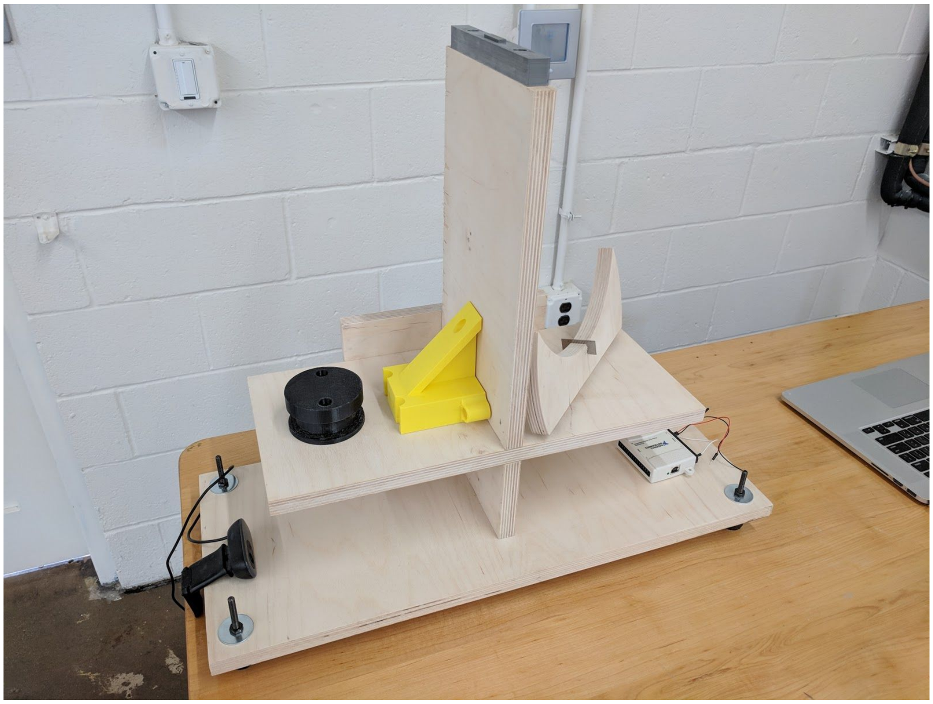

Figure 6: Wooden components for prototype assembled. 3D printed mount for pivot in grey, support for nylon guide rods in yellow, and coil housing in black. Webcam for velocity measurement and NIDAQ roughly placed.
Taken By: John Evans