FROM PARALLEL PLATES TO LABVIEW PROGRAM DESIGN: AN EFFECTIVE CAPACITIVE-BASED LIQUID LEVEL INSTRUMENTATION COURSE PROJECT

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Abstract

We have developed and delivered an integrated multi-week capactive-based oil level instrumentation design project. This project serves as a means to enrich our students with an electrical engineering design experience within our general engineering program. The project consists of four consecutive laboratory activities that cover the entire instrumentation device design process by integrating sensor fabrication using copper plates, signal conditioning using integrated circuit components, signal acquisition, signal analysis, and computer based visualization using LabVIEW, and error analysis. End-of-course survey results for this junior level course show the students are achieving the course laboratory objectives. These results indicate this project serves as an effective tool in teaching design through a laboratory experience. Evaluative feedback from students also reveals the project has features that provide opportunities to use LabVIEW in the design and implementation process within a laboratory environment. The paper emphasizes the integration between circuit design and LabVIEW program design to construct a complete instrumentation system.

Introduction

Liquid level measurements are critical in several applications of industry, health care, and our daily lives. These measurements are often needed in the form of continuous recordings. Several devices have been developed to measure liquid level such as non-contact and contact ultrasonic devices, radar, floats, and capacitive devices. Each device (sensor) has a different liquid level sensitive mechanism, sensitivity, range, size, and cost that is considered when designing an appropriate liquid level measurement system. For example, a non-contact ultrasonic liquid level meter is a component that measures changes in liquid level as a function of echo pulse return time from a fixed point in the vessel to the liquid surface. These devices can be manufactured into small and rugged packages, but they can be expensive. Capacitive fluid level meters measure changes in liquid level as a function in the change in the capacitance associated with the fluid volume between the capacitor plates. [1,2] As the liquid level changes, either the distance between the plates changes, resulting in a change in capacitance, or the area of the electrodes immersed in the liquid changes, resulting in a change in the overall dielectric constant between the plates and thus a change in capacitance.[3,4] Capacitive sensors have been extensively used in a variety of liquid level metering applications ranging from the chemical manufacturing industry to simple systems such as monitoring the level of fuel in automobiles. Although there are several ways to measure liquid levels, capacitive-based fluid level devices are quite common and can be designed and configured for a variety of conditions.

The robustness of capacitive type liquid level sensors and the overall simplicity in function provide nice qualities for students to engage in laboratory experiences in designing and characterizing simple parallel plate capacitors for liquid level instrumentation systems. By using common materials to construct a simple parallel plate capacitor, as the sensor for a fluid level meter system, students can more easily engage in the theory of capacitance and make solid connections between the physical components and the electrical signal that represents a physical quantity, in this case fluid level. From a circuit analysis point of view, the students are provided the opportunity to apply time constants associated with RC circuits as a way to quantify the capacitance and convert the value to a useful, more convenient signal. In terms of instrumentation, the students can experience the advantages that capacitance level indicators feature, such as high sensitivity, continuous monitoring capabilities, usability in viscous and slurry systems, no moving parts in contact with the fluid, and how various probe materials can be chosen based on fluid characteristics. By the same token, students will appreciate the challenges associated with capacitive level sensors, such as sensitivity to dirt and other contaminants on the capacitor material as well as changes to temperature and if the measured liquid changes in composition. Any contaminants in the liquid or any changes to the composition will alter the dielectric characteristics of the fluid and cause changes in the output of the sensing element.

Here we present the development, delivery, and assessment of an integrated, systematic 4-week laboratory design project for a capacitive-based digital liquid level meter. This laboratory series is geared to provide instrumentation system design and analysis as part of an electrical engineering component to a core curriculum for a general engineering program. This laboratory module provides experience in instrumentation system design and analysis, including sensor design and fabrication, analog signal conditioning design, data acquisition and analysis in LabVIEW, instrumentation calibration, and error analysis. A block diagram of the project is provided in Figure 1. This diagram is used to help the students follow the signal path, and the type of signal (physical level, capacitance, frequency, and digital/computer display) through the instrumentation system. The students fabricate copper plates with leads as the sensing elements to measure oil level in a plastic container. The students design and build a circuit that produces an oscillating electric signal proportional to the physical level in the container sensed by the parallel copper plates configuration, acquire the signal using LabVIEW, analyze and process the the signal in LabVIEW, and display the measured liquid level graphically on a computer display.

Theory

Parallel Plate Capacitance

The underlying principle of capacitive-based fluid level meters is based on the physics of capacitors and their ability to store charge. Consider the simple configuration of a parallel

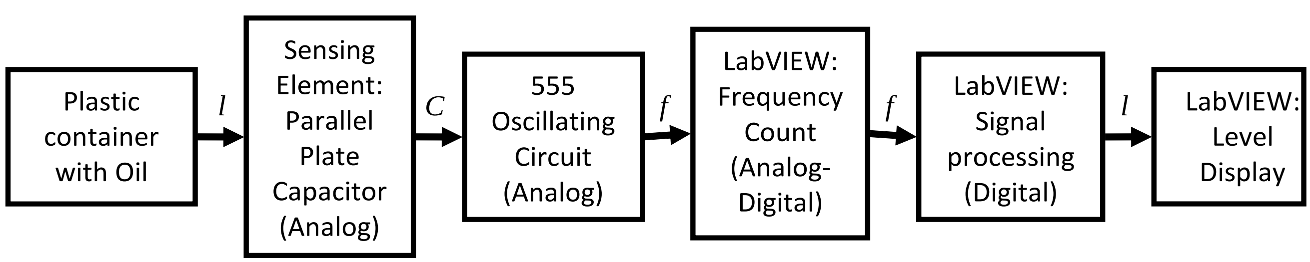

Figure 1. Parallel plate capacitor liquid level meter design project block diagram. Main components and concepts of the instrumentation are provided to illustrate the workflow and interconnectivity of the device. Interconnectivity signals are denoted as *l* for the physical oil level, *C* for capacitance of the parallel plate sensor, and *f* for frequency generated by the oscillating circuit.

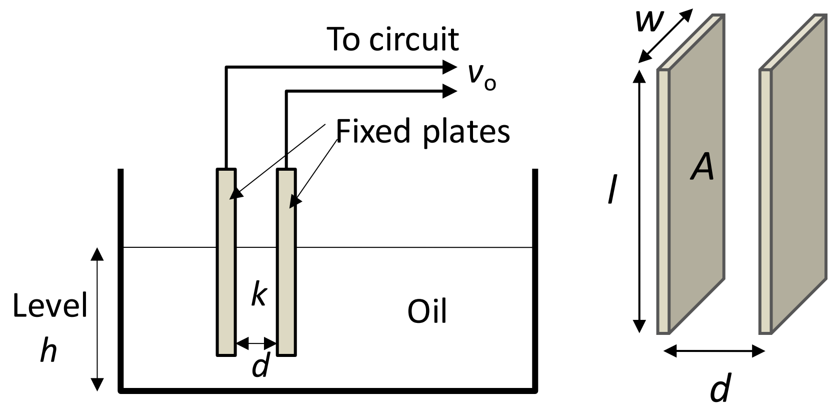

Figure 2. Capacitive liquid level sensor setup using parallel plates. Changes in oil level produce changes in the dielectric constant between the plates causing proportional changes in capacitance.

plate capacitor partially submerged in a tank of liquid shown in Figure 2. The two fixed metal plates make up the capacitive elements that can store electric charge. The capacitance (with units of Farads) is based on the common overlapping area (exposed to the liquid and the air) of the two plates ($A = A_o + A_a$) in square meters, the distance between the plates (d) in meters, the permittivity of space (ε_o) in Farads/meter, and the relative permittivity of the dielectric material between the plates (k_o) and that of the air (k_a), which are unitless. The capacitance is therefore given by,

$$C = \frac{k_o \varepsilon_o A_o + k_a \varepsilon_o A_a}{d} . \quad (1)$$

A change in any one of the parameters of equation (1) can be used in the sensing process. Based on the configuration of the parallel plates in Figure 2, a change in liquid level will produce a change in the value of the overlapping area exposed to the oil, A_o, and that to the air, A_a. Hence, the sensing element produces a change in capacitance (an electric measurand) with respect to a change in liquid level (a physical measurand). This relationship between the capacitance C and the oil level h can be represented by the following equation:

$$C = \frac{k_o \varepsilon_o wl + k_a \varepsilon_o w(L-l)}{d} \quad (2)$$

where,
C = capacitance in Farads (F)
ε_o = permittivity of space in Farads/meter (F/m)
k_o = relative permittivity of the oil (unitless)
k_a = relative permittivity of the air (unitless)
A_o = overlapping area of the copper plates in the oil (m^2)
A_a = overlapping area of the copper plates in the air (m^2)
L = length of the copper plates (m)
l = length of the copper plates immersed in the oil (m)
d = distance between the plates (m)
w = width of the copper plates (m)

RC Time Constant

The parallel plate capacitive sensor is integrated into an instrumentation circuit that can convert the capacitance of the sensor in Farads into a signal that can easily be analyzed and converted into an oil level measurement, say in units of millimeters. A useful circuit for the meter would be one that can run on a DC power supply source (batteries) rather than an AC source. Use of a DC source simplifies the instrument so it can be used as a portable system. One issue however, is that a capacitor is a dynamic energy storage device. The current through the capacitor is proportion to the change in voltage with respect to time,

$$i(t) = C\frac{dv(t)}{dt}. \quad (3)$$

Therefore, if there is no change in voltage across the capacitor, as is the case with a DC voltage source, there is no current through the branch of the circuit containing the capacitor (sensor). This is of little use for a liquid level meter. However, in a simple RC circuit, the voltage across a capacitor changes at a rate which is a function of resistance, *R*, in Ohms, and capacitance, *C*, in Farads as illustrated in Figure 3. When a DC voltage is first applied to an RC circuit at $t = 0$ (Figure 3a.), in which the capacitor holds no charge, the rate of the change in voltage across the capacitor is proportional to the values of *R* and *C*. The time it takes for the voltage across the capacitor to reach 0.63 of the DC supply voltage is called the time constant $\tau = RC$ (Figure 3b.). Since the sensor capacitance C changes with liquid level, the time constant τ changes proportionally to liquid level when the resistor *R* is held constant. Thus, a measurement of the time constant will provide a measurement of the fluid level.

Measuring the time constant is not a trivial matter, especially when using a DC voltage source and needing continuous measurements of the fluid level. A straightforward way to measure the time constant τ is to design an oscillating circuit whose frequency corresponds to the time constant of the RC circuit. The oscillating frequency would therefore change with respect to the liquid level. Measuring frequency of an oscillating circuit using a microprocessor-based system or software, such as LabVIEW, is relatively straightforward.

Oscillating Circuit

Producing an oscillating circuit is made easy with the use of the incredibly versatile integrated circuit 555 timer.[5] The 555 can be configured to oscillate (astable operation). The oscillating frequency and duty cycle in astable mode can be accurately controlled with two external resistors (R1 and R2) and one capacitor (C) (Figure 4a). The corresponding square wave output has a frequency in inverse proportion to the time constant τ (Figure 4b). The design formula for the frequency of pulses is given by,

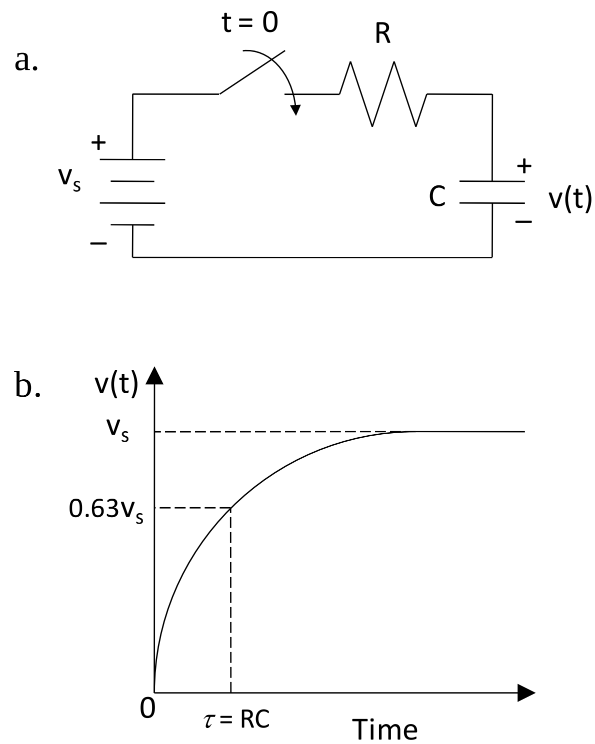

Figure 3. Step response of an RC circuit and the voltage behavior across a capacitor. a.) Schematic of an RC circuit illustrating the step response using a switch and DC voltage source. b.) Time constant (τ) determination based on the step response behavior of an RC circuit.

$$f = \frac{1.44}{(R1 + 2R2)C}. \quad (4)$$

By connecting two appropriate external resistors and the parallel plate capacitor sensor to the timer, the frequency output of the 555 circuit is proportional to the capacitance. Therefore, the change in liquid level is converted to a change in output frequency of a square wave. This square wave signal can then be acquired by LabVIEW and analyzed for frequency.

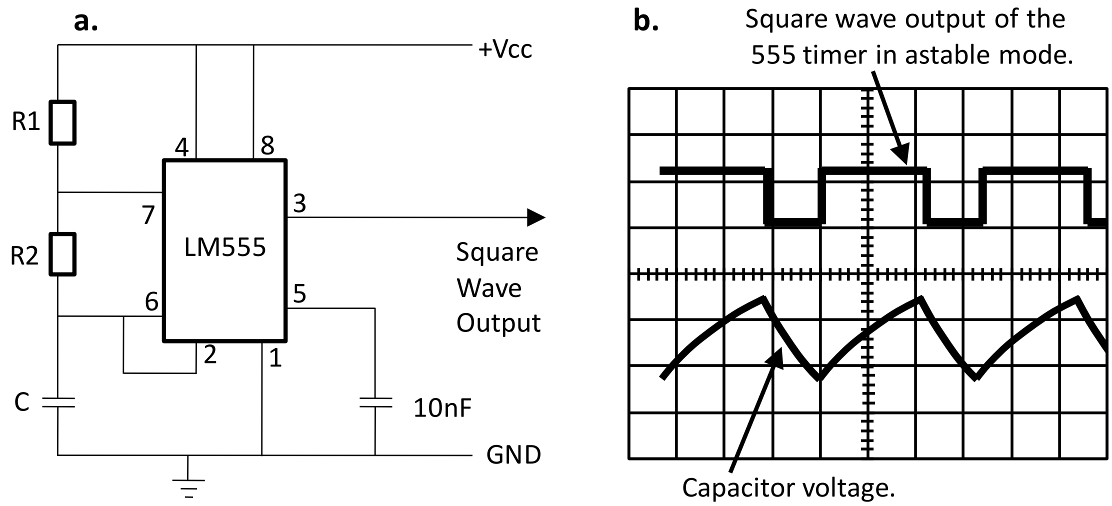

Figure 4. LM555 timer circuit in astable mode. a**.** Oscillating configuration of the 555 timer. External resistors R1 and R2 and external capacitor C can be designed to provide an oscillating circuit with a given frequency. b**.** Waveforms generated in the oscillating configuration (adapted from [5]). Top waveform is the square wave output from pin 3 of the 555 chip and the bottom sawtooth waveform represents the voltage across capacitor C.

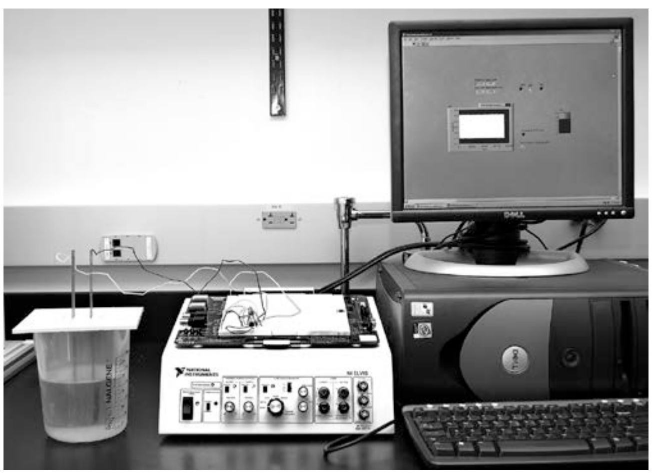

Figure 5. Capacitive liquid level meter *instrumentation system*. Parallel copper plates immersed in oil are connected to a 555LM oscillating circuit on a NI-ELVIS station. A PC running LabVIEW is used to acquire the oscillator frequencies, analyze the signal, and display the relative liquid level on the front panel.

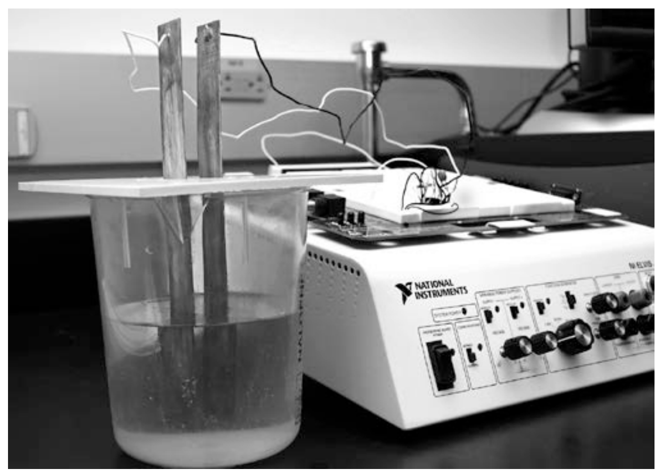

Figure 6. Parallel plate capacitor sensor. Copper plates with soldered leads are passed through slits in a sheet of Plexiglas that is fitted over a plastic beaker. The plates are held in parallel and suspended in the contained oil.

Project Development

Project Overview

The setup for the Capacitive Liquid Level Meter laboratory design project, shown in Figure 5, includes a capacitive sensor inside a plastic container with oil, a National Instruments ELVIS station, and a computer running LabVIEW. The computer includes a PCMCIA, multifunctional input/output card (DAQCardTM-6062E) from National Instruments to interface the ELVIS station with LabVIEW. The parallel plate capacitor sensor (Figure 6) is fabricated from two copper strips with soldered leads. The plates are held in parallel using a piece of Plexiglas with multiple slits to position the plates at different distances. This holder is also used to suspend the plates in the oil by resting on the top of plastic container.

This laboratory design project is divided into four 2-hour laboratory sessions. Each week's design achievement integrates into the following week's design. Each week the students are required to complete a pre-laboratory assignment. These assignments primarily focus on important concepts to help aid in the design process. Background material and introduction to new material is provided in the handouts along with the pre-lab assignment to help set the stage for each design phase.

Week 1 – *Sensor Preparation and Circuit Design Development*

In the first week, the students are introduced to the project and prepare materials to characterize the parallel plate capacitor. The goals of the first week are outlined and discussed below.

<u>Sensor fabrication:</u> The students first fabricate the parallel plate capacitor sensor apparatus by soldering wire leads to copper strips. The copper strips are placed in the provided slits of the holder and the students are instructed to ensure the plates are parallel as possible to each other. The following sensor and apparatus dimensions are then measured to help characterize the system: i) distance between the plates; ii) width of the plates; iii) dead space distance between the bottom edge of the plates and the bottom of the plastic container (beaker), and iv) the distance from the bottom of the plastic container to the major milliliter gradation markings on the beaker. Since the radius of the beaker is not constant from the bottom to the top, the markings will provide the relationship between oil level and oil volume in the beaker.

<u>Oscillating circuit design and assembly:</u> The students design the 555 timer circuit in astable mode to produce a duty cycle close to 50% with frequencies in the kHz range. Since the capacitance of the plates is very small, the students are instructed to design the circuit using resistors in the MΩ range. This design calls for choosing appropriate resistor values R1 and R2 (Figure 4) to meet the design specifications.

<u>Mapping the relationship between oil level and square wave frequency:</u> To find the relationship between the oil level in the plastic beaker and the square wave oscillating frequency, the students are instructed to connect the 555 timer circuit output to the virtual oscilloscope on the ELVIS station and measure frequency using the frequency counter function. The students record the frequencies corresponding to the oil level in the plastic beaker over the measurable demarcated volume range. The students then analyze this data using Excel by fitting a linear trend line to the plot of oil height versus inverse frequency. From this data the students are asked to determine the relative permittivity of corn oil, the frequency range of the sensor, the capacitance range of the sensor, the volume range, and the height range.

Week 2 – *Software (LabVIEW VI) Design*

In the second week, the students design a LabVIEW VI to acquire the square wave signal from the 555 timer circuit and to measure the frequency of the signal. This VI is used throughout the project and the students are instructed to design their acquisition parameters carefully to accurately acquire the square wave signal and measure the oscillating frequency.

Nyquist sampling criterion: As a pre-laboratory assignment, the students are required to research the Nyquist sampling criterion and to revisit a LabVIEW laboratory project assigned earlier in the semester on data acquisition and analysis. The students were assigned to develop a frequency counter VI that displays the acquired waveform, digital displays of the frequency and duty cycle of the waveform, and LED indicators of in range or out of range values for given limits. This will help them understand the details and the requirements for accurate signal acquisition and to validate proper sampling rate for their instrumentation system.

LabVIEW VI: The students are assigned to enhance their LabVIEW VIs to include the following features:

a. A numeric indicator showing the acquired frequency from the 555 timer circuit.
b. A formula node that contains the conversion/calibration functions from frequency into oil volume/level.
c. A numeric indicator of the measured oil volume in milliliters.
d. A numeric indicator of the measured oil height in millimeters.
e. Visual representations of the oil volume in milliliters and oil level height in millimeters on the front panel.
f. Logics to compare measured level with upper and lower level limits and LEDs to indicate level status.

Week 3 – *Signal Calibration and Instrument Finalization*

In the third week, the students learn about calibration curves in instrumentation design and how to build a calibration curve for their oil level meter system. They also program the final touches to their system in LabVIEW.

Calibration curve data: Using the LabVIEW program developed in week 2, the students measure the frequency of the square wave from the 555 timer circuit with respect to oil volume in milliliters. This oil volume in this data set is then converted to oil level based on the volume versus height relationship obtained in the first week. Using EXCEL, the students are instructed to plot the calibration curve oil height in millimeters with respect to the inverse of the frequency and to fit a linear trendline to the plot. The students are then asked to compare the fitted lines between the data collected in week 1 using the ELVIS virtual oscilloscope frequency counter function and the frequency measured by the LabVIEW program. The students are also asked to use their EXCEL spreadsheet to calculate the relative permittivity of corn oil.

Final LabVIEW VI design: After all the data is collected, the calibration curves determined, and the foundation VI completed, the students are required to finalize their Oil Level Meter into a complete package. That is, they are instructed to finalize their LabVIEW VI to a point where someone not associated with the class may come in and use their VI and know what the oil level in the beaker is in terms of volume and height. The students need to fill the formula nodes with the calibration coefficients obtained from the calibration curve data.

Week 4 – *Sensor Characterization, Error Analysis, and Instrument Specification*

In the fourth and final week of the laboratory project, the students characterize their oil level meter design and perform an error analysis on the determination of the oil permittivity.

Oil Level Meter Characterization: As part of the design process, the students need to fully understand all the details of their particular oil level meter design and be able to expertly discuss all aspects of the meter. The students are instructed to compose a professional and informative discussion on the specifications of their design. The discussion is to include the operating range, linearity over the entire measurable range, possible errors, reproducibility, resolution, accuracy in percentage, sensitivity, advantageous features of the meter, and the limitations.

Error analysis: The students are instructed to calculate the relative permittivity of the oil using the formula below (derived from Equation 2):

$$k_o = \frac{Cd - k_a \varepsilon_o w(L-l)}{\varepsilon_o wl}. \qquad (5)$$

Many of the parameters on the right-hand side of Equation 5 are experimentally measured during the previous weeks' laboratory sessions. These measurements inherently introduce error to the permittivity calculation. A major component of this project is analysis of the errors introduced by the experimental measures and the affect on the resultant relative permittivity. The error analysis requirements provide a degree of quality and reliability in the design and calibration of the instrumentation system. To guide the students in the error analysis of their system the students are asked to select two sources of error they believe most seriously affects the permittivity calculation. They are to analyze these errors and determine the following: i) Are the errors random or systematic; ii) estimate the fractional error of each source; and iii) Use the error combination method to mathematically derive how each error contributes to the oil permittivity error.

LabVIEW VI Design

The central component of the oil level meter design project is the square-wave signal acquisition and analysis from the 555-timer circuit. The students were required to use LabVIEW to design a VI to aquire the square wave signal representing the oil level detected by the parallel plate capacitor and convert the signal into a visual representation of oil level and oil volume. Use of modern engineering tools, such as LabVIEW, provide the students a life-long learning experience and an opportunity to learn and develop new skills in engineering design.

LabVIEW Front Panel

The oil level meter LabVIEW front panel is used to graphically (and numerically) monitor the oil level as well as the corresponding square-wave frequency generated by the 555-timer circuit. A sample front panel is shown in Figure 7. The vessel-like representations on the front panel provide visual measures with relative capacity magnitudes. The front panel also provides LED indication for in range or out of range values for the sensor. Sometimes students include a chart to visualize the square wave signal from the timer circuit.

LabVIEW Program Diagram

The overall LabVIEW design structure for the oil level meter was relatively similar between the different student groups. A typical LabVIEW block diagram for the capacitance based oil level meter is presented in Figure 8. Each design requires a signal acquisition system, a signal analyzer, equation nodes, some boundary logics, and the visual outputs for the front panel.

Analog Input: The DAQ Assistant subVI was exclusively used by the students to acquire the square wave signal from the 555 timer circuit. The students had to configure data acquisition parameters as part of their design exercises. The DAQ Assistant is easily programmable to handle desired sampling rates and conditions. This is a significant component in the design process that forces the students to understand the theory and apply analog to digital conversion to the square wave signal. Use of an overall "while-loop" structure is encouraged to help the students understand the data acquisition process.

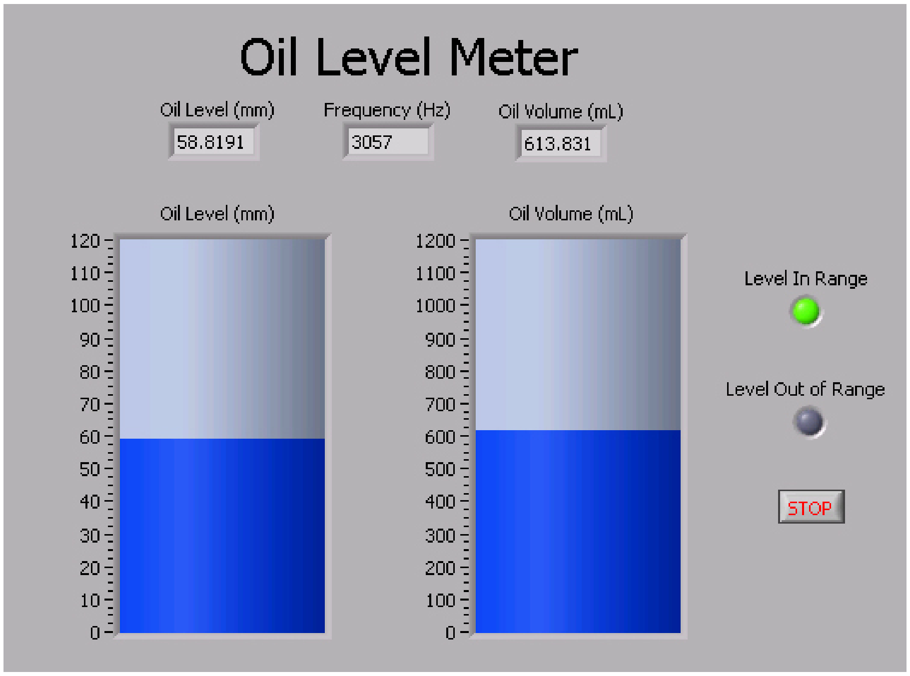

Figure 7. Oil Level Meter LabVIEW front panel. Visual indication of oil level is provided graphically and numerically in terms of depth in millimeters (mm) and volume in milliliters (mL). Frequency of the 555-timer circuit is provided as a secondary indicator. LED indicators are used to inform the user if the oil level is physically out of range and cannot be measured.

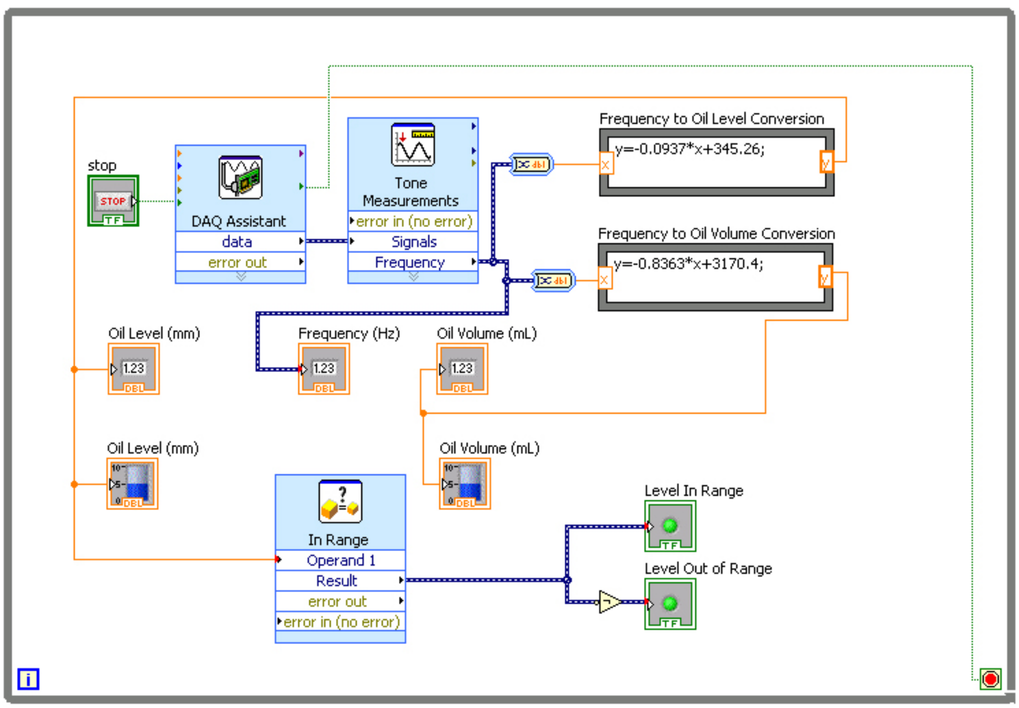

Figure 8. Oil Level Meter LabVIEW block diagram. DAQ assistant subVI is used to capture the square wave produced from the 555-timer circuit. The students are required to provide appropriate sampling parameters for data acquisition. The frequency of the square wave is measured with the Tone Measurements subVI and converted to oil level and oil volume using equation nodes programmed with the calibration curve equations.

Signal Analysis: Square-wave frequency determination was mostly realized by the students using the Tone Measurements subVI. This is a straight forward program that analyzes amplitude, frequency, and phase of signal. As part of the lab exercise, the students were asked to compare the square wave frequencies measured using the ELVIS virtual oscilloscope program and the Tone Measurements subVI. Although similar results were achieved, this exercise nonetheless impresses the differences achieved using different instrumentation mechanisms.

Instrument Calibration: To convert the measured frequencies to oil level and oil volume readings the students used equation nodes to enter calibration equations representing linear fits to their measured data using Excel. The calibration curves were obtained by physically measuring the oil level in millimeters and the oil volume in milliliters and recording the corresponding square wave frequency.

Oil Level Boundary Logics: Full scale range for the oil level meter is based on the length of the copper plates immersed in the oil and the available graduations on the beaker/container. The students were required to measure the dead space between the bottom of the plates and the base of the beaker and use this as a minimum limit for level. The students were also instructed to use the top most gradation printed on the beaker as the maximum level. The students were required to include a comparator in their program and program it with the maximum and minimum levels to ensure the user has a visual indicator to ensure oil level readings were within the operable range of the system.

Results

To assess the effectiveness of this laboratory design project in teaching students the aspects of instrumentation design, student surveys consisting of a series of self-assessment questions were conducted. The surveys focused on how well the students believe they are meeting the course objectives associated with the laboratory project. The students were asked to rank their confidence in their engineering skills gained from this design laboratory experience in areas such as their ability to use mathematical knowledge, design experiments, conduct experiments, use LabVIEW, understand instrument error analysis, understand signal acquisition and sampling parameters, and understand 555 timer-based circuits. Likert scale surveys (5-Strongly agree; 4-Agree; 3-Neutral; 2-Disagree; and 1-Strongly disagree) were conducted to collect the students' opinions. Two similar surveys were used for the first two administrations of the project. The second survey differed slightly from the first in terms of emphasizing error analysis and signal conditioning. Table I shows the student self-assessment survey results for the first administration (10 students who responded) of the design project using the following survey questions:

Table I. Project Student Self-Assessment Survey Results First Semester.

Question	5-Strongly Agree	4-Agree	3-Neutral	2-Disagree	1-Strongly Disagree	Mean	% Rated 4 or Higher
1	2	6	2	0	0	4	80
2	6	4	0	0	0	4.6	100
3	5	5	0	0	0	4.5	100
4	5	4	1	0	0	4.4	90
5	2	7	1	0	0	4.1	90
6	2	7	1	0	0	4.1	90
7	2	6	2	0	0	4	80

1. The capacitive fluid level meter design project helps me see how mathematical knowledge is applied to engineering problems.
2. The capacitive fluid level meter design project improves my ability to design experiments.
3. The capacitive fluid level meter design project improves my ability to conduct experiments.
4. The capacitive fluid level meter design project improves my LabVIEW programming skills.
5. The capacitive fluid level meter design project helps me understand instrument error analysis.
6. The capacitive fluid level meter design project helps me understand signal acquisition and sampling parameters.
7. The capacitive fluid level meter design project helps me understand 555 timer-based circuits.

The students were also asked to comment on the following questions:

8. What did you like most about the capacitive fluid level meter design project?
9. What did you like least about the capacitive fluid level meter design project?
10. What would you change in the capacitive fluid level meter design project?

Table II shows the student self-assessment survey results for the second administration (35 students who responded) of the design project using the following survey questions:

1. The capacitive level sensor design project helps me understand what a capacitive sensor is and how a capacitive sensor works.
2. The capacitive level sensor design project improves my ability to design experiments.
3. The capacitive fluid level meter design project improves my ability to conduct experiments.
4. The capacitive fluid level meter design project improves my LabVIEW programming skills.
5. After the capacitive level sensor design project, I am able to characterize an instrument with the key rating parameters.
6. After the capacitive level sensor design project, I am able to identify causes of errors and perform error analysis with statistical methods.
7. After the capacitive level sensor design project, I am able to describe basic signal conditioning techniques.

The students were also asked to comment on the following questions:

8. What did you like most about the capacitive fluid level meter design project?

Table II. Project Student Self-Assessment Survey Results Second Semester.

Question	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**	**Mean**	**% Rated 4 or Higher**
1	16	10	6	3	0	4.11	74.3
2	17	12	5	1	0	4.29	82.8
3	14	11	10	0	0	4.11	71.4
4	14	9	12	0	0	4.06	65.7
5	13	12	10	0	0	4.09	71.4
6	10	14	9	2	0	3.91	68.6
7	12	14	9	0	0	4.09	74.3

9. What did you like least about the capacitive fluid level meter design project?
10. What would you change in the capacitive fluid level meter design project?

Discussion

The assessment results of the Capacitive Liquid Level Meter laboratory design project presented in this paper is from the first two offerings of the project in its present form. The first version had the students working with distilled water, to allow them to gain an appreciation for the sensitivity and challenges of designing capacitive-based liquid level sensors to measure water. The media was changed to oil in the second week of the first administration, but this water lesson was not implemented in the second administration due to timing issues. This laboratory project was used as an active learning element to assist the students in gaining experience in an electrical engineering-based design environment. At the same time, this project is used to teach important skills and abilities that will transfer in the core general engineering curriculum. The effectiveness of our laboratory design project is reflected in the student survey.

Based on the self-reporting of students on the project surveys (Tables I and II), this laboratory series is effective in several important areas, all of which are important aspects of general engineering-based design, such as the ability to use mathematical knowledge, design experiments, conduct experiments, use LabVIEW, understand instrument error analysis, understand signal acquisition and sampling parameters, and understand 555 timer-based circuits.

First Administration

The survey results from the first administration (10 responses from 13 enrolled students) demonstrate that, out of those students who responded, most of them expressed they achieved the laboratory objectives and are confident with their abilities. The students responded with a 4 or 5 at a rate of 80% or higher for each question. Notably, the students reported with high confidence (100% agree and strongly agree responses) in their ability to design and conduct experiments. This confidence can be transferred to other engineering subdisciplines in applying hands-on techniques to solving engineering problems. This sense of self-accomplishment is reflected in the students' responses indicating the project improved their LabVIEW programming skills (90% agree and strongly agree). This confidence is also transferred to the students' ability to learn and understand signal acquisition and sampling parameters through the use of LabVIEW (90% agree and strongly agree).

As a primary design component in this project, LabVIEW is used extensively in the development and characterization of the capactive-based liquid level meter. Of the 8 students who responded to the survey question asking what they liked the most about the project, 4 indicated appreciation for the opportunity to use such a powerful program as part of their engineering laboratory design experience. From a pedagogical point of view, LabVIEW offers the development of critical learning skills through the use of powerful and easy to use functional components for data acquisition and signal processing through a highly functional and intuitive graphical interface. The other responses centered on the development of the capacitor sensor itself and the circuitry required to generate the corresponding signal. What seems to have made an impression on the students was engagement in the lab through which they designed a sophisticated liquid level meter out of "household" materials and a robust interface with LabVIEW. Student responses for what they liked least or would offer as suggestions to improve the laboratory design project focused entirely on the nuisance of using oil for the liquid media, such as cleaning difficulties, smelliness, and having to switch to oil compared to the relative ease of handling water.

Second Administration

The survey results from the second administration of the laboratory design project (35 responses from 41 enrolled students) also indicate that most of the students expressed they achieved the laboratory objectives and are confident with their abilities. Although the numbers are lower compared to the first administration, the students responded with a 4 or 5 at a rate of 65.7% or higher for each question. One contribution for the lower scores may be the students' perception for Question 6 (error analysis) and their confidence in performing the assigned error analysis. Error source identification is indeed a broad and complicated topic and the error combination method requires students to perform partial derivatives of the oil relative permittivity with respect to multiple parameters, which usually poses challenges to many students. On a puzzling note, the students expressed a lower confidence that the design project improved their LabVIEW programming skills (65.7% agree and strongly agree). While no student disagreed or strongly disagreed, 34.2% had a neutral response to the question. However, when asked what they liked most about the project, 54.3% of the students indicated working with LabVIEW and 34.2% indicated the hands-on experience.

The lower overall self-reporting scores in the second administration may stem from a different laboratory environment than what the students experienced in the first administration. The laboratory sections were almost twice the size with more members per group. Also, a teaching assistant was not available this semester to assist the instructor in the laboratory. Several students indicated they disliked the size of the section and the number of students per group. Although these unfortunate, but now rectified, conditions may have affected the students' impression of the lab, there are still strong indications this design project had a positive impact on the students' ability to learn through hands-on design experiences. Based on the results in Table II, 72.6% of the total student responses were rated as strongly agree and agree, whereas only 2.4% were rated as disagree, while no student rated anything lower.

Overall Laboratory Experience

This laboratory project guided to students engage in understanding the physical aspects of a capacitor gained from using parallel copper plates in a fashioned apparatus. The students can see the area, distance, and dielectric medium and they use the change in the overlapping parallel plate surface area of the oil as the mechanism for a change in level, which in turn changes the capacitance value. Although not an ideal sensor, the raw physicality of the parallel copper plates sensor inspires an appreciation for the challenges involved with making good sensors and that in a feedback system, the sensor is an integral component. Along with this laboratory engagement, the multiweek design project format in a instrumentation and controls class provides a sense of ownership in the project and allows the students to engage in the laboratory experience over a longer period rather than a single lab session where data is collected then analyzed and then the lab moves to something else the following week.

Conclusions

Overall, the four week capacitive-based oil level design project series described in this paper represents a successful approach to laboratory training of undergraduates engineering students in a general engineering degree program. The laboratory activities and the design experience influenced the students' confidence in many skill areas that are key to being successful engineers. The project provided the students with hands-on experience in electrical engineering techniques using laboratory bench equipment, prototype circuit boards, ELVIS station, and LabVIEW programming.

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