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Development of A Low-Cost Rotational Motion Test System Through Interdisciplinary Senior Design

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Development of A Low-Cost Rotational Motion Test System
Through Interdisciplinary Senior Design

Abstract

This paper presents the development and implementation of a low-cost rotational motion test system created through a one-semester interdisciplinary senior design project involving undergraduate mechanical and electrical engineering students. The device, which was designed for integration into an undergraduate engineering mechanics laboratory, measures centripetal force, angular velocity, angular acceleration, and related rotational dynamics while remaining under a $400 budget constraint. The paper describes the evolution of design requirements, subsystem integration challenges, and the iterative engineering process conducted by the student team. The project is mapped to ABET student outcomes and illustrates how the capstone project can reinforce technical competencies, professional skills, and safety considerations. Lessons learned are discussed.

Introduction

Senior design courses provide undergraduate students with a meaningful educational experience through the design of multidisciplinary systems, components, and/or processes, by utilizing modern engineering techniques and tools to research, formulate, model, simulate, optimize, fabricate, test and access developed components and systems [1, 2, 3]. Throughout the semester, undergraduate engineering students are expected to implement previous learned knowledge, work in multidisciplinary environment, develop professional oral and written skills, and build functional prototypes with industrial or academic sponsors along with course instructors. In the School of Engineering and Computer Science at Oakland University, senior students from Mechanical Engineering (ME) and Electrical and Computer Engineering (ECE) collaborate in every semester on industry-sponsored or faculty-sponsored engineering design projects.

This paper presents one such project: the development of a low-cost rotational motion test system intended for lab implementation in another mechanical engineering course, ME 3200 - Engineering Mechanics. The goal of the selected senior design team was to design an educational lab device capable of demonstrating centripetal force, angular velocity, moment of inertia, and conservation of energy through hands-on experimentation. Students were required to meet functional, safety, and budget specifications while producing a prototype device that could support future course laboratory activities.

The project serves as a case study in interdisciplinary collaboration, student-centered product development, and resource-conscious engineering design, offering insights into how senior design projects can successfully contribute to curriculum enhancement.

Project Sponsor Expectations

The rotational test system was a faculty-sponsored project, and it would be used to precisely measure various rotational motion variables and parameters including but not limited to centripetal force, angular velocity, angular acceleration, mass moment of inertia, angular momentum, and rotational motion. The specific objectives include:

- Prototype Budget: $400
- Portable table-top unit
- Repeatability use in teaching labs
- High measurement accuracy (±1 N for force, ±10 deg/s for angular velocity)
- Manual and motor-driven flexibility
- Safety and ease of operation for undergraduate students

The project high-level tasks and deliverables include:

1. Conduct fundamental study on the centripetal force, mass moment of inertia, conservation of angular momentum, and other key principles of rotational motion.
2. Design a comprehensive structural system including a stable base, rotating platform, central post, rotational weights/components, and a rotation mechanism.
3. Develop a centripetal force measurement device, a motion sensor for speed and acceleration, and a data acquisition system.
4. Ability to adjust speed/velocity, acceleration, rotating mass, and radius of rotation.
5. Build a functional prototype of the test system with a detailed operation manual.

Project Description

Interdisciplinary Team Structure

Based on submitted student preferences, an interdisciplinary team was constructed with three Mechanical Engineering students with focus on fundamental mechanism, mechanical structure, machining, finite element analysis, motion analysis and testing; two cross-functional ME student focusing on MATLAB integration, control systems and data processing; one Electrical Engineering student focusing on sensors, Data Acquisition (DAQ) design, and circuit development. Two team leads (representing the ME and ECE scopes) were selected and responsible for project management, internal documentation and cross-team interface definitions.

Original Design Requirements

The project team translated project sponsor's input and overall expectation into formal engineering specifications, and the key prototype requirements include:

- System footprint within 0.5 m × 0.5 m × 0.5 m
- Interchangeable power methods (gravity-driven and motor-driven)
- Modular components for future laboratory experiments
- Near-frictionless rotation and high-precision measurement

  - Real-time data acquisition through Arduino and/or MATLAB
  - Safety mechanisms including guards and an emergency stop

During the development process, as students gained understanding through prototyping and analysis, some specifications, such as maximum mass and maximum rotational speed, were adjusted in consultation with the sponsor to achieve more instructive laboratory performance.

System Design and Fabrication

Conceptual Design and Prototype

Based on the developed original design requirements, the group brainstormed and proposed the initial conceptual design, as shown in Figure 1. The design solution is shown in Figure 2. It consists of mechanical, electrical and data acquisition, and computer/software subsystems.

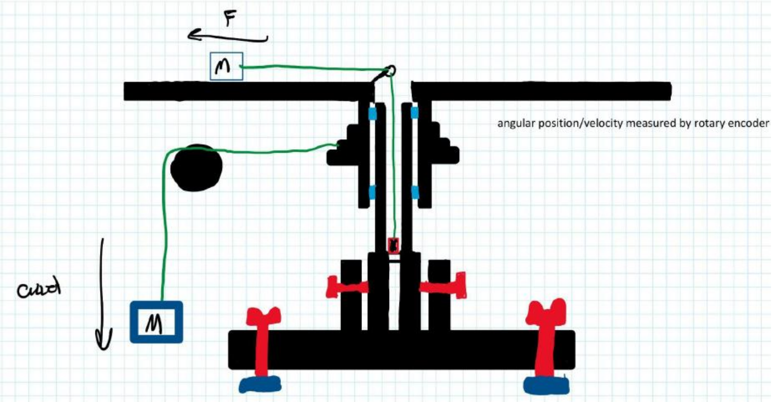


***Figure 1** Conceptual model of design*

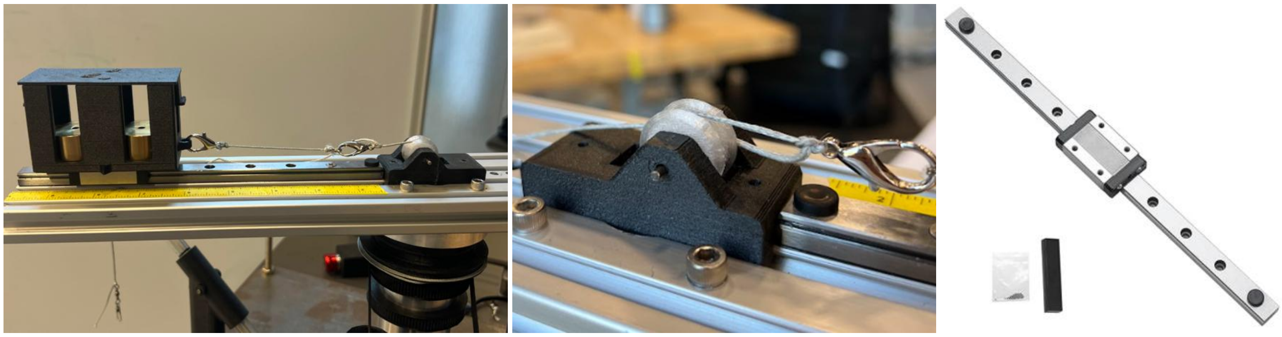
***Figure 2** Prototype of design*

Mechanical Subsystem

The mechanical subsystem comprises the following key components:

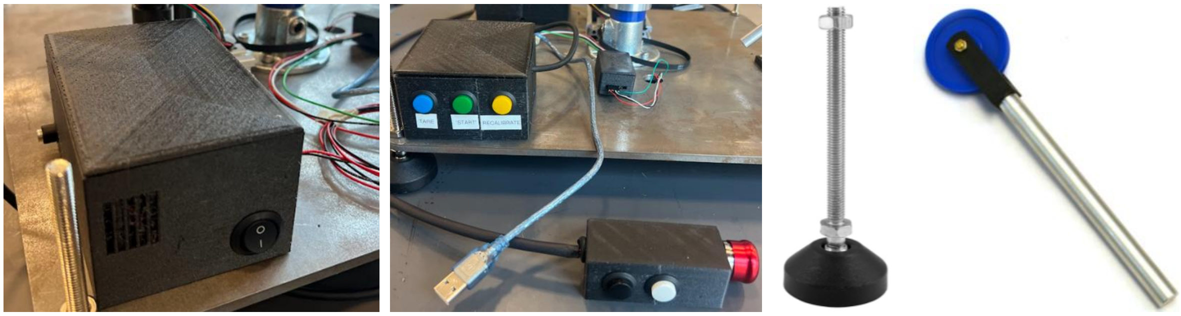
- A ¼-inch steel base for stability
- A stationary hollow inner shaft for cable routing

- A rotating flanged outer shaft supported by ball bearings
- An extruded aluminum bar carrying a linear-guide-mounted sled, as shown in Figure 3.
- A modular gravity pulley allowing adjustable radio and speeds
- Auxiliary components include gravity pulley, housing, force sensor, motor, encoder, coupling, adjustable feet, etc. Some are shown in Figure 4.



(a) *(b)* *(c)*

Figure 3 *Bar System (a)bar with weight sled, (b)force redirection pulley on bar, (c)linear guide*



(a) *(b)* *(c)* *(d)*

Figure 4 *Sample Auxiliary Components (a) housing for motor power source, (b)housing for force sensor and motor controls, (c)base feet, (d)low friction pulley*

The team employed Pugh decision matrices, as reported in other capstone designs [4], to guide the selection and design of key components, including base and coupling, with consideration given to cost, manufacturing time, and ease of operation.

Additionally, the students conducted force and stress analysis using both theoretical methods and the finite element analysis to verify that the aluminum and steel components met the established safety factors (> 2.5) under maximum operating loads. Fatigue performance of selected components was also evaluated and quantified. Most designed plastic components were 3D printed with robust PETG-CF filament material. Motion analysis verified that the sled and pulley configurations could reach the desired RPM range without exceeding mechanical limits.

During the design process, some practical challenges were encountered and addressed, including tolerance issues (e.g., oval steel tubing), the behavior of 3D-printed components, and assembly alignment.

Electrical and Data Acquisition System

The primary objective of the electrical system is to power all hardware and accommodate all signals necessary for the computer subsystem to function, to minimize sensor error as well as any modular implementations.

The Data Acquisition DAQ subsystem, as shown in Figure 5, includes:

- A load cell + HX711 amplifier for force measurement
- A 600-PPR quadrature encoder integrated via GT2 belt
- An Arduino Uno R3 for data sampling
- Three push buttons (tare, start, recalibrate)
- A modular auxiliary power port supporting a future motor drive

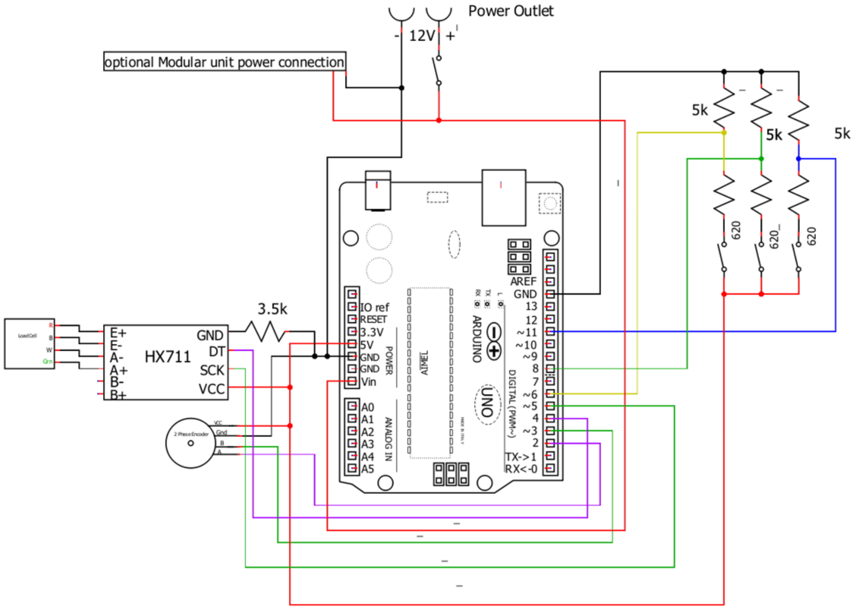


***Figure 5** DAQ (Data Acquisition) Wiring Diagram*

The motor wiring system is also developed. The selected motor is 25GA370 Bemonoc 12v DC motor with built-in quadrature encoder, a MOSFET motor control chip, a TM1637 4-digit 7-segment display, and an Arduino Nano. The built-in 408 PPR quadrature encoder allows fast, accurate analysis for motor speed so that the Arduino Nano can maintain a specified constant RPM.

During the design process, the students compared alternative sensing approaches using Pugh matrices, ultimately prioritizing accuracy, cost, and classroom practicality.

Computer/Software Subsystem and User Interface

The primary objective of the computer systems is to collect and interpret data and present it as a live readout. The proposed approach employs a master-slave system, where an Arduino R3 serves as the master system and MATLAB functions as the slave system that operates entirely based on serial input from Arduino. The computer engineering flowchart is shown in Figure 6.

In this setup, the Arduino acts as a data acquisition system (DAQ), while a PC running MATLAB receives the data via serial communication and populates a text file with timestamps and the corresponding readings. These data are then used by students for manual calculations as part of the lab exercise. In addition, the recorded data are also graphed in real time.

The software architecture consists of:

- Arduino firmware for synchronized sensor sampling
- Serial communication of raw data to MATLAB
- A MATLAB script for live visualization, data logging, and output generation

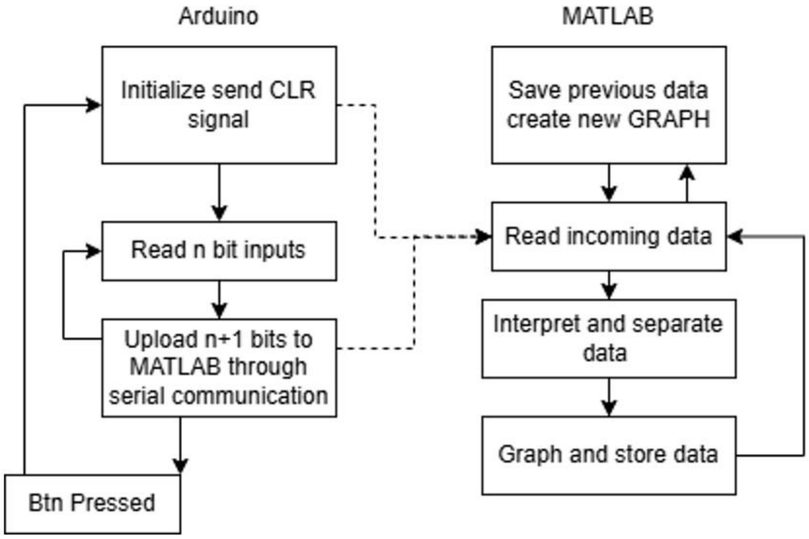


Figure 6 *Computer Engineering Flowchart*

Outcomes and Assessment

Prototype Technical Performance

Figure 7 illustrates the relationship between angular velocity and centrifugal force for five repeated tests with 500g rotating mass at a rotational radius of 193.7mm from the center of the rotation and using a 200g hanging mass to drive the system. The results are stable, repeatable and in good agreement with the theoretical values.

The finally developed rotational motion test system met many of the initial design specifications and, in some aspects, exceeded them. The real-time MATLAB visualization also demonstrated reliable and repeatable performance. Safety features were incorporated, and the final system supports both manual operation and potential future upgrades to a motorized drive. However, several specifications were not fully satisfied. Table 1 listed the comparison of the rotational device design requirements with prototype performance.

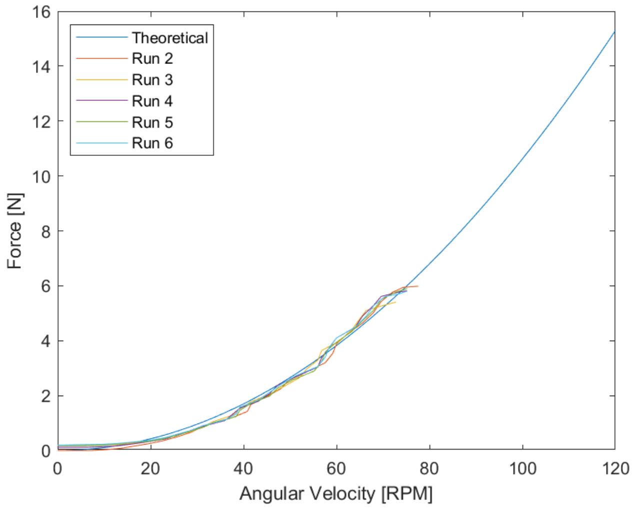


***Figure** 7 Validation Tests: 500g rotational mass with 193.7mm rotational radius and 200g gravity mass*

***Table 1** Comparison of the Rotational Device Design Requirements with Prototype Performance*

Design Requirement	Target Specification	Prototype Performance	Requirement Met
Overall Dimensions	≤ 500 × 500 × 500 mm	420 × 420 × 350 mm	Yes
Portability	Portable, table-top unit	~23 lbs total weight, compact size	Yes
Material Cost	≤ $400	$367.5	Yes
Force Accuracy	±1 N	± 0.3 N	Yes
Max. Rotational Speed	≥ 60 RPM	240 RPM	Yes
Max. Rotational Weight	≥ 400 g	800 g	Yes
Safety feature	Adequate user and equipment protection	emergency stop, sled mass limit and portable protective guard implemented	Yes
Angular Velocity Accuracy	≤ 10 deg/ s	12 deg/s	No
Friction Condition	Near-Frictionless operation	~5% error due to bearing drag and cable routing	No
Overall System Accuracy	Close agreement with theoretical calculation	bearing break-in, cable alignment, and timing offsets	No
Visual Quality	High quality finish	Machining marks, retrofitted holes, and rough 3D print surfaces	No

Student Learning Outcomes

Over the 16-week semester, the interdisciplinary team of ME and ECE students met weekly with course instructors and project mentors. The team collaborated closely to design and develop the rotational device and completed all required deliverables, including individual weekly progress reports, a project proposal, a midterm presentation, a final presentation, and a final report. The following student learning outcomes were observed:

1. Interdisciplinary teamwork and subsystem integration: ME and ECE students worked collaboratively to integrate mechanical, electrical and software subsystems.
2. Manufacturing Awareness: Hands-on machining and final assembly improved student's understanding of manufacturing tolerances, material behavior, component selections, and production management.
3. Analytical Proficiency: The integration of sensors and MATLAB for data acquisition and analysis, along with validation of the measured centrifugal force and other kinematic parameters, helped students connect theoretical concepts with experimental results.
4. Professional skills: Extensive individual and team-based documentation, iterative decision-making throughout the design process, and effective communication within the group and with external stakeholders were essential to project success.

ABET Student Outcomes

A critical dimension of senior design courses is their role in demonstrating compliance with ABET Engineering Accreditation Commission (EAC) requirements. This project, considering its interdisciplinary nature, system-level complexity, and structured documentation, aligns strongly with ABET Student Outcomes 1-7. The following illustrate how the project supports each outcome and how the student work can be used for accreditation evidence.

Outcome 1: Problem-Solving. The students formulated engineering requirements, performed theoretical analysis, and resolved friction, alignment, and measurement issues. The design proposal with Pugh matrices, individual weekly reports, theoretical derivations, test data and error analysis could be used to support this outcome assessment.

Outcome 2: Engineering Design. The project required balancing safety, cost, manufacturability, accuracy, and educational usability. Final CAD and FEA reports, bill of material with cost, and justification of major design decisions could be used to support this outcome assessment.

Outcome 3: Communication. The students produced a design proposal, a final report, MATLAB documentation, and user instructions as part of their written communication. In addition, students also delivered individual weekly presentations, and the group conducted one midterm and one final oral presentation.

Outcome 4: Ethics and Professional Responsibility. The students addressed safety, liability, environmental considerations (material waste, PETG-CF vs. PLA/ABS), and balancing cost with reliability for long-term educational use. The professional and societal context section in the final report could be used to support this assessment.

Outcome 5: Teamwork. The students coordinated efforts across ME, EE, and CE roles throughout the semester, documenting subsystem integration and collaborative debugging (such as encoder noise, bearing friction, MATLAB sync issue) during the system validation.

Outcome 6: Experimentation and Analysis. The students conducted calibration and validation tests, compared data to theory, and identified systematic errors.

Outcome 7: Lifelong Learning. The students acquired knowledge beyond coursework, such as PID motor control, load-cell amplification, machining tolerances, and MATLAB serial parsing.

Project Future Work and Course Reflections

From the senior design project perspective, the student team identified several opportunities for future student groups:

- Improve modularity with quick-swap bar lengths, sled designs, and pulley modules.
- Enhance software usability by adding GUI-based calibration and Python or Excel integration.
- Refine aesthetics and ergonomics through better cable management, resin 3D printing, and standardized mounting patterns.
- Add advanced experimental capabilities, such as damping, unbalanced rotation, or PID-controlled angular acceleration.
- Conduct comprehensive quantitative performance testing to evaluate the accuracy and durability of the test system.
- Develop a practical and comprehensive laboratory manual for use as a lab assignment.

From the senior design course standpoint, several challenges were also observed that should be addressed and improved in future semesters.

- Sustained student engagement throughout semester: develop effective strategies to encourage consistent student and group effort throughout the semester, including the better use of weekly meetings and progress reports, etc.
- Effective and efficient multidisciplinary communication: further improve communication efficiency within ME - ECE teams, both in technical collaboration and project management.
- Assessment of individual contributions: establish more effective methods to evaluate individual performance and project contributions for course grading.
- Prototype testing and validation: ensure sufficient time and effort are allocated for thorough prototype testing and experimental validation at the end of semester.

Some published methodologies and strategies [5] could be adopted to foster inclusive sub-team integration and enhance cross-sub-team collaboration along multiple disciplines. Filippas and Ozgur [6] also introduced a well-structured capstone course framework that includes numerous effective rules of engagement, which could be applied to our senior design course structure.

Conclusion

This senior design project successfully produced a functional, low-cost rotational motion test system that enhances the ME 3200 laboratory with a custom-engineered instructional solution. The project demonstrates how senior design can directly support and enrich undergraduate laboratory education.

The project served as a ME and ECE senior design experience and highlighted the value of interdisciplinary engineering education. The project required students to navigate and reinforce mechanical system design, electronics and sensor integration, data acquisition, control and instrumentation, and professional communication skills. Through this learning experience, students practiced system-level thinking and learned to manage technical trade-offs across disciplines.

Overall, the project along with the course education aligns well with ABET student outcomes and provides a good example of how senior design projects can generate lasting curricular impact.

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