IN-SITU RADIO FREQUENCY IDENTIFICATION (RFID)

MOISTURE METER

A THESIS IN
Electrical Engineering

Presented to the Faculty of the University
of Missouri-Kansas City in partial fulfillment of
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MASTERS OF SCIENCE

by
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ABSTRACT

An in-situ moisture meter, utilizing a Radio Frequency Identification (RFID) to detect hidden moisture in walls is studied. Both commercial and household building moisture problems call for a better way to measure moisture within the building envelope. The presence of moisture within the insulating material of the building walls can attribute to the possibility of mold growth. Simple resistor divider type moisture meters are easily realizable but do not always provide the best methodology for detecting moisture levels accurately. An embeddable and unobtrusive means to detect moisture within the wall cavity is studied. The methodology used for detection is an improved type of resistive probe utilizing an integrating amplifier to determine moisture content in typical celluose insulation. To compliment the resistive measurement, a humidity sensor has been added along with a built-in temperature sensor embedded in the MSP430 microcontroller.

The faculty listed below, appointed by the Dean of the School of Computing and Engineering have examined a thesis titled "In-Situ Radio Frequency Identification Moisture Meter", presented by Brian J. Swafford, candidate for the Masters of Science in Electrical Engineering degree, and certify that in their opinion it is worthy of acceptance.

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CHAPTER 1

INTRODUCTION

1.1 Insulation within Building Envelopes

Insulation of buildings in the United States dates back to the 19th century. However it was not until 1937 that building insulation gained official acceptance by any building or construction agency in the United States [1]. The building or thermal envelope defines the living or conditioned space within a building. Within the building envelope the thermal bridge exists which allows heat conduction to occur. The idea of building insulation is to provide a high resistance within the thermal bridge so that heat conduction is impeded. There are several methods which can be used to insulate buildings. The building can be insulated externally with rigid foam or reflective type insulation and also insulated internally, within the wall cavity, using fiberglass batting, spray-in foam or cellulose insulation. In some cases the insulation may be a combination of both batting and spray-in or blown-in type insulation.

The usual practice for insulating the building envelope is to place some type of insulating material within the cavities of the building walls. Within residential homes, the most common type of insulating material is either batting (fiberglass) or spray-in cellulose. Commercial buildings may utilize both batting and spray in type, depending on the cavity which will hold the insulating material. The rigid and reflective type insulating material is usually not the culprit in moisture problems associated with in the building envelope. With the pursuit of more energy efficient buildings, the envelope is made to allow the least amount of air penetration into the building. While this is good for the thermal properties of the building envelope, it allows very little air to be present within the cavities of the building where the insulation resides. The lack of air coupled with the possibility of moisture does not allow the insulating material to dry should it come in contact with an anomalous moisture source. The mixture of both moisture, along with lack of air, provides an environment in which mold can grow and thrive. While ultraviolet lighting can be used to kill mold spores, it is not practical to embed lighting within a wall cavity where changing the bulb, let alone knowing if the light is working, would be very difficult and destructive. The presence of mold, within the indoor environment can lead to mold allergies which can cause asthmatic attacks in people whom have asthma.

Advances in insulation material and techniques can help stem the tide of mold growth should a moisture problem occur, within insulating materials but cannot provide with 100 per cent certainty the elimination of mold growth within moisture compromised insulating material.

1.2 Research Objective

The objective of this research is to investigate an unobtrusive, embeddable device which can be used to measure moisture content with in the wall cavity. The device must be wireless so as to provide a non-destructive method of data retrieval. The device must also not interfere with construction or cause bias when determining moisture content of the insulating material. Cost, ease of use and ease of manufacture will also be considered. To ensure the objectives stated above are met, a commercially available microcontroller (MCU), humidity sensor and integrating amplifier will be investigated to provide a solution for the stated problem. Several methods for detecting moisture are included in the paper by Whiting [2]. The thesis will explore: 1) the effects of mold on personal health; 2) several different methods for measuring moisture within materials, and 3) eventually the method decided upon for implementing an embeddable moisture measurement solution along with the results from a prototype RFID moisture meter.

1.3 In-Situ Moisture Meter

The basis for thesis research is to develop an in-situ moisture sensor which can be used within the building envelope. An in-situ sensor is needed so that during construction, the sensor can be placed so as not to alter or hinder the normal construction process. The need for a non-intrusive and non-destructive method for obtaining the moisture content of the insulation is paramount. A sensor which would need removal to read would not be practical and would defeat the purpose of being non-destructive. In order to avoid costly wiring, the sensors employ Radio Frequency Identification (RFID) technology as the means to retrieve data from various sensors and provide power through the antenna coil. RFID tags are powered by harvesting the radio frequency waves used by RFID readers. The use of RFID technology also eliminates the need for costly batteries to power the sensor. Battery use would also defeat the purpose of a non destructive device since when the battery voltage drops below a certain value, the sensor would cease to operate. Another important aspect of the sensor would be the ability to produce a low cost device. Since many sensors would be needed to be placed throughout the building envelop, cost becomes a factor when considering sensor development. A high cost sensor prohibits the use throughout a large building envelope. Due to the nature of the construction process, the ideal sensor would be durable as it will be embedded within the wall cavity of the building envelope. The sensor must be operational for years at a time without the need for repair. Ideally the sensor would be durable enough that it would last the lifetime of the building. This is especially true for residential homes where the home owners do not want to worry about the need for replacing a sensor which has already been embedded within a finished wall.

While requiring rigorous physical requirements, the electrical requirements are easily met due to the availability of commercially off-the-shelf technology. Even providing for wireless communications is made easier by utilizing components which readily support RFID protocols. Since these sensors will be embedded within the cavity walls constantly ready to report any anomalous moisture events, the requirements for data acquisition are actually quite trivial when compared to the physical aspects. There is no need to provide real time monitoring of events. Moisture anomalies may take several days to months before manifesting into a full blown problem. Therefore the need to acquire data on a continuous basis does not make sense for this type of sensor. This allows the user to read data from the sensor at a rate of no more than once per hour. A more realistic data gathering time frame could be on the order of several hours or perhaps twice a day. Because of this requirement, the amount of data required for transmission is rather small and manageable for ease of offline analysis. Environmental conditions for the sensor will be benign due to the fact that rarely will the sensor see temperature or atmospheric extremes. Temperatures for building cavities may range from -30°C to 45°C [3]. The environmental condition which could be the most problematic would be the moisture itself. Because of the possibility of corrosion due to moisture, some type of conformal coating will be required to protect the components.

CHAPTER 2

MOLD AND MOISTURE

2.1 Mold

Molds are considered fungi and are categorized as neither plant nor animal. In 1969 they were recognized as their own kingdom. There exists more than 100,000 species of molds scattered throughout the Earth. Recently mold has received media attention due to the possible negative health effects associated with its presence. There have even been reports of alleged “toxic molds” present in homes, schools and other commercial buildings although there is limited scientific evidence to support this theory [4]. Molds produce tiny spores which are used to propagate mold growth. Since mold spores are virtually ubiquitous, the elimination or limiting of mold spores is not practical; therefore steps should be taken to help eliminate the conditions for mold growth.

2.2 Mold Growth

The characteristics of mold growth are sometimes described as an “earthy” smell within the home or office building. In some cases, where mold growth is rampant, it can be visibly seen. In order for mold to grow, four critical elements must be available. These four critical elements are: mold spores, a food source, appropriate temperature and considerable moisture. By eliminating any one of the four critical elements, mold growth can be stopped or eliminated. As stated in section 2.1, mold spores are virtually ubiquitous and their elimination is not practical. Therefore, this critical element will not be investigated. The second critical element, a food source, cannot be eliminated or we would be eliminating our means of providing some type of thermal resistance within the wall cavity. Temperature is normally controlled by some type of environmental system such as Heating, Ventilation and Cooling (HVAC) therefore this element is considered to be a controlled variable. Considerable moisture however is a concern for both homeowner and office building. A moisture content of insulating material that provides a relative humidity of 70 per cent or greater is defined as considerable moisture [5]. An anomalous moisture event is often the trigger for mold growth [6]. Left undetected an anomalous moisture event could provide the needed considerable moisture for mold growth to begin. Mold growth can begin in as little as 24 hours [6].

2.3 Mold Health Effects

Mold affects people differently. Common symptoms of people sensitive to mold are nasal stuffiness, eye irritation and wheezing [7]. Those with severe sensitivity may experience fever and/or shortness of breath [7]. The Institute of Medicine (IOM) found there was sufficient evidence of association which links indoor mold exposure to the exacerbation of asthma in sensitive individuals [8]. In 2009 the World Health Organization published additional guidelines for indoor air quality concerning mold. The report lists mold as a possible cause for exacerbation of asthma, along with the need to determine moisture content in several household items, which provides a fertile growing medium for molds [9].

2.4 Mold Detection

Detection of mold, in the home or office building is the key to immediate remediation. However detecting mold may not provide the source of mold growth. Visible mold detection such as that shown in figure 2.1, indicates that it is already too late to stop the mold growth before it becomes out of control.

Figure 2.1 Black molds on wall

It is therefore important to identify any anomalous moisture source before mold growth becomes out of control.

2.5 Moisture Detection

Moisture detection within the building envelop is key to preventing mold growth, mildew and a host of other problems associated with moisture. The moisture sensor must be unobtrusive, non-destructive, reliable and be able to accurately measure the moisture content within the wall cavity. Moisture content refers to the amount of water which is present in a solid material. This is different from humidity which is the measure of water present in air. The standard test method used for measuring moisture content within organic and non-organic insulating material is defined in ASTM C1616-07e1. This method compares the weight of the specimen before and after performing the oven drying method as described in the standard. The moisture content is given by the following equation,

$$MC = 100\left[\frac{(W_I - W_{MF})}{W_{MF}}\right]\% \tag{1}$$

Where

MC = moisture content weight, percent,

W_I = initial specimen weight, lb (g),

W_{MF} = specimen weight moisture free, lb (g)

The specimen is placed in an air-circulating oven at a temperature no higher than 230 ± 10° F for a minimum of 2 hours. The specimens are then cooled in a desiccator to room temperature and then weighed. This weight will be recorded and used as the specimen weight, moisture free. This process is repeated until the specimen weights are within 0.2% of the last recorded weight. The method used for this research will dry the specimen at the desired temperature and then the specimen will be weighed. Because of equipment limitations, the exact drying method as discussed in ASTM C1616-07e1, cannot be performed. However every attempt is made to ensure a moisture free specimen is maintained within the equipment limitations.

Due to the hazardous nature of insulation and the requirement for personal protective equipment when handling, a cellulose sponge was proposed for use to investigate the concept of the moisture meter decided upon for this thesis research but proved too unreliable. This is discussed further in section 5.1 as to the drawbacks of using a cellulose sponge. Discussion about use with commercially available insulation will be discussed in the future work section.

2.6 Moisture Measurement Techniques

In determining whether a moisture problem exists, it is useful to measure both the moisture content and the surrounding humidity. Another useful measure is temperature. Temperature can determine whether the insulation material has been compromised by degradation due to moisture. Two quantities which are related are humidity and moisture content. A high humidity in the air surrounding the wall cavity will tend to lead to higher moisture content with in the insulating material. The used of both moisture content and humidity can lead to a more accurate measurement of the moisture within solid materials, specifically in this case insulating material. There are several methods which can be used to determine moisture content within a building envelope. The following paragraph discusses the methods that could be incorporated for an in situ type moisture detection system.

2.6.1 Gravimetric Plugs

As discussed in 2.5, one of the more accurate methods of determining moisture content is to weigh known dry samples versus a moisture laden sample. This can be accomplished with the use of removable plugs, which are situated in the wall, at various intervals, and then removed periodically to be weighed. This would determine the value of the initial specimen weight. By utilizing the method of drying discussed in ASTM C1616-o7e1, the specimen is then weighed again to determine the moisture free weight. Utilizing this method can yield accuracies which are both excellent and repeatable. This method, although accurate, provides for several drawbacks. The construction material must be drilled to provide a space for the plug. This method also requires several areas be drilled so as to provide a good distribution of area to be measured. Drilling holes in walls and the subsequent removal for measurement would be extremely labor intensive. This type of measurement would be extremely difficult to automate. Another disadvantage of this method is the hole drilled may be slightly larger than the intended plug. This would leave an air gap between the insulating material and the plug itself which could alter moisture transport from material to plug material. The plug itself would also be subject to degradation over time and would tend to provide inaccurate moisture measurement.

2.6.2 Nuclear Method

By utilizing a collimated beam of gamma rays, a method for measuring the attenuation of gamma rays through a dry porous medium when compared to the attenuation of gamma rays through a wet medium, moisture content can determine [10]. Another method is the use of Nuclear Magnetic Resonance (NMR). Utilizing this method applies a known magnetic field to the specimen. This causes the hydrogen atom to be excited from its initial ground-level energy state. This is related to observing spin-lattice relaxation time and spin-spin relaxation time [10]. The energy levels are monitored constantly and the decay time is used to indicate the amount of hydrogen. Since water molecules contain two hydrogen atoms, the amount of hydrogen is related to the amount of water [10]. NMR has been in use to examine the moisture content of building materials since the late 1970s [11]. This method of determining moisture content while although can be very accurate, has its drawbacks. One of the bigger drawbacks is the size of components. The smallest of sensors are still 85 mm in diameter and 53 mm in depth. The other factor in limiting the use of NMR is the cost of components which does not appear to be decreasing anytime in the foreseeable future.

2.6.3 Thermal Conductivity

Moisture within a material will affect its thermal conductivity. Changes in moisture content thermal conduct both sensitively and linearly as to yield a good measure of moisture content within the material [12]. One method known as the hot wire method, introduces a known temperature change along a wire and then the resulting change in temperature is measured over time. Another method is utilizing a thermistor. This is similar to the hot wire method except the thermistor introduces short pulses of heat into the insulating material and is then used to measures the transient decay of the insulating material [12]. The only drawback to this method of moisture content measurement is accuracy discrepancies.

2.6.4 Electrical Method

There are two main electrical methods which will be discussed here. The first method is electrical resistance. This remains one of the most popular techniques for determining moisture content [10]. Utilizing two probes, the direct current resistance can be measured through various solids. This method utilizes the medium which is to be measured for moisture content as the resistor. It has been shown that the introduction of moisture to a solid affects the resistance of the solid. Wood for instance has a very high electrical resistance when dry, but when moisture is introduced into wood the electrical resistance decreases. The other method in determining the moisture content of a material is through the use of electrical capacitance. This technique involves using the buildings insulating material as the dielectric material between to conductors. The capacitance of water is about 10 to 20 times greater than that of insulation material. This would make detecting moisture presence within the insulating material ideal utilizing the capacitance method. Conductors placed within the wall cavity form a capacitor with the insulating material providing the dielectric between the two conductors. Moisture introduced into the insulating material will affect the capacitance which can be translated to moisture content. The problem with this method is the area where the moisture resides may encompass a large area making exact location of the moisture anomaly difficult to pinpoint. Another problem affecting the use of capacitance as a means of detecting moisture is their low accuracy [3].

2.6.5 Infrared Technique

The use of infrared techniques in the past has been used as a means of detecting temperature variations within the building envelope. This method involves using an infrared camera to detect temperature anomalies and determining whether the anomaly is related to moisture content. This type of measurement does not suit the needs for an in situ type device. Use of infrared LED devices is an area which may prove to hold some success in the detection of moisture anomalies but as of this writing, no literature was found that is trying to utilize this technique.

2.6.6 Humidity Method

Utilization of humidity sensors to measure the moisture content within the wall cavity has been utilized in the past. Due to the availability of various types of humidity sensors, in situ type moisture detection systems, utilizing this method, can be quite easily realized. Commercial off the shelf parts also make this type of sensor very cost effective. There are many papers which discuss this technique for determining moisture content which go beyond the scope of this paper. As of this writing the most accurate humidity sensor, suitable for in situ type devices provides an accuracy of ± 3%. There has been research completed where small humidity sensors were embedded in the wall cavity and using sorption isotherms the humidity readings were translated to moisture content [3].

The main drawback with using humidity sensors is that as the humidity approaches 100% the sensors are prone to damage. The humidity sensor also requires temperature corrections to provide accurate readings. Another drawback is the relationship for sorption isotherms are not well established for a wide range of materials.

2.6.6 Commercially Available Meters

Commercially available solutions for in-situ type meters is non-existent as of this writing. No commercial products could be found. However there are several commercial solutions for measuring moisture in various types of building materials. These materials include wood, gypsum and concrete. Typical moisture meters for measuring moisture content in wood require physical contact with the material. Two, sharp probes are used to penetrate the wood and measure the moisture content. Typical wood moisture meters can costs several hundred dollars. However there are commercially available products which can measure moisture content in all three mediums discussed above. The main drawback to these meters, other than concrete, is they require physical contact which causes damage to the material.

CHAPTER 3

MOISTURE CIRCUITS

3.1 Moisture Sensor Circuits

As discussed in section 2.6 there exists many different means to measure moisture content within the wall cavity. This section focuses on the electrical methods as a means of determining moisture content within the building envelope. The two methods described in section 2.6.4 were the resistive and capacitive type methods. The first electrical circuit is the voltage or potential divider which utilizes the medium in question as one of the resistors in the divider network. The capacitance method utilizes the medium in question as the dielectric material for a capacitor. A method for utilizing the resistive method in an alternative form will also be discussed.

3.2 The Voltage Divider

The voltage or potential divider is a basic linear circuit which provides an output voltage that is a fraction of the input voltage. A typical voltage divider is shown in figure 3.1.

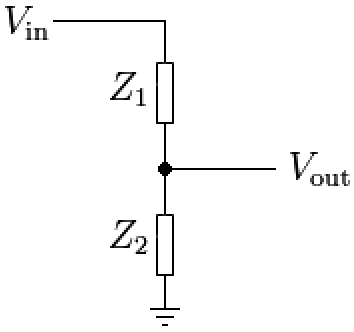


Figure 3.1 Basic voltage divider

The input voltage V_{in}, induces a current *i* through the two impedances Z_1 and Z_2. Since the current is the same through the series resistance the voltage drop across the impedance must follow ohms law. This causes a fractional output voltage V_{out}. The output voltage for a divider is given by the equation.

$$V_{out} = V_{in} \frac{Z_2}{(Z_1 + Z_2)} \tag{2}$$

The method for utilizing the voltage divider in a moisture measuring circuit would be to fix either Z_1 or Z_2 and let the non-fixed impedance be the impedance of the insulating material. When utilizing the voltage divider style of measurement a problem arises with the impedance value of the insulating material, which when dry, tends to be extremely high, usually on the order of hundreds of mega-ohms perhaps even giga-ohms. If Z_2 is used as the insulating materials impedance then dry insulation would cause the output voltage to be very close to the input voltage. If Z_1 is used as the insulating material impedance the dry insulation would cause the output voltage to be a very small fraction of the input voltage. Large impedance values such as those found in dry insulating material are subject to noise problems. A small fluctuation in current through large impedances will cause larger voltage drops and therefore more error.

3.3 Capacitive Technique

A basic capacitor consists of two conductors separated by a non-conducting or dielectric material. The capacitor equation is given by.

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} \tag{3}$$

Where

A = area of the conductors,

d = distance between the two conductors,

ε_r = relative static permittivity,

ε_0 = electric constant of air ($\approx 8.854 \times 10^{-12}$ F m^{-1}).

In the case of utilizing a capacitive type detection scheme, two conductors are made available on the circuit board. This method would require two conductive pads, on the same layer of the board with the insulating material providing the dielectric material. When the insulating material is dry, the dielectric would be of a fixed value determined by experimental measurement techniques. The dielectric constant of water is $\varepsilon_0 = 83$. The typical dielectric constant for cellulose insulation is $\varepsilon_r = 3.2 - 7.5$ pF/m and fiberglass insulation dielectric constant is $\varepsilon_r = 4 - 6$ pF/m [13]. The introduction of moisture to either of the materials would cause an increase in the dielectric constant which would cause as change in capacitance as shown in equation 3.

There are several different methods available by which the capacitive technique can be used. Two of the techniques are discussed here. The first technique is the oscillator technique. Utilizing the oscillator technique involves setting the frequency of an oscillator via the capacitor. As the capacitance changes, due to moisture content, so does the frequency of the oscillator. This change can be measured and translated into a moisture content reading. The second method is the charge based technique. This requires a reference capacitor which is charged via a reference voltage, the moisture measuring capacitance is then switched into the circuit. Ideally the total charge would remain the same and by measuring the output voltage the capacitance for the moisture content could be determined by the following equation.

$$C_{MC} = C_{REF}\,(V_{REF} / V_{OUT} - 1) \tag{4}$$

Unfortunately ideal systems do not exist and the circuit is prone to errors due to leakage currents [14]. As with the resistive technique, a method for calibration will need to be developed to ensure the accuracy of moisture content values.

3.4 Integrating Amplifier Approach

Another approach used for this research was to implement an integrating operational amplifier or integrator for short, to attempt measurement of the moisture content of the insulating material. The integrator utilizes a capacitor in the feedback. Although this method utilizes a resistance to measure moisture content the integrator approach mitigates the effects of large resistances by using the small current flowing through the resistance to charge the capacitor which produces a linear output that can be used to measure the resistance of the material and relate the measurement to moisture content. The complete operation of this method will be discussed in chapter 4. This technique could also be measured against a commercial meter to provide accuracy ratings and to develop a method to calibrate the sensor depending on the sensing medium.

CHAPTER 4

INTEGRATOR MOISTURE METER

4.1 The Integrator Approach

As discussed in 3.3, the integrator can be used to charge a fixed capacitance in the feedback loop. Figure 4.1 shows a basic integrator circuit.

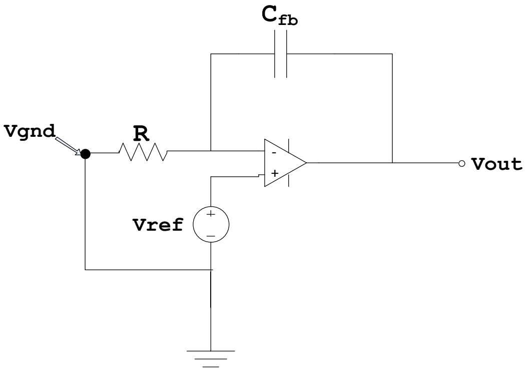


Figure 4.1 Basic integrator circuit

As the name implies the purpose of the integrating op amp is to provide the mathematical equivalent of integration. The output of the circuit responds to changes in the input voltage over time. The output signal depends on how long the input signal is present as the feedback capacitor is charged by the input signal. For the basic integrator circuit presented in figure 4.1 the output voltage is given by

$$V_{out} = V_{ref} + V_C \tag{5}$$

An ideal op-amp will draw no current into the input terminals therefore we will look at the current through the capacitor which is given in the following equation

$$i_c(t) = C\ \frac{dV_C}{dt} \tag{6}$$

Rearranging equation 6 to get the voltage across the capacitor yields

$$dV_C = \frac{i_c}{C}dt \tag{7}$$

Integrating both sides equation 7

$$V_C = \int \frac{i_c}{C}dt \tag{8}$$

Using equation 8 and substituting into equation 5 V_{out} becomes

$$V_{out} = \ Vref + \int \frac{i_c}{C}dt \tag{9}$$

Substituting for i_c

$$V_{out} = \ V_{ref} + \int \frac{V_{gnd}}{RC}dt \tag{10}$$

Integrating and setting $V_{gnd} = V_{ref}$ using the virtual ground properties of an ideal op-amp yields

$$V_{out}(t) = V_{ref} + \left(\frac{V_{ref}}{RC} \, x \, T\right) \tag{11}$$

This circuit provides an output voltage that is proportional to the time-integral of the input voltage, with RC being the integration time constant [14]. For the research project in this thesis, the circuit is implemented as shown in figure 4.2.

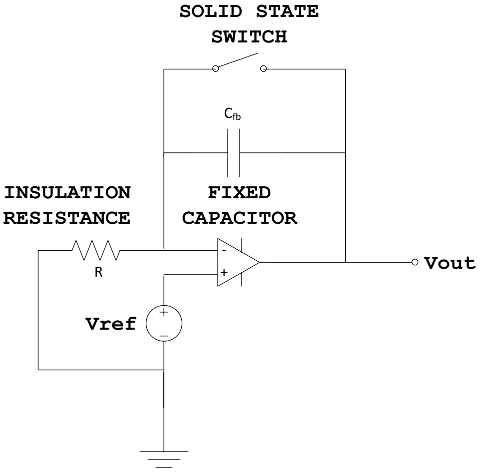


Figure 4.2 Moisture meter integrator circuit

The circuit in figure 4.2 utilizes the integration amplifier to measure the insulation resistance. The value of the insulation resistance will determine the integration time constant as the value of C_{fb} is held at a fixed value. The solid state switch is implemented with a FET which is used to reset the capacitor at the beginning of the moisture reading. Holding the voltage of V_{ref} to a known value and utilizing a LDO regulator to provide a known value for the supply voltage, the integrator will be used to measure the time required for the circuit to go from V_{ref} to the supply voltage. Equation 11 is then manipulated to provide the resistance of the medium material so that an algorithm can be developed to determine moisture content. Another obstacle which must be overcome is a way to query multiple moisture meters at once utilizing a large scale RFID reader scheme. The method for this is beyond the scope of this research and would provide an excellent platform for another research project. The overall schematic used for the moisture meter is discussed in chapter 5.

4.2 Utilizing RFID

Radio Frequency Identification or RFID can be traced back to World War II with the implementation of Identify Friend or Foe (IFF). The modern version more widely know today was developed in the 1970's. Los Alamos National Laboratory, under the Department of Energy, developed a method to passively interrogate a tag, via a radio frequency device, and receive data back from the tag [15]. Thus began the age of RFID. There are several ISO standards which govern RFID technology but there is no globally governing body to regulate the use of frequencies for RFID. The RFID circuit must be able to use the harvested energy from the RFID reader to perform the necessary operations. The thesis presented here utilizes RFID to perform the necessary operations for measuring moisture content. The ISO standard 15693, vicinity cards, was chosen for implementation of this project. ISO 15693 utilizes the frequency of 13.56 MHz to perform interrogation of the RFID device. Although the standard states the operational range to be 1 to 1.5 meters, the actual distance was found to be much less, being more in the maximum range of about 4 to 5 inches depending on the type of antenna used [16]. The approach used in this thesis utilized an antenna made with several turns of copper wire. The overall diameter of the antenna is about 1-1/4 inches. The size of the antenna along with the limited power of the reader is the cause which restricted the useable distance. The structure of commands utilizing the ISO 15693 standard is covered in part 3 of the standard. For this project the command structure is not covered as it is considered to be common knowledge.

An important part of the RFID device is the design of the antenna. The antenna is tuned via a tuning capacitor which is placed in parallel with the antenna. This type of antenna offers two distinct advantages over an integrated antenna. One is that the PCB design can be simple and will not require methods to reduce RF interference. The second is the PCB may be made smaller thus allowing a more compact design to be used. The disadvantages to an off-board antenna are the design may not be compact and may be prone to breakage during installation. The antenna size will also determine the read range of the RFID device. Again the design of the antenna is considered to be beyond the scope of this research and would provide an area for another research project. For this research project, we employed ST Microelectronic's M24LR64-R contactless memory as a modem to handle the RFID communication protocol. The M24LR64 memory is unique in that the memory may communicate via RFID or I^2C [17]. Utilizing this feature, the temperature, humidity, rectifier voltage and moisture content reading is written via I^2C and the values are read via RFID via the ISO 15693 standard. This greatly simplifies the design and allows integration with an MCU to perform all the necessary measurement operations.

4.3 Microcontroller (MCU)

The use of an MCU for providing the controls behind the in situ moisture meter stems from the requirement that the measuring devices must be small. A self imposed requirement was the need for low power devices. Several manufacturers offer low power MCUs with varying options and packages. The MCU chosen for this project is the Texas Instruments MSP430. The specific MCU used is the MSP430F2012. Programming the MCU is accomplished using the C language protocol. This particular MCU was chosen for its low power operation and fast wakeup times from the low power mode. The MSP430F2012 offers a 10-bit Analog to Digital Convertor (ADC). It also includes a 16 bit timer with two capture/compare functions [18]. The 10-bit (ADC) will be utilized to measure temperature, rectifier voltage level, humidity and the timer function will be used to measure the voltage level of the integrator at a predetermined time which will be used to determine moisture content. The MSP430F2012 also has built in I^2C port which will be used to communicate with the M24LR64 memory. An I/O port of the MCU is used to control the application of a write voltage to the memory when utilizing the I^2C protocol. The MCU also controls the switch used to reset the capacitor of the integrator utilizing the P2.6 output port. The programming flow chart which describes the method of data acquisition is detailed in figure 5.3.

4.4 Humidity and Moisture Sensing

As discussed in the various techniques for measuring moisture content, humidity is a valid method for determining moisture content within the wall cavity. Combining both a method to determine moisture content and humidity is one of the thrusts of this research. Utilizing humidity sensor and moisture circuitry, a method is developed for increasing the overall robustness of the moisture meter. The Honeywell HIH-5031 humidity sensor was chosen for this project because of size and the low power consumption of the device [19].

4.5 Temperature Measurement

Providing temperature measurement for this project provides two benefits. The first is to provide temperature readings to determine if there is damage to the insulating material which would inhibit the ability to provide thermal resistance. This may include the settling of loose insulating material or thin spots of sprayed insulation. The second benefit which is easily overlooked; wet insulating material retains heat from warmer daytime temperatures which can easily be detected by nighttime temperature readings. This method is used primarily by infrared scanning techniques but is an added benefit for the moisture meter circuit [20]. The MSP430 provides an integrated temperature sensor in the MCU and is utilized to measure the temperature for this thesis project.

CHAPTER 5

EXPERIMENT

5.1 RFID Moisture Meter Circuit

The moisture meter circuit discussed in section 4.1 block diagram is detailed in figure 5.1.

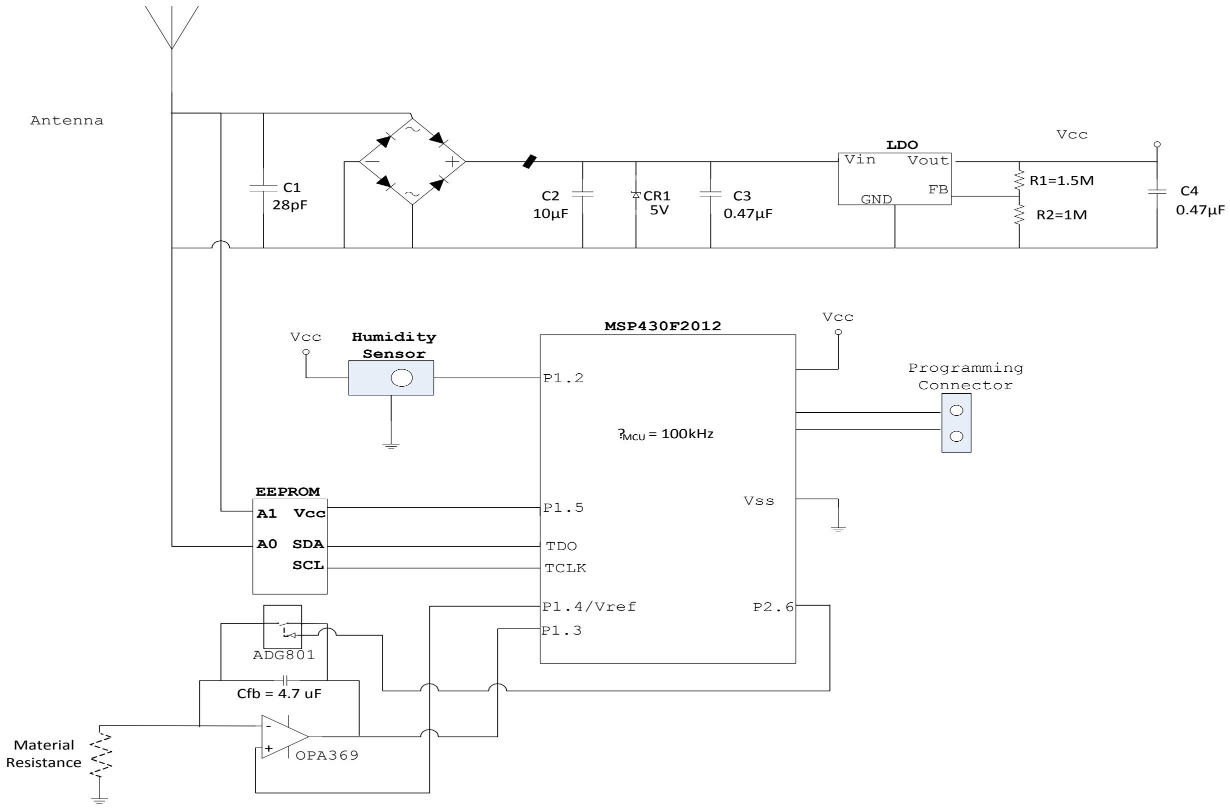


Figure 5.1 Simple block diagram of moisture meter

The MCU provides the controls of the moisture meter by controlling all sensor readings and handles the I2C communications to the EEPROM memory. The MCU also executes the user commands as issued by the user as to which sensor will be read. Figure 5.2 shows the diagram for the antenna, board and laptop computer. A detailed schematic of the entire circuit is in Appendix A.

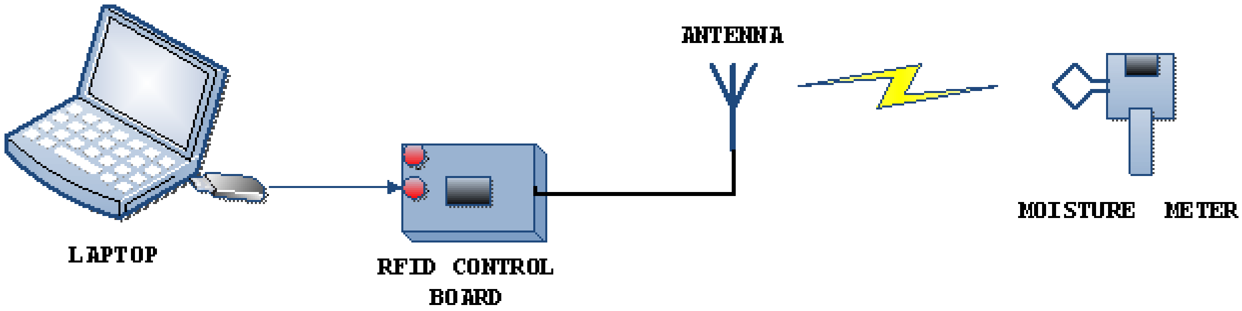


Figure 5.2 Communication block diagram

The MCUs firmware was written in C. Figure 5.3 presents the flow chart diagram of the MCUs firmware program.

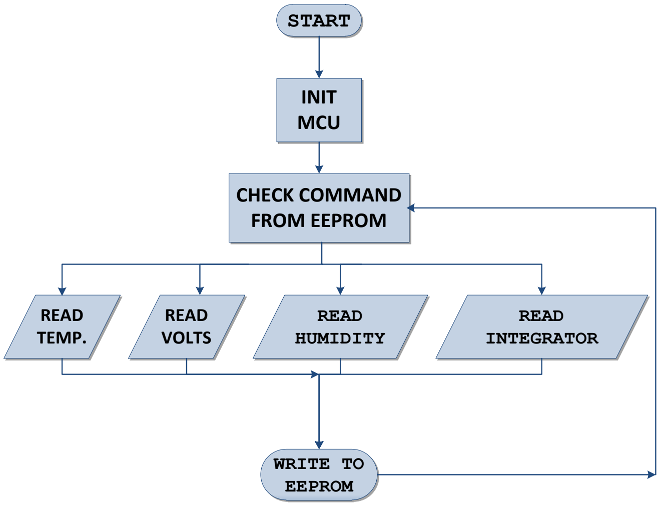


Figure 5.3 Flow diagram MCU program

The program initializes the MCU to utilize the built in I2C function, ADC and timer along with the internal voltage reference which is utilized to bias the integrating amplifier at 1.5 volts. The MCU also provides the unique access to the EEPROM. Asserting the *Vcc* pin high on the EEPROM, allows the data to be communicated via the I2C interface. When reading the EEPROM memory with the RFID reader, the power is provided via the antenna pins.

Utilizing both the humidity sensor and integrator as the moisture sensor, a more robust method to determine the moisture content is to be investigated for this thesis paper.

5.2 Experiment Setup

Ideally, we would like to use an experimental setup to measure moisture in both cellulose and fiberglass batting insulation. Due to the hazards involved in handling both types of insulation, a cellulose sponge was proposed as the chosen medium to measure moisture content. The cellulose sponge proved to be a poor choice for testing moisture content because cellulose sponges can hold many times their weight in water and proved to be unreliable as a medium to measure moisture content. To simulate insulation electrical resistance, several different values of resistors were used. To test how well the board would work with real world building materials, a small piece of cedar, with two nails driven into the board, was used to measure resistance with varying moisture content. Resistance of the test resistors ranged from 249 kilo ohms to 10 Mega ohms. Wood has a resistance around 10^{14} when dry to 10^{3} to 10^{4} at fiber saturation [21]. Figure 5.4 shows the moisture meter board for the experiments conducted for this thesis paper.

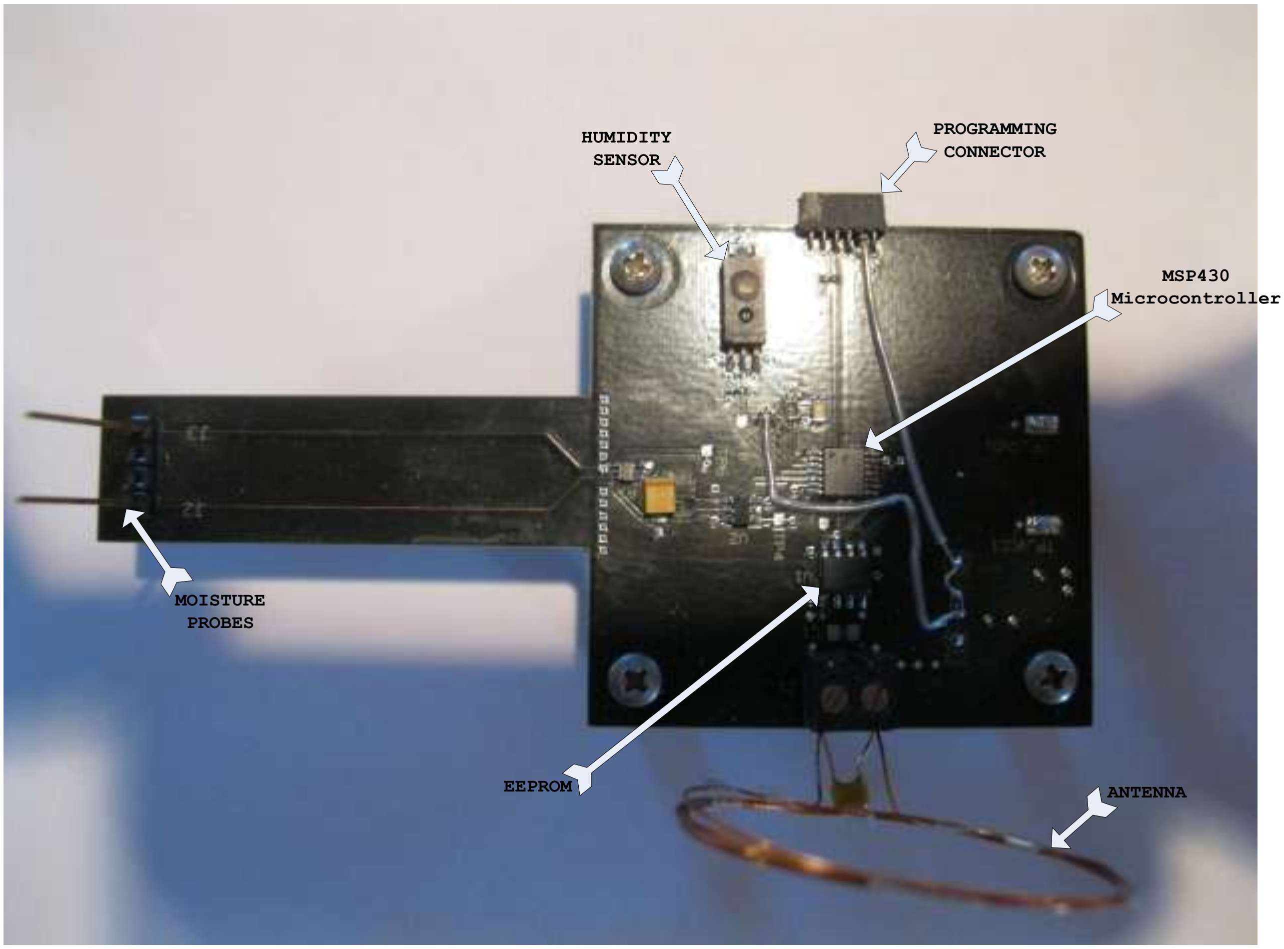


Figure 5.4 RFID moisture meter board

The board shows the makeshift antenna and tuning capacitor used along with the moisture probes on the left side of the board. The intent of the design is to allow the probes to be placed in the insulating material, while being wetted, without affecting the other parts of the circuit board. To use in a wet area the board would need some type of conformal coating and the humidity sensor would need to be the enclosed type.

5.3 Detecting Moisture Content in Insulation

To simulate the moisture content of insulation, different resistors of varying values were used. This method is proved to be much easier to control and the resistors could easily be changed with little difficulty. The ability to measure resistance is the main focus in measuring moisture content. In this thesis paper, the integrator circuit is used to calculate an unknown resistance of a particular medium. Moisture content of wood at 28 percent is considered to be very wet and decay begins to happen until the moisture content reaches below 20 per cent [22]. The prototype board utilizes the integrator amplifier as stated in section 4.1 with C_{fb} of 4.7 μF. The capacitance was chosen so that at high moisture content, the microcontroller timer function used to measure the ramping voltage could provide a mid-range scale. While measuring dry insulation, the board will report a voltage close to or at *Vref* of 1.51 volts. With the timer of the microcontroller set to provide a mid-range voltage of the ramp, simulated wet insulation will yield a voltage of between 2 and 2.2 volts. This provides a range of about 0.5 to 0.7 volts to measure the moisture content. Figure 5.5 shows the timing graph of the voltage ramp measuring schema.

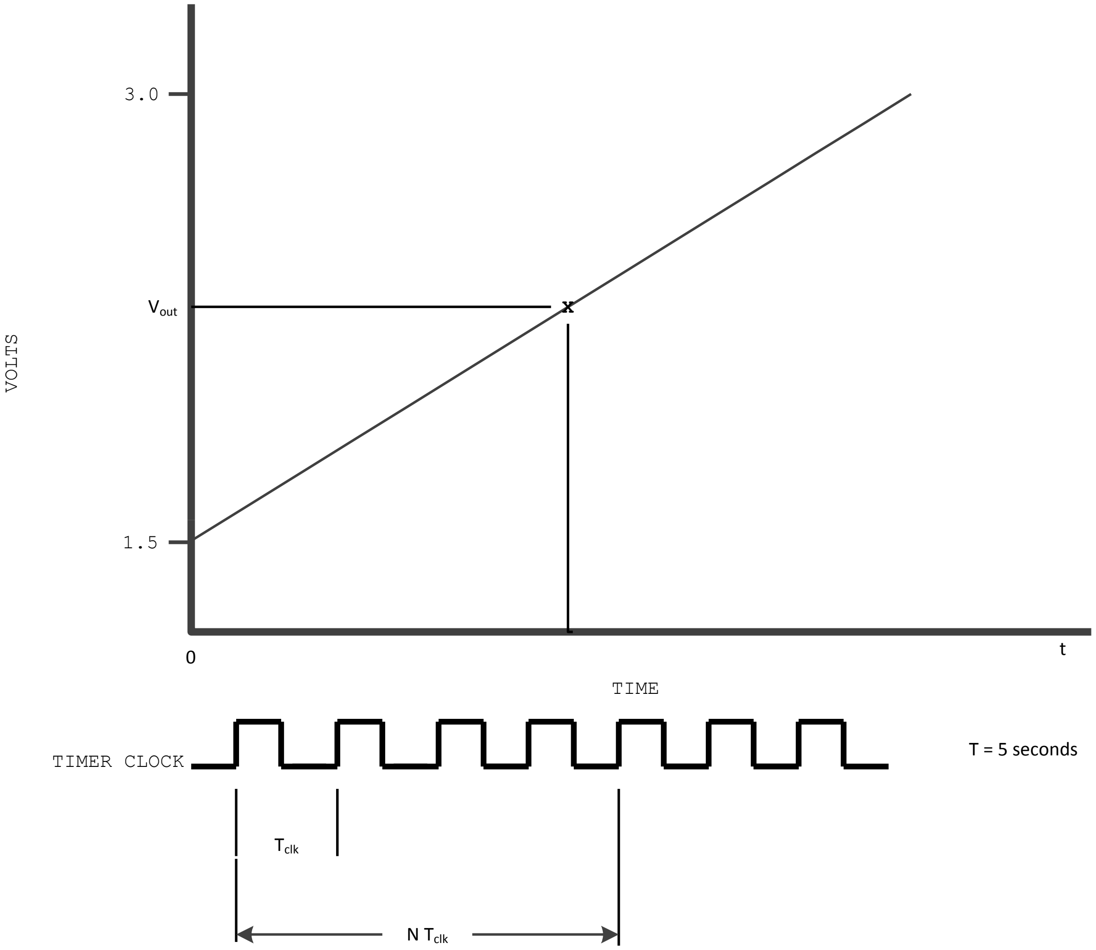


Figure 5.5 Integrator output voltage measurement

5.4 Humidity and Temperature

As discussed in Section 2.6.6 a method can be developed which utilizes the humidity reading to use isotherm tables to determine moisture content. Humidity levels of 70 percent or higher present an excellent environment in which mold can thrive as discussed in section 2.2. Utilizing the humidity sensor is expected to help make the designed moisture meter more robust in detecting moisture anomalies. The temperature reading will also help to provide better insight into the environment within the enclosed wall. The temperature sensor also adds the benefit of being able to detect cold and hot spots within the wall cavity which could be an indication of deteriorating insulation. This also helps to eliminate the need to use costly and time consuming infrared camera readings.

5.5 Use of Proposed RFID Moisture Meter

The use of RFID will eliminate the need to use destructive testing to find moisture anomalies within the wall cavity. By utilizing RFID, the moisture meter can harvest the RFID interrogation energy to provide power to the circuit via a rectifier and Low Dropout (LDO) regulator. The setup for this experiment utilizes an LDO to provide a regulated 3.0 volts to power the sensor board. Harvesting the RFID reader's energy eliminates the need for batteries which would defeat the purpose of a non-destructive method of measuring moisture content. The use of ST Microelectronic's RFID EEPROM greatly simplifies the circuitry necessary to handle communications. To aid in easily reading the moisture meter, a MATLAB program is used to query the meter using a commercially available RFID reader (Melexis DEMO9012LR). The MATLAB program queries the board to provide the following readings: 1) temperature, 2) humidity, 3) rectifier voltage and 4) integrator output voltage, the latter which will be used to determine moisture content. The MATLAB program provides a platform to perform all necessary data conversions. A production style meter would require a small handheld device which could query the meter via RFID and readily provide the above information. Because our sensor fully supports the RFID standard ISO 15693, any other RFID commercially available reader can be employed.

5.6 Experimental Procedure and Data

The moisture meter setup, with RFID transponder, is shown in figure 5.4.

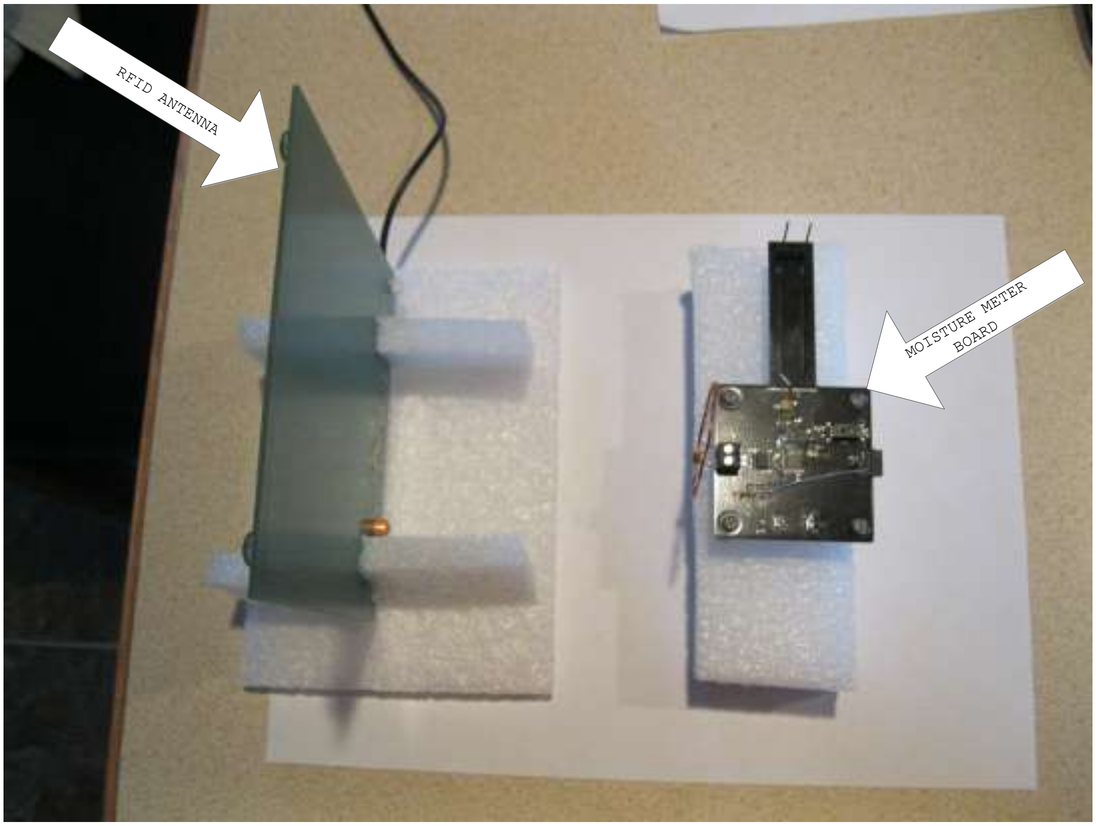


Figure 5.6 Experimental setup

The board was placed at a distance to ensure the LDO would provide a steady 3.0 volts output. The best distance found was to be about 4.5 inches from the RFID reader antenna board. This provided consistent readings and no lost information. MATLAB communicates to the Melexis reader via a USB to RS-232 converter.

Once the MCU is programmed, via the USB programmer, the board is removed from the programmer and placed in front of the reader. A chosen resistance is placed across the two moisture probes on the board and the integrator output voltage reading is taken. Temperature and humidity samples were also taken although they provided only ambient readings. A small handheld meter was used to measure the accuracy of the moisture meter board's temperature and humidity sensor. This setup is shown in figure 5.7.

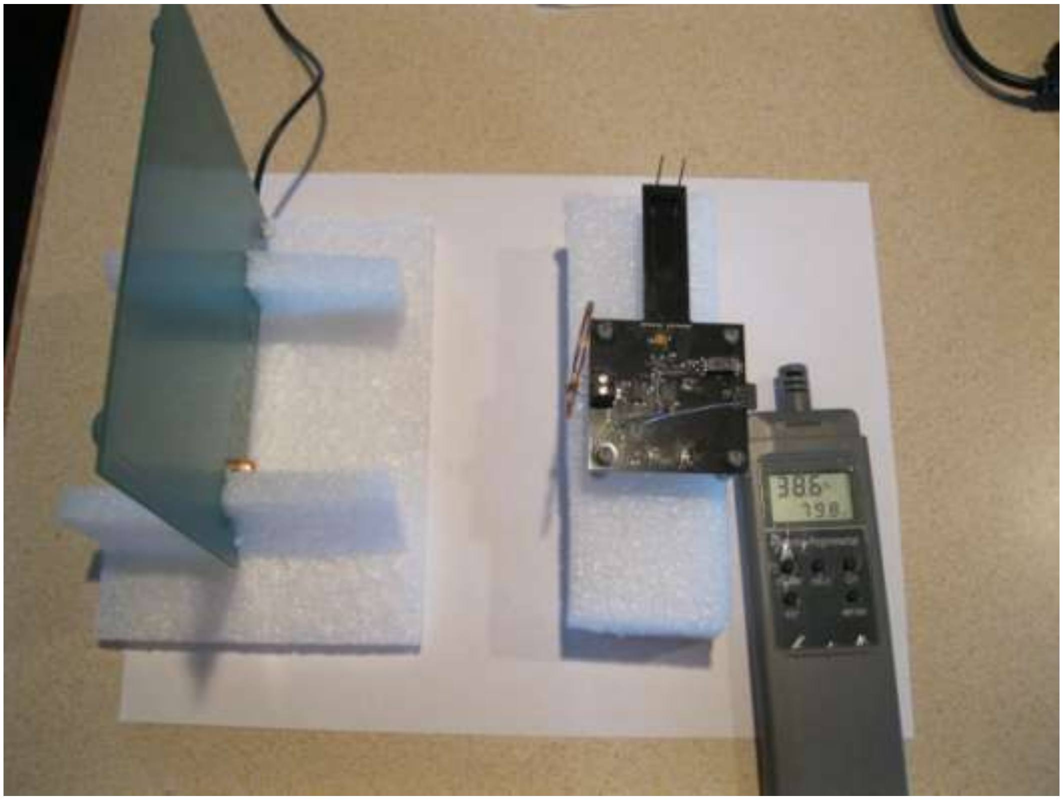


Figure 5.7 Experimental setup

Table 5.1 shows the temperature and humidity readings that were taken from the moisture meter board via RFID and those of the hand held meter. The results show good accuracy for the RFID-based humidity sensor which was expected to have an accuracy of about 5 percent. The temperature readings also show the MCUs onboard temperature sensor can provide accurate temperature readings. Three readings were taken for each device.

TABLE 5.1 Temperature and humidity readings

	Handheld device reading 1	RFID board reading 1	Handheld device reading 2	RFID board reading 2	Handheld device reading 3	RFID board reading 3
Temperature	79.8 ° F	80.2° F	79.8 ° F	80.2° F	79.8 ° F	80.2° F
Humidity	38.6 %	39.2 %	38.6 %	39.2 %	38.6 %	39.2 %

The temperature reading is calculated with the following formula as given in the datasheet for the MSP430F2012.

$$Temp\ {}^{\circ}\mathrm{C} = \frac{V_{temp} - 0.986}{0.00355} \tag{12}$$

Where

$$V_{temp} = \frac{ADC\_OUTPUT}{1024}\, x\ 3 \tag{13}$$

The humidity reading is calculated with the following formula as given in the data sheet for the HIH-5030 humidity sensor.

$$RH = \frac{V_{humid} - 0.4545}{0.0198} \tag{14}$$

Where

$$V_{humid} = \frac{ADC\_OUTPUT}{1024}\, x\ 3 \tag{15}$$

The humidity sensor agrees with the handheld device within 1 percent which is better than expected according the HIH-5030 humidity sensor data sheet [19]. An accuracy of 3 percent is considered good for humidity sensors given they are some of the most difficult sensors to calibrate. With the humidity readings proving to be very close to the handheld device, it is believed this will provide an excellent means to ensure the robustness of the moisture probes since moisture content can be related to sorption isotherms, for differing material, as discussed in section 2.

To measure simulated moisture across the probes, a known resistance was inserted between the two probes. This method is shown in figure 5.8.

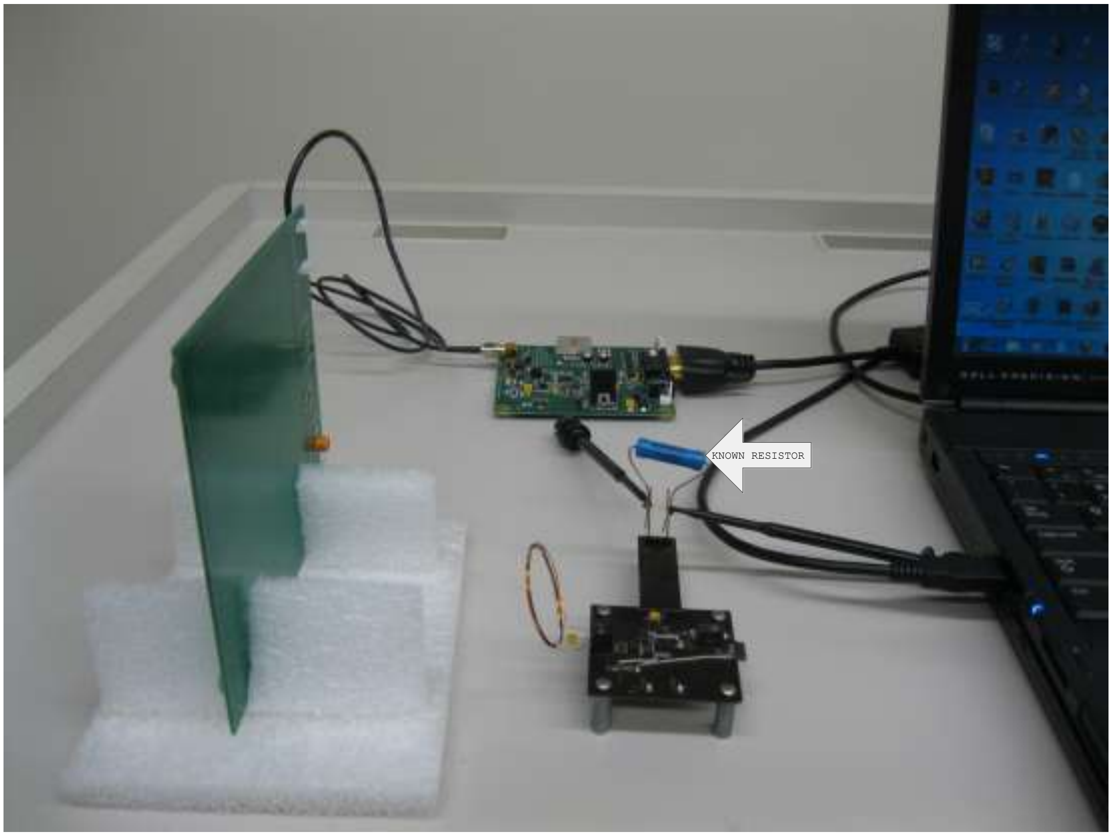


Figure 5.8 Simulated moisture with known resistance

The integrator output provides a linear response which can be measured by measuring the voltage output of the integrator after a set amount of time set by the MCU's internal timer. The timer value, in seconds, is then used to calculate the resistance using the following equation.

$$R = \frac{V_{ref}\, x\, T}{C_{fb}(V_{out} - V_{ref})} \qquad (14)$$

Where

V_{ref} = 1.51 volts,

T = time (in seconds) of microcontroller countdown timer, approximately 3.5 seconds

C_{fb} = Feedback loop capacitance 4.7 µF,

V_{out} = Integrator output voltage reading

This method of experimentation is easily controlled and can yield results which can be used to determine moisture content of differing materials. The known resistance was measured with a Fluke 87 Series III digital multi-meter (DMM). Using an oscilloscope, the output of the integrator is shown in figure 5.9.

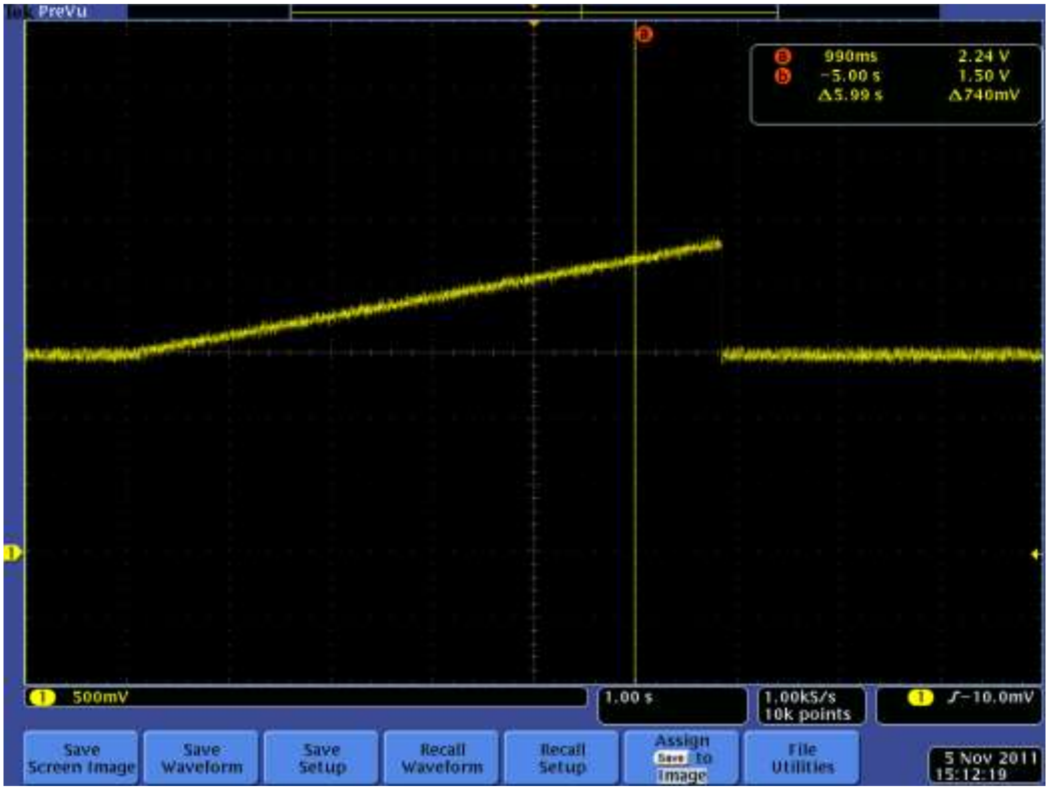


Figure 5.9 Oscilloscope picture of integrator output

Once the resistance is measured with the DMM, the specimen is connected to the moisture meter board and the resistance is read. To check the accuracy of the moisture board several test resistors were used. Table 5.2 shows the results of the known resistances as measured by a Fluke 87 Series III DMM and the moisture board. The table also lists the percent error of measured resistance between the two devices.

TABLE 5.2 Resistance measurements

Nominal Value	FLUKE 87 Series III (ohms)	Moisture meter board (ohms)	Error in per cent
249 kΩ	249.7 k	263.2 k	5
1.5 MΩ	1.504 M	1.473 M	2.07
2 MΩ	1.997 M	1.959 M	1.9
5 MΩ	5.12 M	4.91 M	4.03
10 MΩ	10.02 M	9.05 M	9.68

To check the ability of the moisture board to measure moisture in actual building materials, a piece of wood with two nails driven into it at the same distance as the moisture probes is used. The board was dried in a gas oven at 400° F for 30 minutes to provide drying. Although this does not follow the ASTM standard for drying wood, this is the best method that was available due to equipment limitations. The board was weighed after removing from the oven and a resistance measurement was taken with the Fluke 87 DMM. The board was then wetted to try and simulate a 20 per cent moisture content. Once the board was wetted, the resistance was measured with the Fluke 87 DMM. Figure 5.10 shows the setup for measuring the moisture in the piece of wood.

Figure 5.10 Measuring resistance of wood with Fluke 87 DMM

After the resistance reading of the wood is taken with the DMM the resistance is then measured with the moisture board as shown in Figure 5.11.

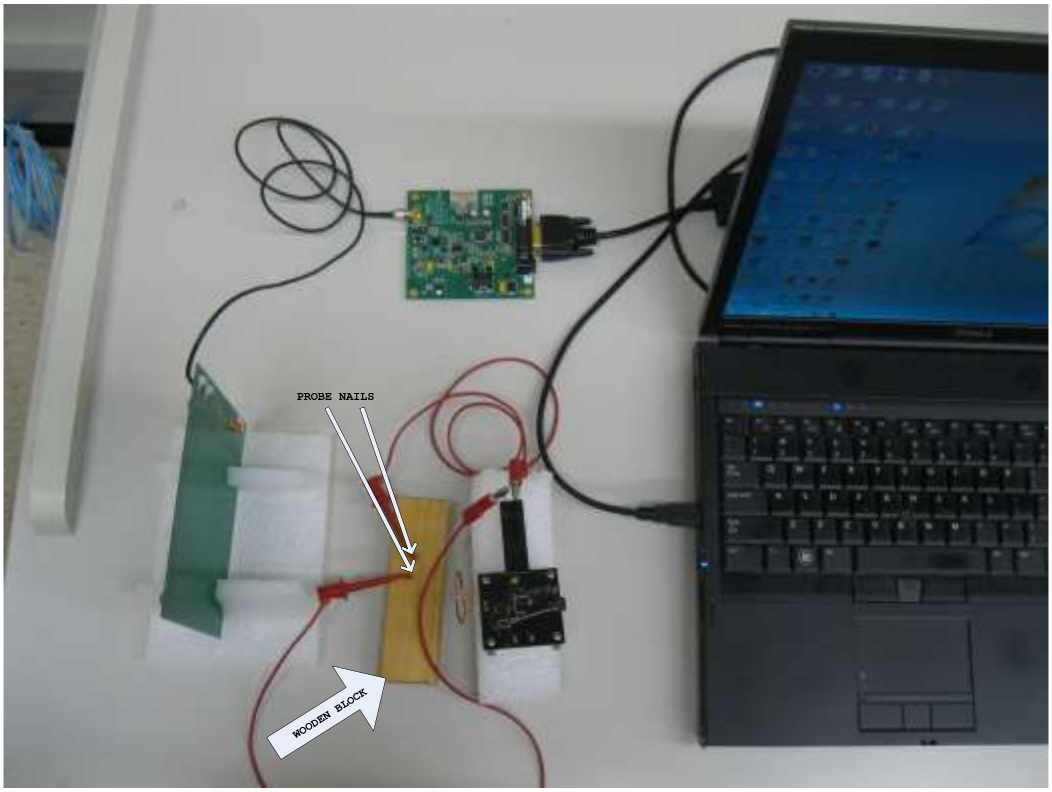


Figure 5.11 Measuring resistance of wood with moisture board

Table 5.3 documents the values read with the Fluke DMM and the moisture board.

TABLE 5.3 Wood resistance measurements

	FLUKE 87 Series III (ohms)	Moisture meter board (ohms)	Error in per cent
Dry cedar	Open	Open	
8 per cent moisture content	3.2M	2.88M	10
20 per cent moisture content	578k	782k	35

The moisture board shows how difficult it is to measure the moisture content in building materials. Accuracy of wood moisture depends on many variables including thickness, moisture distribution, wood types and temperature [22]. Accuracy is determined by the ASTM standard 4442-92. Since the equipment needed to perform the accuracy measurement, an accuracy statement for this board could not be determined. Several commercial meters were checked for accuracy such as the Wagner MMC220 and a Delmhorst RDM-3 and each meter referred to the ASTM standard for determining accuracy. A method to calibrate the meter could be determined and the ASTM standard used to measure the accuracy if developed as a commercial solution.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

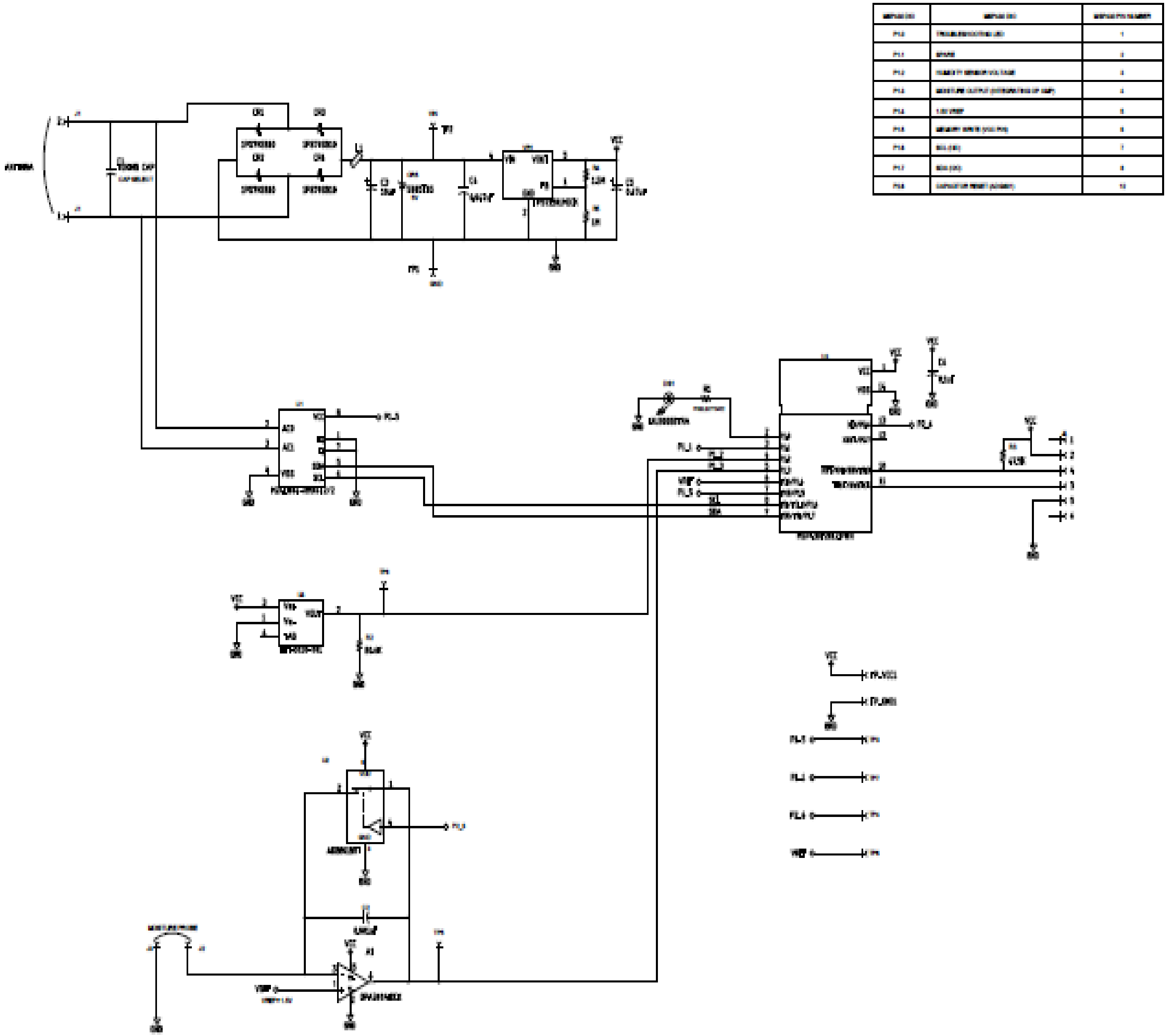
As shown in chapter 5 the moisture meter board provides for accurate temperature and humidity readings. The moisture meter area of the board provides for resistance accuracy of 5 per cent. The accuracy provides the ability to determine if building materials such as insulation or wood is being subjected to any type of moisture anomaly. Utilizing a selectable capacitor network, controlled by the MCU, a resistance range selector could be made, similar to a digital multi-meter range selector. This would allow for higher resistances to be measured more accurately. The use of the moisture meter along with the humidity sensor combine to add to the robustness of the overall moisture meter detection scheme since humidity can be directly related to moisture content through the use of isotherms. The on-board temperature sensor in the MSP430 microcontroller provides a backup ability to measure either thinning insulation or a moisture anomaly as discussed in section 2.6.7. The ability to read data with commercial RFID readers provides the added benefit of utilizing non-destructive methods of moisture measurement.

6.2 Future Work

To help with design miniaturization, an integrated antenna, embedded in the PCB would help to further the rugged features of the moisture board. Careful consideration must be given to ensure the most compact layout without sacrificing operability and to ensure noise interference from an RFID reader is kept to a minimum.

There also exists opportunities to make the reader more flexible for different kinds of material. This would include re-programming via the RFID interface, material measurement selection and self calibration to provide even more accurate results.

APPENDIX A: Moisture Meter Schematic



APPENDIX B: MSP430F2012 Control Program

```
// Version 2.0 of RFID Moisture uController firmware
// Author:  Brian Swafford
// Date: 19 September 2011
// Acknowledgement:  i2c.h courtesty of Dr. Leon-Salas


#include  <msp430x20x2.h>
#include "i2c.h"

//#define TURN_ON_LED          P1OUT |= 0x01        //P1.0
//#define TURN_OFF_LED         P1OUT &= ~0x01
#define TURN_ON_SWITCH         P2OUT |= 0xC0        //P2.6
#define TURN_OFF_SWITCH        P2OUT &= ~0xC0

#define VREF_INTERNAL               1
#define VREF_VCC                    0
#define BASE_ADDRESS                4
#define STATUS_ADDRESS              3

#define NO_COMMAND                  0
#define COMMAND_READ_TEMP           1
#define COMMAND_READ_RVOLT          2
#define COMMAND_READ_HUMIDITY       3
#define COMMAND_READ_INTEG          4

#define STATUS_IDLE                 8
#define STATUS_READING_TEMP         16
#define STATUS_READING_RVOLT        32
#define STATUS_READING_HUMIDITY     48
#define STATUS_READING_INTEG        64
```

```
//========= Function Prototypes ==========
void init_MCU(void);
void set_ADC(unsigned char, unsigned char);
void stop_ADC(void);
void start_Conversion(void);
void VREF_ON(void);
void VREF_OFF(void);
void __delay_ms(unsigned int);

void MeasureRVoltage(void);
void MeasureTemperature(void);
void MeasureHumidity(void);
void MeasureInteg(void);



//========= Variable Definitions =========

unsigned int MemAddress;
unsigned char reader_command;
unsigned int cmd_wait_time;

//============ Main Function =============

void main(void)
{

  init_MCU();

  Setup_USI_Master();
  I2C_PresentPassword(SLV_Addr, 0x00, 0x00, 0x00, 0x00);

  while(1) {

      I2C_ReadMem(SLV_Addr, 0, 0, I2C_Buffer, 4);             //
read command in EEPROM
      reader_command = (I2C_Buffer[0] /*& 0x7F*/);
      __no_operation();
```

```
      if(reader_command == COMMAND_READ_TEMP) {
         MeasureTemperature();
      } else if(reader_command == COMMAND_READ_RVOLT) {
         MeasureRVoltage();
      } else if(reader_command == COMMAND_READ_HUMIDITY) {
         MeasureHumidity();
      } else if(reader_command == COMMAND_READ_RAMP) {
         MeasureRamp();
      };

       if((reader_command & 0x08) == 0) {
/ / check bit 3 to see if the IDLE status bit has been set

         __delay_ms(1000);
         I2C_Buffer[0] = (reader_command | STATUS_IDLE);

// update status to IDLE
         I2C_WriteMem(SLV_Addr, 0, 0, I2C_Buffer, 1);
      }

      __delay_ms(1000);                                  // wait
1 second before checking for next instruction
  }


}



//----- read Temperature Sensor and store result in buffer
void MeasureTemperature(void){

    stop_ADC();
    set_ADC(10, VREF_VCC);         //Read Internal Temp Sensor
    start_Conversion();
    _BIS_SR(LPM0_bits + GIE);
// Enter LPM0
    I2C_Buffer[0] = ADC10MEM%256;
```

```
    I2C_Buffer[1] = (ADC10MEM>>8)%256;
    MemAddress = BASE_ADDRESS;
    I2C_WriteMem(SLV_Addr, MemAddress>>8, MemAddress%256,
I2C_Buffer, 2);
}


//-------- Read rectifier voltage through divider 11:1
void MeasureRVoltage(void){

    stop_ADC();
    set_ADC(1, VREF_VCC);           //A1 is connected to resistor
                                    divider
    start_Conversion();
    _BIS_SR(LPM0_bits + GIE);
// Enter LPM0
    I2C_Buffer[0] = ADC10MEM%256;
    I2C_Buffer[1] = (ADC10MEM>>8)%256;
    MemAddress = BASE_ADDRESS+2;
    I2C_WriteMem(SLV_Addr, MemAddress>>8, MemAddress%256,
I2C_Buffer, 2);
}


//-------- read Humidity Sensor ------------
void MeasureHumidity(void) {

    stop_ADC();
    set_ADC(2, VREF_VCC);             //Read Humidity output
    start_Conversion();
    _BIS_SR(LPM0_bits + GIE);
// Enter LPM0
    I2C_Buffer[0] = ADC10MEM%256;
    I2C_Buffer[1] = (ADC10MEM>>8)%256;
    MemAddress = BASE_ADDRESS+4;
    I2C_WriteMem(SLV_Addr, MemAddress>>8, MemAddress%256,
I2C_Buffer, 2);
}
```

```
//-------------  Read Integrator Output -----------------
void MeasureRamp(void){

    TURN_ON_SWITCH;
    stop_ADC();
    set_ADC(3, VREF_VCC);
    TURN_OFF_SWITCH;
    CCTL0 |= CCIE;
    CCR0 = 32768;                       //delay for timer
    TACTL = TASSEL_1 + MC_1;            //ACLK and up mode
    _BIS_SR(LPM0_bits + GIE);
    start_Conversion();
    _BIS_SR(LPM0_bits + GIE);
    Moisture = ADC10MEM;
    I2C_Buffer[0] = ADC10MEM%256;
    I2C_Buffer[1] = (ADC10MEM>>8)%256;
    MemAddress = BASE_ADDRESS+6;
     I2C_WriteMem(SLV_Addr, MemAddress>>8, MemAddress%256,
I2C_Buffer, 2);
TURN_ON_SWITCH;
}


//================================================
//========= Interrupt Service Routines ============
//================================================

// ADC10 interrupt service routine
#pragma vector=ADC10_VECTOR
__interrupt void ADC10_ISR (void)
{
  LPM0_EXIT;
// Exit LPM0 on return
}
```

```
#pragma vector=TIMERA0_VECTOR
__interrupt void Timer_A(void)
{
  LPM0_EXIT;                              // Exit LPM0 on
return
//  _BIS_SR(LPM0_bits + GIE);
}


//==================================================
//=============== User Functions ===================
//==================================================

void init_MCU(void) {

  WDTCTL = WDTPW + WDTHOLD;           // Stop watchdog

  DCOCTL  = 0x10;                     // DCOx=0, MODx=16
  BCSCTL1 = XT2OFF + DIVA_1;          // XT2 off, RSELx=0,
XTS=0, DIVAx=1 (/1 for ACLK) --> DCOCLK = 50 kHz
                    (DC0=0, RSEL=0)
  BCSCTL2 = 0x00;                                      //
MCLK=DCOCLK/1,
                                   SMCLK=DCOCLK/1, internal DCO
                                   resistor
  BCSCTL3 = LFXT1S_2;                              //
ACLK=VLOCLK (~12kHz)

  P1DIR    = 0x20;         // P1.5 output
  P1REN    |= 0xC0;        // P1.6 & P1.7 Pullups
  P1OUT    = 0xC0;         // P1.6 & P1.7 Pullups, others to 0
  ADC10AE0 |= 0x1E;        // A1 (P1.1), A2 (P1.2) and A3
                         (P1.3) as analog inputs P1.4
                    option select ADC
  P2DIR    = 0xC0;         // P2.6 & P2.7 as outputs
  P2OUT    = 0;
  P2SEL    = 0x0C;         // set to secondary function as DIO
```

```
TURN_ON_EEPROM_VDD;
//  TURN_ON_LED;
TURN_OFF_SWITCH;


//----------------- Initializes the ADC ----------------------

ADC10CTL1 = INCH_5 + ADC10DIV_7 + ADC10SSEL_0;
// Channel 1, ADC10CLK/8, ADC internal OSC as clock source
ADC10CTL0 = SREF_0 + ADC10SHT_3 + REFON + REFOUT + ADC10ON +
ADC10IE;         // Ref=Vcc, SHT=64x, Ref. On, 1.5V,
__enable_interrupt();
// Enable interrupts.

}

//----------------- Initializes and turns ON the ADC -----------
-----------
void set_ADC(unsigned char channel, unsigned char Vref){
// Vref = 0 --> Vcc as ref. voltage, Vref = 1 --> internal
ref.as ref. voltage

ADC10CTL1 = (channel<<12) + ADC10DIV_3 + ADC10SSEL_0;
// temp. sensor , /8 clock, ADC internal OSC (~5 MHz)
  ADC10CTL0 = ADC10CTL0 & 0x1FFF;
     // blanks bits 15 to 13
               so we can select a
                    different voltage
                         referece
  ADC10CTL0 += (Vref<<13);
// sets new reference voltage and turns ADC on
  ADC10CTL0 |= ADC10ON;

}

void stop_ADC(void) {
  ADC10CTL0 &= ~ENC;
}
```

```
void turnOFF_ADC(void) {
ADC10CTL0 &= ~(ADC10ON);                //turn off A/D to
                                          save power
}

void start_Conversion(void) {
  ADC10CTL0 |= ENC + ADC10SC;           //Sampling and
                                          conversion start
}


void VREF_ON(void) {
  ADC10CTL0 |= REFOUT;
}

void VREF_OFF(void) {
  ADC10CTL0 &= ~ENC;
  ADC10CTL0 &= ~REFOUT;

}

void __delay_ms(unsigned int delay) {
 unsigned int i;

 for(i=0; i<delay; i++)
   __delay_cycles(94);
}
```

APPENDIX C: Moisture meter board parts list

TABLE C1: Individual parts price

PART	DESCRIPTION	PRICE
OPA369	Operational Amplifier	$2.28
1PS79SB10	Schottky Diode	$0.38
SD05T1G	Zener Diode	$0.69
C0805C102K5RAC	1000 pF Capacitor	$0.05
EEVFK1C100R	10 uF Capacitor	$0.31
C0603C473K8RAC	0.047 uF Capacitor	$0.06
T491A474K025AS	0.47 uF Tantalum Capacitor	$0.15
C0402C104K4RACTU	0.1 uF Capacitor	$0.04
LNJ308G8TRA	Green surface mount LED	$0.24
1776113-2	2 position connector	$1.08
851-93-006-20-001000	6 position socket	$10.64
BLM31AJ260SN1L	Ferrite chip	$0.08
CRCW04028062FB02	80.6k 402 Resistor	$0.83
CRCW04024752FB02	47.5k 402 Resistor	$0.43
ERJ3GEYJ155	1.5M Resistor	$0.02
CRCW0603105JB02	1.0M Resistor	$0.08
M24LW64-RMN6T2/2	64Kb EEPROM	$3.08

ADG801BRT	SPST NC IC Switch	$2.52
MSP430F2012IPWR	Low power microcontroller	$2.71
HIH-5030-001	Humidity sensor	$11.45
TPS71501MDCK	3.0 V LDO	$4.05
RMM	Printed circuit board	$250
	TOTAL	$541.23

TABLE C2: Production parts price (per 1000)

PART	DESCRIPTION	PRICE
OPA369	Operational Amplifier	$0.87
1PS79SB10	Schottky Diode	$0.14
SD05T1G	Zener Diode	$0.13
C0805C102K5RAC	1000 pF Capacitor	$0.02
EEVFK1C100R	10 uF Capacitor	$0.07
C0603C473K8RAC	0.047 uF Capacitor	$0.05
T491A474K025AS	0.47 uF Tantalum Capacitor	$0.07
C0402C104K4RACTU	0.1 uF Capacitor	$0.02
LNJ308G8TRA	Green surface mount LED	$0.14
1776113-2	2 position connector	$6.38
851-93-006-20-001000	6 position socket	$4.58
BLM31AJ260SN1L	Ferrite chip	$0.06
CRCW04028062FB02	80.6k 402 Resistor	$0.02
CRCW04024752FB02	47.5k 402 Resistor	$0.01
ERJ3GEYJ155	1.5M Resistor	$0.003
CRCW0603105JB02	1.0M Resistor	$0.02
M24LW64-RMN6T2/2	64Kb EEPROM	$1.41
ADG801BRT	SPST NC IC Switch	$1.27
MSP430F2012IPWR	Low power microcontroller	$1.24

HIH-5030-001	Humidity sensor	$5.52
TPS71501MDCK	3.0 V LDO	$2.02
RMM	Printed circuit board	$2.00
	TOTAL	$26.04

APPENDIX D: Power consumption

TABLE D1: Part power consumption (average power)

PART	DESCRIPTION	POWER
OPA369	Operational Amplifier	2.4 µW
1PS79SB10	Schottky Diode	1.6 µW
CRCW04028062FB02	80.6k 402 Resistor	37.2 µW[1]
ERJ3GEYJ155	1.5M Resistor	2.16 µW
CRCW0603105JB02	1.0M Resistor	1.44 µW
M24LW64-RMN6T2/2	64Kb EEPROM	300 µW[1] 600 µW[2]
ADG801BRT	SPST NC IC Switch	5 µW
MSP430F2012IPWR	Low power microcontroller	210 µW
HIH-5030-001	Humidity sensor	200 µW
TPS71501MDCK	3.0 V LDO	4.5 µW
	TOTAL	764.3 µW[1] 1.064 mW[2]

[1] Maximum power during READ operation.

[2] Maximum power during WRITE operation.

REFERENCES

[1] Ostrander, C., and Satko, J. History of Insulation with Masonry. Available from http://www.maconline.org/tech/rvalues/historyofinsulation/historyofinsulation.html; Accessed 21 August 2011.

[2] Whiting, D. (1983). Assessment of potential techniques for in situ, real time moisture measurements in building envelope systems – A literature survey. ORNL/SUB/83-40122/1. Oak Ridge, Tenn. : Oak Ridge National Laboratory.

[3] Healy, W.M. Moisture Sensor Technology: A Summary of Techniques for Measuring Moisture Levels in Building Envelopes. ASHRAE transactions, , February 2003, Vol. 109, No. 1, pp. 232-242.

[4] American Academy of Allergy, Asthma, Immunology. Spring Allergies. Available from http://www.aaaai.org/Aaaai/media/MediaLibrary/PDF Documents/Libraries/EL-Spring-Allergies-patient.pdf; Accessed September 2011.

[5] Fairey, P., Chandra, S., and Moyer, N. Mold Growth. Florida Solar Energy Center. Available from http://www.fsec.ucf.edu/en/consumer/building/basics/moldgrowth.htm; Accessed August 2011.

[6] United States Environmental Protection Agency., A Brief Guide to Mold, Moisture, and Your Home; Available from http://www.epa.gov/mold/moldbasics.html; Accessed September 2011.

[7] Centers for Disease Control and Prevention. Facts about Mold and Dampness. Available from http://www.cdc.gov/mold/dampness_facts.htm; Accessed September 2011.

[8] Andrews, S., Mold: A Growing Concern. Available from http://www.ecometrex.com/Mold A Growing Concern.pdf; Accessed September 2011.

[9] Institute of Medicine., Clearing the Air: Asthma and Indoor Air Exposures. National Academy Press, Washington DC, 2000.

[10] World Health Organization, Europe., WHO guidelines for indoor air quality: dampness and mould. World Health Organization Regional Office for Europe, 2010.

[11] Wantanabe, S. Models and Characterization of Transfer Properties. International Workshop on Mass-Energy Transfer and Deterioration of Building Components (Paris, France 9 -11 January 1995).

[12] Dielectric Constants. K-TEK Corporation. Available from http://www.asiinstr.com/technical/Dielectric Constants.htm; Accessed September 2011.

[13] Bull, K. Methods of Accurately Measuring Capacitive RH Sensors. 5th International Symposium on Humidity and Moisture. (Rio de Janeiro, Brazil May 2006).

[14] Sedra, S., and Smith, K. Microelectronic Circuits., Oxford, 2004.

[15] Roberti, M. The History of RFID Technology. RFID Journal. Available from http://www.rfidjournal.com/article/view/1338/1; Accessed October 2011.

[16] International Organization for Standardization. Identification cards -- Contactless integrated circuit cards -- Vicinity cards -- Part 1: Physical characteristics ISO/IEC 15693-1:2010. (September 23, 2010).

[17] ST Microelectronic. 64 Kbit EEPROM with password protection & dual interface: 400 kHz I²C serial bus & ISO 15693 RF protocol at 13.56 MHz datasheet. Available from http://www.st.com/internet/com/.../**DATASHEET**/CD00217247.pd. *October 2011.*

[18] Texas Instruments. MSP430F20x2 Mixed Signal Controller Datasheet. Available from http://www.ti.com/general/docs/lit/getliterature.tsp?genericPartNumber=msp430f2012&fileType=pdf. August 2005. Revised August 2011.

[19] Honeywell Sensing and Control. HIH-5030/5031 Series, Low Voltage Humidity Sensors datasheet. March 2010

[20] Fluke Corporation., Moisture Detection: A key to prevent mold growth. Available from http://www.fluke.com/fluke/usen/solutions/ti/thermal-imaging-moisture-detection.htm; Accessed October 2011.

[21] James, W.L., Electric Moisture Meters for Wood. General Technical Report FPL-GTR-6. United States Department of Agriculture, Forestry Service. 1988.

[22] Simpson, W., and TenWolde A. Physical Properties and Moisture Relations of Wood. In Wood Handbook: Wood as an Engineering Material. Madison, WI : USDA Forest Service, Forest Products Laboratory, 1999. pp 3.1 – 3.24.

VITA

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