2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #52260

Laboratory on Experimental Verification of Four-bar and Crank-slider Linkages in a Senior-level Design and Modeling Course

Samuel David Gervasi, Worcester Polytechnic Institute
Prof. Pradeep Radhakrishnan, Worcester Polytechnic Institute

Prof. Pradeep Radhakrishnan is an Associate Professor of Teaching in Mechanical and Materials Engineering at Worcester Polytechnic Institute. He is also affiliated with the Robotics and Electrical&Computer Engineering Departments. Prof. Radhakrishnan teaches fundamental courses in mechanics and design at the undergraduate level.

Laboratory on Experimental Verification of Four-Bar and Crank-Slider Linkages in a Senior-Level Design and Modeling Course

Abstract

This paper explains a laboratory exercise on experimental verification that was developed and implemented into a senior level design and modeling course at Worcester Polytechnic Institute. Two linkages, a four-bar with revolute joints and a crank-slider, were fitted with wired and wireless inertial measurement units (IMUs) for angle and angular velocity measurement of various links. Students collected data at various input speeds and compared them with theoretical data to compute the root mean squared error (RMSE). Detailed instruction guides were presented to the students for data collection and data analysis portions of the exercise. Over 200 students participated in this activity during multiple instances of the course and the procedures were fine-tuned after each iteration. As part of the lab activity, students were also required to evaluate the linkage as well as compare the performance of various low-cost sensors. Detailed observations on the performance of the linkages, sensors as well as student expectations and outputs were examined and processed. Students also provided feedback on the lab activity along with learnings and other improvements that could be implemented from their perspective.The paper will provide implementation details along with various results (including student evaluation) and future work recommendations that involve development of smaller prototypes to implement these laboratory exercises in similar courses at other universities.

Keywords: four-bar linkage; verification; senior-level curriculum; planar mechanisms; kinematics; sensors

1. Introduction

Analyses of four-bar and crank-slider linkages are core topics in any mechanical engineering curriculum. Topics include kinematics, forces, stresses, etc. Students use linkage-specific software tools (such as PMKS+ [1], Working Model [2], or MotionGen [3]) or MATLAB to calculate relevant dynamics of the linkage. In certain courses, students may also be prototyping table-top linkages to demonstrate their understanding. In the above approach, there is one drawback, which is the lack of experimental verification of linkage prototypes with design criteria. A review of senior capstone project reports involving linkages carried out at our university showed that in over half of the projects, there is insufficient, or no data collected on the prototype to verify that it meets the design criteria. In many cases, the qualitative condition of the linkage moving is considered as satisfactory verification, which is not sufficient from an industry standpoint. Industrial sponsors of different capstone projects expect rigorous quantitative verification, and it is important to train students on this vital skill.

An evaluation of different courses in the mechanical engineering curriculum at our university points to the lack of topics in quantitative verification in the curriculum. There are many reasons for not being able to integrate quantitative verification into existing curriculum. There may be lack of bandwidth in courses for laboratory exercises, lack of time in capstone projects, lack of resources and exercises necessary to provide adequate exposure among others.

A review of literature points to different implementations targeting verification and validation. Sieving et al. [4] share their work on evaluating students who have undergone various verification and validation protocols through traditional laboratory work. They highlight the experience of leveraging courses and laboratories from the second year to senior year to enhance outcomes in these laboratories in Biomedical engineering. Tulpule et al. [5] highlight the importance of considering modeling, analysis, verification and validation from a systems perspective and not in isolation. They used a virtual hardware simulator and combined optimization and system dynamics to develop a verification and validation laboratory. Horáček [6] provides a review of different types of experiments such as scaled models or life-size models that could potentially be used to explain control theory. Utschig et al. [7] showcase various 3D printed models and equipment used to study vibrations and controls along with extensive user evaluation. Based on the review, it was clear that hands-on work as well as learning about verification are indeed important tasks.

In the senior level design and modeling course in the mechanical engineering department at our university, students are exposed to various types of mechatronic systems as well as modeling techniques such as the lumped parameter modeling and bond graph modeling techniques. This elective course was selected to implement this verification laboratory due to topics in linkage analysis being covered in the course. There were multiple objectives of this laboratory exercise. The first one was to showcase the importance of experimental verification and the process of doing the same. The second objective was to demonstrate the need for using multiple sensors in such verification activities. The third was to emphasize the repeatability and reproducibility aspects, which are critical in an industrial setting. Each student carried out data collection activities individually using a four-bar and a crank-slider linkage. The collected data was processed by comparing with theoretical calculations and computing the root mean squared error (RMSE). A survey was conducted that showed value in such exercises along with significant learning.

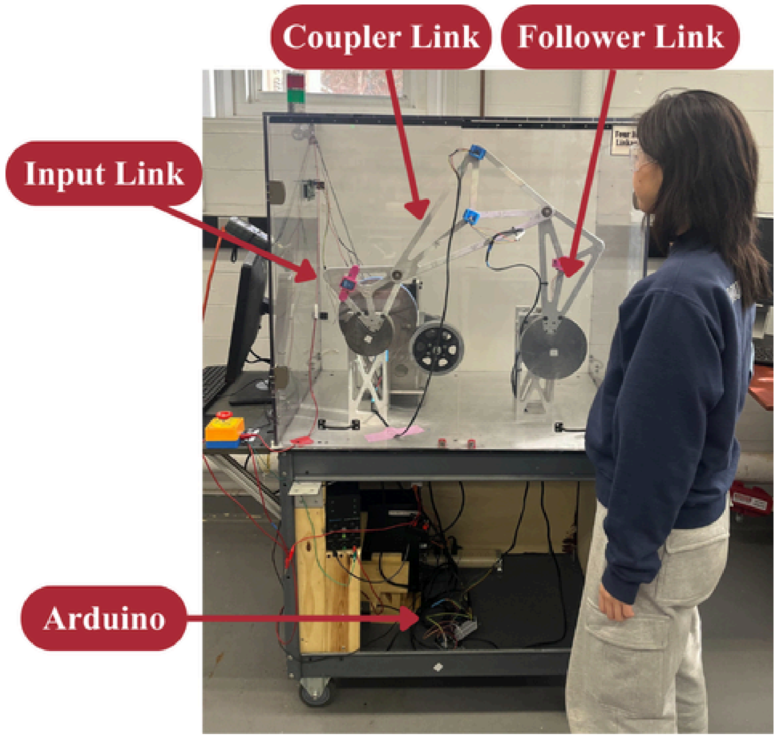
The paper is organized as follows. Section 2 describes the equipment, experiment, expectations of the laboratory and the survey design. This will be followed by discussion of the survey results, teaching team's insights and a discussion on the next steps in Section 3. Section 4 will provide conclusions and future steps followed by listing of sample work and laboratory handouts as appendices.

2. Methods

This section will describe the equipment details followed by the laboratory activity, reporting expectation and survey design to capture student thoughts.

2.1 Equipment and Instrumentation

The laboratory utilizes two primary mechanical assemblies consisting of a Four-Bar Linkage (shown in Figure 1) and a Crank-Slider Linkage (shown in Figure 2). The systems were designed in senior capstone projects in 1990 [8] and 2013 [9] respectively. These were subsequently refurbished in senior capstone courses as a demonstration model first and then for the experimental verification laboratory. PMKS+ models for the four-bar and crank slider linkages are shown in Figures 3 and 4 respectively. Both systems are driven by an AndyMark 2.5" CIM motor [10] coupled to a friction wheel that drives a flywheel (as shown in Figures 1 and 2). This flywheel provides the necessary rotational inertia to regulate the input speed of the mechanisms. The four-bar linkage is designed to operate at speeds up to 170 RPM, while the crank-slider reaches speeds up to 110 RPM.



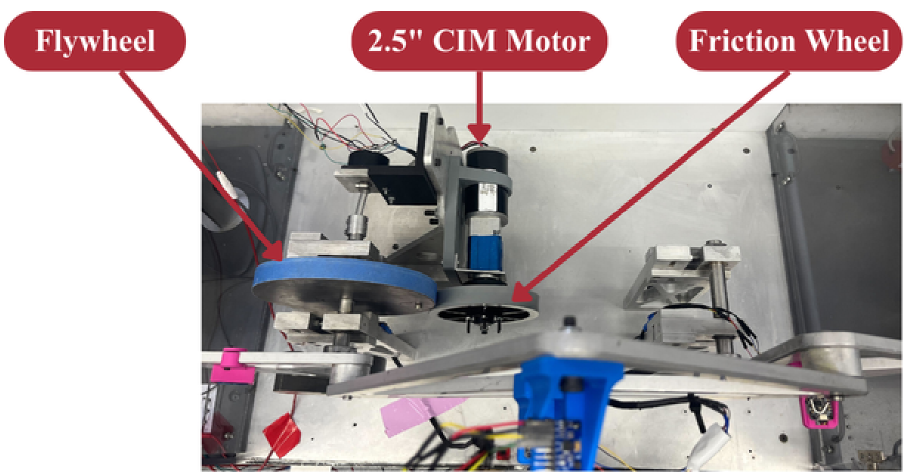


Figure 1: (top) Four-Bar Linkage Annotated with Important Components; (bottom) Top-down view of the Four-Bar Linkage Annotated with Important Components

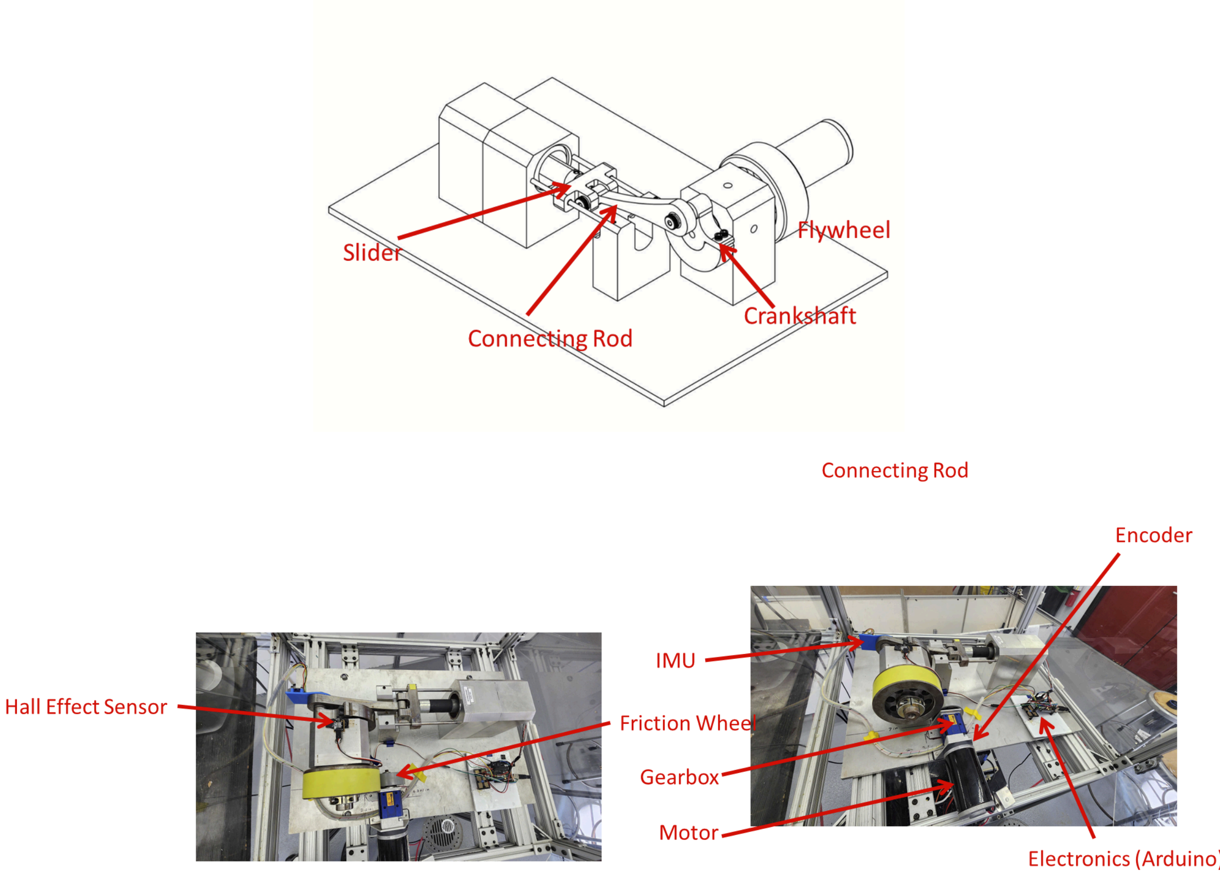


Figure 2: (top) Crank-Slider Linkage Annotated with Important Components; (bottom) Top-down view of the Crank-Slider Linkage Annotated with Important Components

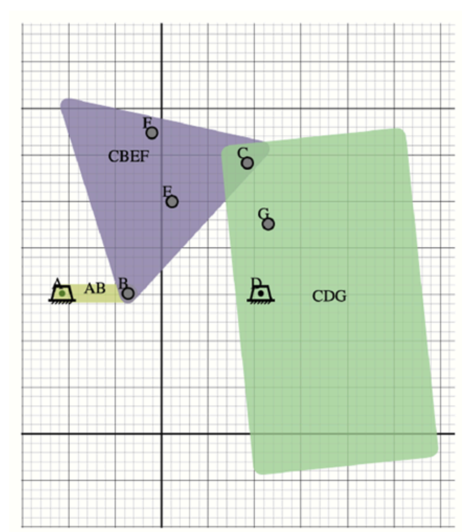


Figure 3: Theoretical Model of the Four-Bar Linkage (PMKS+ URL)

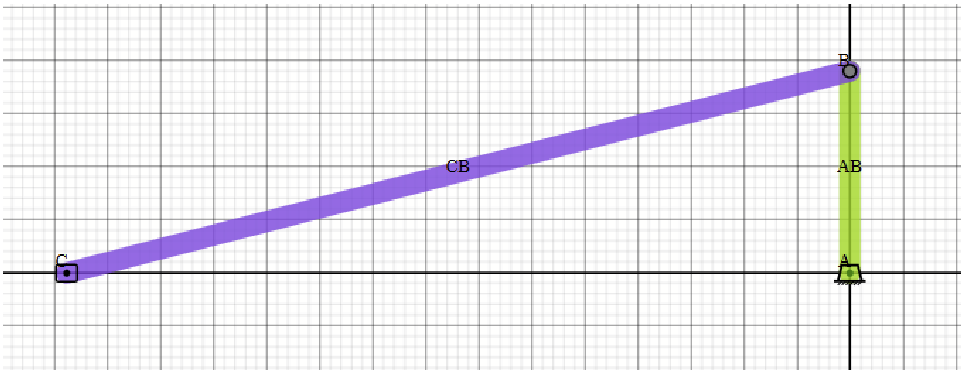


Figure 4: Theoretical Model of the Crank-Slider Linkage (PMKS+ URL)

To capture kinematic data, both assemblies are outfitted with a suite of Inertial Measurement Units (IMUs) and Hall-effect sensors as shown in Figures 5 and 6 respectively for four-bar linkage and crank linkage. The four-bar system features a WT9011DCL wireless IMU on the input link, which provides high-precision orientation data using an internal Kalman filter [11]. The coupler link carries an absolute orientation BNO055 sensor [12], which performs onboard sensor fusion to output ready-to-use Euler angles, alongside a standard MPU6050 [13] 6-axis sensor for raw acceleration and angular velocity. A second BNO055 and a wireless IMU are located on the follower link to provide redundant data for error analysis. The crank-slider system carries a singular BNO055 sensor on the connecting rod. In both setups, Hall-effect sensors [14] and magnets track flywheel rotations to provide a physical reference for cycle counts. All sensor data is processed via an Arduino microcontroller [15] and captured through a serial monitor for post-processing.

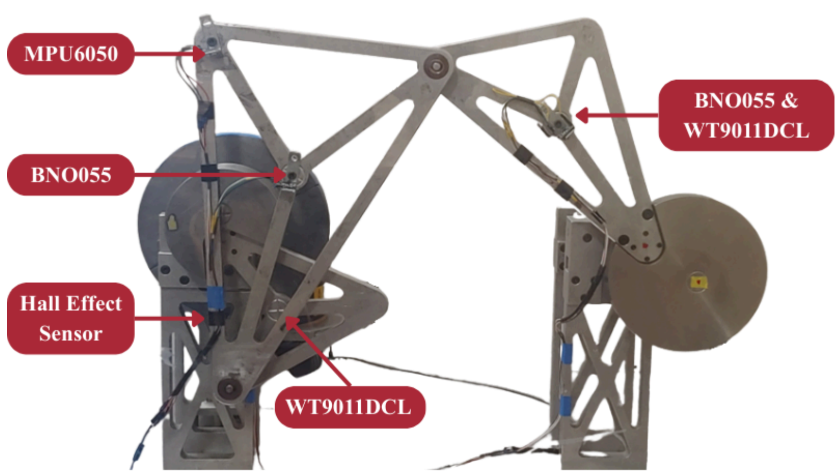


Figure 5: Four-Bar Linkage shown with IMUs and Hall Effect Sensor

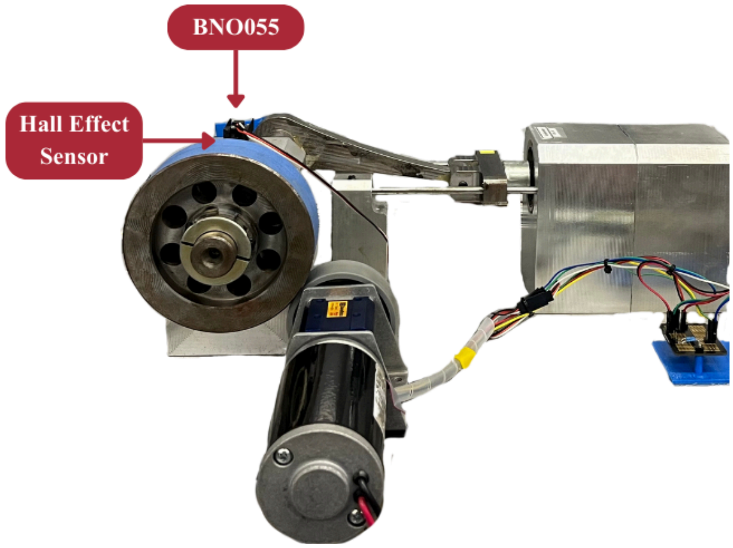


Figure 6: Crank-Slider Linkage shown with IMU and Hall Effect Sensor

2.2 Experiment and Laboratory Setup

The laboratory is structured as an out-of-class activity facilitated by the teaching assistant. To ensure preparation and safety, students are provided with a lab handout (linked in the appendix) and specific target speed values prior to their scheduled sessions. Students arrive at the laboratory equipped with safety glasses, close-toed shoes, and pants. They proceed to run the mechanisms at their assigned speeds. There are two parts to this activity namely Data Collection and Data Processing as shown in the process flow in Figures 7 and 8 respectively.

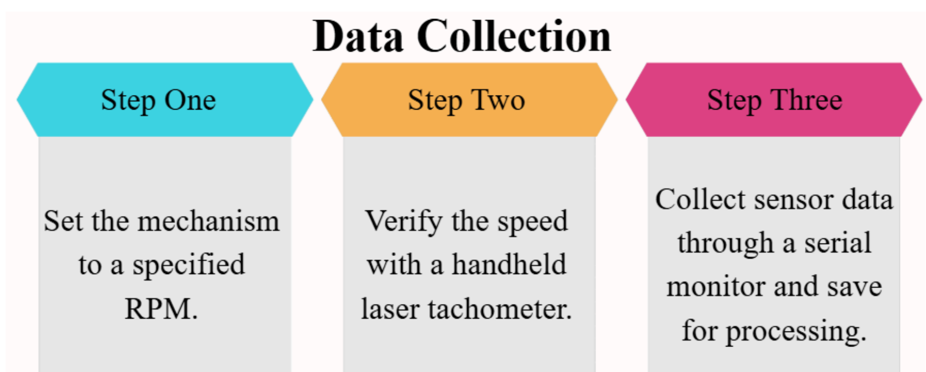


Figure 7: Data Collection Flowchart

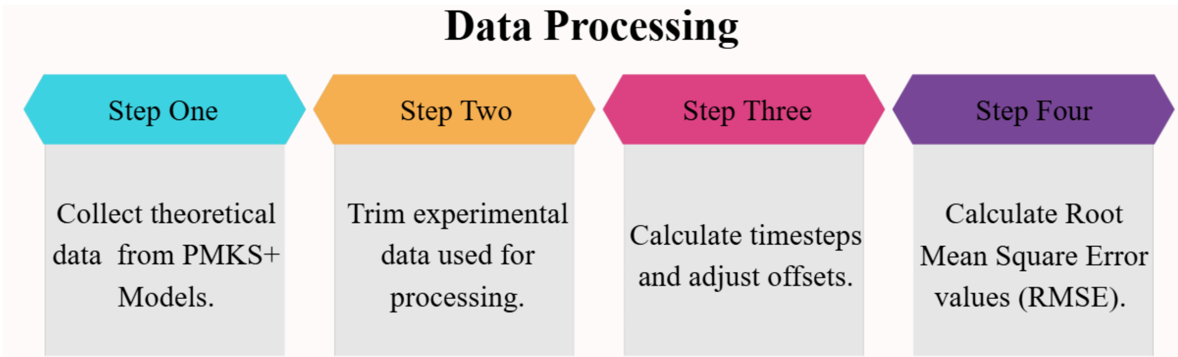


Figure 8: Data Processing Flowchart

Students begin the experiment by turning on the machine during which time, the sensors are autocalibrated. The students set the speed of the flywheel to a specified level and then validate the flywheel speed using a handheld tachometer to ensure it matches their assigned speed. They then collect at least three full cycles of kinematic data. Before concluding the session, students use a spreadsheet program to plot their results, which allows them to verify that the data is continuous and free of any errors. Figure 9 (left) shows an example of correct data while Figure 9 (right) shows an example with errors. The data collection usually takes anywhere between 30 to 45 minutes during which students also spend studying the mechanism's design and construction along with actuators, sensors and other electronics used.

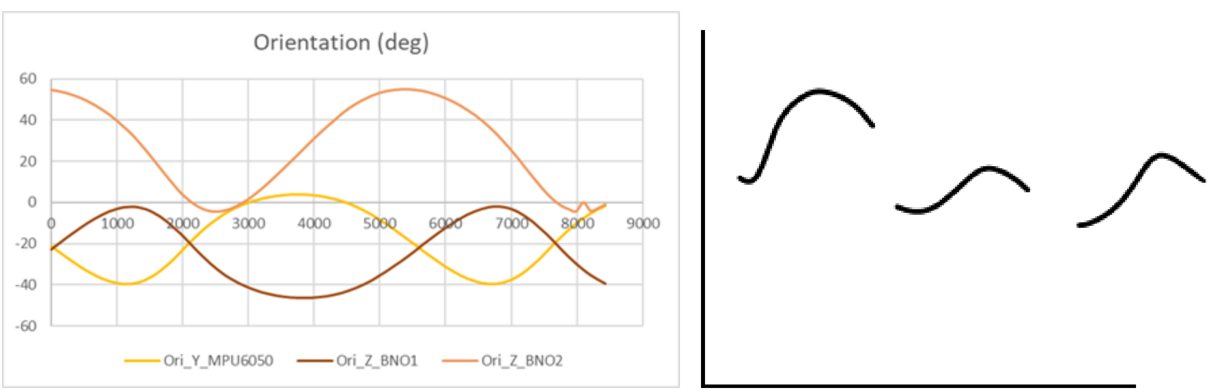


Figure 9: (left) Example of Correct Data (right) Example of Data with Errors

The second part of the lab activity involves the data processing and report writing phases. Data processing involves extracting the theoretical data from PMKS+. The experimental data is then trimmed to select data for one cycle. The theoretical data is then adjusted to account for sensor mounting offsets as well as to fix errors related to timesteps in the software. This allows the theoretical and experimental data to have similar patterns. Note that the 360 data points are available for theoretical data while experimental data can vary between 30 points to 150 points depending on the input speed of the linkage. The final step in data processing involves computing the Root Mean Square Error (RMSE). These are explained in the process flow shown in Figure 8. Data processing is further supported by a combination of in-person assistance and video-guided tutorials (linked in the appendix).

Students are given the option to write the report either individually or as a group. The report involves summarizing the experimental setup, results of data processing as well as inferences from data processing and general learning observations. This is detailed in Section 2.4.

2.3 Experiment Results

While specific data points vary based on the assigned speed, a typical result yields angle, angular velocity, and acceleration curves. Our focus with data processing is related to comparing angle and angular velocity data. There are two main areas of learning. One is the comparison between theoretical and experimental data. The other is to compare the performance of the IMUs. By comparing theory and experiment, students are able to see how close the machine is to replicating their intended design.

By comparing the experimental data against theoretical kinematic models, students calculate the Root Mean Square Error (RMSE) for each sensor. This process highlights the performance differences between entry-level sensors like the MPU6050 and more advanced units like the BNO055 or WT9011DCL. These sensors produce different RMSE values and that highlights the need to use multiple sensors and not relying on just one.

Shown in Figure 10 are examples of typical graphs that students and the teaching team used to compare data and extract inferences.

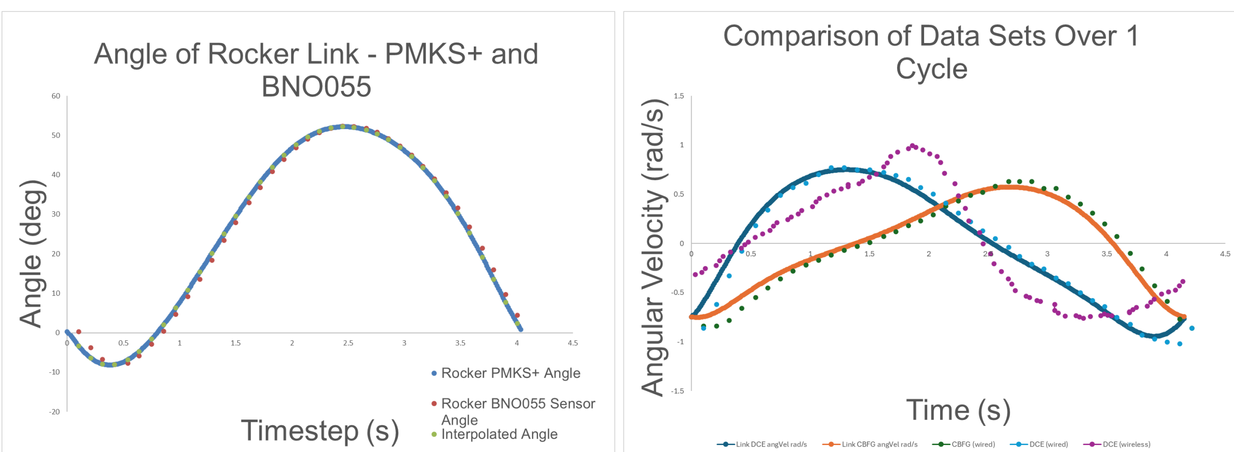


Figure 10: (left) Teaching Team Processed Data Example; (right) Student Processed Data Example

2.4 Lab Report and Submission Requirements

The primary deliverable for this experiment is a formal technical lab report. Within this document, students must detail the technical specifications of the equipment and the specific processes followed during the lab. A critical component of the report is the tabulation of RMSE values for each IMU. Students are expected to discuss the accuracy of these sensors and determine whether their performance aligns with the manufacturer-provided specifications, encouraging a critical evaluation of real-world hardware limitations. Sample lab reports are linked in the appendix.

2.5 Survey to Ascertain Learning Objectives

To conclude the experiment and assess its impact, students completed a brief survey regarding their experience during Fall 2025 (after two full years of implementing and improving the laboratory activity). This feedback mechanism was designed to capture thoughts on the usability of the equipment, the effectiveness of the instructional materials, and the overall clarity related to verification experiments. The survey was distributed through an online Google Form. Students were informed that their survey responses would be anonymous and used in academic works regarding the laboratory experiment. A 5-point Likert scale (ranging from Strongly Disagree to Strongly Agree) was used for quantitative assessment, alongside open-ended prompts for qualitative feedback. A total of 28 out of the 32 total students responded to the survey. Anonymous survey results are discussed in Section 3.2 and the original responses are linked in the appendix.

The results of this survey provide the primary data for evaluating student engagement and the success of the lab's learning objectives and is detailed in the next section.

3. Results and Discussion

This section details more details on the class performance, results of the survey, thoughts of the teaching team as well as a discussion on the learning objectives.

3.1 Student Performance and Teaching Team's Observations

Twenty-eight students carried out this experiment during Fall 2025 and responded in an anonymous survey. A majority of students successfully carried out data collection and data processing independently. Roughly 25% of students, however, relied on the teaching team staff to explain the laboratory procedure steps in greater detail, specifically in the area of data processing.

The average class score in this laboratory was 78%. The most significant impact on student grades occurred in the Processed Data section, where students lost an average of 24.5 points out of the 100 available. Many reports were missing tabulated summaries that clearly displayed sensor types, mounting locations, the number of data points analyzed, and the resulting RMSE values. Furthermore, points were frequently lost for incomplete data sets, such as missing angular velocity graphs for specific links or failing to include data from every team member. Basic errors, including the omission of axis labels and chart titles, also contributed to lower scores in this category.

While the Processed Data section carried the most weight, the References category saw the highest proportional loss, with students losing nearly 40% of the possible points in that area. Other notable deductions were found in the Discussion and Methodology sections, which saw average losses of 18.9% and 15.2%, respectively. Many students successfully determined RMSE values of various sensors, but few compared them with manufacturer specifications or discussed the quality of the linkages themselves. Students had the most difficulty calculating RMSE values despite the in-person and guided video tutorials.

3.2 Survey Results

To establish a baseline for the student's prior knowledge, the survey first assessed familiarity with the core concepts of the lab as shown in Figure 11. Results indicated that a majority of the cohort entered the laboratory with limited practical experience in mechanism analysis and sensor application. Specifically, 57.1% of students reported having no prior experience working with physical linkages, and 60.7% had never worked with IMUs.

The gap between theoretical knowledge and practical application was most evident regarding the concept of verification. While 71.4% of students were familiar with the term Root Mean Squared Error (RMSE), only half of the participants (50.0%) possessed a baseline understanding of what the verification process entails in an engineering context. Furthermore, 75.0% of the students had never performed a formal verification task, such as comparing theoretical kinematic models to actual sensor data. Familiarity with more specialized industry standards was also low, with only 10.7% of students recognizing the term Gage Repeatability and Reproducibility (Gage R&R) prior to the exercise.

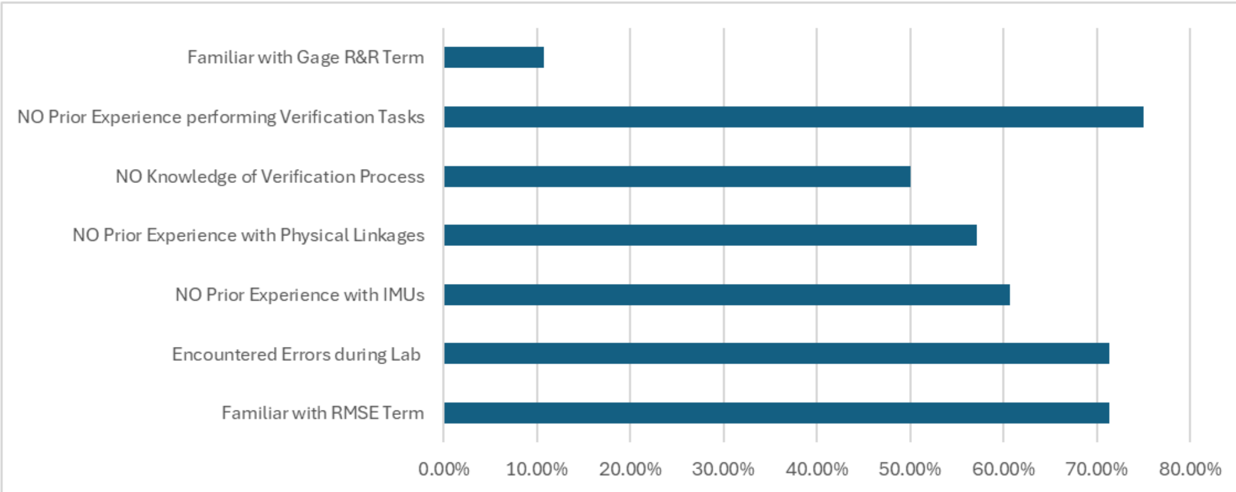


Figure 11: Prior Experience and Background Knowledge of Students

The data collection process presented significant real-world engineering challenges, as 71% of students reported encountering errors during their sessions. Qualitative feedback identified these issues as primarily related to sensor reliability, including intermittent connectivity with WitMotion wireless sensors and inconsistent readings from the Hall-effect sensors. While these errors required some students to re-collect data, they served as a practical introduction to the unpredictability of physical instrumentation particularly with low-cost sensors, reinforcing the necessity of the verification tasks assigned in the lab.

Instructional materials, including the introductory lecture and experiment handouts, were generally well-received with mean scores of 3.93 and 4.04, respectively. However, the data processing handouts and the in-class processing sessions received slightly lower marks, with mean scores of 3.64 and 3.71. Open-ended comments suggested that while the processing steps for the crank-slider were clear, applying those same principles to the four-bar mechanism required additional conceptual leaps that could be better supported in future iterations of the lab.

Despite the technical hurdles, the survey results indicate strong achievement of the intended learning outcomes. Students expressed a high level of confidence in their understanding of the need and process for verification, which earned the highest outcome-related mean score of 4.46. Understanding the necessity of data manipulation for RMSE calculations also scored well at 4.25. Furthermore, students recognized the long-term value of the laboratory, with a mean score of 4.04 regarding the utility of these data processing techniques in their future professional or educational careers. While the improvement of report writing skills received a slightly lower mean of 3.79, the overall consensus suggests that the laboratory successfully bridged the gap between theoretical kinematics and practical sensor verification. These results are consolidated in Figure 12.

Figure 12: The Average Response of Survey Questions Ranked 1-5, with 1 Indicating a Need for Improvement and 5 Indicating Satisfaction

3.3 Discussion

The main objectives of the laboratory experiment were to emphasize the importance of experimental verification along with comparing the differences in performance between various low-cost sensors. Students collected data using different sensors attached to a four-bar linkage and a crank slider linkage and compared the theoretical estimation with experimental data. While the data extracted varied due to the overall performance of these machines, the laboratory activity still provided good exposure to students on verification, reproducibility and repeatability.

In terms of verification, if RMSE of 0.03 rad/s is obtained, then that's an indication that the machine is designed well and is meeting specifications. At the same, students may encounter RMSE values of 3 deg for angle, which indicates that there may be significant backlash in joints that are not captured in the angular velocity comparison. Besides, we emphasised to students that while the lab is just asking them to compare angle and angular velocity measurements, an actual verification requires comparing all kinematic parameters - position, velocity and acceleration, both in linear and angular terms.

There were also instances where the same experiment was repeated and students were not able to obtain the same data but had a similar performance. Students were also able to witness that different sensors mounted on the linkage had varying performance (RMSE values). This performance variation existed between students who took readings at the same speed and at different speeds. All these point to challenges in reproducibility and repeatability, which are essentially in any industry setting.

While striving to provide a good learning experience to students through this laboratory exercise, the teaching team experienced some challenges pertaining to the machines. Given that low cost sensors were being used, their performance fluctuated and this meant that frequent recalibration and maintenance activities are required. From a student's view, this is a challenging lab given that they are not probably not experienced or equipped to handle this much data processing. For the four-bar linkage, angle and angular velocity comparisons had to be carried out for five sensors while for the crank slider, it was with one sensor. From a teaching standpoint, this highlights that data is an integral part and students will experience this in their future work - either industrial or research activity.

In terms of future work, we plan to integrate a distance sensor for the crank slider linkage to compare linear slider positions. Updated tutorials are being planned with audio explanation along with a checklist for additional student guidance. Besides, smaller desktop variations of the linkage are being planned to scale this activity to larger class sizes.

4. Conclusion

A laboratory experiment on experimental verification is presented in this paper. A four-bar linkage and a crank-slider linkage attached with inertial measurement units are used in this experiment where students compare the experimental data with theoretical values and compute RMSE. These RMSE values are used to ascertain the quality of these two machines while at the same time, emphasizing the challenges related to repeatability and reproducibility. The laboratory's objectives were well received by students who also pointed to some improvements in the teaching guides to further enhance outcomes. This lab activity also highlights how low-cost sensors are useful but at the same time may not necessarily produce the ideal results.

5. Acknowledgements

The authors would like to acknowledge the participation of students in the survey as well as lab assistants who helped on various aspects of this experiment.

References:

[1] "PMKS+," accessed Jan 16, 2026, https://pmksplus.mech.website/.

[2] "Working Model 2D - 2D Dynamic Motion Simulation," accessed Jan 15, 2026, https://www.design-simulation.com/wm2d/.

[3] "MotionGen Pro," accessed Jan 15, 2026, https://www.stonybrook.edu/commcms/motiongen/.

[4] Allison L. Sieving *et al.*, “Development of Verification and Validation Engineering Design Skills through a Multi-year Cognitive Apprenticeship Laboratory Experience,” Atlanta, Georgia: ASEE Conferences, Jun. 2013. doi: 10.18260/1-2--19448.

[5] P. Tulpule, A. Rezaeian, A. Karumanchi, and S. Midlam-Mohler, “Model Based Design (MBD) and Hardware In the Loop (HIL) validation: Curriculum development,” in *2017 American Control Conference (ACC)*, May 2017, pp. 5361–5366. doi: 10.23919/ACC.2017.7963788.

[6] P. Horáček, “Laboratory experiments for control theory courses: A survey,” *Annual Reviews in Control*, vol. 24, pp. 151–162, Jan. 2000, doi: 10.1016/S1367-5788(00)90029-4.

[7] T. Utschig, A. Tekes, and M. Linden, “Impact of 3D-printed laboratory equipment in vibrations and controls courses on student engineering identity, motivation, and mindset,” *International Journal of Mechanical Engineering Education*, vol. 53, no. 1, pp. 3–28, Jan. 2025, doi: 10.1177/03064190231205013.

[8] R. L. Norton, H. K. Ault, J. Wiley, T. Parks, R. Calawa, and M. Wickstrand, "Bearing forces as a function of mechanical stiffness and vibration isolation in a fourbar linkage," in *Effects of Mechanical Stiffness and Vibration on Wear*, Jan. 1995, pp. 21–31. doi: 10.1520/STP15671S.

[9] E. Brigham, C. DeStefano, and Z. Killoy, "*Slider-Crank Demonstration MQP*," Undergraduate Major Qualifying Project No. E-project-042513-103948, Worcester Polytechnic Institute Electronic Projects Collection, 2013. [Online]. Available: https://digital.wpi.edu/concern/student_works/wp988m42x?locale=en

[10] “CIM Motor 2.5" Datasheet,” accessed Jan 16, 2026, https://s3.amazonaws.com/docusync-files/9f2c14096cb651c76ea92520dce95d49694b5a25f88381e01f4df24db3c64e1e/am-0255%20CIM-motor-curve-am-0255.pdf.

[11] “USER MANUAL WT9011DCL-BT5.0,” accessed Jan 16, 2026, https://m.media-amazon.com/images/I/C1yPGuodv9L.pdf.

[12] “BNO055 Intelligent 9-axis Absolute Orientation Sensor,” accessed Jan 16, 2026, https://cdn-shop.adafruit.com/datasheets/BST_BNO055_DS000_12.pdf.

[13] "MPU-6000 and MPU-6050 Product Specification Revision 3.4," accessed Jan 16, 2026, https://invensense.tdk.com/wp-content/uploads/2015/02/MPU-6000-Datasheet1.pdf.

[14] "DRV5023 Digital-Switch Hall Effect Sensor," accessed Jan 16, 2026, https://www.ti.com/lit/ds/symlink/drv5023.pdf?ts=1769022065723&ref_url=https%253A%252F%252Fwww.google.com%252F.

[15] "Arduino® UNO R3 Datasheet," accessed Jan 16, 2026, https://docs.arduino.cc/resources/datasheets/A000066-datasheet.pdf.

Appendices:

Lab Handout: Handout | Data Processing - Four Bar | Data Processing - Crank Slider

Sample Student Submission: Example 1 | Example 2

Anonymised Survey Results: Link