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A Smart Fluid Level Instrument in a Sports Drink Bottle

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Abstract

Students in a mechanical engineering program are given the task of converting parts from a sports drink bottle into a capacitive fluid level probe. The project begins in a third-year instrumentation course when student teams develop a prototype instrument design. During a subsequent computer data acquisition and control course, the students use their prototype with the addition of an embedded processor (microcontroller) to create a “smart” instrument. The students are given loose specifications for the design of their fluid level probe. The specifications have enough freedom to allow for creative variation in designs but key factors are tightly defined such that the performance of all of the designs can be compared. The students must then develop a detailed written specification for the prototype that they actually produce. A popular sports drink bottle is used as the envelope into which the design must fit. The lid of the bottle serves as the bulkhead for the probe and all required electronics. The bottle itself serves as a protective case for transport of the probe and a containment vessel for any residual fluid present after testing the probe in the test chamber. Lightweight mineral oil is used as the measurement fluid due to its desirable electrical properties and its odorless and non-flammable characteristics. This paper presents and discusses the details of the prototype development from specification writing to prototype testing. Student-developed software is also presented and discussed. Project objectives and course outcomes are also presented.

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.[1] Hands-on experience for mechanical engineers in instrumentation courses is also very beneficial. [2,3] In the work presented here, third-year mechanical engineering students designed and fabricated simple capacitive fluid level probes using readily available parts in an instrumentation course. A common integrated circuit oscillator (555 timer) together with a custom-fabricated capacitive probes were used to form fluid level measurement devices. Instrument performance was predicted from elementary equations for the capacitive probe geometry, fluid properties, and 555 timer specifications.[4,5,6] Student team designs were then tested using a laboratory vessel containing lightweight mineral oil. Data collected during testing was then used to create a calibration curve for each design. One year later in a microcomputer interfacing course, the capacitive fluid level 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 year’s test vessel calibration data into their embedded software to provide a complete solution with a simple serial data output interface.

A hardware-in-the-loop test system was used to simulate the capacitive probe and oscillator. This allowed the students to design and debug their embedded system code without needing the mineral oil test vessel. The practice of hardware-in-the-loop for embedded system development is becoming widely used in industry and provided the students with an excellent exposure to this technique.[7]

The structure of this project encompasses many objectives in a manner that is designed to emulate real-world engineering practice and procedures. The students design their instrument based on a “customer” specification that allows them freedom to choose some parameters while still keeping it bounded. The teams must then develop their own detailed specification such that an instrument just like their prototype could be reproduced by a subcontractor. The objective of the second year of the project is to expose them to industry-standard techniques for making their instrument design “smarter” along with the benefits and pitfalls of such efforts.

Sensor Designs

The third-year students in the instrumentation course were given very broad specifications for their capacitive fluid level probe designs. The probe was required to utilize the lid of a Gatorade sports drink bottle as the bulkhead to support the probe and associated electronics. The bottle then served as the containment vessel for catching mineral oil drips and to protect the probe during transportation and storage. A small budget (about $20) was also provided for each of the seven teams. The broad specifications for the probes were as follows (and as depicted in Figure 1):

- The entire assembly shall weigh no more than 0.5 lbs.
- Spacing between capacitive probe conductive surfaces shall be no less than 0.050" to prevent wicking of fluid.
- All penetrations of lid shall be sealed to prevent leaks.
- Sensing element shall extend at least 0.4" below minimum fluid level.
- Sensing element shall extend no more than 1.0" below minimum fluid level.
- Assume a fluid dielectric constant of 2.1 for all calculations.
- The ideal capacitance of the probe shall be no less than 30pF when completely dry.
- The oscillator output frequency shall be no more than 30kHz when the probe is dry.
- The oscillator output frequency shall decrease with increasing fluid level (range TBD).
- The oscillator shall operate from 5VDC (max current TBD).
- The oscillator circuit board shall be mounted to the lid in a removable manner. (mounting hardware can be glued to lid but the board cannot be directly glued).
- Circuit board must reserve 1.0" x 1.5" area for future development.

- External connecting wires must be 12" +/- 1" long, stranded (not solid) of #22 - #26 AWG. Colors as shown on diagram.

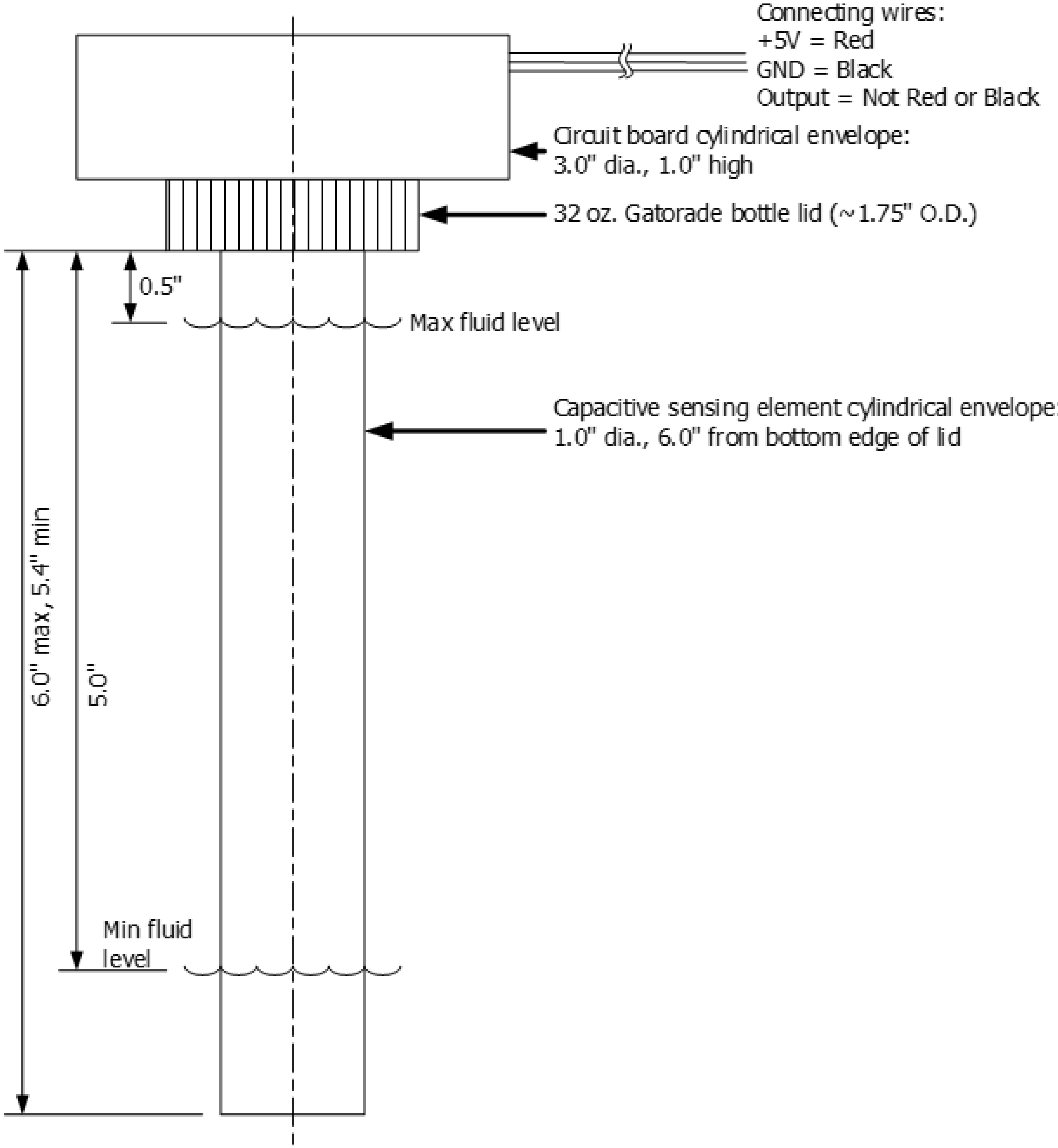


Figure 1. Capacitive Fluid Level Probe Specification Diagram

An integrated circuit oscillator, the ubiquitous 555 timer, was strongly suggested to be used by the groups as the capacitance-sensitive device. The 555 timer provides is a very convenient and inexpensive means for converting changes in capacitance to measureable changes in signal frequency.

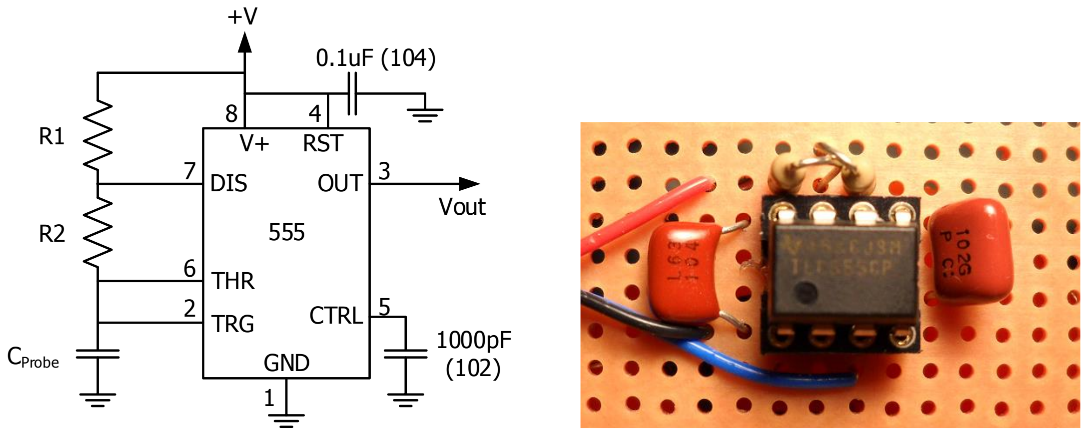


Figure 2. 555 Timer Oscillator Circuit Schematic and Suggested Circuit Board Layout

The teams were advised to use ideal (textbook) relationships for the capacitance of their probe structures (mostly variations on the parallel plate capacitor). This, together with the well documented performance of the 555 timer, and the customer-specified maximum oscillator output frequency when the probe is dry, allowed the teams to compare various geometry designs for their probes. A dielectric constant of 2.1 was assumed for the mineral oil test fluid for all calculations.[8]

Due to the symmetry of the probe construction, the capacitance varies linearly with the depth of the fluid, h, to be measured with an initial offset of the dry probe (air dielectric). Thus the capacitance of the probe could be modelled as,

$$C(h) = Kh + C_{empty} \tag{1}$$

where, K is the sensitivity of the probe's capacitance to the fluid level. Combining equation (1) with the equation for the 555 Timer frequency, the oscillator output frequency as a function of fluid depth can be found as,

$$f(h) = \frac{1.44}{(R1 + 2R2)\left(Kh + C_{empty}\right)} \tag{2}$$

After preliminary design tradeoffs were performed by the seven teams, three types of capacitive fluid level probe styles emerged. Some teams opted for multiple layers of rectangular copper-clad fiberglass boards. Other teams chose to use concentric copper pipes to form the plates of the capacitive probe. After extensive independent research, one ambitious team elected to try constructing a pair of helical conductors by wrapping bare copper wire around a 3D-printed spiral form. Figure 3 shows photographs of a sample of the student designs.

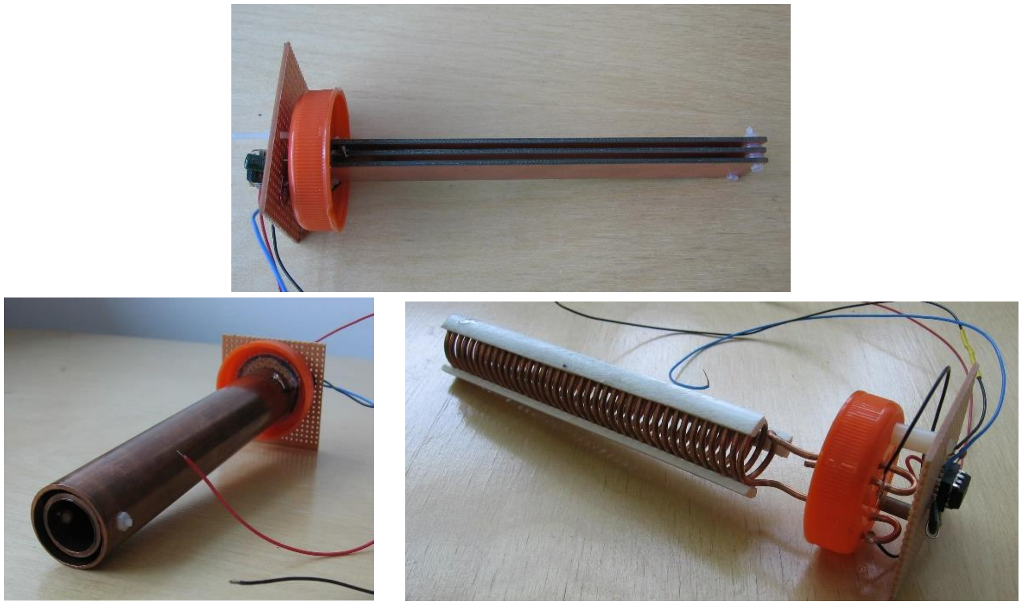


Figure 3. Examples of Student Capacitive Fluid Probe Designs

Testing and Calibration

The prototype probes for each team were tested in a custom laboratory calibration vessel (two shampoo bottles and some plastic tubing) that allowed the mineral oil level to be easily changed and measured. Figure 4 shows the test setup with one of the probes in place.

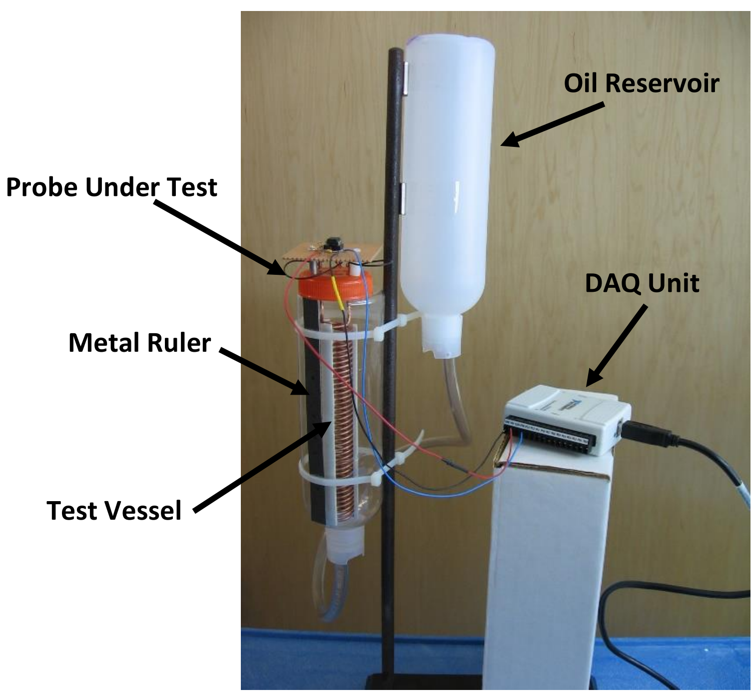


Figure 4. Probe test and calibration setup

The oil level in the test vessel was controlled by moving the oil reservoir up and down along the center rod of the test setup. The reservoir was held to the rod with magnets to allow for easy height adjustment. The oscillator circuit of the probe-under-test was powered from and measured by a National Instruments USB data acquisition (DAQ) unit, USB-6009. The output frequency of the probe oscillator was measured using the counter input of the DAQ unit. LabVIEW software was used to process the pulse count and display the signal frequency. Data was obtained over the full range of oil depths for each probe. Figure 5 shows a sample of the data for several probe designs.

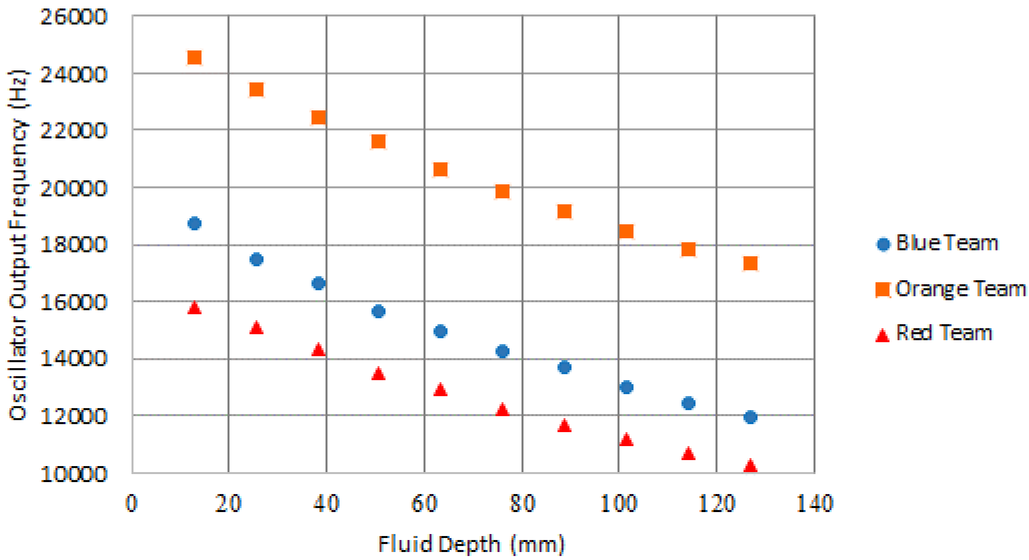


Figure 5. Sample of student probe data

Although it was tempting for the students to fit a straight line to the data shown in Figure 5, they were reminded that the expected form of the input-output relationship for their probes was better modelled using equation (2) in its general form:

$$f(h) = \frac{A}{h + a} \tag{3}$$

Taking the reciprocal of equation (3) yields a linear relationship between the *period* of the oscillator output signal and the fluid depth:

$$T(h) = \frac{1}{A}h + \frac{a}{A} \tag{4}$$

Using equation (4), a least-squares best-fit line can be placed through the data. The equation of the best-fit line can then be used to solve for the desired constants, A and a. Figure 6 shows a plot of the reciprocal expressions and the equations of the best-fit lines. The values of the calibration constants, A and a, for a few of the probe designs are shown in Table I.

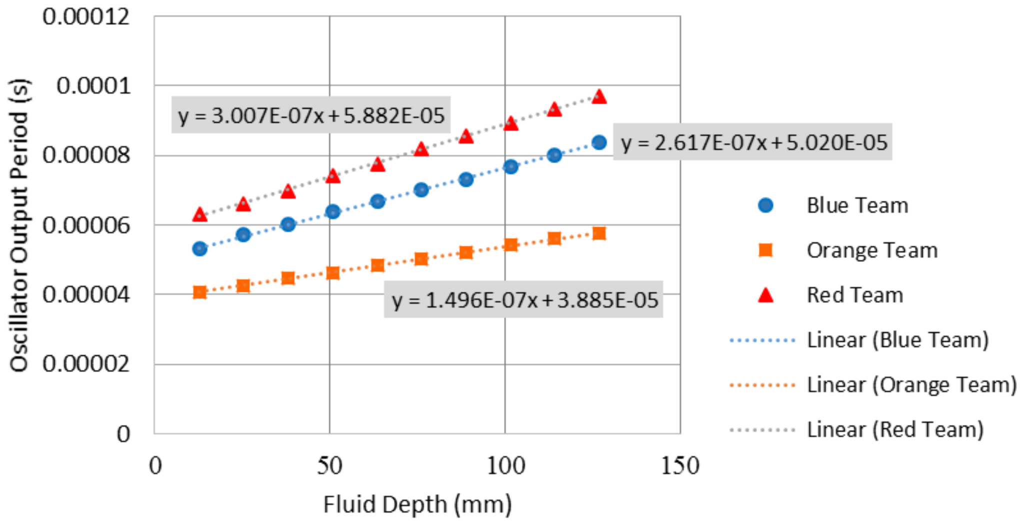


Figure 6. Sample of probe data manipulated to find desired calibration constants

Team	A (mm/s)	a (mm)
Blue	3820995	191.83
Orange	6683258	259.65
Red	3325083	195.59

Table I. Sample calibration constants

Specification Writing

Once a working prototype was achieved, the students could write a detailed specification that would provide the necessary information such that the form, fit, and function of their design could be replicated by a subcontractor. The form of the specification was taken from that used by the United States military.[9,10] This format greatly helps the students to compartmentalize every aspect of the design and fabrication of their instrument. It is also a good exposure to the way things are done in practice. They learn that *every* question that could be asked by their subcontractor *must* be answered by at least one section of their written specification.

Making the Instrument "Smarter"

Due to the small size of the program, nearly all of the students that take the instrumentation course in the third year also take the fourth-year course, Microcomputer Interfacing. In this course, the students learn the basics of LabVIEW and get a great deal of hands-on experience programming and using microcontrollers for simple measurement, control, and communication tasks. In the Microcomputer Interfacing course, the students revisit their instrument design from the previous year and enhance its interface capabilities with the addition of an embedded microcontroller. As noted in the preliminary specification, the design teams must allow room for this enhancement in the original design of their instruments.

The original probe designs simple provided a pulse train output. Each team's design provided a different range of frequencies as a function of fluid depth. The burden of converting the frequency of the pulses to actual fluid depth was placed on the receiving end. This task was easily handled with the DAQ unit and LabVIEW software however, it was still different for each design.

With the addition of a microcontroller to the design, the pulses could be counted, the calibration constants applied, and the actual fluid depth value could be transmitted to the user via a serial communication interface. By doing this, the "personality" of each probe is removed and only one design for the receiving end is required. This essentially makes all of the probes interchangeable and greatly reduces the hardware complexity of the receiver (just a serial port).

Using the calibration constants, A and a, determined for each specific probe, each team developed C code to perform the tasks shown in the flowchart of Figure 7. The target microcontroller was the PIC18F13k22 from Microchip. The MPLAB X IDE and XC8 compiler also from Microchip were used to develop the code and program the device.[11] Microchip products were chosen for their excellent documentation and support, deep embedded market penetration, and low cost and availability. An excerpt of one team's C-code is shown in Figure 8.

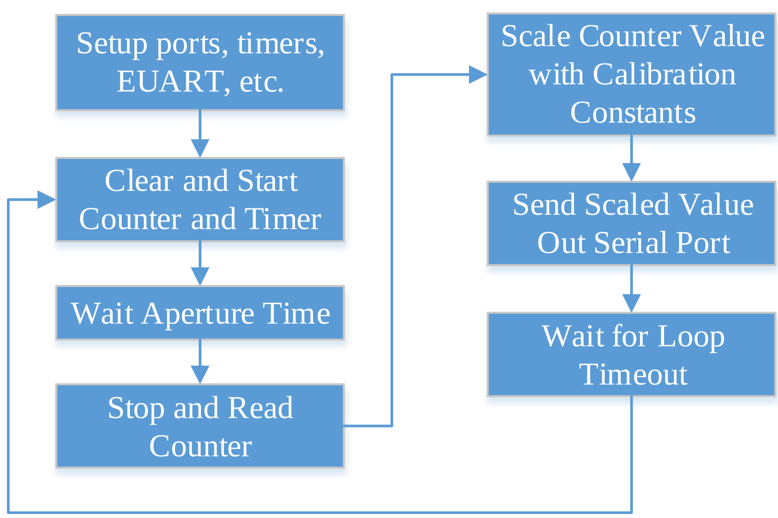


Figure 7. Flowchart of microcontroller code

```c
void main(void)
{
    Init();     //4Mhz clk, I/O, TMR0, TMR1 setup
    InitUART(); //EUART setup, 9600 baud, etc.
    while(1)    //main loop
    {
        TMR0H = 0x0B;           //preload TMR0 for 1sec rollover
        TMR0L = 0xDC;
        TMR1H = 0;              //clear TMR1
        TMR1L = 0;
        T1CONbits.TMR1ON = 1;   //Start TMR1
        for (i = 0; i < 5; i++) //delay aperture time of 0.5s
        {
            _delay(100000);
        }
        T1CONbits.TMR1ON = 0;   //Stop TMR1
        Count = TMR1H << 8 | TMR1L; //Combine TMR1 high and low bytes
        h = (1910498/Count) - 191.83;  //scale using calibration constants
        SendIt(h);  //send unsigned char result out serial port
        while (INTCONbits.TMR0IF == 0); //wait for 1s timeout
    }
}
```

Figure 8. Excerpt of C-code from one team's design

Hardware In the Loop (HIL) Testing

Testing of the actual instrument hardware proved to be a time-consuming and messy task. There was only one test vessel and the potential for an oil spill was high. The initial testing of the probes during the third-year course was accomplished with careful control of the process by the instructor. However, to facilitate code development and testing of the smart instruments, a powerful industrial technique was employed; Hardware In the Loop (HIL) testing. The use of HIL testing was found to be an excellent experience for the students.

To implement HIL testing, a repeatable method for producing a variable frequency pulse signal was required. The signal should be able to mimic that of the 555 Timer circuit of the original probe design. To truly simulate the actual probe, the frequency of the test signal should be a function of a selectable value equal to the fluid depth experienced by the probe. To execute this HIL task, a computer-controlled signal generator and LabVIEW software were used.

Using the calibration constants for each design, the inverse relationship could be implemented in LabVIEW code. For a chosen fluid depth, LabVIEW calculates the resulting frequency and commands the function generator to produce it. The Agilent 33210A Function Generator with a USB interface was used for this HIL system. The LabVIEW code also configured the output of the function generator such that it produced a 0 – 5V rectangular pulse like that of the 555 Timer. Figure 9 shows a photograph of the complete HIL testing setup.

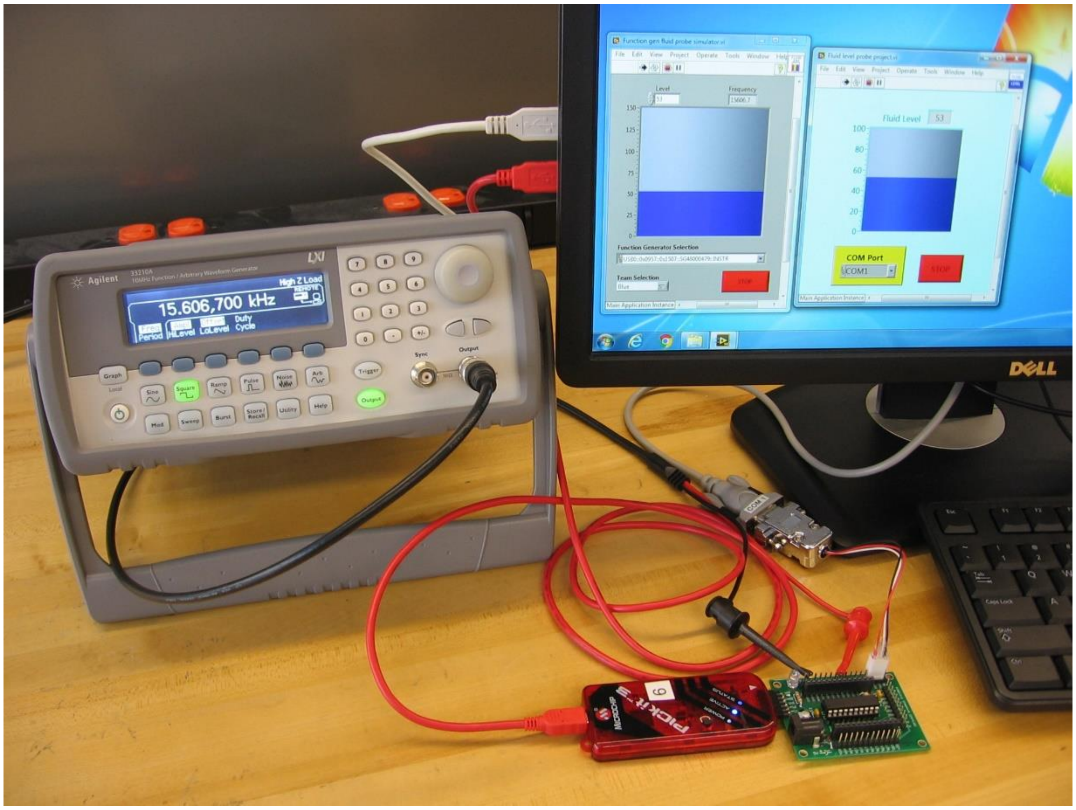


Figure 9. Hardware In the Loop testing setup

As shown on the PC monitor in Figure 9, the leftmost LabVIEW VI front panel controls the frequency of the function generator based upon the user selected fluid level (also shown in the "Tank" display graphic). The rightmost LabVIEW VI front panel shows the value received from the PIC microcontroller that is equal to the depth of fluid in millimeters. This method gave excellent results for all of the teams. The laboratory had an ample supply of Agilent 33210A function generators such that all teams could design and debug their C code without waiting to use test facilities or risking the mess of a mineral oil spill. The LabVIEW VI block diagram of the HIL fluid level probe simulator is shown in Appendix A.

Objectives and Outcomes

The pertinent objectives of the third-year course that are covered by this project are as follows:

1. Implement computer data acquisition systems to collect data.
2. Apply engineering principles to design a measurement system, given performance specifications.
3. Write clear and effective technical reports and product specifications.

The effectiveness of the course to cover these objectives is easily measureable from the written specification and performance test data.

In the fourth-year course, the enhanced project covers the following course objectives:

1. Analyze, design and build microcomputer interface circuits
2. Understand and connect computer peripherals using standard interfaces (RS-232, USB)
3. Use oscilloscopes, power supplies, and function generators.
4. Implement computer data acquisition systems to collect data.
5. Apply engineering principles to design a measurement system, given performance specifications.
6. Write clear and effective technical reports and product specifications.

Here again, the effectiveness of the course to achieve these objectives is very apparent from the project written report which includes the C code and LabVIEW VI development.

Conclusions

Using the same core project for two consecutive courses gave the work a better sense of continuity. The students were made well aware of the fact their prototype design would be seen again in the following year. Knowing this, the students had more incentive to do a better job and were more invested in their work.

The practical nature of the project allowed the students to see what could be achieved without expensive equipment. The hands-on work proved to be a challenge for many of the students that were accustom to only working on paper or with sterile academic laboratory apparatus.

The specification writing exercise really made the students aware of the details of their project. Small items that are easy to overlook had to be carefully specified or they may not be fabricated as originally intended. Ambiguities had to be removed. This level of attention to detail is not often naturally found in the traditional student population.

The students learned to appreciate the ability to fix problems or tweak the performance of their fluid level probes using software rather than having to remove and replace soldered components. Enhancing the design by changing a few lines of code can become very enticing and almost addictive. They also learned that not all problems could be fixed in software alone.

The impromptu change of plans to include Hardware In the Loop testing was perhaps the most interesting topic in the two courses for many students. They understood how it would be necessary to implement HIL testing on large complex systems. One student shared his knowledge of HIL testing from a summer internship with a large industrial equipment manufacturer. HIL techniques will now become a regular part of the course.

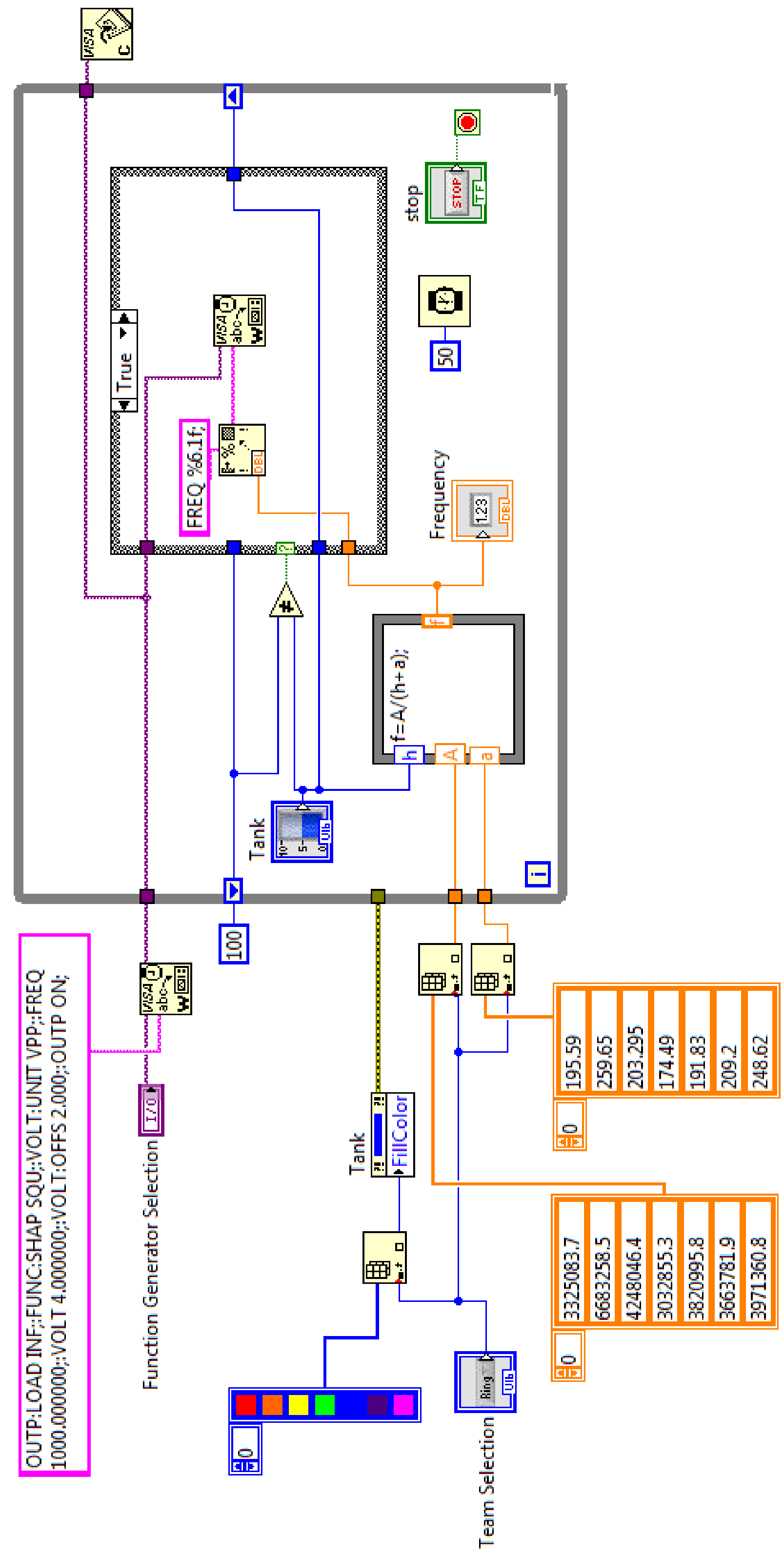
Acknowledgements

The author wishes to thank the cohort of students that endured the detailed work required to develop the fluid level probe hardware and software spanning over one year and two courses. Their feedback and suggestions were very useful and appreciated.

References

1. Litwhiler, D. H., "A Two Semester, Multi-Approach Instrumentation Project for Mechanical Engineering Student," Proceedings of the American Society for Engineering Education Annual Conference and Exposition, 2015.
2. Radian G. Belu, Eric Carr, Irina Nicoleta Ciobanescu Husanu, and Michael G Mauk P.E.. "A New Approach in Teaching "Measurement Laboratory" Courses Based on TRIZ". 2011 Annual Conference & Exposition, Vancouver, BC, 2011, June.
3. Jerry Keska. "Instrumentation Emphasis In Undergraduate Mechanical Engineering Programs". 2010 Annual Conference & Exposition, Louisville, Kentucky, 2010, June.
4. Doebelin, E. O., Measurement Systems: Application and Design, 4th ed., McGraw-Hill, Boston, MA, 1990, pp. 720-722.
5. Haladay, D., and Resnick, R., Fundamentals of Physics, 2nd ed., John Wiley & Sons, New York, NY, 1981, pp. 485-488.
6. http://www.ti.com/lit/ds/symlink/lm555.pdf
7. http://www.ni.com/hil/
8. http://www.engineeringtoolbox.com/relative-permittivity-d_1660.html
9. http://www.navair.navy.mil/nawctsd/Resources/Library/Acqguide/SpecTop.htm
10. http://www.esm.psu.edu/courses/emch213d/links/standards/military_specification_example.php
11. http://www.microchip.com/

Appendix A



LabVIEW Block diagram for HIL fluid level probe simulator