

SOCIETY OF PHYSICS STUDENTS

An organization of the American Institute of Physics

SPS Chapter Research Award Proposal

Project Proposal Title	SPS-ENTR: A Student-Built Electronic Torque Realizer for Undergraduate Metrology Research
Name of School	The University of Tennessee – Chattanooga
SPS Chapter Number	7170
Total Amount Requested	\$1999.32

Abstract

The University of Tennessee at Chattanooga chapter of the Society of Physics Students proposes to design, construct, and test a model of a tabletop torque standard inspired by the National Institute of Standards and Technology's (NIST) Electronic NIST Torque Realizer (ENTR) [1]. This device will serve as a low-cost, educationally accessible torque calibration standard capable of generating and measuring torques in the range of 10^{-2} to 1 N·m. The project will combine mechanical fabrication, electronics, and programming to build a simplified version of the ENTR using both machined and 3D-printed components. Through this project, students will learn precision metrology techniques, gain experience with electromagnetic actuation, and develop Python-based data acquisition and control software. The final apparatus will be used to calibrate small torque tools, serve as an instructional device for metrology demonstrations, and contribute to undergraduate research and outreach at the UTC Physics Department.

Proposal Statement

Overview of Proposed Project

The University of Tennessee at Chattanooga chapter of the Society of Physics Students proposes to construct, calibrate, and test a model of an electronic torque realizer. This device will allow for the precise calibration of torque tools while being low-cost and compact. We will compare it to known torques from lever arms and then calibrate our own torque tools.

We have chosen this project as our chapter research project for 2026 because:

- Our chapter has done several hands-on research projects funded by SPS National (funded in 2022, 2024 and 2025), and many of us wanted to work on more projects. The previous projects gave our members experience in electronics, 3D printing, programming, and basic machining. Through this project, we hope to further master these skills that we can apply later as we pursue graduate studies and careers.
- This project stems from our first project, the LEGO model of the Kibble Watt balance [2, 3], a model of the machine that has redefined the System International unit of kilogram based on

the fundamental Planck's constant. Working on that project allowed us, among other things, to meet and develop collaboration with NIST scientists. In the current project, we will use a similar physical approach, however, instead of measuring force, we will be measuring torque, therefore the geometry will change. This model will be a replica of the actual device being created at NIST. A counterpart of the LEGO Kibble balance model for the torque measurements which can serve as "a put-together-outreach-project" for any audience has not been developed yet, so our work in collaboration with NIST scientists will not only help us to further our physics skills and execute an interesting project, but also contribute to creation of a blueprint that can be disseminated to and used by any audience (i.e. other SPS chapters). The opportunity to work together and learn from NIST scientists is invaluable to us, which makes this project very attractive for our chapter.

- This project aligns well with our university and chapter's goal of promoting experiential learning and giving students new skills, like working with magnets and circuits, to a deeper level than they would get in a conventional physics lab. The experimental nature of this project allows us to practice our experimental skills in a more realistic way than we do in a typical physics lab.
- Most of our members have taken or will be taking a class on electricity and magnetism, so they will have a good basis for the theoretical side of this project to effectively contribute. We have several members with backgrounds in machining, which will help to keep the cost down, as we can create all of the pieces of metal we need.
- Programming in Python is required to run this device, which will teach students an extremely important skill needed for careers in STEM.
- We will use this project in demonstrations to promote our chapter of SPS as well as our physics department at UTC. We hope it will spark interest in our program for prospective high school students or current UTC students from other departments.
- We will acknowledge that the apparatus was constructed with the help of the SPS Chapter Research Award to make students and other community members aware of our local SPS chapter and SPS National.
- The construction of the electronic torque realizer will give students the chance to participate in rigorous and challenging scientific research while in a supportive community of fellow SPS members.

Background for Proposed Project

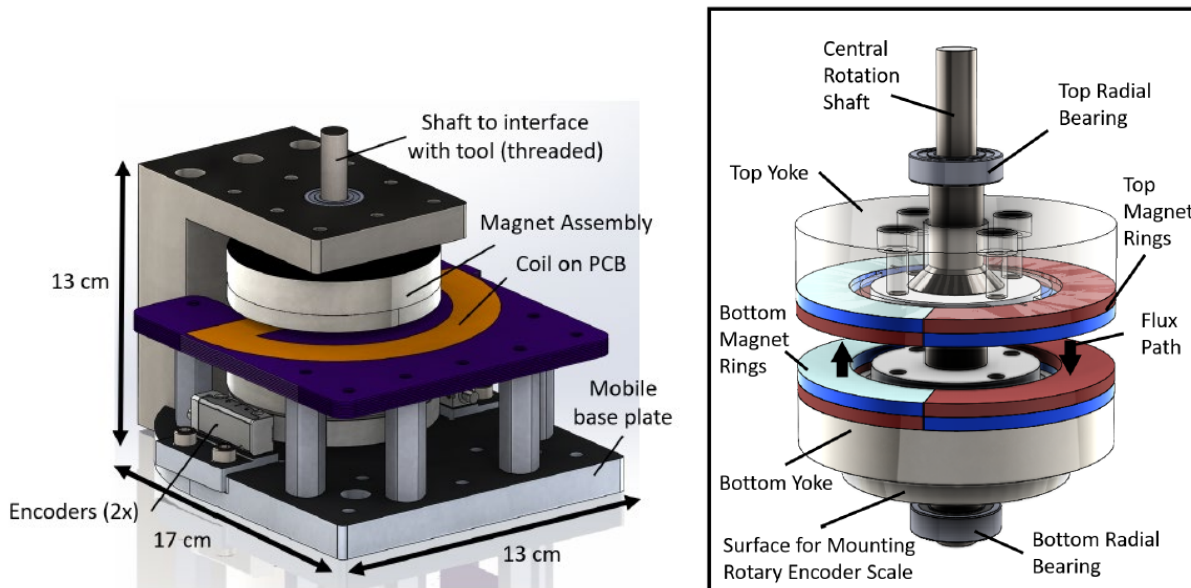
In 2019, there was a revision of the International System of Units (SIs). This change set the kilogram to be defined by the value of Planck's constant and to be realized by quantum-electrical standards using the Kibble principle. This principle relates the mass of an object to the electromagnetic force that perfectly counteracts the force of gravity. One can apply this principle of realizing the kilogram to the realization of torque through electrical measurements [1]. For small torques, in the order of 10^{-2} N m, measuring the torque becomes burdensome and irreproducible. That is why the National Institute of Standards and Technology (NIST) collaborated with the U.S. Air Force to create a tabletop electromagnetic torque calibration device that can measure torque from 7×10^{-4} N m to 1 N m with 0.1% uncertainty [1].

There is a relation between force and torque. Linear momentum is changed by force, and rotational momentum is changed by torque. This is why the Kibble principle can easily be switched to a rotational system to realize torque. For this device, a magnet system spins with respect to a fixed

coil. There will be two modes of operation, spin mode and torque mode. The torque can be measured by

$$\tau_m = IV(\phi_0)/\omega(\phi_0)$$

where I is the current in the coil, V is the voltage in the coil from the spinning magnet and ω is the angular velocity. Both V and ω are dependent on θ which is the initial angular position.



- *Figure 1 & 2 showing the NIST ENTR main assembly and central rotor assembly [1]. Our SPS chapter will be building a tabletop model of this device.*

Devices with this kind of precision can easily cost over \$10,000 and are not commercially available to a program like ours at UTC. This device we are proposing will cost a fraction of the price and use readily available components, many of which we can make ourselves. Many of the components can be 3D-printed or machined by students in our chapter, which heavily reduces the cost of materials. The machine will be controlled by a computer with a Python-based software which will be mostly provided by NIST, with any needed modifications made by our students in collaboration with NIST. We will test our device on-standardized torques realized with known masses and lever arms. Once the device is properly calibrated and in the acceptable range of uncertainty, we will use it to test and calibrate precision torque tools.

Expected Results

The expected result of this project is a functional electronic torque realizer for precision calibration of torque tools, in the range of 7×10^{-2} N m to 1 N m with 2-1% uncertainty. Once assembled and calibrated to reach the desired torque uncertainty, we will be able to compare our measurements to the torques measured by known masses and lever arms, as they did at NIST [1]. The UTC-SPS team expects to gain much experience in machining, programming, designing, electronics, and experimentation through this project. This will give our students much deeper experiences in electronics than they would ever get in a traditional electricity and magnetism lab. Our physics program does not give students the chance to build things from scratch or program

electronics through the regular curriculum, so this project will serve as the only way to achieve those skills at UTC. In the past, with the help of the SPS Chapter Research Award, we have been able to construct a LEGO-based model of the Kibble watt balance, which is what the ENTR is based on, a LEGO-based Low-Cost Autonomous Scientist (LEGOLAS), and a 3D-printed laser autocollimator for precise angular measurements. All three of these projects have been a huge successes for our chapter. Not only did they give our students valuable experiences, but they also created community within our department and inspired the growth of our chapter by showing many students the fun work that we did in SPS. They were also used for outreach and recruitment and presented at the 2025 Inagural Quantum Camp for high school studens, which made a huge impact. We believe that this project will continue to spark excitement within our chapter and within the UTC and Chattanooga community. This project can be added to our collection to use for outreach events at our local museums and schools to show how fun physics can be.

Description of Proposed Research - Methods, Design, and Procedures

The UTC-SPS team will construct a model of a tabletop electronic torque realizer inspired by the National Institute of Standards and Technology's (NIST) Electronic NIST Torque Realizer (ENTR). While the ENTR is a high-precision metrological instrument designed to directly realize torque traceable to the SI, our project will focus on creating a simplified, educational version that allows undergraduate students to study the same underlying physical principles through hands-on construction, measurement, and calibration.

1. Mechanical Construction and Fabrication

All major structural components—including the base plate, rotor hub, bearing housings, alignment blocks, and coil supports—will be machined by SPS members at a local machine shop, with primary machining performed by the SPS president. The parts will be machined from raw 6061-T651 and 7075-T651 aluminum stock, precision-ground low-carbon steel rod, and Delrin homopolymer. This approach reduces costs significantly compared to purchasing pre-machined components and provides valuable hands-on experience in fabrication, metrology, and the interpretation of mechanical drawings. Other fixtures and supports will be produced using 3D printing.

2. Electromagnetic System and Circuit Design

The torque generation system consists of a set of high-grade neodymium ring magnets forming a rotating magnetic assembly and a PCB torque coil fabricated from stacked FR-4 copper-clad boards. The coil's electromagnetic coupling factor will be established using spin-mode operation, analogous to the procedure employed in NIST's ENTR design [1].

3. Sensors, Electronics, and Power Delivery

Angular position and velocity will be measured using a Renishaw RM22 high-resolution magnetic encoder. Coil current and power will be monitored using two INA260 precision current/power sensors. An Arduino Uno microcontroller will perform real-time control tasks, while a Raspberry Pi 4 will run Python-based data acquisition and analysis software. A Rigol DP711 programmable linear DC power supply will provide a stable, low-noise current source for torque-mode operation.

4. Experimental Operation

Voltage, current, and encoder signals will be recorded using a Measurement Computing USB-234 (16-bit, 100 kS/s) data acquisition module. The apparatus will be operated in two modes:

1. Spin Mode – The rotor is driven externally, and induced voltage is measured as a function of angular velocity to determine the electromagnetic calibration constant.
2. Torque Mode – A controlled current is applied to the torque coil to generate a measurable, calibrated torque.

These measurements will give students practice with calibration methods, and data visualization as they compare their measured torques to theoretical predictions.

5. Educational Outcomes and Integration

By the end of the project, students will have assembled a fully functional tabletop model of a torque standard that can be used for:

- Demonstrating the connection between electromagnetic and mechanical quantities in physics labs.
- Teaching students how modern standards of mass and torque are realized through quantum and electrical principles.
- Serving as an interactive outreach exhibit at departmental and community events.

In building and operating this system, SPS members will gain valuable experience with the full experimental process—from design and fabrication to calibration and data acquisition and analysis—mirroring the procedures used in advanced research laboratories like NIST.

Plan for Carrying Out Proposed Project

All members of the UTC Society of Physics Students (currently 20 students) will contribute to this project. The group will be divided into smaller working teams based on members' interests and skills, allowing everyone to gain experience with different aspects of the building process while keeping progress organized and efficient.

Team Structure and Roles

- **Mechanical Team:** Responsible for designing and fabricating the mechanical components of the torque realizer, including the rotor, base, and bearing housings. Members of this team will work with the SPS president on the machining and the 3D printing to produce and assemble the structure.
- **Electronics and Wiring Team:** Tasked with assembling the PCB coil, wiring the circuit, and integrating the current sensors, power supply, and control components. This group will also be in charge of testing connections and ensuring electrical safety.
- **Programming and Data Team:** Focused on developing and implementing Python code for data acquisition and analysis. This includes reading encoder data, controlling the current through the coil, and calculating torque values. Members will also handle uncertainty analysis and data visualization.

All groups will meet weekly to work on the project, report progress and coordinate tasks. Project leaders will oversee scheduling, purchasing, and final system integration. Regular check-ins with our chapter advisor, Dr. Tatiana Allen, will ensure that the project stays on track and that safety and lab protocols are followed.

Project Timeline

- **January – February:** Order bearings, raw materials, magnets, circuit components, and sensors. Begin 3D printing and machining structural parts such as the base, bearing housings, and coil mount.
- **March:** Assemble the mechanical structure and integrate the rotor and magnet system. Begin constructing the PCB coil and wiring the circuit.
- **April:** Test the electromagnetic system, verify basic coil operation, and begin developing Python code for data acquisition and control. Conduct preliminary calibration runs using known torques from lever arms.
- **May:** Refine alignment, collect initial torque data, and analyze early measurements. Prepare and submit the *Interim Report* to SPS National by May 31, 2026.
- **August – September:** Resume work by reviewing spring progress and reassembling the apparatus. Finalize data acquisition code and begin full calibration runs.
- **October:** Conduct repeated torque measurements, refine uncertainty analysis, and compare results to theoretical predictions.
- **November:** Prepare poster and presentation materials for the *South Eastern Section of the American Physical Society (SESAPS) 2026 Meeting* and organize outreach demonstrations at UTC and local schools.
- **December:** Complete all testing and documentation. Submit the *Final Report* to SPS National by December 31, 2026.

Budget Justification

To construct the tabletop electronic torque realizer, we request funding for the following components and materials. The proposed budget prioritizes educational value, cost efficiency, and accessibility, ensuring that the project can be completed entirely by undergraduate students using campus facilities.

Mechanical Components: Two high-precision 7200C P5 angular contact bearings provide low-friction, high-stability support for rotor measurements. This category includes all aluminum (6061-T651 and 7075-T651), Delrin homopolymer, precision-ground steel rod, and round stock required to machine the rotor hub, bearing housings, base structures, coil mounts, and alignment components.	\$465.64
Magnetic and Electromagnetic Materials: This includes four K&J neodymium ring magnets used to construct the rotating magnetic assembly, and copper-clad FR-4 boards used to fabricate the PCB torque coil. These components form the core of the electromagnetic torque generation system.	\$95.92
Sensors and Electronics: A Renishaw RM22 encoder, two INA260 current/power monitors, Arduino Uno, and Raspberry Pi for system control and data acquisition. A Rigol DP711 programmable linear power supply provides a stable, low-noise current source for the torque coil.	\$641.07
Data Acquisition and Software Materials: A Measurement Computing USB-234 16-bit, 100 kS/s data acquisition module records high-precision voltage and current signals from the system. Additional wiring, connectors, and cables are included to ensure reliable integration of the sensors, DAQ, Raspberry Pi, and power system.	\$531.95

Mechanical Mounting and Assembly Tools: This includes clamps, brackets, and a high-grade stainless steel M5/M6 fastener assortment for assembling and securing machined components. This category also includes a set of Sorbothane anti-vibration feet, which reduce environmental vibrations coupling into the apparatus and improve measurement stability and repeatability.	\$149.93
Shipping and Handling: Covers estimated shipping costs for heavy aluminum, Delrin, steel stock, neodymium magnets, encoder hardware, electronics, and DAQ equipment from multiple vendors.	\$114.70
Total	\$1999.32

Bibliography

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