122nd ASEE Annual Conference & Exposition
June 14 - 17, 2015
Seattle, WA
Making Value for Society
Paper ID #11860

A Two Semester, Multi-Approach Instrumentation Project for Mechanical Engineering Students

Dr. Dale H. Litwhiler, Pennsylvania State University, Berks Campus

DALE H. LITWHILER is an Associate Professor at Penn State, Berks Campus in Reading, PA. He received his B.S. from Penn State University, M.S. from Syracuse University, and Ph.D. from Lehigh University all in electrical engineering. Prior to beginning his academic career, he worked with IBM Federal Systems and Lockheed Martin Commercial Space Systems as a hardware and software design engineer.

A Two Semester, Multi-Approach Instrumentation Project for Mechanical Engineering Students

Abstract

As part of a third-year mechanical engineering instrumentation course, students are challenged to design, fabricate, test, and characterize a custom air speed measurement instrument. The same instrument is then used, and enhanced, by the same students in their senior year in a microcomputer interfacing course. The enhanced instrument is then retested and characterized. The enhancements are evaluated by the students for their merits and improvement in overall instrument functionality. Specifically, the students design a Pitot-static probe to comply with loose specifications for size, weight, and materials. An electronic gauge pressure transducer with analog voltage output is used as the measurement device. The third-year students test the performance of and develop a calibration curve for their designs in a wind tunnel. The students also write a specification for their instrument such that it could be commercially produced. As seniors, the same student teams enhance their instrument's design by including an embedded microcontroller. The microcontroller includes analog-to-digital converter and serial port peripherals. The students develop microcontroller firmware to perform measurements of the pressure transducer output voltage, apply the calibration curve information, and transmit the airspeed to an external computer via a serial data line. By using the same instrument for both courses, the students get to experience the tradeoffs associated with different approaches to the same problem. This paper presents the projects and the tradeoffs encountered by the students as each design approach is implemented. Design team dynamics due to the time span between courses is also presented and discussed.

Introduction

Providing engineering students with multiple plausible options for solving a problem allows them to make their own decisions about which way best fits the current application. Tradeoffs between options can then be explored and discussed. In the work presented here, third-year mechanical engineering students designed and fabricated simple Pitot-static probes using readily available parts (no 3-D printing) in an instrumentation course. An inexpensive analog electronic pressure sensor was used as the measurement device.[1] Instrument performance was predicted from elementary moving fluid measurement theory.[2, 3] Student team designs were then tested using a wind tunnel facility. Data collected during testing was then used to create a calibration curve for each design. One year later in a microcomputer interfacing course, the Pitot-static probes were again used by the same teams of students as the basis for an enhanced instrument design which now added an embedded microcontroller. The students incorporated the previous wind tunnel calibration data into their embedded software to provide a complete solution with a simple serial data output interface.

A Pitot-static probe was chosen as the first project due to its simplicity of design and previous successful experience with students designing similar probes. The inherent nonlinearity of the pressure sensor output voltage with respect to the air speed provides an opportunity for students to apply theory and achieve very good results.[4] The nonlinear nature of the probe also lends itself well to the use of an embedded lookup table to simplify its use.

Managing a multi-year project involves a little forward-thinking and resource planning. The students are given the requirement to allow space in their instrument enclosures for future expansion and enhancements. Gluing, potting, or sealing the enclosures in any way is not permitted. The test data obtained by the students during the first year must be properly archived for use in the following year. The fabricated instruments must be carefully stored by the school to ensure that they are available for use the following year. The test equipment and facilities must be available for use during both of the project years to allow for a proper comparison of methods. These precautions are necessary to preserve the flow of the project and allow for the possibility of students leaving and/or entering the mechanical engineering program between the years of the project. If the student teams change significantly, the handoff between years can be difficult to manage.[5]

Round One

The third-year students in the instrumentation course were given very broad specifications for their Pitot-static probe designs. They still had to think “inside the box” but the box was fairly large and forgiving. The pressure sensor, electrical connector, and mounting flange were defined and provided but the remaining materials were left open to the students’ discretion and creativity (within the broad specifications). A small budget ($20) was also provided for each of the four teams. The broad specifications were as follows:

- The probe shall weigh no more than 1.0 pounds
- The probe shall fit within a 8.5” x 11” x 3” box
- The probe shall operate over wind speed range of 0 – 90 mph
- The probe shall survive, without damage, a wind speed of 150 mph
- The probe shall operate from a power supply of 4.5 – 5.5 VDC
- The probe shall provide suitable area on which to attach the provided mounting flange
- The probe shall provide suitable area on the rear (downwind side) of the enclosure through which to install the provided electrical connector
- The probe must provide enclosure for the provided pressure sensor PCB

- The probe must provide empty enclosure volume of 1.5” x 1.0” x 0.5” for future hardware expansion

An integrated, temperature compensated, and calibrated pressure sensor, the MPXV5004G manufactured by Freescale Semiconductor, was used for the project.[6] The students had used the pressure sensor for previous experiments and were therefore familiar with its characteristics and use. The sensor was pre-mounted to a PCB which provides screw terminals for all electrical connections as shown in Figure 1.

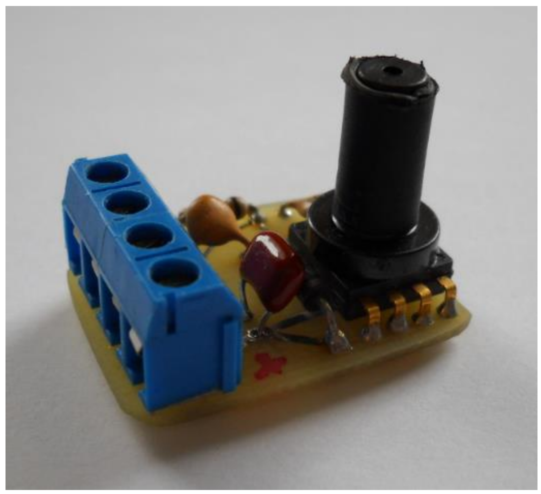

Figure 1. Pressure sensor mounted on PCB

The electrical specifications for the Pitot-static probe were predetermined by the choice of pressure sensor so the students did not have much design activity in this area. They did however need to understand and plan for the expected output voltages for the expected range of wind speeds. Electrical power (nominal 5VDC) to the probe and the output signal from the probe were passed through a simple 3-conductor, 3.5mm audio headphone jack as shown in Figure 2.

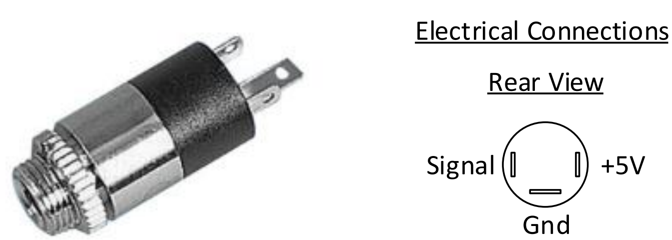

Figure 2. Pitot-static probe electrical connector

The wind tunnel facility at a neighboring institution was used for testing the Pitot-static probe designs. Within the wind tunnel, a thin vertical beam is provided onto which test specimens can be mounted. Each probe design was therefore required to contain a mounting flange that could quickly be attached to and removed from the wind tunnel's mounting beam. Figure 3 shows the flange (L-bracket) that was provided to each group.

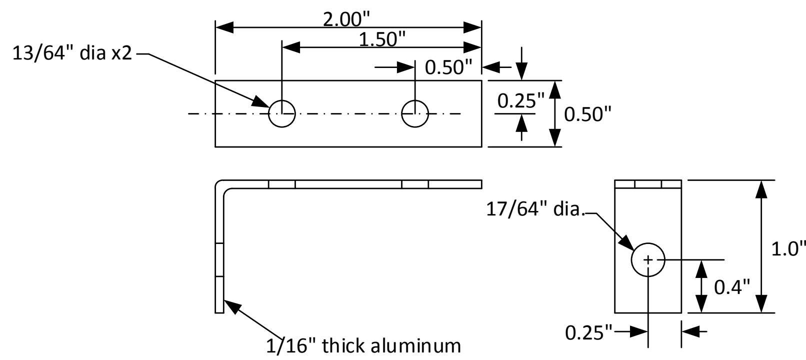

Figure 3. Pitot-static probe mounting bracket

The class size for the first round was such that four design teams of two or three students each were formed. The resulting designs from the four teams were each quite different as can be seen from the photographs shown in Figure 4.

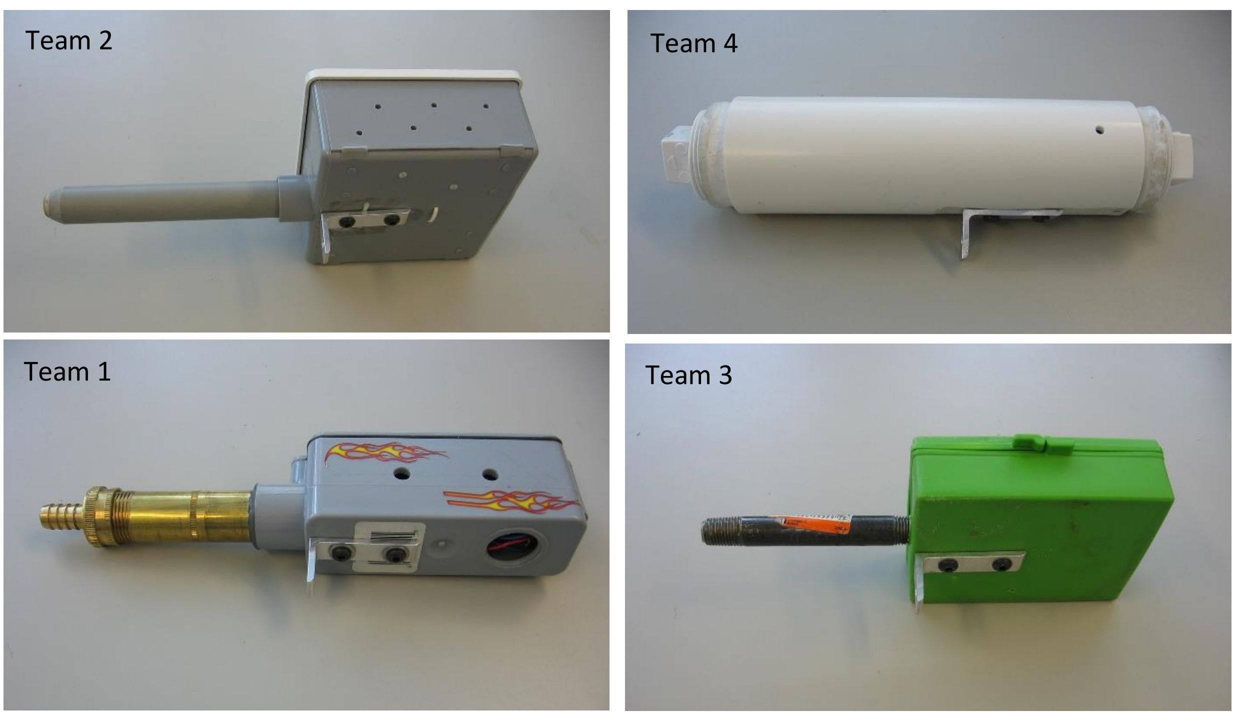

Figure 4. Student team Pitot-static probe designs

The teams were able to construct their probes and perform preliminary electrical tests on the bench. Each team's probe contained the same pressure sensor PCB that they had previously characterized using a column of water connected to the input port to vary the pressure. They applied input voltage and measured the zero-pressure output offset voltage via the installed connector. This allowed them to check for proper connections.

The final performance testing of the Pitot-static probes was performed using a wind tunnel facility. Each probe was mounted in the wind tunnel and the air speed was varied from zero to about 40 m/s by adjusting the frequency of the fan motor drive. Figure 5 shows photographs of the probes mounted in the wind tunnel.

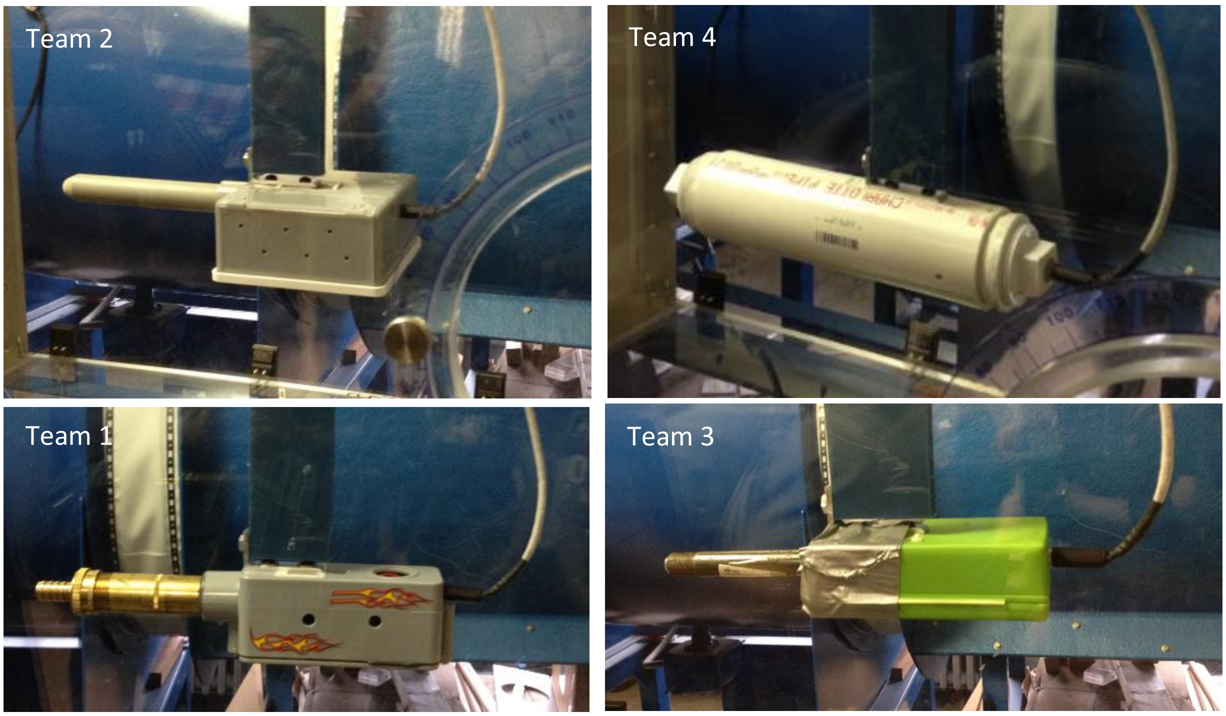

Figure 5. Pitot-static probes mounted in wind tunnel

The calibrated airspeed for each motor frequency was obtained from a calibrated Pitot tube installed in the wind tunnel. The pressure sensor output voltage and supply voltage were measured at each air speed using a National Instruments USB-6009 data acquisition unit. The +5V supply voltage for the pressure sensor was also provided by the USB-6009. The pressure sensor output is ratiometric with supply voltage. The ratio of the output voltage to supply voltage for each speed is plotted for each probe in Figure 6.

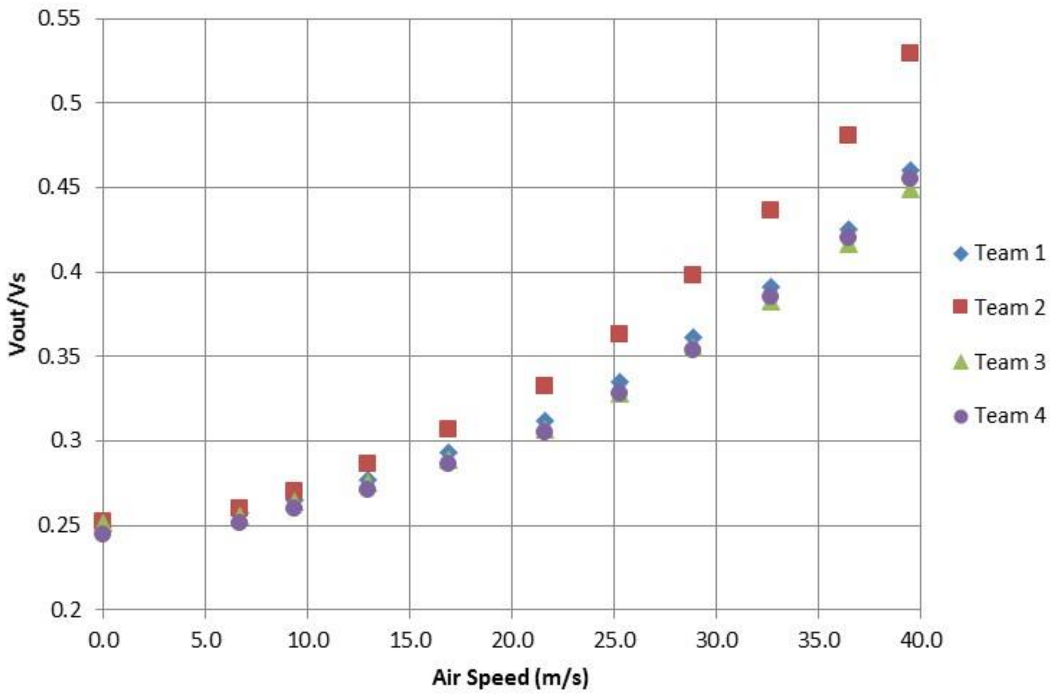

Figure 6. Pitot-static probe wind tunnel test data

Round Two (senior year)

Now during their senior year, the same group of students (minus one old student, plus one new student) were enrolled in a Microcomputer Interfacing course as part of the BSME program. The content of this course includes basic LabVIEW programming, an introduction to embedded processors (using PIC microcontrollers), and exposure to the practical considerations of connecting input and output devices to personal computers and microcontrollers.

In the LabVIEW programming portion of the course, students became familiar with developing code to communicate with USB and RS232 connected devices. Students also developed user interfaces for controlling serial communication and displaying information. The skills acquired through these exercises were very useful for the Pitot-static probe project.

PIC® microcontrollers manufactured by Microchip Technology were used for the embedded processor part of the course. A custom trainer PCB for the 18F13k22 8-bit microcontroller was used in the laboratory exercises to develop and debug C code. The free Integrated Design Environment (IDE), MPLAB, and the C compiler, xc8, from Microchip Technology were used for all code development and debugging.

During the semester, students became proficient with using the microcontroller to make voltage measurements, perform measurement averaging, manipulate lookup tables, and communicate with other processors via the serial port. For the enhanced Pitot-static probe project, the students developed C code to perform measurements of the pressure transducer output voltage, apply the calibration curve information using a lookup table, and transmit the airspeed to an external computer with a serial connection. The data was then received and displayed on a PC using custom LabVIEW code written by the teams.

The student teams also modified their probe enclosures from the previous year to accommodate the additional microcontroller PCB. The same electrical connector was used but now the terminal that had previously carried the analog output voltage of the pressure sensor was now used as the serial data output line from the microcontroller. Figure 7 shows photographs of the modified probes with their covers removed to reveal the embedded microcontroller PCB.

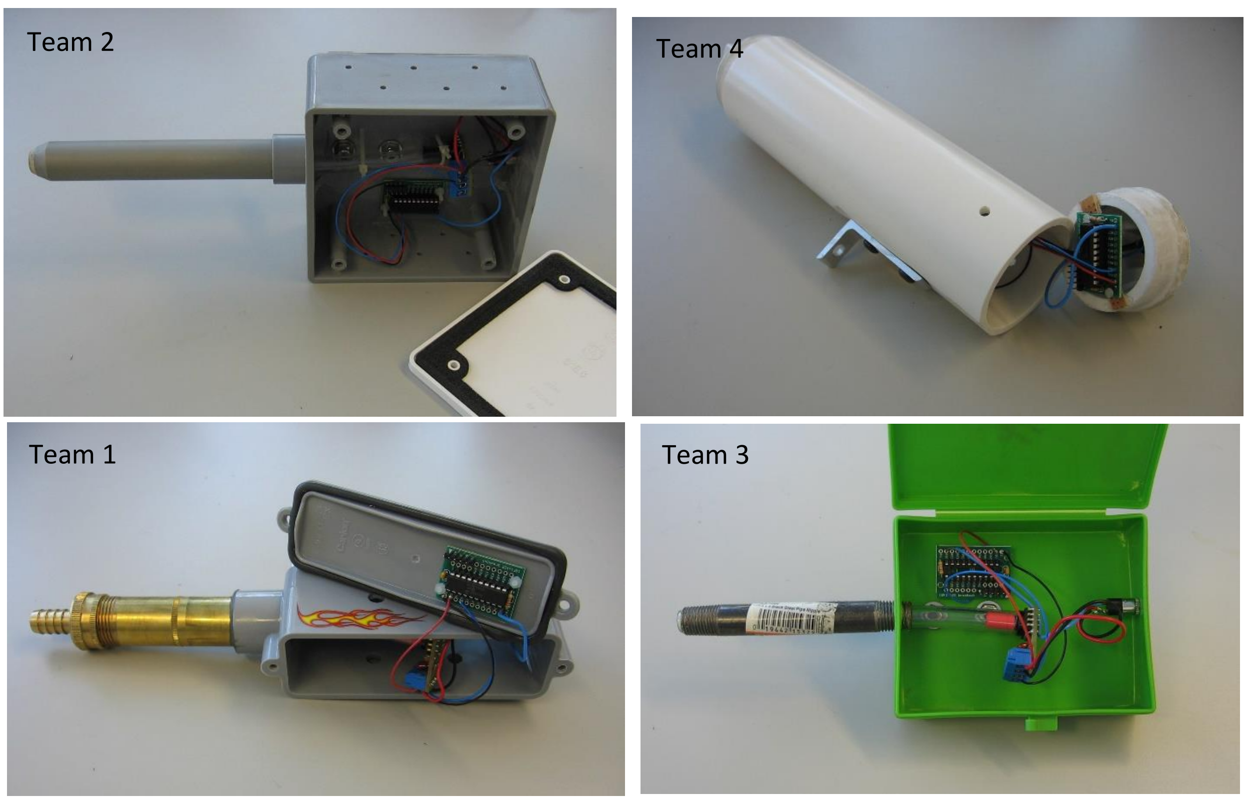

Figure 7. Enhanced Pitot-static probes

The wind tunnel data obtained during the previous year was used by each team to create an inverse function lookup table. The equivalent 8-bit A-to-D conversion value was calculated from the data and plotted against the wind speed as shown in Figure 8. A quadratic curve fit was used by all teams to determine the inverse function values. The measured pressure sensor voltage, converted to an 8-bit digital value, was used as the input to the lookup table while the airspeed was the output value. Although the microcontroller contains a 10-bit A-D converter, only the eight most significant bits of the conversion result were used here to simplify the data handling. It was specified that the output value should be numerically equal to the air speed in meters per second multiplied by five. This pre-scaling was employed to make better use of the available 8-bit range of the table values. This, in turn increased the resolution of the airspeed. The receiver then simply divided the received value by five to obtain the airspeed. This type of real-time data manipulation was an excellent example of how embedded processors can be used to enhance instrument performance.

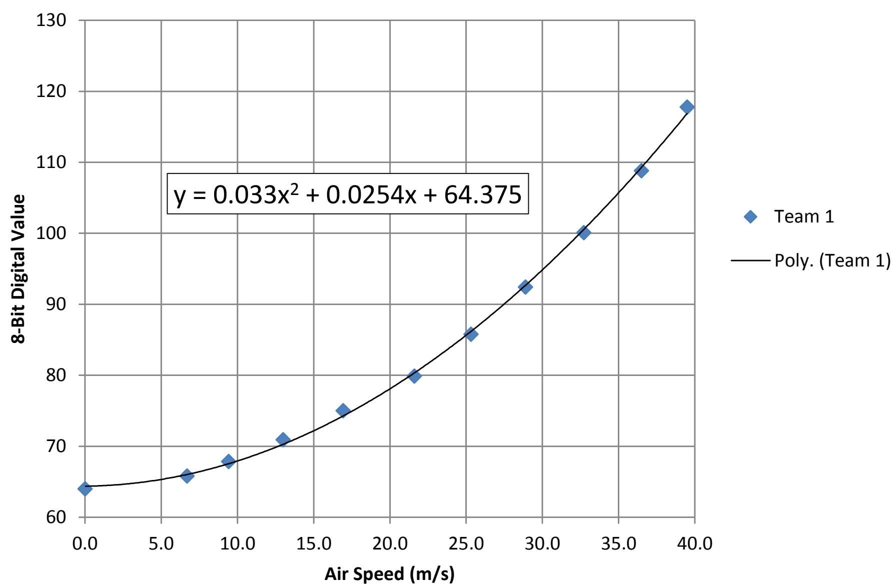

Figure 8. Wind tunnel data converted to 8-bit digital equivalent and quadratic curve fit

The teams returned to the wind tunnel with their enhanced designs and ran them through the same range of wind speeds as there year before. Each probe was connected to a laptop computer via a USB to RS232 converter (the laptop did not have an RS232 serial port). +5VDC power was also patched into the wiring harness from the laptop's USB port to power the microcontroller and pressure sensor. Each team used their own LabVIEW application to properly scale and display the wind speed information sent from their probe's microcontroller. Figure 9 shows an example of the LabVIEW VI developed by one of the teams. Table 1 shows a compilation of each team's test data and the calibrated reference Pitot tube value for each wind speed. As shown in Table 1, there is very good agreement between the student results and the calibrated wind tunnel Pitot probe readings, particularly at the upper end of the wind speed range.

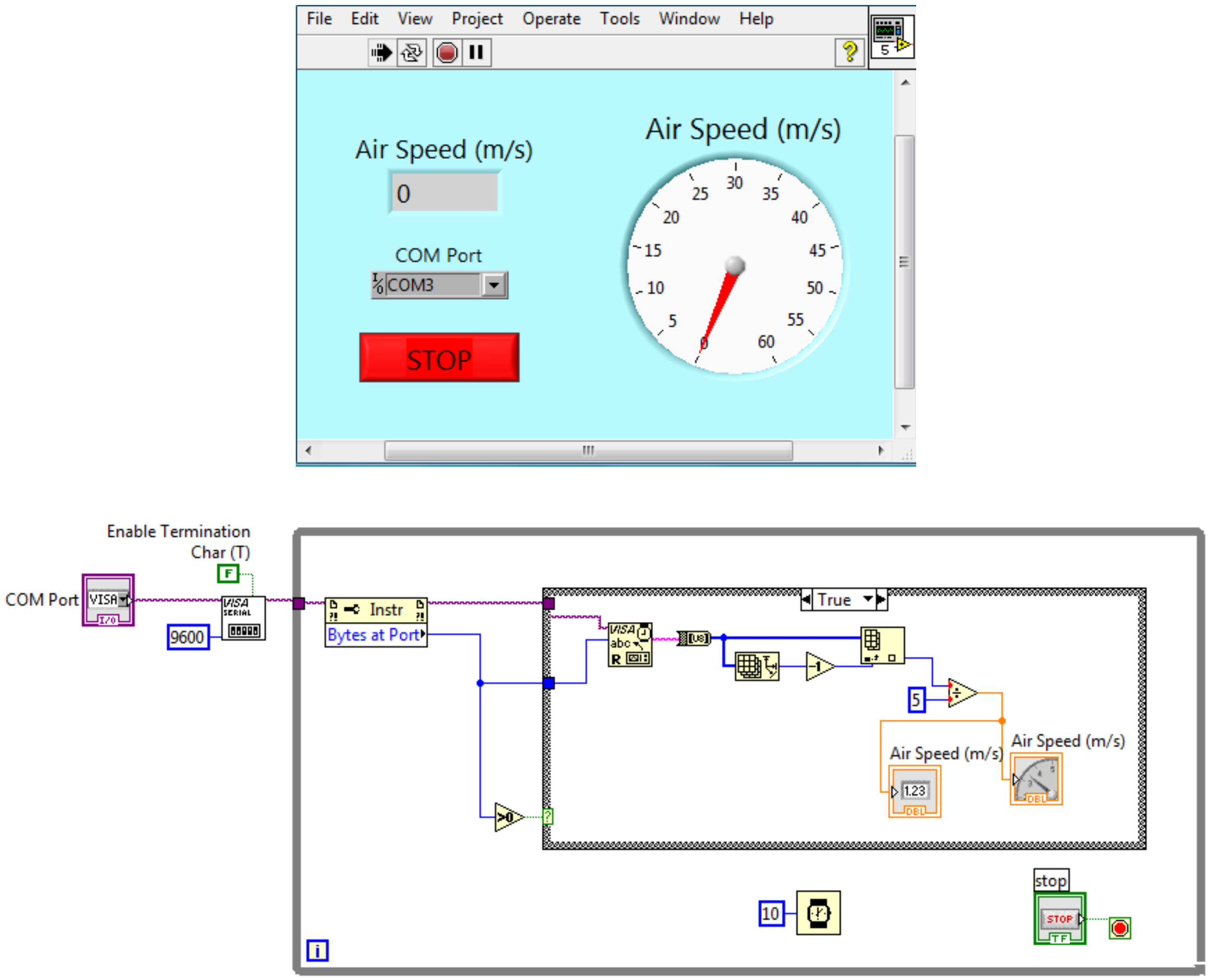

Figure 9. Example of student LabVIEW VI for receiving probe serial output data

Wind Tunnel Calibrated Values		Team 1	Team 2	Team 3	Team 4
Motor Freq (Hz)	**Air Speed m/s**	**Air Speed m/s**	**Air Speed m/s**	**Air Speed m/s**	**Air Speed m/s**
0	**0.00**	0.0	0.0	0.0	0.0
15	**6.68**	6.6	5.8	4.0	6.6
20	**9.41**	10.2	9.6	9.2	10.2
25	**12.98**	13.8	13.0	13.4	12.8
30	**16.93**	17.6	16.8	16.6	17.8
35	**21.60**	21.4	20.4	20.0	20.8
40	**25.31**	24.6	24.4	23.6	24.8
45	**28.89**	28.6	27.4	27.2	28.6
50	**32.72**	32.4	31.2	31.0	32.6
55	**36.49**	36.0	34.6	34.4	36.4
60	**39.49**	39.6	38.4	38.2	39.4

Table 1. Enhanced Pitot-static probe wind tunnel test data

Conclusions

The two-semester multi-approach instrumentation project has yielded very good outcomes during its first run. By revisiting a previously covered topic, the students get a chance to reinforce their knowledge on the topic and take it to the next level with the new approach. Also, by using the same instrument that they previously designed and built themselves, they are familiar with its performance and can quickly apply the enhancements.

Since the course ended, I have had many of the senior students meet with me to discuss how they can incorporate an embedded processor into their capstone design projects. Other students from the course have purchased microcontrollers for personal use in their homes and vehicles for various sensing and control applications. Some of the projects are very innovative and show that they were really inspired by their course project work.

During the span of the two semesters, one of the students transferred to another campus to complete his degree and another student transferred into the program. The new student joined the team vacated by the exiting student and, with the help of the other team member, came up to speed very quickly. He was also able to add new ideas to the design of the probe such that the enhanced model was a success.

The students overwhelmingly felt that the enhanced version of the probe was superior to the analog output model. They appreciated the ability to make changes to the enhanced model by upgrading the software rather than costly hardware changes. Even with their brief exposure to embedded processors, they could see the advantages to having a little processing power built into their designs.

Acknowledgements

The author would like to thank Terry Hart, Professor of Practice in the Mechanical Engineering and Mechanics department at Lehigh University for his help with using the wind tunnel facility. A special thank you to the mechanical engineering students that helped make the first run of this multi-approach method successful.

References

1. Litwhiler, D. H., “Wind Tunnel Evaluation and Calibration of Model Rocket Nosecone Pitot-Static Probes,” Proceedings of the American Society for Engineering Education Annual Conference and Exposition, 2008.
2. Figliola, R. S., and Beasley, D. E., Theory and Design for Mechanical Measurements, 5th ed., John Wiley & Sons, Hoboken, NJ, 2011, pp. 396-407.
3. Klopfenstein, R., “Air Velocity and Flow Measurements Using a Pitot Tube,” ISA Transactions 37 (1998), pp. 257 – 263.
4. Beck, B. T., Payne, G., Heitman, T., “The Aerodynamics of the Pitot-Static Tube and its Current Role in Non-Ideal Engineering Applications,” Proceedings of the American Society for Engineering Education Annual Conference and Exposition, 2010.
5. Ellingson, J. L., Greene, C. S., Morgan, S. E., and Silvester, M. A., “An International Multiyear Multidisciplinary Capstone Design Project,” Proceedings of the American Society for Engineering Education Annual Conference and Exposition, 2012.
6. http://www.freescale.com/files/sensors/doc/data_sheet/MPXV5004G.pdf.