Teaching Wireless Sensor Technology to Undergraduate Students through Research Projects

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ABSTRACT: *This paper presents a survey of three undergraduate research projects being developed jointly by the Electrical and Computer Engineering and the Mechanical Engineering Departments of the University of Puerto Rico. The projects consist in the development of wireless sensor circuits designed to monitor the health condition of mechanical components. Our aim is to provide students with an introduction to the area of sensors and instrumentation by performing a meaningful research experience. The research objective is to develop the technology to integrate sensors into composite structures to monitor performance and structural health during operation.*

Emphasis is placed on developing low-cost circuits on plastic substrates to assure compatibility with ball bearings and similar devices. The circuits are powered by an RF signal, and therefore can operate without batteries. The measured quantity is transmitted to a receiver, or reader, in a short-range wireless fashion. Thus wires are not needed to connect the components attached to the moving part. Our focus is on measuring temperature and strain. However, the technology can be used to measure other mechanical or structural variables.

Three undergraduate research projects are discussed in this document. In the first, a circuit to measure strain was developed. In the second project, students developed a circuit that uses a capacitive transducer and an oscillator to sense and transmit temperature information. In the third project students developed a circuit that replaces the oscillator with an ultra-low power microcontroller. To transmit the information, the microcontroller changes the inductance of the power-receiving coil. The reflected impedance of the power-transmitting coil is monitored in order to read the temperature.

The article first provides a general introduction. Next, the three sensor circuits are described in detail and experimental results are presented. Finally, we discuss our conclusions and plans for future work.

1 INTRODUCTION

It is difficult to overestimate the impact of semiconductor science and technology on today's society. Over the past few decades, semiconductor electronics has become the driving force of human progress. Integrated circuits have transformed the world in which we live and now play an essential role in practically all aspects of technology. In so doing, they have spawned industries that generate hundreds of millions of dollars in profits and provide jobs to millions of people around the globe. Semiconductor technology is the backbone of the modern society and thus it is of utmost importance to the international infrastructure.

It is generally recognized that research in micro-sensors will enable similar advances in the near future. Progress in these enabling technologies will produce significant advances in key areas like communications, transportation, medicine, aeronautics, mechanics, and information technology. Consequently, the study of sensors is rapidly expanding in technical scope and applications. There is a need at all levels in industry for professionals that can deal with the complexity and challenges of these technologies.

Due to its intrinsically multidisciplinary nature, students of sensor technology are exposed to a variety of subjects that go beyond the traditional boundaries of their profession. It is thus particularly important to promote interaction and collaboration between students of different areas of engineering. Sensor research and development is now related to most disciplines in engineering and is the focus of courses at a variety of departments in many major universities. Because virtually all modern microsensors strongly depend on electronic signal conditioning for proper operation, there are significant advantages in the joint development of sensors and the associated electronics.

This article presents three undergraduate research projects that have been developed at the University of Puerto Rico to provide students with a background in wireless sensor technology. The projects have been developed as part of the Industrial Affiliates Program (IAP), administered by the Electrical and Computer Engineering Department (ECE) at the University of Puerto Rico at Mayagüez (UPRM). IAP aims at enriching the educational experience of undergraduate students by providing the opportunity to be exposed to the different aspects of academic and professional life such as research, development, team work, report writing and public speaking. The program has been described in [Toledo-Quiñones et al, 2003].

The projects described here are part of a collaboration between the Electrical and Computer Engineering and the Mechanical Engineering departments in the area of sensor technology for mechanical applications. The integration of sensors in mechanical components has been a topic of research in recent years. Integrated sensors can be used to monitor the performance of mechanical components and structural health in high-performance applications. This technology has the potential to revolutionize monitoring, damage detection, and non-destructive evaluation. Small sensor size, integration into the monitored structure, and the capability to transmit the signal in a convenient fashion are some of the features that are needed.

A recent trend is to investigate the feasibility of embedding wireless sensors into functional composite structures. [Krantz et al, 1997] developed micro-machined sensors and an associated remote-querying capability that allows self-contained micro-sensors to be embedded in a composite structure and queried using methods that do not require physical connections. [Hautamaki et al, 2000] used embedded Micro-electromechanical Systems (MEMS) to measure strain in a composite. These small-scale sensors were designed to function as part of a wireless sensing system. The sensing element, signal conditioning, and telemetry circuitry were developed and integrated on a single silicon wafer. However, order-of-magnitude differences between the bulk modulus of silicon and most metals prevent the transference of strain from most mechanical components to MEMS sensors. The use of micro-sensors preinstalled on a thin film insulting carrier, like Dupont Kapton® polyimide film, could solve most of these problems. The sensor small size will allow it to be placed close to the points of interest. The sensors would therefore offer an effective means of monitoring damage in critical components and assessing local failure characteristics.

The projects described here are aimed at exploring the development of a reliable and cost-effective technology for making wireless strain micro-sensors for the real-time monitoring of strain and temperature in mechanical parts. This will allow the detection of damage and prevent catastrophic failures in aerospace, military and commercial applications. The specific objectives of each project can be enumerated as follows:

- Project 1: To develop and test a wireless strain micro-sensor based on integrating a semiconductor strain sensing element into a Dupont *Kapton*® thick film layer in order to monitor the strain variation of moving mechanical components during operation.
- Project 2: To develop a battery-less wireless sensor to monitor the temperature variation of a bearing cage during bearing operation.
- Project 3: To develop a battery-less wireless temperature sensor interface using a microcontroller of the MSP430 family as the main component, and to evaluate methods of wireless data transmission.

A total of 17 undergraduate students have participated in different aspects of these projects.

2 STRAIN SENSOR

The first project consists in the development of a wireless strain sensor and its associated interface electronics. The device employs a semiconductor resistive strain gauge to sense strain. The sensor was fabricated on 25 um thick Dupont *Kapton*® film carriers. This material can be either surface mounted on the objects whose strain will be measured, or integrated into them during fabrication.

Strain is closely related to factors that determine the functional life of mechanical parts. Strain information can only be obtained by placing sensors near the points of interest. For several years, embedded optical fibers have been the predominant type of sensor for these applications [D. Krantz et al, 1999]. There are, however, well-known limitations that have prevented the widespread use of optical fiber sensors, including their high cost, fragility, and the need to provide ingress and egress from the structure.

The wireless strain sensor developed in this project is based on a semiconductor strain sensing element integrated into a resistor bridge, shown in figure 1. We used resistive strain gages, shown in figure 2, made by Micron Instruments that are sensitive to extremely small amounts of force.

The strain gage measurement circuit, shown in figure 3, consists of a difference amplifier followed by a AD654 voltage-to-frequency converter and a TX-2 RADIOMETRIX transmitter. A RADIOMETRIX receiver was used to wirelessly detect the signal. The signal frequency was measured with a handheld multi-meter. Printed circuit board fabrication methods and surface mount technology (SMT) were used to construct the circuits, which are shown in figure 4.

In order to calibrate the wireless strain sensor, a cantilever steel beam with a thin rectangular section instrumented with the wireless strain sensor was employed. The calibration setup is shown in figure 5. The beam was rigidly supported at one end while force was applied at the free end using deadweights. A theoretical analysis of the beam provided values of the strain generated due to the applied deadweights at a known location. The application of deadweight at the free end produces strain at the sensor location and hence changes the sensor frequency. The output frequency was recorded as a function of the applied load on the beam as shown in figure 6.

3 OSCILLATOR-BASED TEMPERATURE SENSOR

Temperature is one of the most important parameters affecting the functional life and performance of rolling element bearings. There are four elements in a rolling bearing: inner race, outer race, rolling elements and cage. Inner and outer race temperatures are relatively easy to measure. The stationary race temperature can be measured directly by using standard equipment such as a thermocouple. For the rotating race, slip rings or a commercially available telemetry unit can be added to the shaft in order to transmit the data to a stationary observer. However, measurement of cage and rolling element temperatures is significantly more difficult within very limited space inside bearing, which requires specially designed equipment. The small, lightweight nature of the bearing cage prohibits the use of any measuring device with substantial size or weight, and the complex motion of bearing cage prevents the use of slip rings.

During bearing operation, the macroscopic motion of the cage is primarily guided by the motion of the rolling elements. However, the microscopic motion of the cage is quite random since the cage is not attached or fixed to any of the bearing component. Currently, there is no way to directly monitor the temperature of the bearing cage. Wireless micro-sensor technology allows the examination of environmental parameters without requiring a physical wire connection. Therefore, a wireless sensor could be an ideal solution to this problem.

Several manufacturers (Micron Instruments, Microstrain and IR Telemetrics, for example) sell battery powered radio transmitters that can telemeter sensor data from a moving machine component to a stationary receiver. These products are multi-channel, general-purpose designs, often able to handle a variety of sensor types. The “strainLink” transmitter from Microstrain, Inc. is representative of current products in this category and weighs 9.5 grams. This weight is for the transmitter circuit only and does not include the sensor. While some of these products are certainly small enough for many applications, they are too large and heavy for practical use on a bearing cage. Therefore, a much smaller, simpler circuit design, low power consumption and robust wireless sensor is needed. The sensor could be powered by a miniature cell battery. However, changing a battery in regular intervals is not practical (or possible) for many applications requiring long-term, unattended operation.

This project aims at exploring the development of a remotely-powered wireless sensor for bearing-cage temperature measurement. The wireless sensor developed in this project is based on the principle of operation of an inductor-capacitor (L-C) tuned electric oscillator. The temperature-sensitive capacitor installed on a bearing cage is integrated into an L-C oscillator as a frequency-controlling element. The change in the value of the capacitor due to temperature variation is translated into modulation in the oscillator frequency. Remote power is provided to the circuit by inductive coupling between two coils – one integrated with the sensor circuit while the other is stationary and connected to an alternating power source. Due to the magnetic coupling between the coils an alternating voltage is generated and induced into the other coil on the sensor. This ac voltage is further rectified into a dc voltage that powers the sensor unit.

A Colpitts oscillator was employed as a telemeter circuit. Figure 7 shows a schematic diagram. The inductor L and the capacitors C_{s1} and C_{s2} form an LC tank that determines the oscillation frequency, which is given by:

$$f = \frac{1}{2\pi}\sqrt{\frac{(C_1 + C_2)}{LC_1C_2}}$$

Temperature sensitive capacitors (C_{S1} and C_{S2}) are used in the tank, thereby making the telemeter frequency a function of temperature. In order to sustain the oscillations, the transistor amplifier adds energy to the tank to replace the energy lost. A detail analysis of the Colpitts oscillator can be found in [A.S. Sedra and K.C. Smith, 1997].

The remote power for the sensor operation is supplied by radio energy induced from outside at a specific frequency into coil L_2. Exciter coil L_3 is placed in the vicinity of the inductor coil L_2. A sinusoidal voltage is applied to coil L_3 and is used to excite coil L_2. The resulting alternating voltage is rectified and filtered. The resulting dc voltage provides power to the oscillator. Figure 8 shows an early prototype of the circuit.

Sensor calibration was performed through a heating cycle by immersing the sensor in a temperature controlled oil bath. The sensor setup is shown in figure 9. The calibration was performed by monitoring the oscillator frequency with a small antenna and an oscilloscope while the oil bath was heated. A thermocouple was used to obtain an independent temperature measurement. Figure 10 shows the temperature, measured by the thermocouple, and the detected shift in frequency. Although, in general, the behaviour of the two devices is similar, the received oscillator signal was not completely stable. The circuit construction and perhaps overall system design will be improved to correct this.

5 MICROPROCESSOR-BASED BATTERY-LESS WIRELESS TEMPERATURE SENSOR

This project focuses on the development of an *intelligent* wireless and battery-less sensor circuit. By incorporating a microcontroller in the sensor, the detection of several variables using different transducers becomes feasible. The use of a microcontroller allows the creation of addressable sensor networks arranged so that variables can be monitored at different object positions without interference. In addition, signal conditioning can be done in the microcontroller so the reader circuit is simplified. Last but not least, minor changes in the circuit can accommodate the use of different types of transducers that measure a variable as a change in resistance, capacitance or by generating a voltage.

The objectives of the project are to: (i) develop a wireless temperature sensor interface using a microcontroller of the MSP430 family as the main component, (ii) demonstrate the operation of a MSP430 microcontroller with an RF power source, and (iii) to evaluate wireless data transmission by modulating the reflected impedance seen by the reader.

The device, shown schematically in figure 11, is basically a telemeter that senses the temperature, translates the temperature into electrical quantity and transmits the temperature information. Power will be supplied to the circuit remotely by means of a radio frequency signal. The remote power of the sensor is based on the principle of inductive coupling between two coils – one integrated with the sensor circuit while the other is stationary and connected to an alternating power source. Due to the magnetic coupling between the coils an alternating voltage is generated and induced into the other coil on the sensor. This ac voltage is further rectified into a dc voltage that powers the sensor unit.

Because operation of a transmitter will require a substantial amount of power, an alternative data transmission method is being explored. The approach consists in incorporating a switch in parallel to part of the coil that receives power. To transmit data, the microcontroller will modify the coil's impedance by opening and closing the switch. This will produce a change in the reflected impedance on the power-transmitting coil, which in turn causes the amplitude of the sinusoidal wave present there to chance. This effect can be observed in figure 12, which was obtained in the laboratory in a test setup. Thus, the transmitted information is recovered by detecting the envelope of the signal. Thus, if $V_{RF} = A\cos(\omega_{rf}t)$ and $V(t)$ are the RF and sensor signals, respectively, we expect to observe an antenna voltage of form $BV(t)\cos(\omega_{rf}t+\varphi)$, where B and φ represent a constant amplitude factor and phase. The product of the RF and antenna voltages will be $V_P = AB \times V(t) \times \cos(\omega_{rf}t+\varphi) \times \cos(\omega_{rf}t)$. Applying the trigonometric identity

$$\cos a \times \cos b = \tfrac{1}{2}\left(\cos(a+b)+\cos(a-b)\right)$$

we can see that V_P is proportional to $V(t)\cos\varphi + V(t)\cos(2\omega_{rf}t+\varphi)$. Properly designed, the low-pass filter will greatly attenuate the second, high frequency, component of the signal, while letting the output be proportional to the sensor signal $V(t)$. It will also greatly reduce noise because of the reduced bandwidth.

This project is in the early stages. During the first two months of the project, students have concentrated their efforts in designing the sensor interface, estimating the micro-controller power requirement, developing the RF powering and understanding the data transmission method. Preliminary measurements have been carried out, such as the one shown figure 12, but the construction of a prototype has not been carried out yet.

6 CONCLUSIONS

We have presented three undergraduate research projects that have been developed at the University of Puerto Rico to provide students with a background in wireless sensor technology. The projects have been developed as part of the Industrial Affiliates Program, which aims at enriching the educational experience of undergraduate students by providing the opportunity to be exposed to the different aspects of academic and professional life such as research, development, team work, report writing and public speaking.

Projects such as the ones described here provide an effective, hands-on approach to expose undergraduate students to practical problem solving. Through them, undergraduate students at the University of Puerto Rico have acquired experience on the development of wireless sensors. Due to the multi-disciplinary nature of the subject, the projects have provided students with background in several areas of engineering to 17 students. Some of these areas are:

- Sensor technology,
- Sensor characterization and calibration
- Wireless Communications
- Electronics
- Mechanical measurements
- Applied Electromagnetism
- Micro-controllers

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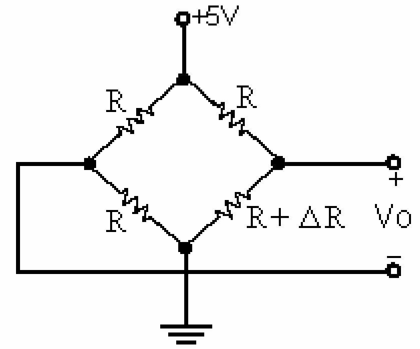

Figure 1 – Wheatstone bridge used for strain measurement.

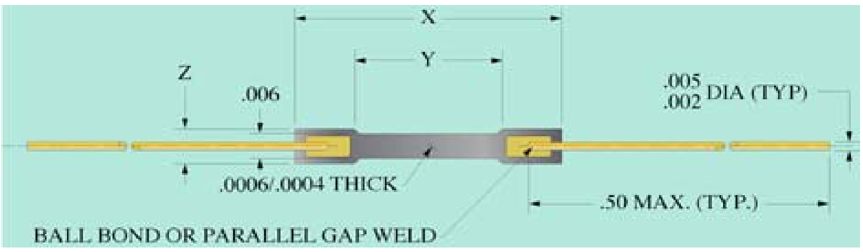

Figure 2 – X=0.027", Y=0.013", Z=0.009" Micro Resistive Strain Gauge

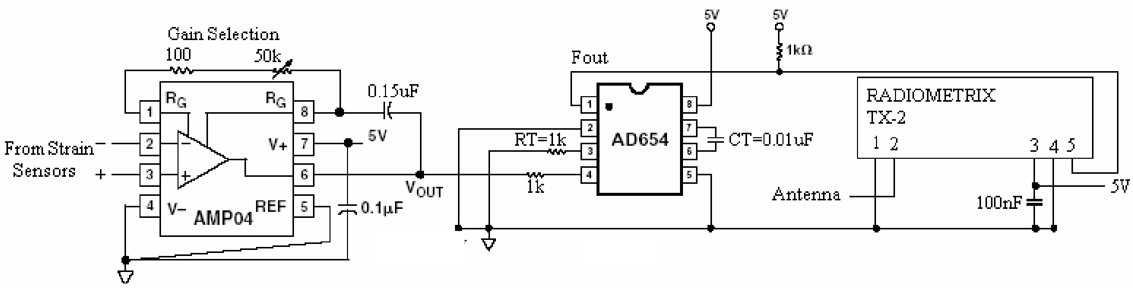

Figure 3 – Schematic for wireless strain measurement circuit.

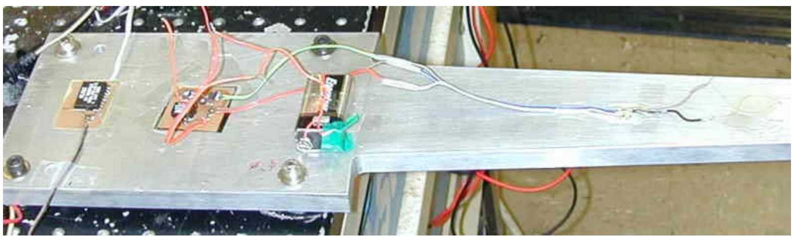

Figure 4 – Photography of the sensor, transmitter and receiver.

Figure 5 – Calibration setup.

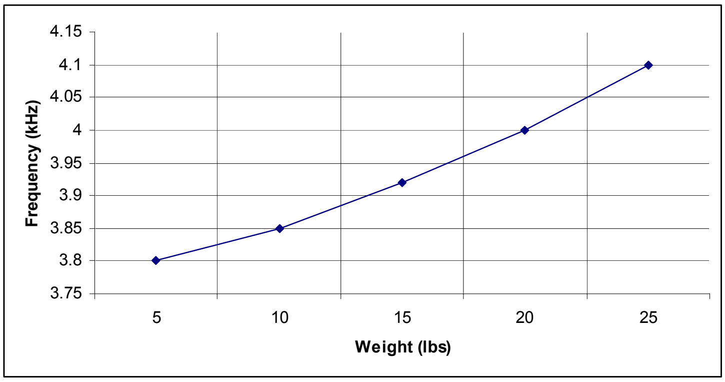

Figure 6 – Results from the rigid beam calibration experiment.

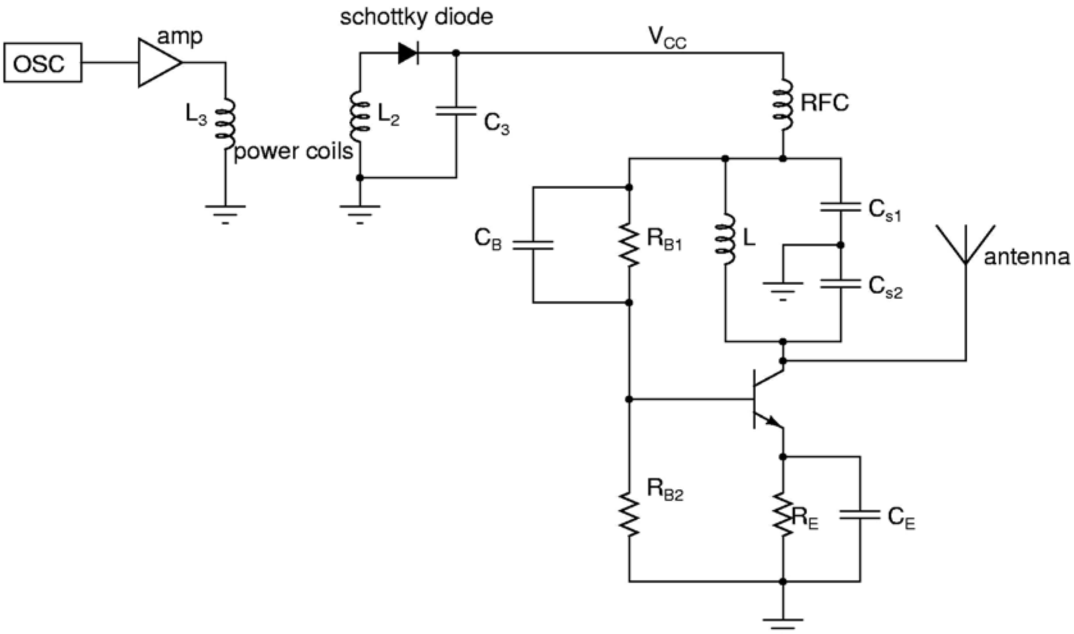

Figure 7 – Wireless sensor circuit schematic.

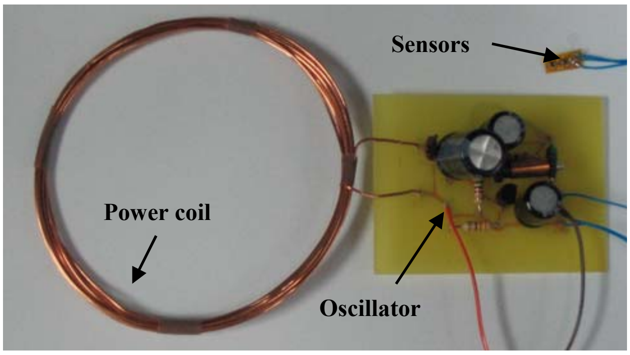

Figure 8 – Battery-less wireless sensor prototype.

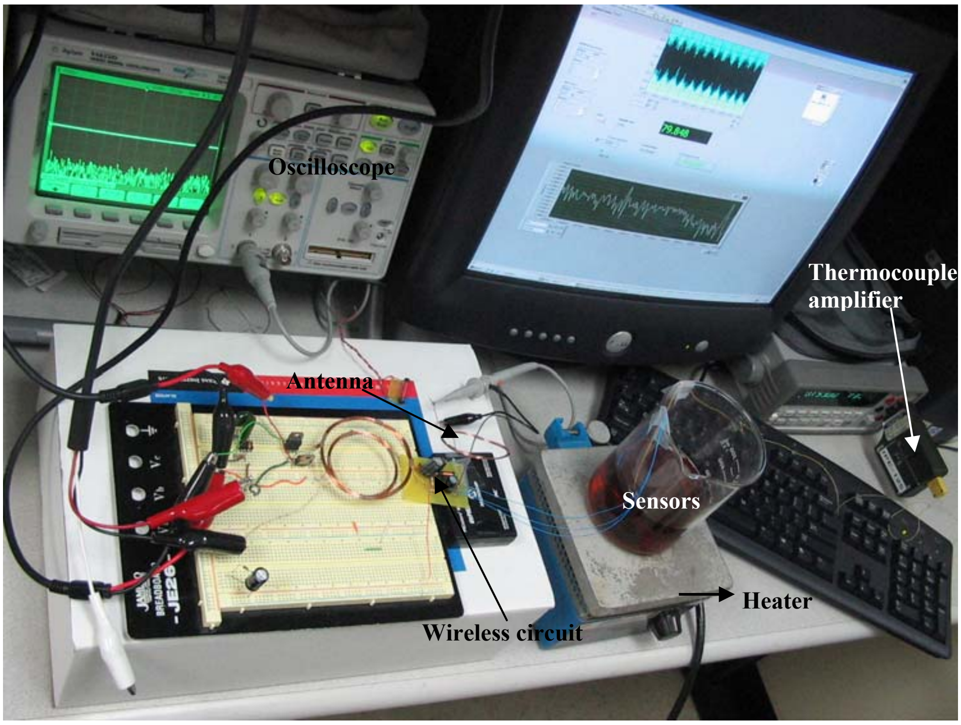

Figure 9 – Sensor calibration Setup

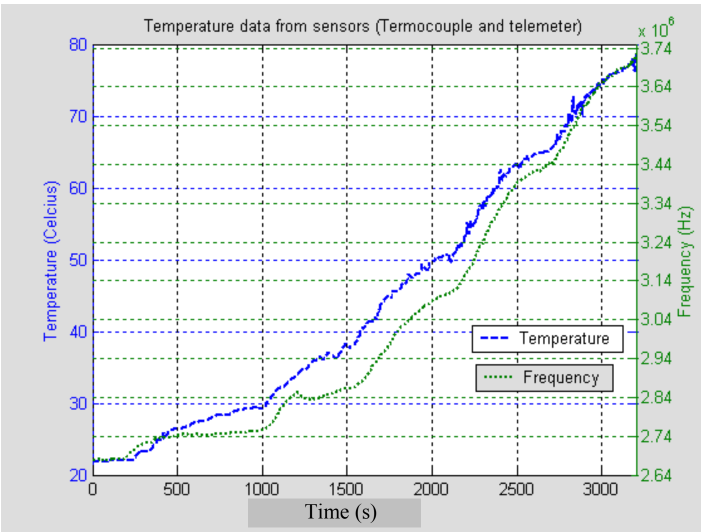

Figure 10 – Sensor calibration data.

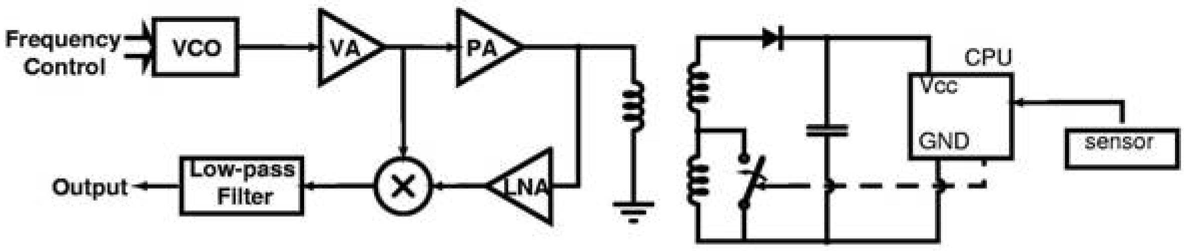

Figure 11 – Micro-processor based wireless sensor interface.

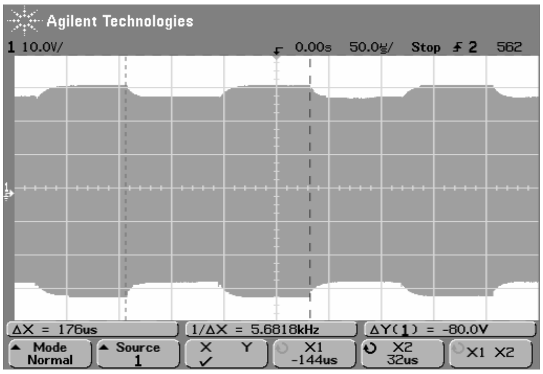

Figure 12 – Voltage change due to changes in the reflected impedance.