DEVELOPMENT OF A DIDACTIC ULTRASONIC LEVEL SENSOR THROUGH A MODULAR APPROACH

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Abstract: *This work presents a didactic and low cost platform of an ultrasonic level sensor to be used by students and educators in laboratories geared to electrical engineering and related courses. The platform design was proposed in a modular way, evidencing the possibility that students who are in various stages of the course can use it. Furthermore, it aims to relate the theory taught in the classroom to practices performed in the laboratory.*

Keywords: *Ultrasonic level sensor, Educational platform, Industrial Instrumentation*

1 INTRODUCTION

A level sensor is a device used to determine the level or quantity of fluids. The main level measurement methods use different principles, such as: Sight glass (COOPER, 2018), floats (SINGH, 2018), displacement measurement (MIYAZAWA, 2016), differential pressure transmitters (VIENS, 2018), and the one used in this work, using ultrasonic waves (CHHANTYAL, 2018; GRASSI, 2014; MERIBOUT, 2004; SPRATT, 2009).

As ultrasonic level sensors use no moving parts, they are ideal for applications in which contact with the medium being measured is impractical. This includes those involving boiling liquids and caustic chemicals. Ultrasonic sensors can also produce accurate point-level or continuous measurements for materials with inconsistent chemical compositions or dielectric constants (HAUPTMANN, 2002). The main disadvantages of this type of sensors are that targets of low density, like foam and cloth, tend to absorb sound energy, which causes errors in measurement, and they are comparatively more expensive than other existing methods.

Due to the high cost of these sensors it is difficult for the Universities to acquire them. Furthermore, another important factor that impedes the acquisition of this type of instrument for the laboratory is due to the bureaucracy existing in the bidding process. The lack of these sensors results in difficulties of relating the theory seen in the classroom with the current practical reality in an industrial environment. With this, the students are unable to perform experiments focused on control and calibration, for example. Table 1 shows some of the prices of these types of sensors for some brands in the market (GLOBAL WATER, 2017).

Table 1 – List of industrial sensors

Model	Price
WL705-003	$ 795
WL705-048	$ 1163
Flowline DS14-00	$ 359
ULS-100	$ 499

Source: adapt from (GLOBAL WATER, 2017).

Thus, in this work, a didactic platform for an ultrasonic sensor is proposed. The platform was designed in a modular way in order to obtain a flexible device in which the student could do each stage of the conditioning circuit in his own module and replace it with the existing platform module.

With this, it is possible to highlight some positive points for this type of implementation, such as: multidisciplinarity, interdisciplinarity and motivation for students. This last one has become a problem for graduations in Electrical Engineering, as it has the consequence of the student’s evacuation, being able to reach the value of approximately 20% of the students who begin the course (INEP, 2016). One of the reasons for greater disaffection in the course of Electrical Engineering is the deficiency of practical experiments in basic cycle subjects and is one of the factors that weigh in the final decision. In view of the high dropout rates an application such as this can help to improve the student’s relationship with the course since it can be applied in practice concepts seen in theory.

So this work has great value for the academic environmentin universities and technical courses, because it allows a low cost and high precision implementation, done in a modular way in order to facilitate didactics with this type of sensor. For this purpose, printed circuit boards were made separately for the conditioning circuit of the transmitter and receiver.

2 ULTRASONIC LEVEL SENSOR

The method used by ultrasonic sensors is based on sound wave and kinematic laws to measure the level of liquid in a tank or vessel (BALBINOT, 2010). Considering a container with total height H and liquid level N shown in Figure 1, if the distance L between the top of the container and the surface of the liquid is known, it is possible to calculate N by Equation (1).

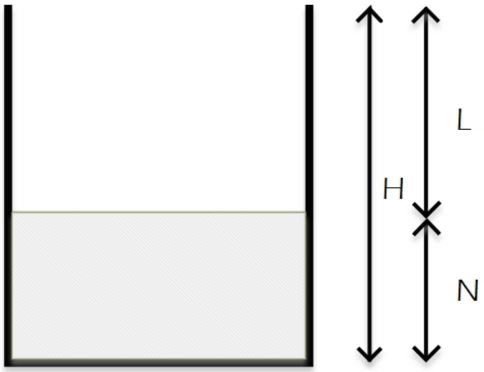
$$N = H - L \tag{1}$$

Therefore, if the sensor is positioned at the top of the vessel and it is able to measure the distance L, it is possible to calculate the level, since the height H is constant.

The sensor used is made of piezoelectric material, that is, it deforms when a voltage is applied on it, with the same frequency of the applied wave and intensity proportional to its amplitude. In this way, a mechanical wave can be created which propagates through the air and obeys all the laws of the wave.

It is known that a mechanical wave passing the division between two media undergoes the reflection and diffraction phenomena, where the reflection reflects part of the wave with angle complementary to the angle of incidence and the diffraction causes a change in the speed and direction of the wave in the middle. The first phenomenon was used for the principle of sensor operation.

Figure 1 – Representation of a tank with liquid for level measurement.



Source: own authorship.

If two parallel transducers are positioned at the top of the vessel, they are arranged in such a way that the surface of the liquid is also parallel and a voltage is applied to one of them (transmitter), the created wave propagates through the air from the free part of the vessel until it reaches the surface of the liquid, where it will undergo reflection, and will return to the top and excite the second transducer (receiver). Because it is a piezoelectric material, the sensor upon being deformed produces a wave with the same frequency of strain and amplitude proportional to the intensity of the deformation. Thus, if the lag between the two waves can be obtained, the value of L can be calculated if the wave velocity and the propagation time are known (BALBINOT, 2010).

The wave will travel twice the distance L (round trip) and that the velocity of sound in the air, at room temperature, can be calculated by Equation (2) (VILLANUEVA, 2009; KAIMAL, 1963).

$$C = 20.074 \cdot \sqrt{T + 273.15} \tag{2}$$

Where T is in degrees Celsius. The temperature as the experiment was performed around 23 °C, so the velocity of sound in the air was approximately 345 m/s. Therefore, it is possible to obtain L from Equation (3) (BALBINOT, 2010).

$$L = \frac{C \cdot t}{2} \tag{3}$$

If the height of the container is known, it is possible to calculate the level. Therefore it is necessary only a sensor that has as output the information of the elapsed time t between the wave sent by the transmitter and the wave received by the receiver.

3 PLATFORM DESCRIPTION

The sensor is designed to measure the level of the platform in the laboratory. To allow use with diverse acquisition circuits, digital and analog outputs have been implemented with values that allow use programmable logical controller (PLC), data acquisition boards and microcontrollers. The project specification values are in the Table 2, in addition to some project specifications.

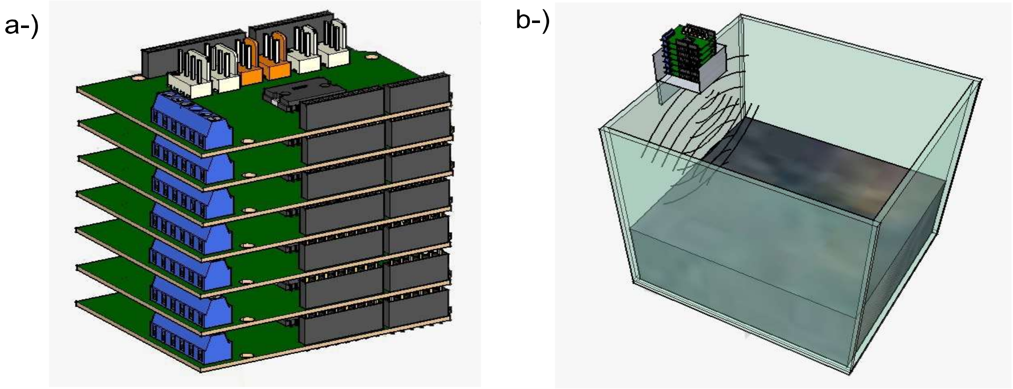
Table2 – Project specifications.

Tank height	17.25 cm
Tank volume	2.484 l
Conditioning Circuit Supply Voltage	5 V
Voltage Output	0 – 10 V
Current Output	4 – 20 mA

Source: own authorship.

In this project, the conditioning circuit for the ultrasonic sensor was designed aiming at interdisciplinarity and to meet the need in the laboratory. In this way, the circuits were designed in a modular way so that students and educators of different stages of the Electrical Engineering course can implement their circuit and test their operation in the application of the measurement of the level of a tank. Figure 2 (a) shows the design of the prototype where in each printed circuit board contains a conditioning stage. In addition, it is possible to see in Figure 2 (b) a simulation of how the level measurement of a liquid present in a tank is made.

Figure 2 – Design of the prototype and measurement of the level.



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For a better understanding, the sensor conditioning process was divided into some stages represented in a block diagram shown in Figure 3. The output of each step was enumerated from I to X. The main waveforms for each output are shown in Figure 4.

Figure 3 – Block diagram of the conditioning circuit.

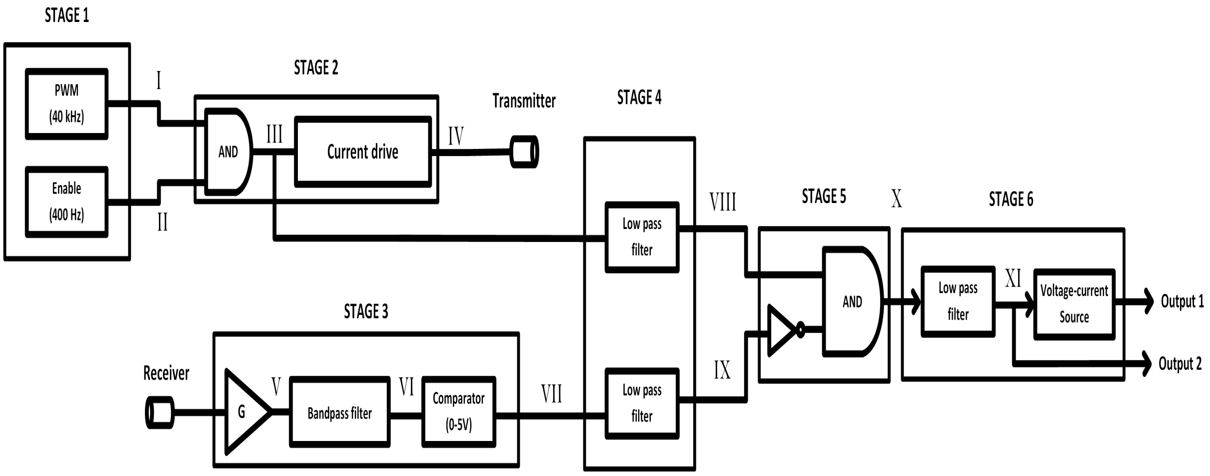

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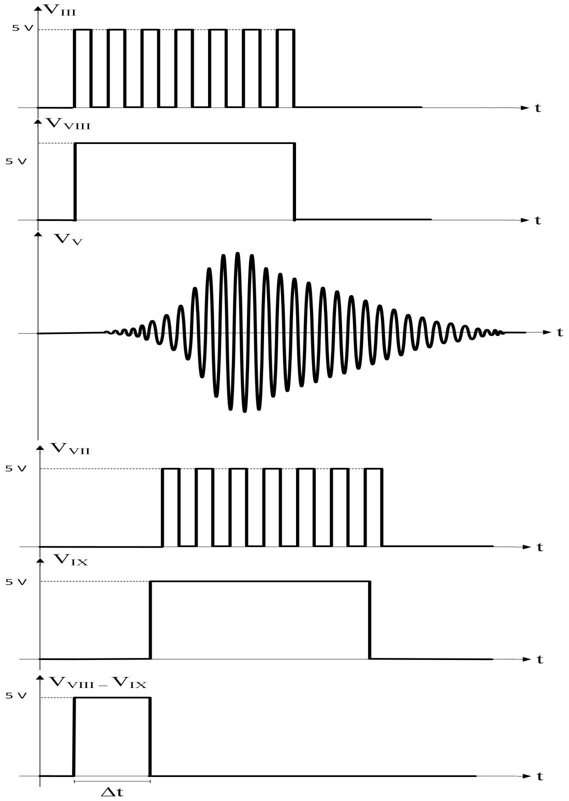
Figure 4 – Main theoretical waveforms for the transmission and reception steps.



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3.1 Stage 1

In order for the transmitter to operate correctly, it is necessary to generate a PWM signal of known frequency. Observing the datasheet of the transducer, it was seen that it has an activation frequency between 38 and 42 kHz, therefore, a PWM signal was generated near 40 kHz (step I). To control the acquisition time of the level value, a signal with a frequency of 400 Hz was generated (step II). This signal has the function of enabling when the 40 kHz signal will be present in the transducer that emits the transmitted wave.

As the project aims at interdisciplinarity and modularity between stages, the student can decide how he intends to generate these signals. The modularity will allow the generation of the signal from a microcontroller, from any integrated circuit that can perform this task, from a data acquisition board or even from bench instruments as a signal generator, for example. In this project the integrated circuit 555 (TEXAS INSTRUMENTS, 2015) was used in astable mode to produce the PWM and it was fed with a voltage of 5 V.

3.2 Stage 2

The student at this stage can implement his conditioning circuit in the way that suits him, using transistors or using operational amplifiers, for example. In this design, the entire conditioning circuit of the transmitter was powered with a voltage of 5 V.

At the AND Gate output (step III), the resulting signal is composed of a 40 kHz enveloped by a 400 Hz signal as seen in Figure 4 (V_{III}). That is done so the Transducer is activated every 2.5 ms, pulsing for 1.25 ms and waiting the return of the sound wave to be detected by the transducer receiver. This logical port will allow high logic level while the steps I and II are high.

The PWM signal didn't supply enough current for the transmitter to work properly, making necessary the use of a current drive system, in this case, a push-pull topology was implemented that will drain the minimum current necessary for the proper functioning of the transducer.

3.3 Stage 3

To measure the receiver signal, the threshold technique (TH) (VILLANUEVA, 2009) was used. In this technique the return time is measured when the receiver voltage reaches a predetermined level.

The receiver signal was measured around 70 mV, and had a sinusoidal behavior, as shown in Figure 4 (V_V). In order to use that signal, it was amplified to the emitter voltage level. Besides, to eliminate noise, and guarantee the signal is coming from the emitter, it was used a band-pass filter (V_{VI}), with a central frequency at 40 kHz. To transform the sinusoidal signal to a square signal, it was used a comparator circuit, resulting in the signal shown at Figure 4 (V_{VII}).

3.4 Stage 4

At this stage, there are two low-pass filters (steps VIII and IX), with a cutoff frequency at 5 kHz. Both are responsible to eliminate the 40 kHz signal, leaving only the envelope at 400 Hz. These two signals should be similar. However, the receiver signal will be lagging behind the transmitter signal. This phase difference between the two signals will result in the level of the measured liquid.

3.5 Stage 5

To measure the time between the signal applied to the transmitter and the signal received by the sensor, a combinational logic has been developed which results in a pulse with phase proportional width between these two signals. This signal is dependent on the time Δt which the sound wave took to bounce back off the liquid surface level.

3.6 Stage 6

Finally, it is necessary to implement a low-pass filter with a cut-off frequency of 10 Hz at the output of the stage 5 circuit (Figure 4 (V_{VIII} - V_{IX})) to obtain the DC level of this signal. Thus, the amplitude of this DC signal is proportional to Δt, therefore, also proportional to the liquid level. This means that the higher the liquid level, the lower the voltage.

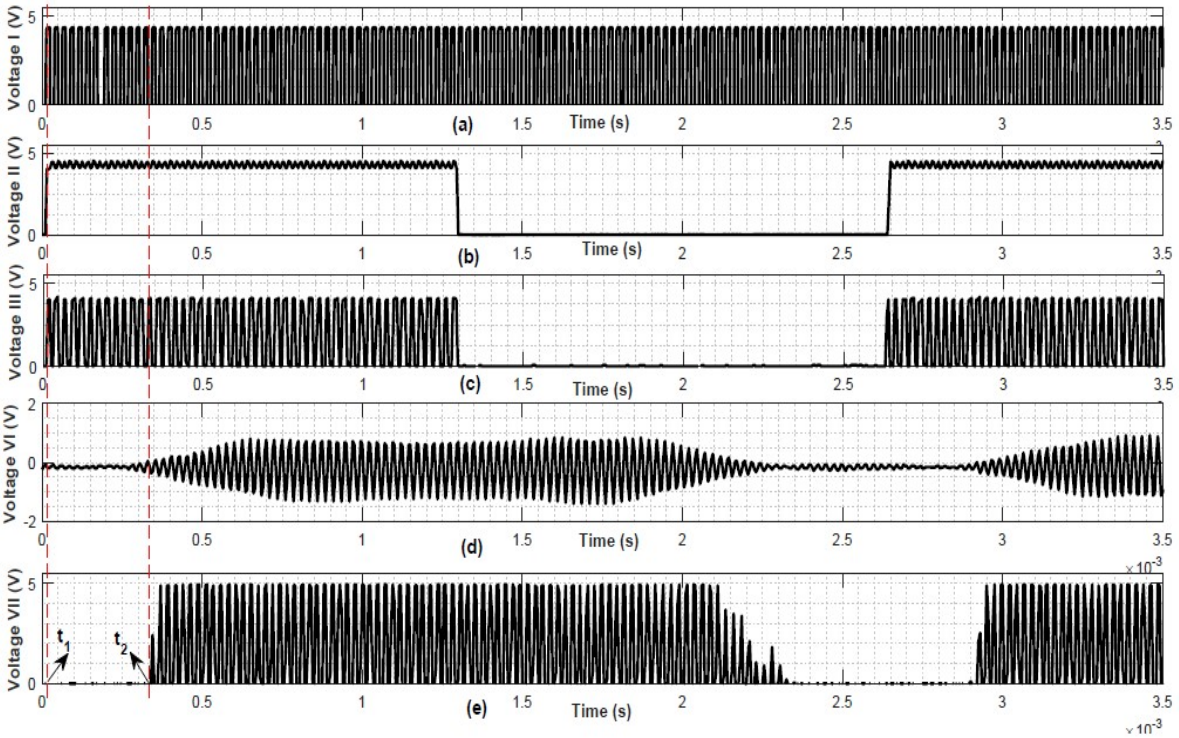
After the low-pass filter, the signal is used as input of a voltage-current source (4 mA – 20 mA), so it can be used with any industrial programmable logic controller (PLC) present at the laboratory.

4 EXPERIMENTAL RESULTS

The assembly of the prototype was carried out, resulting in the validation of the conditioning circuit designed at each stage. The experimental curves obtained correspond to certain points of the diagram shown in Figure 3. The excitation signal, shown in Figure 5 (a), guarantees a frequency of about 40 kHz, ranging from 38 kHz to 42 kHz, which is compatible with the region of operation of the transducer employed. The waveform observed corresponds to step I of the Figure 3. In Figure 5 (b), the enable waveform whose frequency is chosen by

400 Hz is displayed. The shape of the curve corresponds to step II of the Figure 3. The curve relating to the modulated signal that is used to excite the transmitter is shown in Figure 5 (c). The similarity to V_{III} in Figure 4 becomes evident (Figure 3, step III). In Figure 5 (d) it is possible to observe the signal in the receiver after it has been filtered, in order to eliminate disturbances and external noises, such as the frequency of the electric network. The signal at this stage was also amplified, since the signal coming from the transducer of the receiver had very low amplitude. This waveform corresponds to step VI of the circuit. Figure 5 (e) exposes the receiver signal after passing through a comparator (in the range of 0 to 5 V) that matches the V_{VII} signal of the Figure 4 (step VII, Figure 3).

Figure 5 – Experimental curves for the transmitter and receiver (a) 40 kHz PWM signal (V_I). (b) Enable at 400 Hz (V_{II}). (c) Transmitter excitation signal (V_{III}). (d) Signal on receiver after gain and filtering (V_{VI}). (e) Receiver signal after comparator (V_{VII}).



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In Figure 6 (a) we have the signal coming from the 40 kHz PWM after passing through a chosen low-pass filter of 5 kHz, in order to eliminate the frequency of 40 kHz. The signal of the comparator (V_{VII}) after passing through a low pass filter equal to that of the signal of Figure 6 (a) is shown in Figure 6 (b). The filtered signals pass through the stage 5 whose measured output is shown in Figure 6 (c). It is possible to visualize the time interval Δt, which is necessary to calculate the distance to an obstacle, whether solid or liquid. It is important to note that the signal of Figure 6 (c) is digital, wherein the pulse width is directly related to Δt.

With the transducers properly conditioned and in full operation, the calibration was done in a simple way. First, the sensor was positioned in the tank in front of the liquid as shown in Figure 2. The liquid level has been changed and the distance between it and the sensor has been noted, as well as the time difference displayed on the oscilloscope by means of the "delay" function. By means of these measurements the graph shown in Figure 7 was drawn. It is clear that the behavior is linear, even in Figure 7 there are highlights showing waveform impressions and time difference corresponding to distances of 6 cm and 9 cm.

Figure 6 - Experimental curves for the transmitter and receiver. (a) Transmitter excitation signal after passing through low-pass filter 5 kHz (V_{VIII}). (b) Comparator signal after passing through low-pass filter 5 kHz (V_{IX}). (c) Difference between the signals (V_{VIII}) and (V_{IX}), corresponds to the time interval Δt $V_{(X)}$.

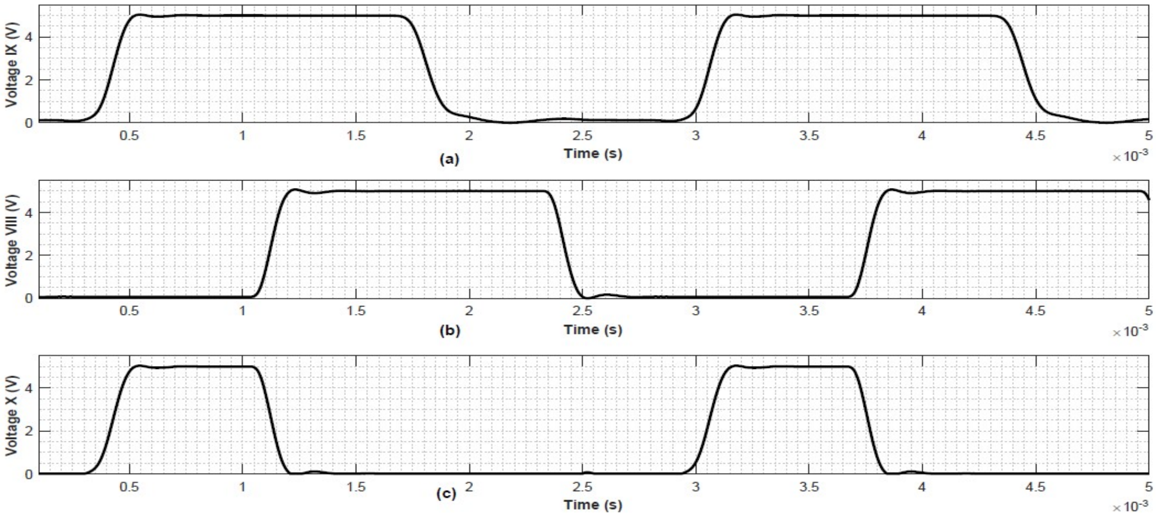

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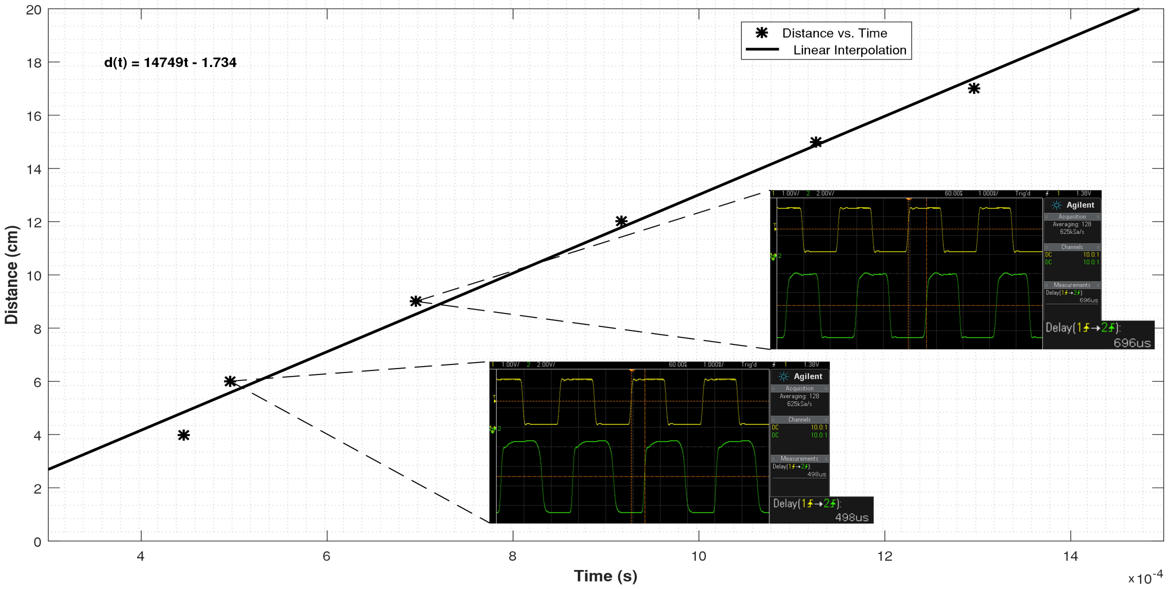
Figure 7 – Calibration curve for the properly conditioned level sensor.



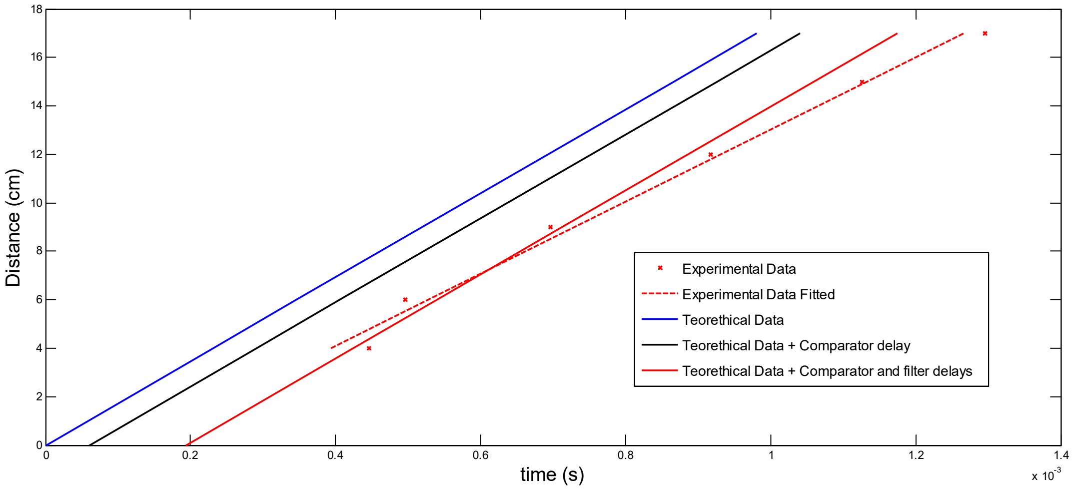
Source: own authorship.

By means of the experimental data we obtain the adjusted curve that determines the value of the distance from the sensor to the liquid: $L = 1{,}4749 \cdot t - 1{,}734$.

To analyze the efficacy of the proposed sensor, the experimental data were compared with the theoretical values. With the values of the distances used for the calibration the respective theoretical values of propagation time were calculated by Equation (3). The results obtained are shown in Figure 8. It is possible to observe that there is a considerable difference between the theoretical and experimental values. This is due to inherent delays in the detection technique and circuits used. The comparator used in the threshold detection technique generates an additional delay Δt_1. This delay is due to the fact that the comparator output only saturates when the signal input is greater than the established level for threshold. When performing the compensation of Δt_1, it is verified that the values become closer to the obtained results. The filter used to obtain the pulse signal at the output of the receiver also generates a delay called Δt_2. Compensating the Δt_2 value, it is verified that the values are much closer to the experimental results obtained. The slopes of the compensated and experimental curves are still different, since the value of Δt_1 varies with the distance. This is due to the fact that the amplitude of the received signal decreases with the distance value due to the attenuation caused by the propagation medium in the ultrasound wave.

Despite the difference between experimental and theoretical values, it is possible to minimize this difference by compensating the inherent system delays. Furthermore, by performing the calibration experiment, one can derive from the experimental data the function that determines the distance value as a function of time measured by the sensor as shown in Figure 8.

Figure 8 – Theoretical, experimental and compensated curves.



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5 CONCLUSION

According to what was presented in the experimental results, it can be concluded that the ultrasonic level sensor and its conditioning circuit is functioning correctly, as expected. By increasing the distance of the liquid to the transducers the time between the emitted and received mechanical wave increases. The behavior of the sensor output relative to the liquid level was approximately linear which is in accordance with what was expected. Using the compensation of the intrinsic delays, we approximate the experimental results of the theoretical result.

From the perspective of the platform presented in a modular way, it is possible to observe the possibility of using this type of platform in a laboratory for students of Electrical Engineering and related, in order to provide: a greater contact between students and industry; students of different periods and disciplines can develop only a certain stage and replace in the sensor; it is possible to acquire the signal generated by the sensor and use it in data acquisition systems; is possible to couple the sensor to a sensor network and work with a concept of communication interfaces and protocols; it is possible to use the proposed sensor in a closed loop to control a level plant; perform calibration experiments in instrumentation disciplines.

The platform has a low manufacturing cost compared to the sensors available in the market, because it uses simple and easy-to-acquire components such as resistors, operational amplifiers and transistors. Although the analog output signal has been obtained through a simple technique, it is possible to implement more advanced techniques through the pure signal obtained at the receiver that is available at the VI output. This can be used in more advanced experiments and academic research.

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