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Fundamental Instrumentation Course for Undergraduate Aerospace and Mechanical Engineering

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Fundamental Instrumentation Course for Undergraduate Aerospace and Mechanical Engineering

Abstract

As part of the Mechanical and Aerospace Engineering curriculum, Embry-Riddle Aeronautical University (Prescott, AZ) has developed a combined lecture / laboratory (lab) course to give students an introduction to the fundamental principles of instrumentation and tools necessary to perform measurements while reducing the data obtained. This Measurements and Instrumentation course will provide essential knowledge and skills that students can use for complimentary engineering lab courses such as Thermal Fluid Sciences [1], Experimental Space Systems, and Experimental Aerodynamics as well as during their yearlong capstone course and numerous student clubs / research activities.

Topics covered in this course are measurement uncertainty, probability and statistics (including confidence intervals), operating principles of sensors such as thermocouples, strain gages, and pressure transducers, and basic signal conditioning. In addition, transient response of measurement systems is evaluated. Students apply the knowledge learned in the lecture portion into measurements taken in the lab while reporting and interpreting the results. Lab experiments range from pre-assembled to open-ended.

Students are introduced to the basic principles of data acquisition and use simple data acquisition hardware and software. Subjects included in this aspect of the course are sampling theorem, quantization, and code width of the measurement device. Students are introduced to the National Instruments (NI) compact data acquisition (cDAQ) platform and the NI LabVIEW programming environment. Additional cDAQ hardware used in this course is available for use outside of the course for student research activities and capstone projects.

In addition to the technical components of making measurements, this course has a very strong communications and teaming component. Students are challenged to critically think about the measurements made during the lab period and report not only the results, but interpret the meaning and significance of the results. Students must report these findings in a clear and concise manner thoughout the term in several different formats.

Introduction

The stated purpose of the Measurements and Instrumentation lecture and lab is to provide students with a basic and fundamental knowledge of mechanical instrumentation and sensors (both in theory and practice), data acquisition systems, and how to process / analyze the measurements in preparation of both industry, subsequent lab courses, and preliminary / detail design (yearlong senior capstone project). The learning outcomes stated in the course syllabus are:

1. Develop a fundamental knowledge of the working principles behind various sensors and transducers, including their response and calibration for static and dynamic responses.
2. Acquire analog signals utilizing benchtop / handheld equipment (multimeter, oscilloscope) and National Instruments* data acquisition (DAQ) hardware with LabVIEW*
3. Conduct, analyze, and effectively communicate / interpret results from lab experiments for fundamental properties
4. Evaluate experimental uncertainty for individual measurements as well as calculated parameters (i.e. multiple measurements).
5. Evaluate basic statistics of a sample and population with parameters such as mean, standard deviation, confidence intervals and outlier analysis for a Gaussian distribution
6. Develop a fundamental knowledge of using LabVIEW to create Virtual Instruments (VIs)
7. Understand basic electronics and circuit analysis for filters, amplifiers, and other signal conditioning circuits such as a Wheatstone bridge, and be able to build such circuit

This course is placed in the recommended curriculum during the first semester of the third (junior) year. There is some minor reliance on prerequisite knowledge gained from general engineering science classes such as Physics, but primarily all material is introduced for the first time in this course.

*Note: the authors of this paper have no relationship with National Instruments other than customer - supplier and receive no special financial considerations other than the academic discount available to all institutions of higher learning for hardware and software.

Course Structure

The course is a three credit course (2 credits lecture, 1 credit lab) which was first offered in the Fall of 2016 as a required class for students majoring in Mechanical Engineering. As of Fall 2019, the course was added as a required class for students majoring in Aerospace Engineering. This resulted in the course changing from being offered once per year to approximately 30 students to twice a year with approximately 180 students as well as more varied needs to suit both disciplines unique needs. The course lecture meets twice a week for 50 minutes while the lab meets once a week for two hours and forty minutes. Both the lecture and lab portions of the course are co-requisites of each other with an overall course grade being assigned based off assignments from each portion. The lecture and lab are taught in a combined lab / lecture room with a capacity of 40 students (lecture) or with 16 students (lab). Typical lab sections consist of 4-5 groups of 3-4 students dependent on enrollment.

The Learning Objectives for the course are met through numerous activities in the lecture and lab portions of the course. Each Learning Objective is met by a minimum of eight activities / lecture topics with the assessment of student proficiency being made through weekly quizzes associated with lecture, pre-lab assignments, written lab reports in multiple formats, and oral presentations. The quizzes provide instant feedback to how students are retaining the course material. In addition, they give feedback before turning in the lab report so as to not be penalized in a higher stakes deliverable. Pre-lab assignments are used to ensure proper preparation for the lab that will occur each week. In addition, preliminary LabVIEW code is typically a required deliverable to allow individual practice as well as ensure better usage of time during the lab section.

The fulfillment of each Learning Objective can be demonstrated in the Table 1 and Table 2. Each lists the lecture topics or lab exercises covered in the course and the Learning Objectives each is targeted to fulfill. A general description is provided for each lecture and lab topic in the subsequent sections to provide context and demonstrate meeting the listed course learning objectives.

Table 1. Learning Objectives met by Lecture Topics

	Learning Objectives						
Primary Lecture Topics	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1 - Introduction to Measurement Systems							
2 - Length, Proximity, Displacement, & Statistics	X				X		X
3 - Instrument Calibration / Errors & Instrument Uncertainty	X			X	X		
4 - Strain, A/D Conversion, & Amplification	X			X			X
5 - Uncertainty Analysis				X	X		
6 - Temperature & 1st Order Dynamic Response	X			X			X
7 - Load, Force, Torque	X			X			X
8 - Acceleration & 2nd Order Dynamic Response & Sampling Theorem	X			X			
9 - Pressure & Outlier Analysis	X			X	X		
10 - Velocity & Rotational Speed	X			X			
11 - Filters and Misc. Signal Conditioning	X			X			X

Table 2. Learning Objectives met by Lab Exercises

	Learning Objectives						
Lab Exercises	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1 - Introduction to Equipment Uncertainty		X	X	X	X		
2 - Introduction to LabVIEW			X			X	
3 - Instrument Calibration & Errors	X	X	X	X	X	X	
4 - Strain Measurement, Signal Conversion, & Quantization Errors	X	X	X	X	X	X	X
5 - Instrument Calibration & Signal Amplification	X	X	X	X	X	X	X
6 - Temperature Measurement & 1st Order Response	X	X	X	X		X	
7 - Structural Response to Static Loading	X	X	X	X		X	
8 - Vibration Testing & 2nd Order Response	X	X	X	X			
9 - Sonic Flow Measurement	X	X	X	X			
10 - Rotational Speed Measurement & Sampling Theorem Investigation	X	X	X	X		X	
11 - Instrument Calibration & Filters	X	X	X	X	X	X	X
12 - Projectile Motion Analysis	X	X	X	X			

Lecture Topics

The course lectures are held twice per week and progress through the lecture topics referenced in Table 1. There is a quiz that is associated with each lecture topic that allows for students to assess their understanding. In order to better keep students engaged, fundamental topics are taught through particular sensors whenever possible. This has been modified and extended from previous course offerings where fundamental topics (such as dynamic response, sampling theorem, statistics, etc.) were being taught prior to and without coupling with sensors (strain, temperature, pressure, etc.). Although an ongoing and evolving effort, this cohesion of course content has resulted in improving retention and student engagement. Although there are more topics that could be added, such as actuators, PLCs, flow measurement, etc., there is not enough allotted time to adequately extend beyond the current lecture topics.

1 - Introduction to Measurement Systems

The first lecture topic is an introduction and high level overview of the entire class. A significant portion of the course vocabulary and introductory terms are introduced to set up subsequent lecture topics as well as to provide an overall road map of where the course progresses. A comparison is made between an instrument sensor and a transducer as well as mechanical vs. electrical signals through commonly used every day measurements such as atmospheric pressure, ambient temperature, weight, distances, etc. The inability to actually measure the true value results in some level of uncertainty in the measurement itself and discussion of common error sources such as systematic and precision errors follows. This initial discussion of errors is limited to conceptual with actual calculations covered in previous note sets. In addition, due to our hardware limitations, it is shown how signal quality is decreased when converted from an analog to digital signal.

2 - Length, Proximity, Displacement, & Statistics

Various sensors used to measure length based quantities are introduced with the physical phenomena used to provide the signal output discussed. Common error sources of each sensor are discussed as well as benefits and limitations of the instruments. For example, a linear potentiometer is discussed in terms of a displacement measurement. The physical construction of the device is demonstrated and related back to errors such as resolution, backlash, and sensitivity by examining the coil of wiring wrapped around the core with limitations such as wiper wear and fixed physical range discussed. In addition, simple signal conditioning and its benefits such as conversion from resistance to voltage is demonstrated. Statistics of a normal distribution for both a population and a sample are taught and then used to develop corresponding confidence intervals. All examples are framed around length based quantities to correspond to the introduced sensors and provide immediate context to the topic.

3 - Instrument Calibration / Errors & Instrument Uncertainty

After introducing some initial sensors and observing how the physical nature of devices can result in common errors, the process for calibrating an instrument and quantifying its errors is provided. An extended example is built for the calibration of a device with multiple cycles of data from sequential tests. The data is used to characterize a calibration curve and common errors such as systematic, precision, hysteresis, non-linearity, zero offset, and total uncertainty. Emphasis is made on selecting appropriate calibration curves based on the physical nature of the system as well as expressing errors in the units of the desired measurement and not simply the output of the instrument used. Confidence intervals are presented that include both systematic and random errors. In the context of calibration, understanding the terminology and calculating errors from manufacturers data sheets are discussed with common forms of presentation such as % reading, % range, # digits, etc. examined.

4 - Strain, A/D Conversion, & Amplification

Strain measurement is discussed as it relates solely to strain measurements. Subsequent sensors that work on the principle of strain measurements such as force, torque, etc are discussed in follow on lecture topics. The principle of change in resistance of an element and how that relates to tension and compression of the gage are used to establish the operating principles. After demonstrating the relatively small output of a strain measurement in change of resistance, a conversion of signal type and sensitivity increase is shown using a Wheatstone bridge. This is also used to demonstrate the ability of the bridge configuration to compensate for considerations such as temperature, bending loads, etc. Strain measurements are then used to frame the context of conversion from an analog input signal to a digital output signal. The resolution and quantization errors as a result of the conversion are demonstrated as an extension to previous strain examples to show the inability to perfectly capture the signal. Finally, amplifiers are introduced and used to demonstrate a reduction in quantization error by using the full range of the A/D converter as opposed to simply using the raw sensor / transducer output. Topics such as bandwidth, saturation, and loading error are discussed within the context of amplifiers.

5 - Uncertainty Analysis

After numerous sensors and fundamentals have been introduced, students begin to have a better understanding of basic errors (systematic and precision). Uncertainty analysis is then introduced to show how errors in individual measurements impact the overall uncertainty of calculated parameters. The partial derivative is used to determine the sensitivity of each parameter for the given measurement / calculation and the root-sum-square (RSS) method is used to couple all errors together. Simplified uncertainty analysis is also provided for cases which are applicable and do not require calculation of a partial derivative. An emphasis on examples from previous engineering courses such as Fluid Dynamics, Solid Mechanics, and Thermodynamics are used to relate that property values, dimensions, measurements etc. used in theoretical examples have some level of uncertainty. This allows students to more easily see the relevance and importance of experimental uncertainty analysis in addition to showing the limitations of course examples used without uncertainty.

6 - Temperature & 1st Order Dynamic Response

Various sensors used to measure temperature such as thermocouples (TCs), thermistors, resistance temperature detectors (RTDs), and infrared (IR), are introduced with the physical phenomena used to provide the signal output discussed. Thermocouples are demonstrated with and without reference junctions. As most temperature measurement systems behave dynamically as a 1st Order system, this behavior is analyzed in conjunction with temperature. Periodic, ramp, and step inputs are used to examine time constants and dynamic errors (error fraction) as a result of measurement time. Emphasis is placed on the physical significance of the time constant (% change, lag, magnitude ratio) as well as the ability to determine its value theoretically from the system's governing equations. In addition, thermal drift is discussed and linked back to its effect on long term temperature measurements.

7 - Load, Force, Torque

Various sensors used to measure force based quantities are introduced with the physical phenomena used to provide the signal output discussed. The link between force and area to pressure are discussed as well as force and distance to torque. Compensation and increased sensitivity are discussed as related to Wheatstone bridge configuration introduced in previous lectures. This lecture topic operates as a stand-alone topic focusing purely on the indicated sensors and not on any new fundamental instrumentation topics. Due to the focused nature of our student body in the propulsion and aerospace industry, specific applications are emphasized more in this section of lecture topics compared to other sections, such as thrust, dynamometers, and structural loading, etc.

8 - Acceleration & 2nd Order Dynamic Response & Sampling Theorem

Various sensors used to measure acceleration such as piezoelectric and micro-electromechanical system (MEMS) are discussed. Signal conditioning such as a charge amplifier are discussed in the context of piezoelectric measurements. As most acceleration measurement systems behave dynamically as a 2nd Order system, this behavior is analyzed in conjunction with acceleration. In addition, examination of predicting velocity and position measurements from acceleration data is conducted. Periodic and step inputs are used to examine damping ratio and natural frequency as well as dynamic errors. In the context of periodic inputs, the sampling theorem is introduced with Nyquist frequency and signal aliasing examined extensively. Examples are shown in which an alias would "appear" to be a correct signal if the engineer was not aware of sampling limitations. A folding diagram is used to calculate possible alias frequencies and to ensure that an appropriate sample rate is chosen. Although filters will be covered in a subsequent lecture topic, the concept of an anti-aliasing filter is foreshadowed.

9 - Pressure & Outlier Analysis

Various sensors used to measure pressure such as piezoelectric, diaphragm, bourdon tube, bellows, etc. are introduced with the physical phenomena used to provide the signal output discussed. Pressure measurement techniques as related to static, stagnation, and total pressure are emphasized. In addition, analysis is introduced to compliment the normal distribution statistics introduced in 2 - Length, Proximity, Displacement, & Statistics using the context of pressure measurements. Emphasis is placed on integrity of data and presentation / reasoning of the basis of outlier analysis.

10 - Velocity & Rotational Speed

Various sensors used to measure velocity such as linear velocity transducers (LVTs), laser, doppler, etc. are introduced with the physical phenomena used to provide the signal output discussed. Various sensors used to measure rotational speed such as photo-strobe, laser, magnetic, etc. are introduced with the physical phenomena used to provide the signal output discussed. Signal aliasing is reinforced with the photo-stroboscope. The link between the need for rotational speed measurements and force / torque measurements are reinforced as it relates to characterizing motors. Note that velocity as it relates to pipe / duct flow and air speed are not covered in detail here as they are a significant focus of complimentary lab courses.

11 - Filters and Misc. Signal Conditioning

Various signal conditioning techniques and why they are needed are covered, with an emphasis on filtering. Simple filters such as low-pass / high-pass are examined in the context of noise and signal interference. Other miscellaneous topics such as band-pass and notch filters, 4-20 mA conversion for process signals, shielding / grounding, signal conversion, single / differential ended connections, etc. are covered as well. While most of these are beyond the scope of significant theory in this class, it provides an introduction to students for future applications.

Lab Activities

In all labs, the uncertainty of the equipment and calculated parameters is a major point of emphasis. LabVIEW is used in conjunction with as many labs as possible to further increase knowledge of data acquisition systems. LabVIEW and National Instrument hardware is specifically used due to its simplicity, quick learning curve, uniform usage across our campuses, and its widespread usage across academia and industry. Although not specifically mentioned, LabVIEW is used with all labs following Lab 2 with the exception of 9 – Sonic Flow Measurement and 12 – Projectile Motion Analysis. A short 5-10 minute pre-lab lecture is held prior to beginning lab each week to ensure understanding of the procedures and objectives. In order to keep students as engaged as possible, the labs are designed to only take ~ 1.5 – 2 hours, with efficiency increased by using prelab assignments to ensure that appropriate planning has been completed prior to attending. In addition, a lab notebook is required to document all exercises with an emphasis on data integrity, and ethics of recording and presentation. Although analysis associated with most lab exercises is done within the lab group, the analysis from four exercises is done individually. Combined with individual effort from the lecture portion of the course, 50% of the grade is individual while 50% is team based. This helps to ensure that students are not simply carried by their teammates.

1 - Introduction to Equipment Uncertainty

The first lab activity introduces students to the benchtop hardware used (multimeters, power supply, oscilloscope, function generator) and focuses on calculation of measurement uncertainty using manufacturer provided instrument data sheets. One example of data collection is to measure the voltage drop over a series of resistors using multiple multimeters and then comparing the data from each measurement to the total voltage drop. While the individual measurements will vary and will not add up to equal the measured total voltage drop, the values with their uncertainties overlap, which helps reinforce the concept of instrument uncertainty. Current and resistance are also the basis of additional measurements.

2 - Introduction to LabVIEW

A series of exercises are used to introduce students to the LabVIEW programming environment and create familiarity with the Front Panel and Block Diagram as well as programming “graphically”. Students use laptops to individually step through these exercises and are exposed to numerous functionality such as indicators, controls, charts, simulating signals, writing to files, numeric controls, etc. This lab exercise has future benefits in that it demonstrates that LabVIEW can be programmed without hardware installed by using simulated signals to verify functionality. In addition, this lab allows for a foundation such that future labs can have preliminary LabVIEW codes assigned as the prelab assignment which students will also complete individually.

3 - Instrument Calibration & Errors

A linear potentiometer is used to demonstrate an instrument calibration exercise. It was chosen based on its simplicity of operation, linear output, and to compliment lecture content coverage. Students are required to collect data, produce a calibration, and complete a generic instrument data sheet. This lab is open ended such that students have to assess the appropriate measurement interval, basis of “known” distance, as well as the number of cycles that are needed for an appropriate calibration. The final completed data sheet must account for errors such as precision, hysteresis, non-linearity, etc. as well as parameters such as threshold, measurement range, physical range, total resistance, etc. This lab exercise challenges student to consider what error(s) and considerations must be made to appropriately calibrate and characterize and instrument without a step-by-step lab handout.

4 - Strain Measurement, Signal Conversion, & Quantization Errors

A strain gage is carefully mounted by students to an aluminum beam using a manufacturer's installation and data sheet. With the gage affixed, the beam is mounted in a cantilever fashion after which a series of weights are suspended to it in a sequential test. The resistance of the strain gage is measured for each series of weights. Next, a Wheatstone bridge is constructed in a ¼ bridge configuration. A series of weights are suspended again in a sequential test after which the bridge output voltage is measured from a handheld multimeter. Finally, the bridge output voltage is measured using a 12-bit A/D to demonstrate quantization errors. This lab exercise allows students to see how the output changes across the three measurements, demonstrates a zero offset of the bridge, and demonstrates quantization error to see how each affects measurements. In addition, the low level output and inability to properly characterize the Modulus of Elasticity of the aluminum beam provide a demonstration of the necessity of additional signal conditioning which will be addressed in the subsequent lab.

5 - Instrument Calibration & Signal Amplification

This lab exercise expands upon the previous exercises and uses the previously mounted gage from 4 - Strain Measurement, Signal Conversion, & Quantization Errors. An op-amp circuit is designed to amplify the signal output to match the total measurement range of the same 12-bit A/D converter used in the previous exercise with a potentiometer used to balance the bridge output for no load. This then allows students to see how the quantization effects can be minimized from the previous exercise and compare the progression from resistance measurement to bridge voltage measurement before / after amplification. After amplifying and accounting for errors, a calibration of the "force" measurement is produced along with the Modulus of Elasticity. These values are then compared to the calibration that would be achieved with the results of the previous lab exercise to demonstrate the care that should be taken to ensure appropriate measurement techniques.

6 - Temperature Measurement & 1st Order Response

A series of temperatures are measured with multiple temperature measurement techniques. A TC, thermistor, and RTD are used to simultaneously measure temperatures ranging from freezing to boiling (water). Temperatures exceeding room temperature are provided by a temperature controlled water bath apparatus. TC temperature measurements are also produced using a second TC at ice-bath reference as well as room temperature reference. In addition, TC temperature measurements are produced using cold junction compensation (CJC) associated with an A/D converter data acquisition module. The relative time constants of each measurement probe is determined by inserting the probe into an ice-bath from room temperature and inserting a probe into room temperature from an ice-bath. This exercise allows for familiarity of temperature measurements as well as 1st order response using an easily understood and intuitive measurement technique.

7 - Structural Response to Static Loading

This lab exercise uses an engineered truss structure instrumented with multiple displacement transducers, load cells, and strain gages. A series of input loads are then applied to the fabricated structure using a hydraulic actuator and the output of each sensor is recorded simultaneously. This exercise focuses on comparing the experimental results obtained to the theoretical results from Static Analysis and FEA to see how the limitations of simplifying assumptions can affect the prediction (i.e. course calculations vs. real world measurements). In addition, the truss structure is large in scale with bolted connections and numerous measurements / assumptions that need to be made such that students have to consider carefully all of the required measurements as well as examine hysteresis due to the nature of energy storage in the truss system.

8 - Vibration Testing & 2nd Order Response

This exercise uses a shaker table instrumented with accelerometers to provide an input to a cantilevered beam which is affixed to the table itself. The beam is instrumented with three accelerometers to allow for characterization of amplitude of response and determination of nodes. A sweep input where the frequency is varied across a given range as well as a step input is applied, both of which simulate a 2nd order response to their corresponding input. A step input is also applied by manually deflecting the beam by a defined distance and measuring the resulting output. In both the sweep and step inputs, a well-defined (length) checkerboard pattern is placed “behind” the beam such that the response can also be recorded with a high speed camera. Various materials, lengths, and orientations are used to further characterize the response and compare to theoretical solutions. Similar to the previous lab exercise, this lab focuses largely on comparing the experimental results obtained to the theoretical calculations to see how the limitations of simplifying assumptions can affect the prediction (i.e. course calculations vs. real world measurements).

9 - Sonic Flow Measurement

This exercise uses an engineered piping system to create a contained shock wave. Two pipes are separated by a flange containing a plastic diaphragm. The first pipe is slowly pressurized until the diaphragm is burst and a shock wave is transmitted down the second pipe, then reflected back through the system. The second pipe is instrumented with two pressure sensors along the line of travel, which allows for determination of the pressure rise as well as velocity of the shock wave corresponding to the initial pass as well as the following reflections. This exercise focuses on comparing the experimental results to the theoretical results from hand calculations to see how the simplifying assumptions affect the prediction. It also allows for a demonstration of the rise time to characterize whether the instrument selected was appropriate for the transient nature of the physical signal.

10 - Rotational Speed Measurement & Sampling Theorem Investigation

This exercise uses a DC motor with a fabricated gear attached to the output shaft. Three different rotational speed measurements are analyzed and compared, which include photo-stroboscope, hall-effect gear tooth pick up, and photo reflective. An emphasis of the photo-stroboscope is to examine aliasing and further reinforce sampling theorem. Future additions to this lab include adding a torque measurement technique to produce the motor's characteristic curve by coupling a DC motor acting as a generator and extending a cantilever arm against a load cell. This can then be used to validate the manufacturer's data sheet.

11 - Instrument Calibration & Filters

After introducing numerous additional sensors, experiencing errors / uncertainty, refining skill level in LabVIEW and increasing knowledge level on instrumentation systems, this lab uses an ultrasonic and IR sensor to replicate / reinforce the previous Lab 3 - Instrument Calibration & Errors. This lab is also open ended such that students have to assess the appropriate measurement interval and technique as well as the number of measurements that are needed. The IR sensor is typically negatively impacted by noise such that a low-pass filter will be designed to allow for greater functionality of the instrument. A completed data sheet must still account for errors such as precision, hysteresis, non-linearity, etc. as well as parameters such as threshold, measurement range, physical range, total resistance, etc. On top of the requirements from Lab 3, this lab requires the user to develop a fully functional LabVIEW code as its end product. The code must take into account the calibration produced and display the output in terms of measured distance for both sensors.

12 - Projectile Motion Analysis

This exercise allows for an entertaining and informative final lab. A pressurized air system is used to launch an engineered projectile containing an accelerometer logger approximately 400 ft across a campus recreation field. The data obtained from the accelerometer is then used to determine the velocity and position profiles and compare to theoretically predicted values. Distance is also manually confirmed by physically walking off the distance traveled by the projectile. The uncertainty of acceleration, velocity, and distance and their propagation as a result of integration of the data are emphasized.

Conclusions

While the material presented in this course shares common threads with other instrumentation courses, there is a significant range of content that is covered across the semester which can happen due to the reinforcement of material across both lecture and lab. Feedback from instructors from follow on lab courses has been positive and has indicated that the course is beneficial. In addition, senior capstone instructors have noticed fewer concerns and questions related to instrumentation over the short time the course has been offered. Although it is clear that there is more work to do to continuously refine this course, including improving lecture topics and refining lab exercises, it is clear that the course is on track to be extremely beneficial in the curriculum. Again, the stated purpose of the Measurements and Instrumentation lecture and lab is to provide students with a basic and fundamental knowledge of mechanical instrumentation and sensors (both in theory and practice), data acquisition systems, and how to process/analyze the measurements in preparation of both industry, subsequent lab courses, and preliminary / detail design (yearlong senior capstone project). While there is insufficient data to examine the preparedness of students of industry, it has been successful in providing prerequisite knowledge for lab courses and senior capstone projects.

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References

[1] D. Dannelley and E. Bryner, "Fundamental Instrumentation Course for Undergraduate Aerospace and Mechanical Engineering," in ASEE Annual Conference and Exposition, Montreal Canada, 2020.