Optimizing Students' Learning Experiences in Instrumentation and Measurement Laboratory

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ABSTRACT

In the recent years, there has been a growing interest in developing simulated and remote laboratories. Traditionally, instrumentation and measurement class consists of hands-on labs. In an effort to optimize student's experience, this study explores the best practices used and illustrates the examples of class activities implemented at the current institution.

The Instrumentation and Measurement Laboratory class was introduced in 2008 as a required class in Mechanical Engineering program. In 2008, with the enrollment rate of 23 students, class content was mostly conveyed through hands-on laboratory experiments. Currently there are 40 students enrolled in fall 2017 offering of the class. Over the years, class has been modified through lessons learned. One of the student outcomes of ABET is an ability to design and conduct experiments, as well as to analyze and interpret data. Regardless of the current challenges such as higher enrollment rate, it is important that this class not only facilitates in achieving the ABET outcome but also provides a productive learning environment to the students.

The primary objective of this class is to introduce students to measurement and data analysis techniques. This is accomplished through hands-on experiments and virtual Matlab/Simulink and LabVIEW simulations. The class is a junior level class. The number of credits dedicated to the class is one credit. The literature review illustrates that at many institutions the instrumentation and measurements class is being offered. Although the course content is similar, there are significant differences in the number of credits assigned, course prerequisites, and the teaching practices used. For example, some schools have both lecture and laboratory component while others have only laboratory time assigned to the class during the semester. This paper summarizes the common practices used at various schools and explains the details of the class that is being offered at the current institution. Finally, the outcomes of student surveys, grade distributions and the recommendations for future offerings of this class are included.

INTRODUCTION

In many institutions, an instrumentation and measurements class is being offered in the mechanical engineering core curriculum. Most of the schools have a format of combination of lecture and laboratory. The class is typically offered during third year of their study. During the lectures, students learn the fundamental topics in the areas of measurement systems, instrumentation and data analysis. While in the laboratory, students apply the knowledge learned through hands-on activities. The number of credits dedicated to this class varies from institution to institution from one credit to four credits. Review of instrumentation and measurements classes at various schools are shown in Table 1.

It is indicated by ABET in the document called Criteria for Accrediting Engineering Programs, 2016 – 2017 that ABET student outcome (b) is an ability to design and conduct experiments, as well as to analyze and interpret data. Thus, main goals of instrumentation class are to introduce students to fundamental instrumentation and measurement systems necessary to design and conduct experiments, and teach them how to analyze and interpret the data gathered.

University	Class Description	Prerequisite/Co-requisite	Lab/Lec	Level
PennState	Instrumentation, Measurements, and Statistics: Students have hands on experience with electronics and measurement equipment. Fundamentals of statistics is also introduced. Students use statistical analysis to analyze and interpret the acquired data. http://bulletins.psu.edu/undergrad/courses/M/M%20E/345/200708SP	Prerequisite or concurrent with Introduction to Electronic Measuring Systems and Electrical Circuits and Power Distribution	Lecture: three - 50 min./week and 3h/week hands on labs. (4 credits)	Junior
MIT	Measurement and Instrumentation: The course introduces experimental techniques for the measurement of force, strain, temperature, flowrate, and acceleration. In addition, the course emphasizes on the principles of transduction, measurement circuitry, MEMS sensors, Fourier transforms, function fitting, uncertainty analysis, probability density functions and statistics, computer-aided experimentation, and technical reporting. The course features a term-long project of student's choice. http://web.mit.edu/2.671/www/	Mechanics and Materials I and Dynamics and Control I or Dynamics I, Numerical Computation for Mechanical Engineers, and Physics II	Lecture and Lab (12-unit)	Junior
Lehigh	Mechanical Engineering Lab. I: This class has hands on experiments that illustrate the use of basic instrumentation for measurement and analysis of mechanical systems. LabVIEW data acquisition is introduced. http://www.lehigh.edu/meche/undergrad/courses.html	Strength of Materials, previously or concurrently	1 credit	Junior
Rutgers	Mechanical Engineering Measurements: The class is an introduction to characteristics of instruments and measurement systems. The topics covered are calibration, sensor selection, error and uncertainty analysis, signal conditioners, data acquisition, and processing systems. http://mae.rutgers.edu/mechanical-and-aerospace-engineering-undergraduate-program	Physics and Mathematics	Lecture and Lab. (3 credits)	Junior

Texas A&M	Mechanical Measurements: Introduction to instrumentation and measurement techniques, signal processing, data acquisition, statistical analysis and control of mechatronic systems. http://catalog.tamu.edu/undergraduate/course-descriptions/meen/	Statics, Principles of EE, Differential Equations, and Principles of Thermodynamics or registration therein.	2 Lecture Hours and 3 Lab. Hours (3 credits)	Junior
Temple	Measurements and Dynamics Laboratory: This laboratory course teaches students measurement and measurement principles by showing experiments and simulations of static and dynamic systems. Students apply statistical analysis and prepare written reports and journals. http://bulletin.temple.edu/search/?search=MEE+2305	Prerequisite or concurrent with Engineering Dynamics or Applied Dynamics	1 credit	Sophomore
Georgia Tech	Experimental Methods Laboratory: This class is an introduction to instrumentation and measurements. Topics of interest include thermal, stress, strain, force, and viscosity measurements, open and closed-loop control using a microcontroller, calibration, precision, accuracy, and error analysis. http://catalog.gatech.edu/coursesaz/me/	Prerequisites: Mechanics of Deformable Bodies and Fluid Mechanics Corequisites: System Dynamics, Heat Transfer, and Probability and Statistics with Applications	2 Lecture Hours and 3 Lab. Hours (3 credits)	Junior
Rose Hulman RHIT	Measurement Systems: This class explains the operating principles of instrumentation including force, torque, pressure, temperature and flow measurements. Also, uncertainty analysis, data analysis, calibration, data acquisition, presentation of results are the additional topics that are presented during this class. http://www.rose-hulman.edu/Class/me/HTML/index.html	Prerequisite: Introduction to Design, Analysis and Design of Engineering Systems, and Engineering Statistics	3 Lecture Hours and 3 Lab. Hours (4 credits)	Junior
Oregon State	Introduction to Instrumentation and Measurement Systems: This class is an introduction to function, operation, and application of common engineering instruments, measurement principles, calibration, uncertainty and statistical analysis. Students also learn about digital data acquisition and process control. http://catalog.oregonstate.edu/CourseDetail.aspx?subjectcode=ME&coursenumber=451	Prerequisite: Electrical Fundamentals II, Introduction to Thermal–Fluid Sciences, Mechanics of Materials, Intermediate Dynamics, Mechanical Engineering Methods, Introduction to Statistics for Engineers	Lecture/ Lab. (4 credits)	Senior

Table 1: Review of Instrumentation and Measurements course descriptions at various institutions.

Instrumentation and Measurements Class at York College of Pennsylvania:

The instrumentation and measurement class is offered to mechanical engineering students at their junior year. It emphasizes on introducing the fundamental principles of instrumentation and measurement. Students have hands on experience with electronics, digital data acquisition, statistics, measurement equipment such as oscilloscopes, filters, function generators, thermocouples, accelerometer, displacement sensors, pressure transducers, etc. The course consists of laboratory experiments along with one design project. It is a 3 hour laboratory (1 credit) class. Although it is assigned as a laboratory class, 30-45 min. of the class is typically dedicated to the introduction of the topic that will be covered that day. Then, it is followed by an activity or an experiment. The course outcomes assigned to this class are:

1. Apply error and uncertainty analysis on experimental data samples.
2. Apply statistical analysis to determine mean and root-mean-square deviation, median, and variance.
3. Use histograms, probability density functions, the Gaussian or normal error distribution, and compare.
4. Apply FFT to data samples to find the frequency content of the signal and compare the results for various sampling frequency and filtering options.
5. Use LabVIEW (Laboratory Virtual Instrument Engineering Workbench) for data acquisition and analysis.
6. Effectively work in teams to perform laboratory experiments.

The prerequisite for the laboratory class is ME270 Mechatronics. There is no assigned textbook but there are three reference books. These books are "Experimental Methods for Engineers", 7th Edition by J.P. Holman, "Measurement and Instrumentation", 2nd Edition by A.S. Morris and R. Langari, and "LabVIEW Signal Processing" by M.L. Chugani, A.R. Samant, M. Cerna.

The evaluation criteria for this class has three components. These components with their respective weighing percentages are: class exercises (20%), written laboratory reports (50%), and team project (project proposal, written report and presentation) (30%). Students prepare five laboratory reports. The reports should include an abstract, introduction, experimental setup, results and conclusions sections. Students also perform data analysis for each laboratory.

Class exercises are completed during the class time. The laboratory reports are due one week from the date on which the experiment is conducted. Reports turned in late, but within one day of the due date receive a 25% reduction. Reports turned in one and two days late receive a 50% reduction. The examples of class exercises are shown below.

Class activities can be outlined as in-class exercises (simulations), hands-on laboratory experiments, and a team project.

In-class exercises:

- Completing "Introduction to LabVIEW handout" from National Instruments webpage. http://www.ni.com/labview/

- Analyzing sound data in class (time and frequency domain analysis).
- Application of signal filtering in Matlab.
- Generating plots, histograms, and probability density function plots.
- Applying statistical and error analysis on a data set provided.
- Using LabVIEW for data acquisition.

It is shown in studies of Ma and Nickerson (2006) that virtual simulations result in better conceptual understanding. During the semester, students practiced some of the concepts learned through virtual simulations. One example of these class exercises is the application of lowpass and highpass filtering functions to pressure data in Matlab as shown in Figure 1. Students first generated an input waveform and then applied signal filtering to suppress certain frequencies. Each student performed the class exercises and virtual simulations individually.
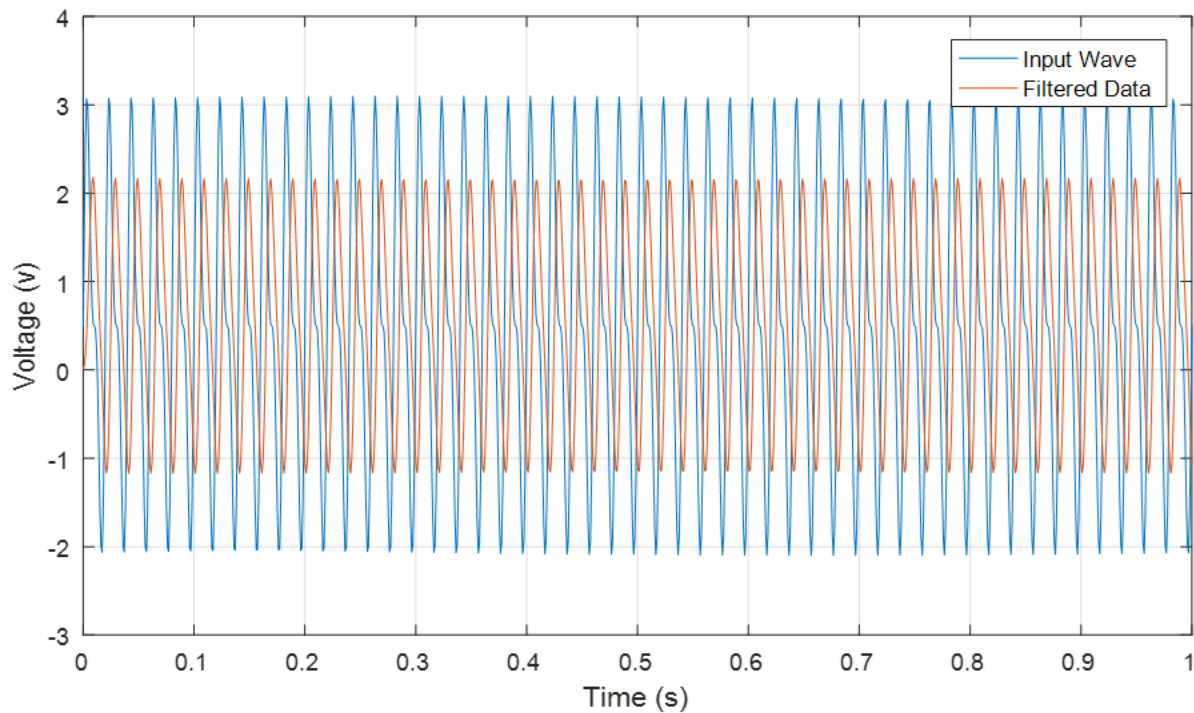

Figure 1: Application of tenth order passive low-pass filter performed in Matlab.

Figure 2 illustrates an in-class simulation exercise on signal analysis. During the lecture session, the importance and use of both time and frequency domain analysis are explained. The lecture topics consisted of Fast Fourier Transformation (FFT) analysis, sampling rate, aliasing, and windowing functions. In the first exercise, students simulated a simple and a complex sine wave with known amplitude and frequencies in LabVIEW and plotted them in both time and frequency domains. For the second exercise, students learned how to read a sound measurement data from a file and then analyzed that data in LabVIEW to obtain time and frequency domain information as shown in Figure 2.
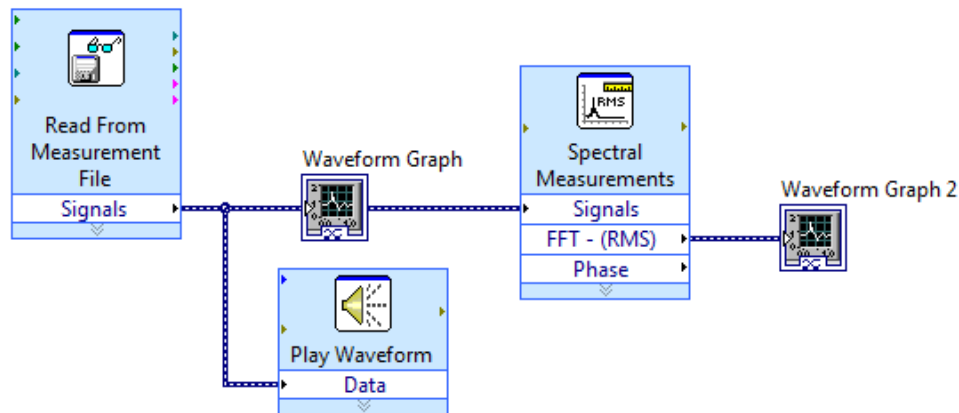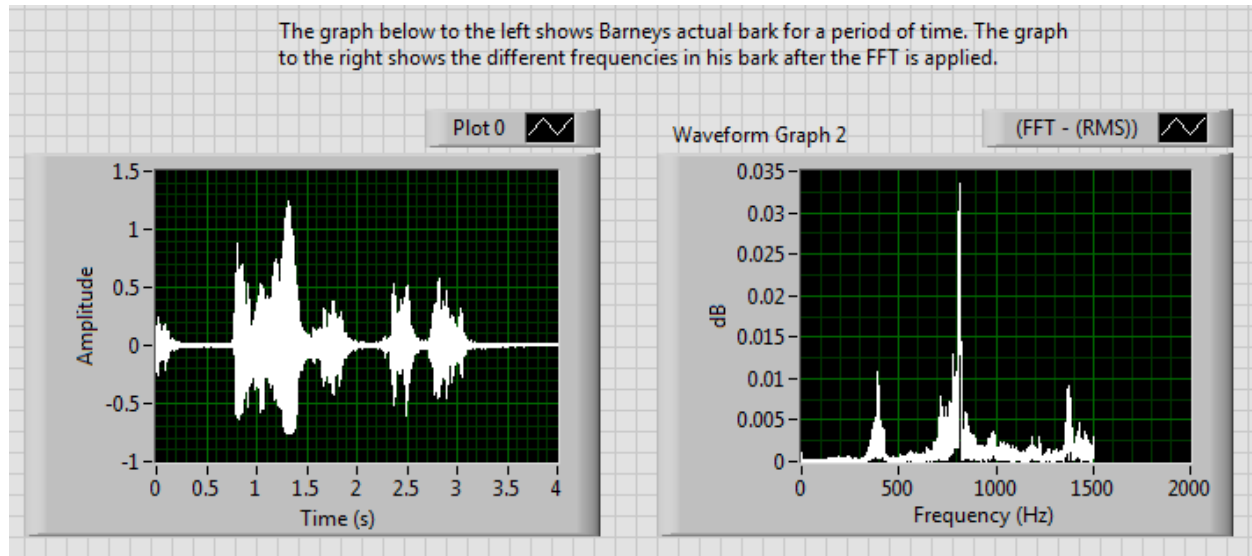
Figure 2: LabVIEW Block Diagram and Front Panel showing time and frequency domain analysis of a dog bark recorded for 4sec.

Hands-on Laboratory Experiments:

In addition to guided class exercises, five hands-on experiments are conducted during the semester. The previous studies have shown that hands-on experiments improve students' conceptual understanding, design skills and professional skills (Ma and Nickerson, 2006). The conceptual understanding enables students to relate the theoretical concepts covered in class to the real world applications. Before each experiment, students are given a laboratory manual explaining the task. Students perform the hands-on experiments in teams. There are typically two to three students in each team. Some of the experiments require students to design and investigate the design criteria for the problem given. At the completion of the experiments, each student prepare a laboratory report. It is important for each student to form their opinion on the experimental findings. Examples of these experiments are outlined in Table 2.

	Experiments	Learning Objectives
1	Temperature Measurements	• Explain the working principle of temperature sensors: thermistor, thermometer, and a thermocouple. • Calibrate the temperature sensors. • Apply digital data acquisition to gather data in LabVIEW. • Apply data analysis on the data collected.
2	Sound Measurements of Music Instruments	• Analyze time and frequency domain representations. • Explain how a microphone works. • Apply signal analysis in LabVIEW environment: sampling, aliasing, windowing.
3	Voltage Measurements on Solar Panels	• Generate a LabVIEW program to measure voltage. • Conduct data analysis by using LabVIEW.
4	Light intensity measurements	• Measure the light intensity of different types of light bulbs. • Explain the working principle of a light intensity sensor.
5	Pressure measurement for piping networks	• Explain the working principle of pressure sensors. • Write a LabVIEW code to perform testing. • Measure pressure for different piping network configurations (series and parallel connection)

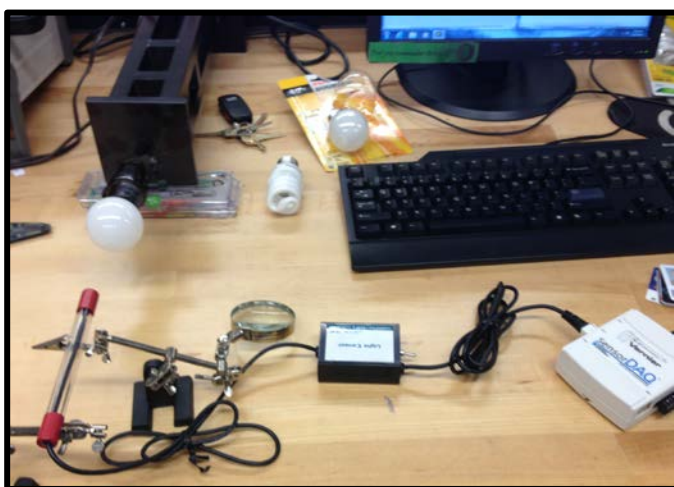**Table 2:** Hands-on experiments performed by students.

Figure 3: Experimental setup for light intensity measurements.

Figure 3 is showing the experimental setup used during light intensity measurements. Students used Vernier SensorDAQ as a data acquisition board along with a Vernier light intensity

sensor. Students generated a LabVIEW code, as illustrated in Figure 4, to record data for three different types of light bulbs. The light bulbs tested were a Halogen bulb, CFL (compact fluorescent lamp), and LED (light-emitting diode) bulbs.
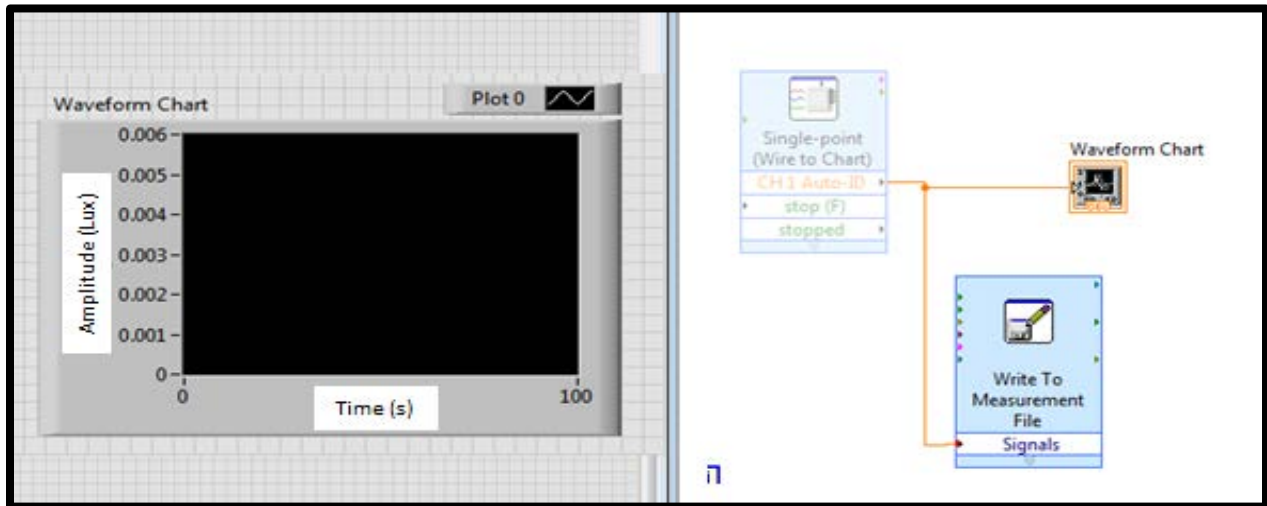

Figure 4: LabVIEW Block Diagram and Front Panel that the students generated to measure light intensity.

Several researchers investigated the effectiveness of instructional methods used in laboratories. These methods are the cookbook approach with step by step detailed instructions, design-based method with only limited instructions, and proposal-based approach in which students propose an idea for the project, design and develop their own experiments. Their findings suggest that each method has its own advantages and disadvantages. All three methods should be used during the semester for a junior/senior level laboratory class (Habibi, et al. 2016). The class activities assigned during the instrumentation laboratory class at York College of Pennsylvania can be categorized as:

In-class exercises: cookbook approach and design-based approach

Hands-on laboratory exercises: cookbook approach and design-based approach

Team Projects: proposal-based approach

Team Projects:

Students work in groups on a final project of their choice which utilizes the principles of data acquisition. Each team has two to three students. Team projects use proposal-based approach. Students decide on the problem to work on and perform background research. After that each team determine the appropriate equipment and the method to perform the experiments. Some of the example projects from previous years were the effect of buildings on wind turbine performance, exhaust sound analysis of various cars, compressed air propulsion car, light intensity measurements, effect of temperature on solar panel efficiency, and pressure measurement for different piping network configurations (series and parallel connection). All the team projects are funded by mechanical engineering program. Most of the projects require a purchase of a new

sensor. However, some projects use the sensors and the data acquisition boards already available in stock. LabVIEW data acquisition system is used to gather data and also to perform data analysis such as obtaining frequency domain from time domain and statistical analysis.

Evaluation of Instructional Methods:

The Instrumentation and Measurement laboratory at York College of Pennsylvania implemented combination of several instructional methods. These methods are in-class exercises, laboratory experiments, and proposal-based team project. To evaluate the effectiveness of these methods, student surveys are conducted on the course outcomes and class activities. The class activity survey include questions on each class activity and how the activity improved their learning experience.

Student Survey Results: Outcomes assessment survey is conducted at the completion of the semester. It is an anonymous survey with a set of questions that target students' understanding of each course outcome. For each statement in the left hand column of the table, students rate the extent to which they agree or disagree with the statement by placing an X in the appropriate column.

Outcomes assessment:

	Strongly Agree	Agree	Disagree	Strongly Disagree
I feel confident in my ability to apply error analysis on experimental data samples.	14, 8, 15	10, 19, 19	2, 0, 0	0, 0, 0
I feel confident in my ability to apply uncertainty analysis. (Calculating expected and maximum uncertainties) on experimental data.	14, 8, 6	10, 19, 27	2, 0, 1	0, 0, 0
I feel confident in my ability to apply statistical analysis to determine mean and root-mean-square deviation, median, variance.	17, 13, 18	9, 13, 15	0, 1, 1	0, 0, 0
I feel confident in my ability to use histograms.	10, 5, 8	12, 16, 23	4, 6, 3	0, 0, 0
I feel confident in my ability to use probability density functions (pdf-z domain)	10, 5, 5	12, 16, 22	4, 6, 7	0, 0, 0
I feel confident in my ability to apply FFT to data samples to find the frequency content of the signal	13, 7, 12	12, 17, 21	1, 3, 1	0, 0, 0
I feel confident in my ability to use LabVIEW for data acquisition and analysis	14, 10, 15	11, 14, 18	1, 3, 1	0, 0, 0

Table 3: Summary of the course outcome surveys. The first number in each cell corresponds to the number of students selected that statement in their responses in 2012 and the second and third numbers are reported for the same questions in 2014 and 2016. Number of students completed this survey are 26 (in 2012), 27 (in 2014) and 34 (in 2016).

Also, students provide a written feedback regarding suggestions and possible course improvements. In the written comments, most of the students suggested that having extra sessions on LabVIEW and possibly introducing the LabVIEW program earlier in the semester would be beneficial.

To assess the effectiveness of the class activities, a student survey is developed. The table below is showing the questions that assess the understanding gained and interest level of the activities. The survey results show that the least helpful and uninteresting activity is measuring temperature by using a thermocouple and a thermistor while the most interesting activity is the team projects. Students considered LabVIEW exercise sessions as the most beneficial among all the class activities. Thirty-eight students contributed to this survey. The summary of the results is shown in Figure 5 and detailed results are included in the Appendix section.

Activities	Rating			
1. Measuring temperature by using a thermistor and a thermocouple	1	2	3	4
2. Statistical analysis	1	2	3	4
3. LabVIEW class exercises	1	2	3	4
4. Solar panel lab.	1	2	3	4
5. Signal analysis and filtering (Matlab simulation)	1	2	3	4
6.Time and frequency domain analysis hands-on lab.	1	2	3	4
7.Team project	1	2	3	4

Question 1: How well the activities listed above contributed to your understanding? (1-not at all, 2-slightly, 3-moderately well, 4-very well)

Question 2: Please rate the class activities based on how interesting they were. (1-not interesting, 2-slightly interesting, 3-moderately interesting, 4-very interesting)

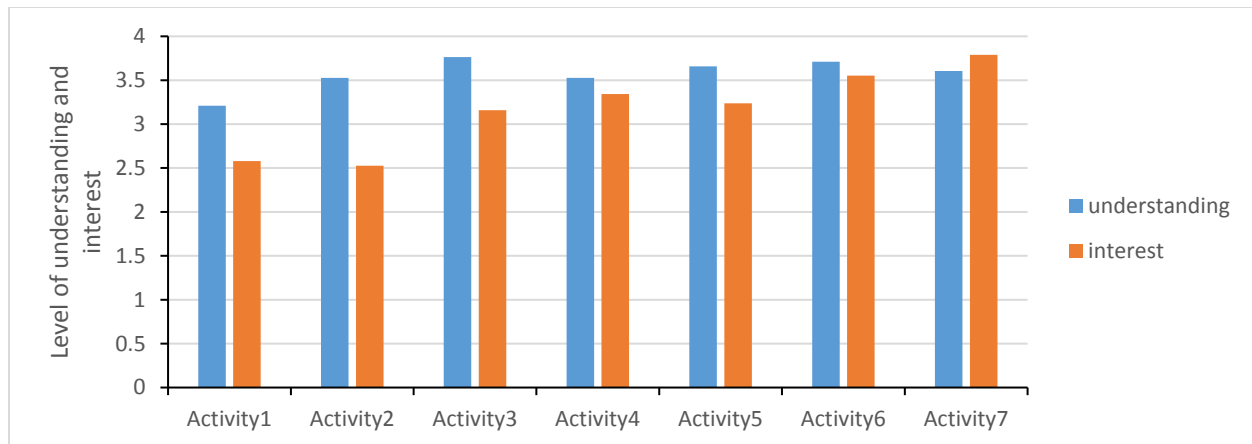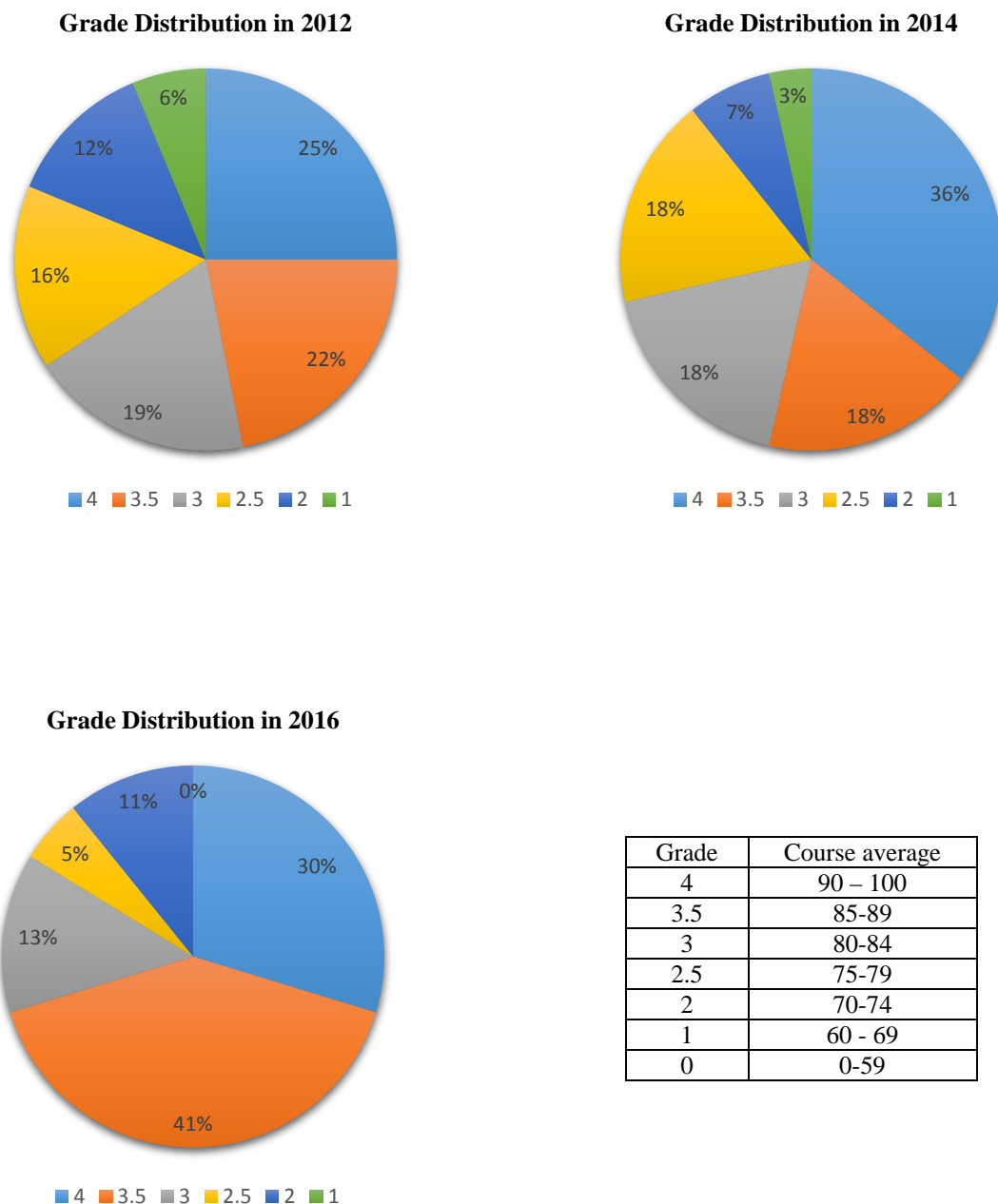**Table 4:** Student survey questions comparing various class activities.

Figure 5: Mean value of the results of the student survey comparing various class activities listed in table 4. (Questions 1 and 2, in table 3, are labeled as understanding and interest in this figure correspondingly)

These class activities can be further divided into three categories: cook-book approach, design-based approach, and proposal-based approach as indicated in the study by Habibi et al. (2016). The activities included in figure 5 can then be categorized as activities 1 and 2 as cook-book, activities 3, 4, 5, and 6 as design-based, and activity 7 as a proposal-based approach. In the cook-book approach, students are given step by step instructions while in the design-based approach, students are provided with guidelines but not with all the steps. To succeed in design-based approach, students need to be self-directed learners. In the proposal-based approach such as in activity 7, team project, students decide on the project or a problem to work on and develop an experimental method and procedure to accomplish that goal. Figure 5 shows that students preferred to work on design-based and proposal-based activities compared to cook-book approach. However, activities 1 and 2 are important to prepare students to the later activities. It can be concluded that a combination of all three types of approaches are necessary to enhance student's learning. Table 3 and Figure 5 are showing student's perception of their understanding in course outcomes and class activities. To get a complete picture, it is important to also look at grade distributions in 2012, 2014 and 2016 academic years.

Grade Distribution in 2012

Legend: ■ 4 ■ 3.5 ■ 3 ■ 2.5 ■ 2 ■ 1

Values: 25%, 22%, 19%, 16%, 12%, 6%

Grade Distribution in 2014

Legend: ■ 4 ■ 3.5 ■ 3 ■ 2.5 ■ 2 ■ 1

Values: 36%, 18%, 18%, 18%, 7%, 3%

Grade Distribution in 2016

Legend: ■ 4 ■ 3.5 ■ 3 ■ 2.5 ■ 2 ■ 1

Values: 30%, 41%, 13%, 5%, 11%, 0%

Grade	Course average
4	90 – 100
3.5	85-89
3	80-84
2.5	75-79
2	70-74
1	60 - 69
0	0-59

Figure 6: Grade distributions in 2012, 2014, and 2016. (4 is the highest grade and 1 is the lowest grade)

The grade distributions has been consistent since 2012. The effective class GPA values are calculated as 3.55 in 2012, 3.21 in 2014, and 3.36 in 2016. The number of students enrolled in this class were 29 (in 2012), 29 (in 2014) and 38 (in 2016). In the grade distribution and effective class GPA calculations, all the students enrolled in class are included.

CONCLUSIONS

Instrumentation and Measurement Laboratory class has a fundamental role in introducing measurement and data analysis tools. To improve the effectiveness of this class the following modifications have been done over the years.

- The class has started as a laboratory course. Currently it has both lecture and laboratory components. Having a combination of laboratory and lecture was necessary to explain analysis of experimental data samples and how to process them.
- Introducing a data acquisition software, such as LabVIEW, is essential. LabVIEW's user-friendly interface is easy to use. It is vital for students to know how to gather and analyze data in real-time.
- Combination of three types of approaches are applied. These approaches are in-class exercises (simulations), hands-on laboratory experiments, and a proposal-based team design project.
    - Simulation class exercises are effective in learning a new software and practicing data analysis tools.
    - Hands-on laboratory exercises allows students to practice what they learned during the lecture portion of the class. While performing the experiments, students work in teams with a rotation of responsibilities such as setting up the experiment, writing the LabVIEW code, and learning how to perform the experiments assigned.
    - The team project allows students to come up with an idea and complete all the stages of experimental design (deciding on the parameters to measure, selecting an equipment, collecting data and analyzing the data).
- Students prepared written reports for the hands-on laboratory experiments and team project.
- Inviting guest speakers is insightful for students. Guest speakers could be from industry and explain students how they do experimentation.

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APPENDIX

In the figures below, student's responses are shown for each activity. Question 1 and 2 are labeled as understanding and interest in the figures. (*Question 1: How well the activities listed contributed to your understanding? (1-not at all, 2-slightly, 3-moderately well, 4-very well). Question 2: Please rate the class activities based on how interesting they were. (1-not interesting, 2-slightly interesting, 3-moderately interesting, 4-very interesting))*

Activities	Rating			
1.Measuring temperature by using a thermistor and a thermocouple	1	2	3	4
2. Statistical analysis	1	2	3	4
3. LabVIEW class exercises	1	2	3	4
4. Solar panel lab.	1	2	3	4
5. Signal analysis and filtering (Matlab simulation)	1	2	3	4
6.Time and frequency domain analysis hands-on lab.	1	2	3	4
7.Team project	1	2	3	4

Figure 1: Student's response to temperature measurement laboratory based on understanding gained and interest level. (1-lowest score and 4-highest score) – (Activity category: Hands-on exercise)
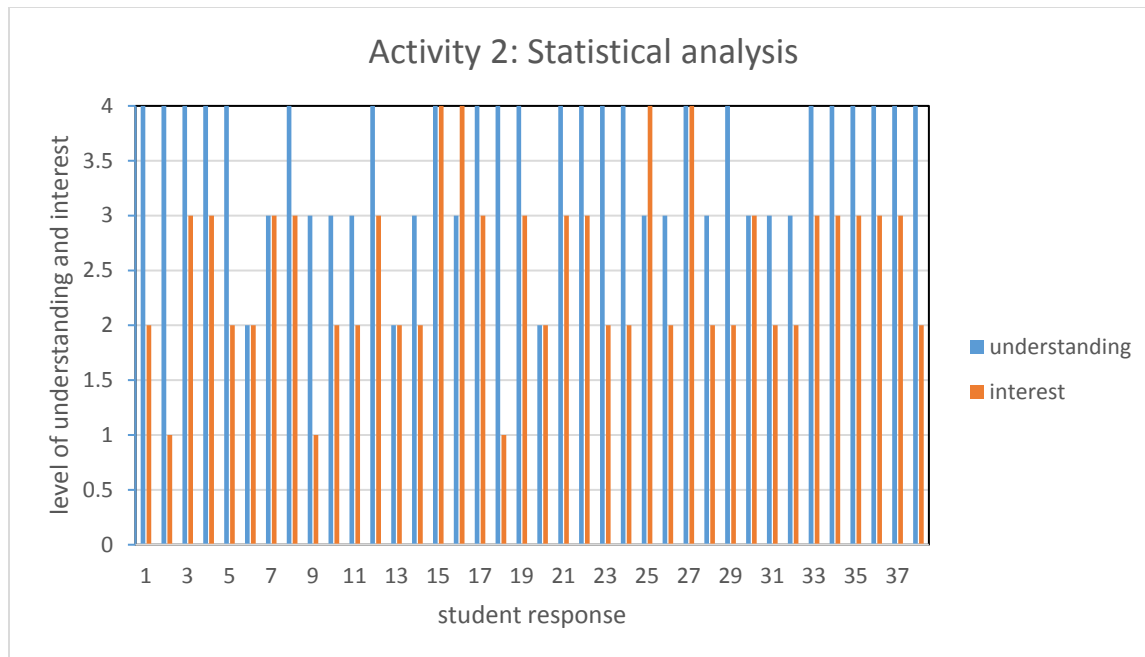
Figure 2: Student's response to statistical analysis based on understanding gained and interest level. (1-lowest score and 4-highest score) – (Activity category: in-class exercise)
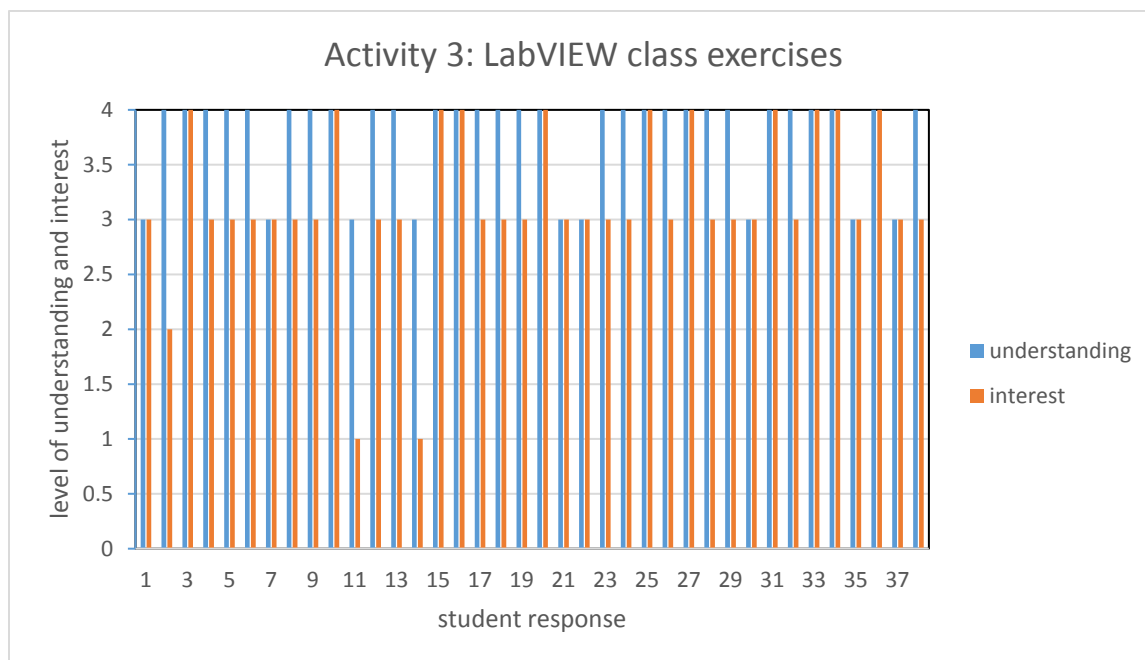

Figure 3: Student's response to LabVIEW class exercises based on understanding gained and interest level. (1-lowest score and 4-highest score) – (Activity category: in-class exercise)
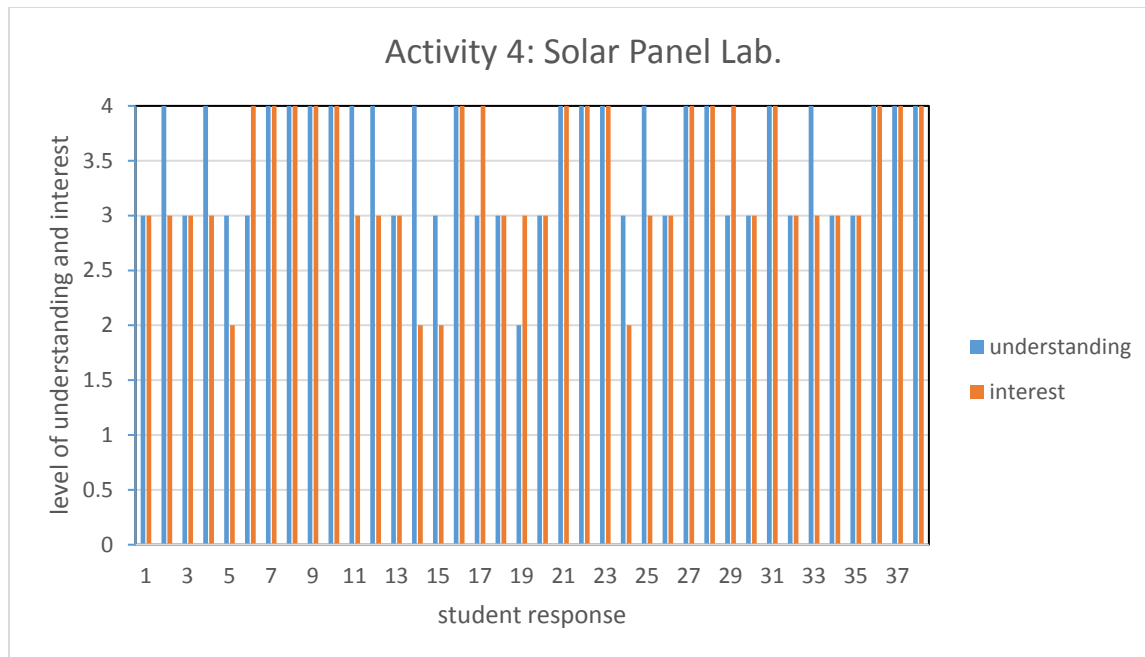
Figure 4: Student's response to solar panel measurement laboratory based on understanding gained and interest level. (1-lowest score and 4-highest score) – (Activity category: Hands-on exercise)
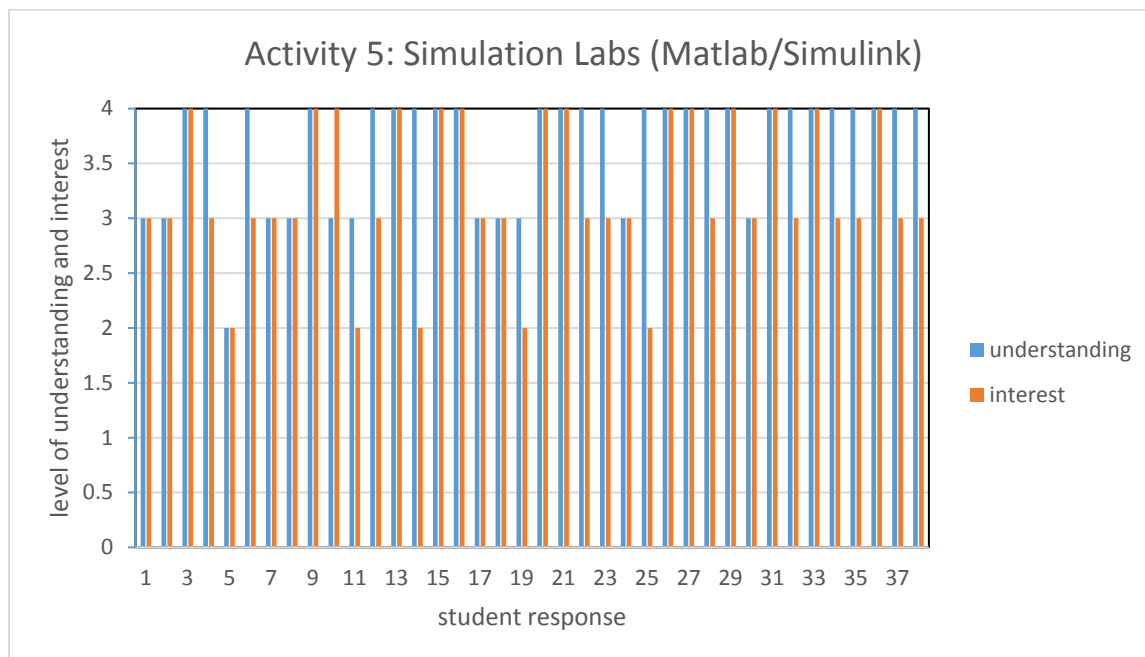

Figure 5: Student's response to Matlab simulations based on understanding gained and interest level. (1-lowest score and 4-highest score) – (Activity category: in-class exercise)
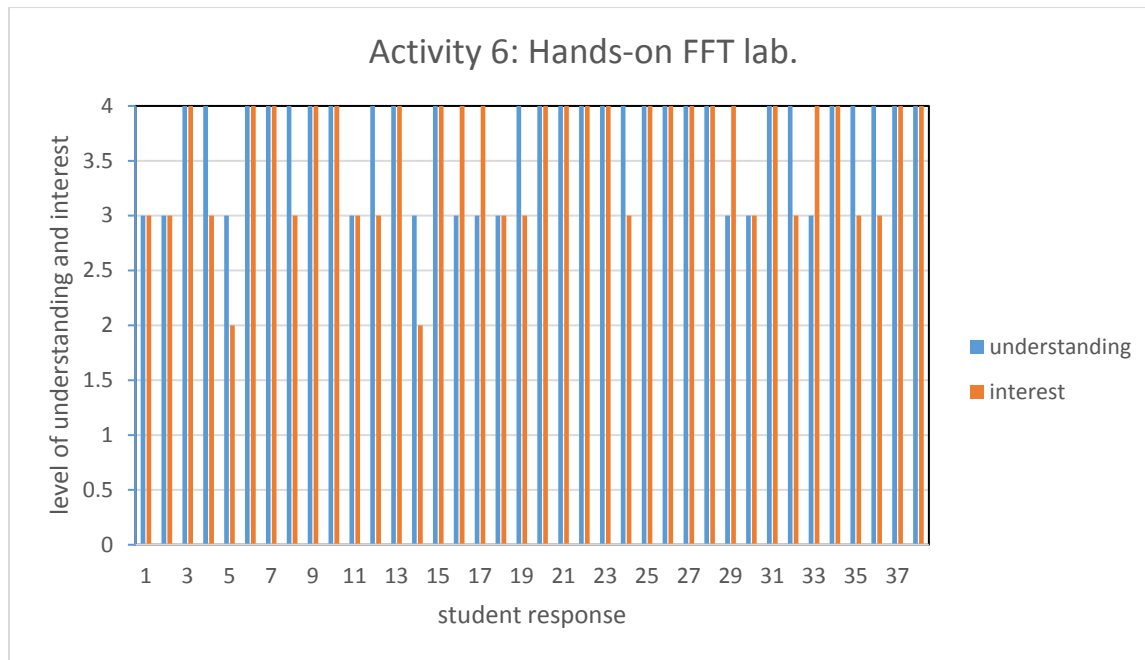
Figure 6: Student's response to time and frequency domain analysis laboratory based on understanding gained and interest level. (1-lowest score and 4-highest score) – (Activity category: Hands-on exercise)
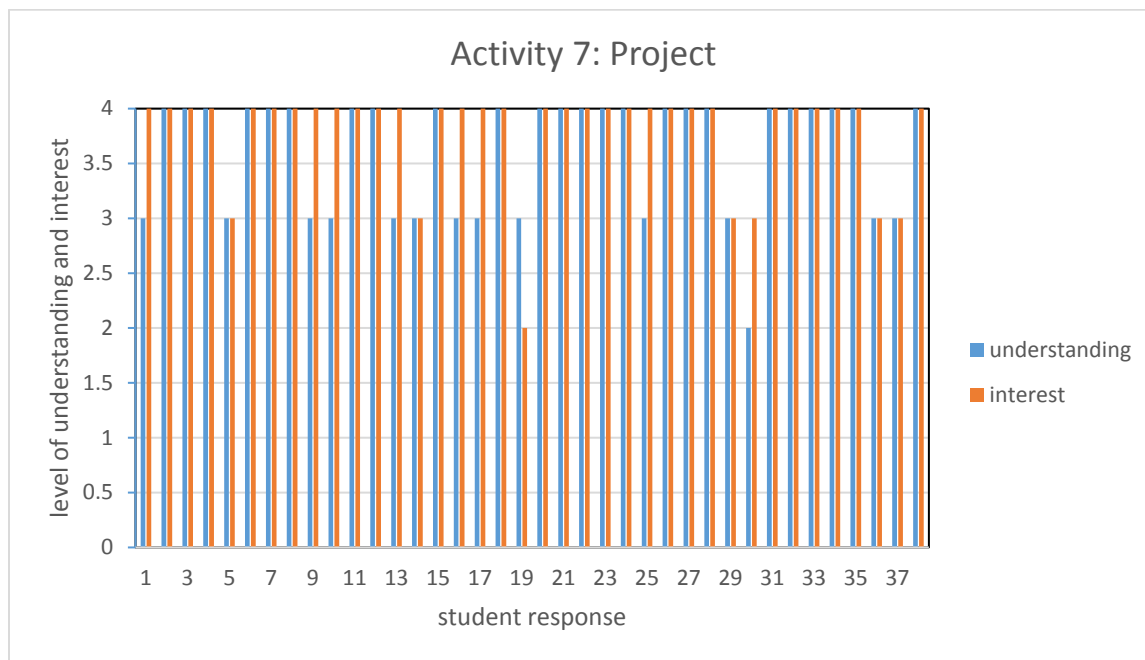

Figure 7: Student's response to team project based on understanding gained and interest level. (1-lowest score and 4-highest score) – (Activity category: team project)