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Analysis of a Temperature Dependent Oscillator as a Temperature Sensor

eldoLED Inc.

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August 21, 2009

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Dear Sir:

This report, entitled "Analysis of a Temperature Dependent Oscillator as a Temperature Sensor", was prepared as my 3A Work Report for eldoLED Inc. This report is in fulfillment of the course WKRPT 300. The purpose of this report is to evaluate the accuracy of using a temperature dependent oscillator to determine the ambient temperature of a product.

eldoLED is a developer and producer of high-performance electronic drivers, networking, and control solutions for high-intensity solid-state lighting applications. Their proprietary digital technologies and software algorithms are the foundation for products with small footprints, low power consumption, and a sophisticated level of configurability.

The eldoLAB division, in which I was employed, is managed by Mr. Mike Slot and is primarily involved with the design and fabrication of prototype devices for upcoming eldoLED product offerings.

I would like to thank Mr. Mike Slot for providing me with the advice and guidance necessary to complete this report. I hereby confirm that I have received no further help other than what is mentioned above in writing this report. I also confirm this report has not been previously submitted for academic credit at this or any other academic institution.

Sincerely,

Jonathan H. Warren
ID 20207681

Contributions

The team I worked with at eldoLAB was relatively small. It consisted of six people, in addition to myself, the university co-op student. The team was lead by Mr. Mike Slot, and consisted of two hardware and firmware designers, one part-time internal applications developer, and one part-time prototype developer.

The team's main goals were to design and fabricate prototype products for eldoLED by reviewing internal specifications and producing schematics, circuit board layouts, and complete physical prototypes. During the production process, whether it is for a generic product or for a custom design to suit the specific requirements of a client, a prototype product will undergo numerous revisions in hardware and component layout. Therefore the role of a prototype development team is paramount in ensuring consistent milestones are achieved in the product development cycle.

My tasks consisted of various projects and routine work including the design and development of electronic hardware to aid in production and prototype development, the creation of software tools and mechanical drawings to aid in product design, and the creation of 3D models of prototypes and products for external use. Custom hardware would be required to aid in quality assurance testing on the production line as well as aid in prototype development. It would be my role to take the specifications developed for the application, produce a complete schematic and circuit board layout for the device, and assemble a working model of the hardware. Additionally, during the design process, as requirements arising from issues or specific needs are encountered by the team, opportunities would become available to develop tools which can mitigate the issues encountered and perform any necessary tasks. It was my role, when presented with these requirements, to create the software tools to perform these tasks. Examples of these tools include analysing the schematic and circuit board layout files for design rule errors, creating a bill of materials (BOM) from parts placed on the circuit board layout, and generating an interactive web-based circuit board layout viewer which would link component information to the company's internal database. These tools aided the team in the design and assembly of prototype products. Frequently, product images would need to be created for use in documentation, or to send to clients. My role would be to take the circuit board layout information and render three-dimensional images of the product using the appropriate software packages. I would often need to add new components to the rendering software library, which involved researching the component dimensions and properties and translating this information into the rendering software language.

The relationship between this report and my job is that it is an investigation of a potential cost and space-saving design for future eldoLED products. An additional electrical component is being used to determine the temperature of the environment which the product is in. This component adds to the size of the product and also increases the production costs for each unit. I was responsible for researching and testing an alternative method to determine the temperature of the product, using components already available to any eldoLED product. As such I have gained a more thorough knowledge of how temperature measurements are performed as well as the accuracy involved with the measurement. This report allows for the demonstration of further testing, research, and critical analysis into one potential alternative to the current temperature measurement design. By writing this report, I am also developing my presentation, organization, and clarity skills. Additionally, I have been able to relate the academic knowledge I have gained from the course *E&CE 222: Digital Computers* in the development of a functional test device which allowed for this investigation to be conducted. Overall, this report serves as both a technical resource for eldoLED and as a record of my work term at eldoLED.

In the broader scheme of things, my task of investigating this potential alternative method of temperature sensing will allow the engineers at eldoLED to develop a clearer idea of the effectiveness of their existing temperature measurement design, and of potential future designs. Future courses of action will be able to be defined with stronger background knowledge of the available solutions due to the analysis in this report.

Summary

The main purpose of the report is to investigate an alternative method of measuring the ambient temperature of a product from what is currently used by using common components which are already available to any circuit board design. Specifically, the report focuses on the analysis of the temperature dependence of the internally integrated oscillator in the microcontroller integrated circuit (IC) package included in every product design. The scope of the report is limited to the microcontroller model, test device, and equipment available for use in this investigation.

The major points covered in this report focus on the analysis of the frequency of the internal oscillator of the microcontroller family of models used in the company's products and its variation with changes in ambient temperature. Additionally, the report discusses the accuracy of the temperature readings made with this method compared to existing technologies.

The major conclusions in this report indicate that there is a distinctly linear relationship between the internal oscillator frequency and ambient temperature that provides very accurate temperature measurements when compared to the external sensors that have been used in eldoLED products.

The major recommendations in this report are based on the investment of time, personnel, and finances to develop a more accurate and effective testing strategy as well as to reduce the costs and footprint of this method of temperature measurement. By using more precise testing equipment, and by testing across multiple microcontroller products, a better understanding of the requirements for the temperature sensor can be reached.

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1.0 Introduction

eldoLED is a developer and producer of high performance, small form-factor drive, network, and control solutions for high power Light Emitting Diode (LED) and Solid State Lighting applications. Through their use of proprietary technologies and software algorithms, they are able to create products with efficiencies of up to 95%, robust thermal management, and an advanced degree of control [1]. Through continuous research and development, eldoLED is able to produce high quality cutting edge products.

eldoLAB is a support department within eldoLED which designs and produces prototype products. These products can be Original Equipment Manufacturer (OEM) solutions designed for integration with a customer's product (such as a fixture for a light) or upcoming products as part of one of the eldoLED standard product families. Specifications for these prototypes are developed by the eldoLED headquarters in Eindhoven, The Netherlands. Additionally, testing apparatuses for these prototype products are produced by eldoLAB.

Solid State Lighting refers to a light source which is composed of some form of Light Emitting Diode (LED). A diode is made out of a semiconductor material with a low conductive property. This material can be altered, and made to be more conductive, by adding impurities through a process called doping. A diode works by passing electrical current across a junction of two doped materials: one which is doped to have an excess of electrons (N-type) to one which is doped to have an excess of electron holes (P-type) [2]. A photon is released when an electron jumps from a higher energy level to a lower energy level, which occurs when current passes from an N-type material to a P-type material. A Light Emitting Diode uses this electrical characteristic of a diode to produce visible light by creating a specific junction which will release photons with energy levels in the visible spectrum [2].

Diodes, and therefore LEDs, are sensitive to operating temperature due to the fact that increases in temperature will cause increased current to flow across the diode junction, which in turn increases the temperature of the junction. This effect is known as thermal runaway, and strongly affects the lifetime of the LED unit [3]. This effect can be remedied by using a power source which supplies a constant current [3]. Additionally, an increase in temperature will negatively affect the long term light output of an LED, and thus will shorten its useful life [3].

The monetary costs of additional temperature sensing components are widespread in the production of an electronic product from eldoLED. Primarily, the cost is through purchasing the component, however there are also costs involved with placing the component during product fabrication. Additionally, the component will add to the amount of space required on the Printed Circuit Board (PCB), and will add to the number of traces, or wires, required for routing. While these costs may seem minimal, on a per-product basis, they quickly become significant when entering full-scale production.

This report focuses on the creation of a test device, the collection of data, and the analysis of this collected data to determine the accuracy of an alternative temperature sensing approach based on components already available to eldoLED. Specifically, this report analyses the effects of temperature on the frequency of the internal oscillator in one of the microcontroller models used by eldoLED.

The following section provides an overview of the current and previous temperature sensing components used in eldoLED products and their accuracy and effectiveness. Section 3 provides an overview of the test device requirements and details about the construction and implementation of the test device. Section 4 contains physical measurements taken on the test device to determine a relationship between oscillator frequency and temperature. Section 5 discusses the potential accuracy of the temperature sensor based on the results of the physical analysis in Section 4.

The analysis within these sections leads to several conclusions and recommendations that would determine the accuracy and effectiveness of using this method of temperature measurement over existing solutions.

2.0 Existing Temperature Sensor Technologies Overview

Temperature measurement is currently integrated into each eldoLED product to ensure an environmental temperature is maintained that will maximize the lifetime of the product and the LEDs it is powering. These sensors are constantly being reviewed to minimize production costs. As such, these sensors have been changed over time, and new, more cost-effective and efficient sensors are being investigated for future use. The following subsections outline the temperature sensors which have been and are currently being used in eldoLED products.

2.1 LM60 Integrated Circuit

The LM60 is a small form-factor integrated circuit which can provide temperature measurement in the range from -40°C to +125°C with an accuracy of ± 4°C [4]. It provides a linear voltage output with a DC offset to allow the sensing of negative temperatures without requiring a negative voltage supply [4]. The LM60 is contained in a SOT-23 size standard package which measures approximately 3mm by 2.5mm [4]. Due to its cost and size, this temperature sensor was discontinued from use in eldoLED products and replaced with a less expensive and smaller technology as described below.

2.2 Negative Temperature Coefficient Thermistor

A thermistor is a special type of electrical element which has a variable resistance that changes with temperature. The Negative Temperature Coefficient (NTC) type of thermistors, which are currently used in eldoLED products, have a resistance that decreases with increasing temperature and offer a temperature range of -40°C to +125°C with an approximate accuracy of ± 5%, or about ± 8°C [5]. The NTC thermistors are available in a variety of sizes, however the European 603 size is used in current eldoLED products, which measures approximately 1.6mm by 0.8mm [5]. While less accurate than the LM60, these thermistors are of a smaller form factor, and are less expensive, making them an ideal choice for eldoLED products. The difference in temperature sensing accuracy does not greatly affect the performance of the eldoLED products as they are designed to operate in a wide range of temperatures.

3.0 Test Device Requirements

In order to observe the effects of temperature on a microcontroller's internal oscillator frequency, a test device must exist which will facilitate the use of external probes to measure all necessary data. As this investigation is only preliminary, this test device will not need to perfectly represent a final product setup, but must adequately demonstrate the principles and theories behind this investigation.

3.1 Microcontroller Device

The microcontrollers used in eldoLED products are Microchip brand Peripheral Interface Controllers (PIC) devices. For the purposes of the testing and analysis discussed in the following sections, a test device was required which would be similar to existing eldoLED products. As such, a demonstration board was obtained from Microchip which contains the PIC16F887 model microcontroller, one similar to those used in many eldoLED products.

The frequency of the PIC16F887 microcontroller's internal oscillator is stated to be sensitive to operating temperature [6]. Table 1 outlines the manufacturer's assessment of frequency variance over specific temperature ranges.

Table 1: Microchip PIC16F887 Frequency Variance due to Temperature [6]

Temperature Range (degrees C)	Variance in Frequency
0 - 60	+/- 1%
60 - 85	+/- 2%
85 - 125	+/- 5%

The internal oscillator is also stated to be sensitive to operating voltage [6], however, a fixed input voltage will be assumed for the purposes of this analysis.

The internal oscillator of the PIC16F887 can be programmed to oscillate at a number of frequencies, ranging from 31kHz to 8MHz, with additional prescalar values available to configure a specific frequency [6]. In order to determine changes in clock frequency, the highest frequency available should be used so as to maximize any measureable differences.

For the purposes of this analysis, the internal frequency of the microcontroller must be measured along with its temperature. As such, the microcontroller was configured to output its internal oscillator to a designated pin, which could then be externally measured by an oscilloscope. Additionally, a thermocouple was affixed with thermal tape to the top of the microcontroller to determine its temperature.

3.2 Reference Frequency Requirements

In order to determine any changes, the internal oscillator frequency must be compared to a stable frequency which does not change with temperature. The PIC16F887 microcontroller contains a comparator circuit which allows the frequency of an external oscillator source to be measured with reference to the microcontroller's internal oscillator [6].

As a stable comparative frequency, an Alternating Current (AC) 12 Volt power source was selected due to its independence from environmental changes, and for its common use in existing eldoLED products. This provides a constant external 60Hz signal that will not be affected by local ambient temperature.

For the microcontroller to interpret this AC frequency without being damaged, it must be converted into a Direct Current (DC) square wave with an appropriate amplitude (in this case, +5VDC). To accomplish this, a circuit was created which uses a half-wave rectifier and an optical isolator device to effectively isolate the AC power source from the microcontroller circuits as well as translate the 60Hz signal to a DC square wave which could be connected directly to the microcontroller's comparator pin. Figure 1 illustrates this circuit.

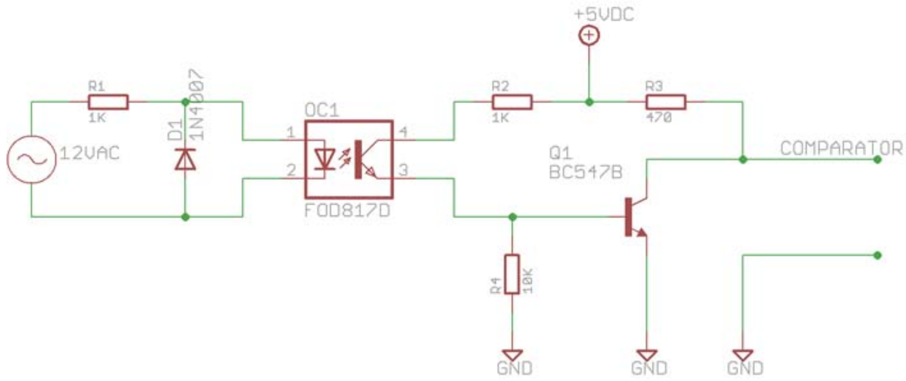

Figure 1: AC Frequency Rectifier and Circuit Isolation

The components chosen for this circuit are done so based on availability in the lab workplace, so as to reduce cost. Figure 2 shows the completed test device with an additional Liquid Crystal Display (LCD) module attached to display debug and measurement data.

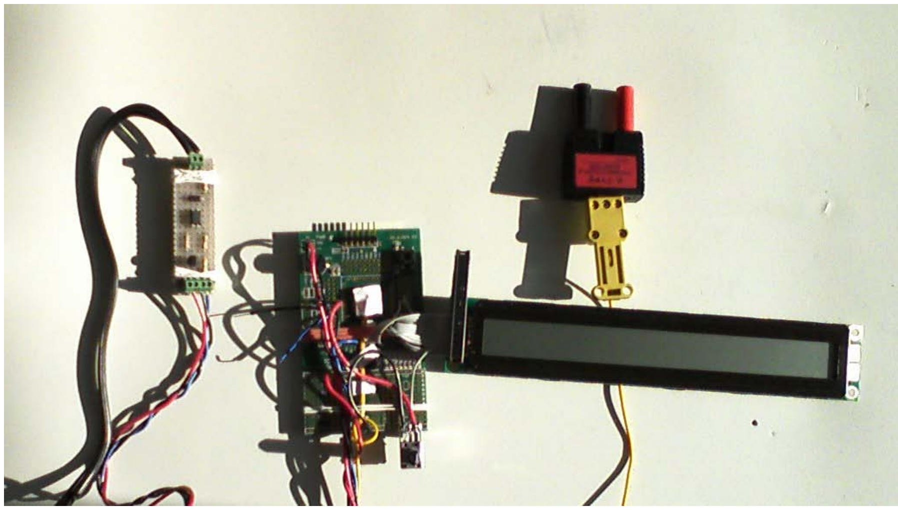

Figure 2: Test Device with Peripherals

For the purposes of testing to determine frequency changes, only the demonstration board and the external thermocouple hook-up are required to be subjected to changes in temperature. As such, the LCD module and AC reference circuit will not be used in the following tests.

4.0 Frequency vs. Temperature Measurements

To determine the effects of temperature on the internal oscillator frequency, the largest range of temperatures must be measured with as many data points as possible. Unfortunately, the equipment available to conduct such testing was limited in accuracy and consistency, so a number of tests were performed in order to obtain reliable data. The devices being used to conduct these tests consisted of an Infra-Red heating oven, designed to bond solder paste to the PCB in the fabrication process, and a conventional freezer. These devices were felt to be capable of producing a range of temperatures which would be sufficiently above or below the rated extremes of eldoLED products.

To collect data, an oscilloscope was used to monitor the frequency of the internal oscillator and a K-type thermocouple was affixed to the top of the microcontroller to determine the approximate temperature of the microcontroller.

4.1 Heating Test

The heating test setup involved placing the demo circuit board inside the drawer of an infra-red oven, closing the drawer, and operating the oven to bring the inside to a temperature of approximately 120 degrees Celsius for several minutes. This was to ensure that a consistent temperature would exist throughout the test device. Once sufficiently heated, the test device would be allowed to cool, and data would be collected as frequently as possible. Figure 3 and 4 show the test setup. Table 2 shows a sample of the data collected during these tests. A complete table of the recorded data can be found in Appendix A. Three tests were performed to ensure reliable, consistent data was collected.

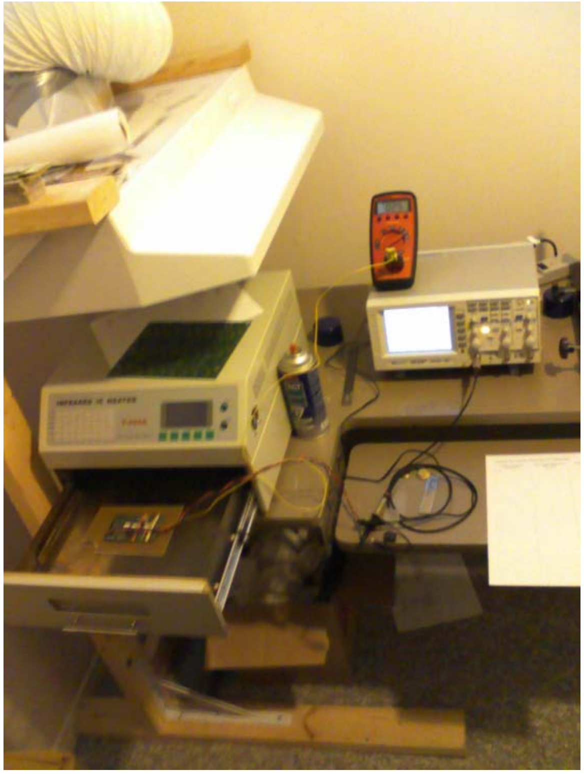

Figure 3: Heating Test Configuration

Figure 4: Test Device Inside Infra-Red Oven

Table 2: Heating Test Frequency Measurements

Temperature (Degrees Celsius)	Trial 1 Frequency (MHz)	Trial 2 Frequency (MHz)	Trial 3 Frequency (MHz)
30	2.00377	2.00394	2.00379
31	2.00407	2.00441	2.00409
32	2.00458	2.00474	2.00436
33	2.00487	2.00521	2.00489
34	2.00544	2.00566	2.00546
35	2.00605	2.00603	2.00582
40	2.00837	2.00824	2.00812
45	2.01023	2.01043	2.01023
50	2.01263	2.01279	2.01267
55	2.01477	2.01488	2.01467
60	2.01712	2.01714	2.01681
65	2.01942	2.01942	2.01914
70	2.02149	2.02158	2.02133
75	2.02316	2.02350	2.02342
80	2.02531	2.02602	2.02539
90	2.02906	2.02978	2.02960
100	2.03229	2.03325	2.03288
110	2.03433	2.03543	2.03533
120	2.03481	2.04005	2.03745

4.2 Cooling Test

The cooling test setup involved allowing the test device, initially at room temperature, to be placed inside the door of a conventional freezer, closing the door, and allowing the test device to cool. Data would be collected as frequently as possible. Figure 5 shows the test setup with the test device already inside the freezer. Table 3 shows a sample of the data collected during these tests. A complete table of the recorded data can be found in Appendix B. Four tests were performed to ensure reliable, consistent data was collected.

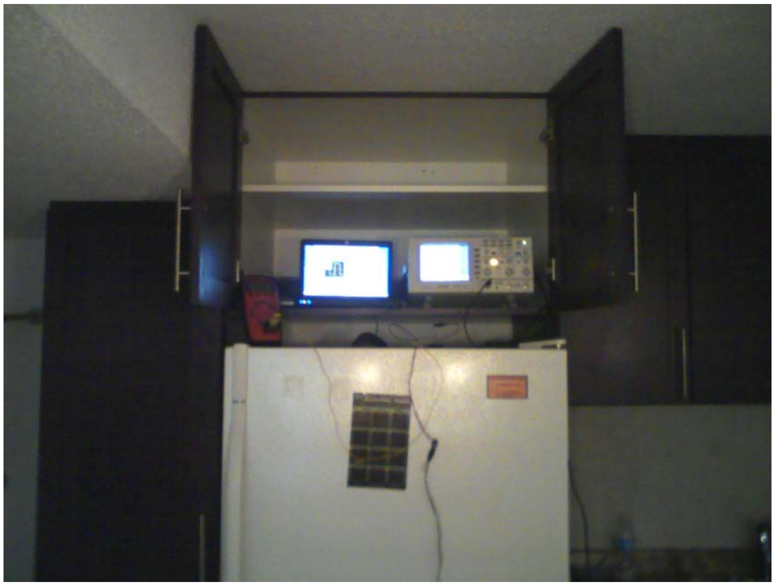

Figure 5: Cooling Test Configuration

Table 3: Cooling Test Frequency Measurements

Temperature (Degrees Celsius)	Trial 1 Frequency (MHz)	Trial 2 Frequency (MHz)	Trial 3 Frequency (MHz)	Trial 4 Frequency (MHz)
-15		1.98550	1.98565	
-14		1.98596	1.98601	
-13		1.98632	1.98650	
-12		1.98667	1.98698	
-11		1.98724	1.98750	
-10		1.98761	1.98804	
-9		1.98799	1.98852	1.98774
-8		1.98854	1.98888	1.98838
-6		1.98949	1.98995	1.98949
-5		1.99007	1.99053	1.98978
-3		1.99054	1.99160	1.99071
-2		1.99096	1.99217	1.99117
0		1.99187	1.99280	1.99186
1		1.99263	1.99358	1.99256
5	1.99313	1.99447	1.99516	1.99450
8	1.99515	1.99563	1.99710	1.99596
10	1.99576	1.99655	1.99818	1.99688
15	1.99821	1.99895	2.00028	1.99924
20	2.00078	2.00138	2.00257	2.00107

Missing data points from Trial 1 and 4 are due to issues with the refrigeration unit. Once sufficiently cooled, the refrigerator compressor would shut off, ceasing the flow of cold air. Thus, localized pockets of warmer air could exist causing the test device to remain at a steady temperature.

4.3 Analysis of Measured Data

From this recorded data, a trend can be observed indicating that as the temperature of the microcontroller increases, the frequency of the microcontroller's internal oscillator also increases. Figure 6 shows a scatter plot of all recorded data.

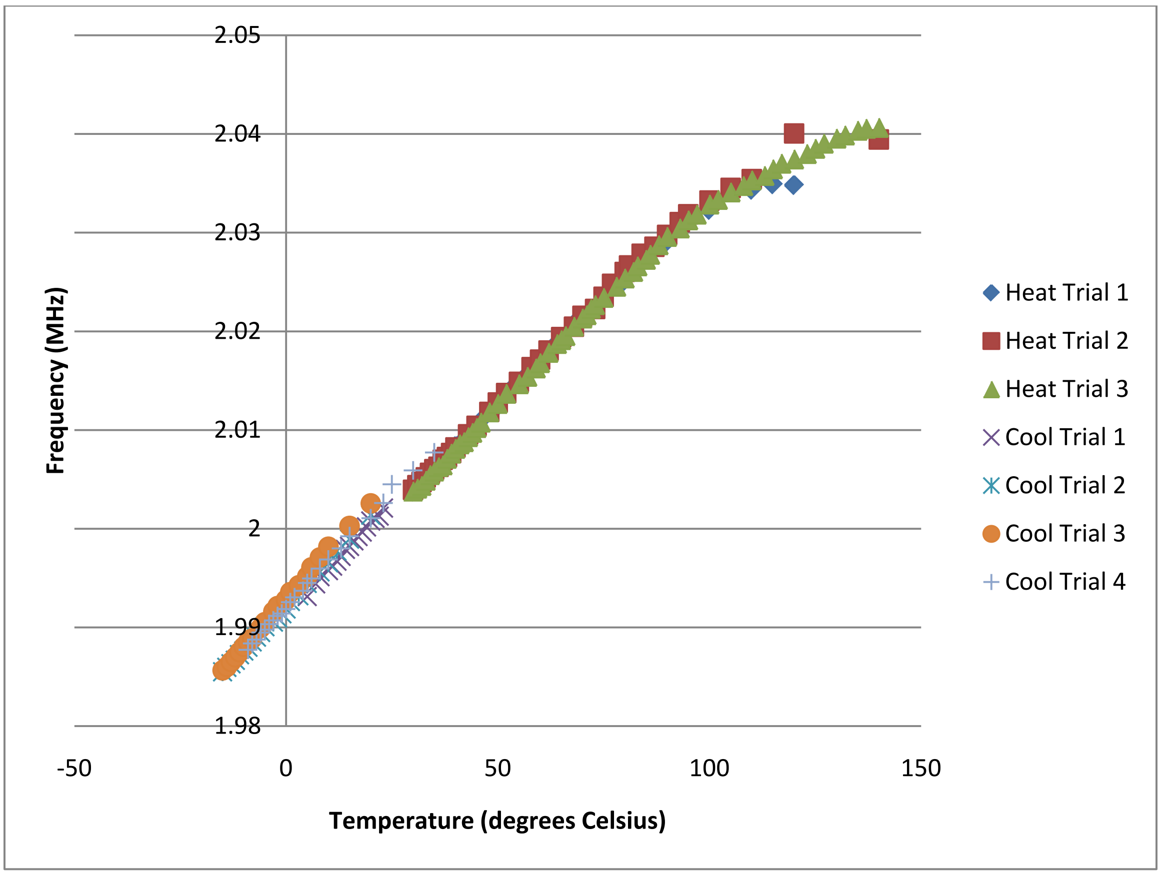

Figure 6: Frequency vs. Temperature Measurements

As can be observed in Figure 6, the relationship between temperature and frequency appears to be linear throughout a majority of the range of temperatures. Therefore, a simple linear equation can be derived from this data which will accurately determine the temperature based on the internal oscillator's frequency.

An upper saturation point appears to occur after approximately 100°C. While the exact reason for this is unknown, it could be speculated that it is due to the phase change in the air (water vapour will evaporate after 100°C) or due to upper limitations on the frequency of the internal oscillator.

5.0 Performance and Accuracy Investigation

Two major factors affect the accuracy of this method of temperature sensing, if used in production. The first issue lies within the accuracy of the AC reference signal. AC frequency is capable of varying slightly, depending on time of day, and the power grid infrastructure [7]. Additionally, the AC frequency of 60Hz is not consistently used around the world, limiting locations in which the product can be used. Furthermore, variances in fabrication of the microcontroller lead to an oscillator frequency tolerance of +/- 1% from microcontroller to microcontroller as discussed in Appendix C.

With these discrepancies in mind, worst-case calculations can be made which will determine the overall accuracy of this method of temperature measurement. To determine these values, certain assumptions and approximations must be made. The first is that every product will have an internal clock set to 2MHz. The second is that, based on the data recorded in Table 2 and 3 as well as in Appendix A and B, the average deviation in the frequency is 400Hz per degree Celsius. Finally, the AC frequency can deviate from 60Hz by a practical maximum of ± 0.05% [7]. Equation 1 shows the relationship between the model of the ideal values used in the temperature measurement calculations versus the hypothetical "actual" values.

$$\frac{frequency \pm frequency\ error}{AC\ frequency} = \frac{frequency \pm frequency\ deviance}{AC\ frequency \pm AC\ deviance} \tag{1}$$

Equation 1 can then be rearranged to solve for the maximum deviation in frequency from the nominal 2MHz value as shown in Equation 2 below.

$$\begin{aligned} \pm frequency\ error_{max} \\ &= (frequency + frequency\ deviance) \\ &\times \frac{AC\ frequency}{AC\ frequency - AC\ deviance} - frequency \end{aligned} \tag{2}$$

Finally, the error can be determined in terms of temperature by using Equation 3.

$$temperature\ error\ =\ \frac{frequency\ error}{frequency\ change\ per\ degree} \tag{3}$$

The following calculations demonstrate the worst case conditions possible. In this situation, the sensors are not calibrated for internal frequency or AC frequency. That is to say, any deviance in the oscillator frequency from the frequency that the sensor was originally calibrated to (for example, using the data collected in Section 4) will affect the measured temperature reading.

Determining the maximum frequency deviation using Equation 2,

$$\pm frequency\ error_{max}\ = (2MHz + 1\%) \times \frac{60Hz}{(60Hz - 0.05\%)} - 2MHz$$

$$\pm frequency\ error_{max}\ = (2.02MHz) \times \frac{60Hz}{(59.97Hz)} - 2MHz$$

$$frequency\ error_{max}\ = \pm 21{,}010Hz$$

Now determining the total temperature measurement error using the above result and Equation 3,

$$temperature\ error\ =\ \frac{\pm 21{,}010Hz}{400Hz/℃}$$

$$temperature\ error\ =\ \pm 52.525℃$$

As can be seen from the above results, the temperature measurement error range is very large. The following calculations determine the maximum temperature deviation provided the sensor is calibrated to the frequency of the internal oscillator. This means that any deviation in the internal oscillator frequency from the original calibration value will be negated.

Determining the frequency deviation using Equation 2,

$$\pm frequency\ error_{max} = (2MHz) \times \frac{60Hz}{(60Hz - 0.05\%)} - 2MHz$$

$$\pm frequency\ error_{max} = (2MHz) \times \frac{60Hz}{(59.97Hz)} - 2MHz$$

$$frequency\ error_{max} = \pm 1{,}000.5Hz$$

Now determining the total temperature measurement error using the above result and Equation 3,

$$temperature\ error = \frac{\pm 1{,}000.5Hz}{400Hz/℃}$$

$$temperature\ error = \pm 2.5013℃$$

The above results clearly illustrate a significant improvement in the accuracy of the temperature measurement and shows that the internal oscillator frequency value is an important factor in sensor accuracy. Furthermore it indicates that any deviations in the reference AC frequency will not greatly affect the measured temperature.

6.0 Conclusions

From the analysis in the report body, it was concluded that the oscillator present in the test device has a linear temperature-frequency relationship, that if appropriately calibrated the test device can provide accurate temperature measurements, and that the test equipment and procedure used in this investigation are quite crude.

As shown in Section 4, the frequency of the Microchip internal oscillator increases linearly with temperature. This allows for simple and effective modelling of the relationship which can be used to provide accurate measurements for a wide range of temperatures.

Section 5 outlines an approximation of the accuracy of the temperature sensor device based on potential deviations in internal oscillator frequency and in the reference AC frequency. The results indicate that each device must be calibrated to their internal oscillators, however no calibration to the AC reference signal is necessary. By doing this, an accuracy of ± 2.5°C can be achieved which is significantly more accurate than the current and previous temperature sensor technologies summarized in Section 2.

Finally, as can be observed from the test environment descriptions in Section 4, the test device, test equipment, and testing procedure used to perform the temperature-frequency analysis are somewhat unsophisticated. Because of this, the experimental results may be subject to an unnecessarily large range of error which may decrease the overall accuracy of the device.

7.0 Recommendations

Based on the analysis and conclusions in this report, it is recommended that eldoLED further investigate the effectiveness of using a temperature-sensitive oscillator as a temperature sensor by pursuing more accurate testing methods over a larger range of test devices and conditions. Furthermore, additional investigation into reducing the size and number of components required to provide a reference frequency to the microcontroller will be required to make this method of temperature measurement more cost-effective than external sensors.

As can be observed from Section 4 and 5, as well as in the conclusions above, the testing equipment, devices and testing process requires significant improvement to produce more accurate results over a wide range of temperatures and products. It is therefore recommended that eldoLED allocate further monetary and personnel resources into acquiring more precise test equipment, such as an environmental chamber, as well as more test devices, such as multiple microcontroller models and current eldoLED products in order to generate accurate test data across multiple products. This way, a better understanding of the calibration requirements and overall accuracy of the temperature sensor can be determined.

Additionally, it is recommended that eldoLED allocate further personnel and time resources into researching improvements and alternatives to the current circuitry required to provide the microcontroller with a stable reference frequency. While an AC signal may always be available to the product, the electrical components required to translate that signal into one that the microcontroller can safely read requires more components and thus a larger physical footprint and additional costs than a single external temperature sensor device.

Glossary

Light Emitting Diode (LED) – a pn junction which emits photons in the visible spectrum

Negative Temperature Coefficient (NTC) Thermistor – a resistive circuit element in which the resistance decreases as the temperature of the device increases

Peripheral Interface Controller (PIC) – a popular microcontroller produced by Microchip Technology

Hertz (Hz) – a measure of the number of cycles per second in a periodic function

Alternating Current (AC) – an electrical current with sinusoidal properties that is commonly used as main utility power

Direct Current (DC) – an electrical current that flows steadily in one direction that is commonly used in electronic circuits

Liquid Crystal Display (LCD) – a digital display device used to display monochrome data

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Appendix A:

Heating Test Measurement Data

Temperature (degrees Celsius)	Trial 1 Frequency (MHz)	Trial 2 Frequency (MHz)	Trial 3 Frequency (MHz)
30	2.00377	2.00394	2.00379
31	2.00407	2.00441	2.00409
32	2.00458	2.00474	2.00436
33	2.00487	2.00521	2.00489
34	2.00544	2.00566	2.00546
35	2.00605	2.00603	2.00582
36	2.00661	2.00628	2.00627
37		2.00699	2.00645
38	2.00751	2.00727	2.00711
39		2.00767	2.00764
40	2.00837	2.00824	2.00812
41	2.00856		2.00858
42	2.00893		2.00880
43	2.00952	2.00957	2.00931
44			2.00974
45	2.01023	2.01043	2.01023
46	2.01091		2.01078
48		2.01184	2.01182
49	2.01191		
50	2.01263	2.01279	2.01267
52		2.01375	2.01370
53	2.01406		
55	2.01477	2.01488	2.01467
57	2.01561		2.01542
58		2.01638	
59			2.01627
60	2.01712	2.01714	2.01681
62		2.01806	2.01785
63	2.01839		
64			2.01875
65	2.01942	2.01942	2.01914
66			2.01955
68	2.02075	2.02047	2.02050
70	2.02149	2.02158	2.02133
71			2.02167
72	2.02204		2.02230
73		2.02227	2.02269
75	2.02316	2.02350	2.02342
77		2.02481	
78			2.02455
79	2.02468		
80	2.02531	2.02602	2.02539

81		2.02668	
82			2.02605
83			2.02662
84		2.02786	
85	2.02724		2.02728
86			2.02779
87		2.02857	
88			2.02876
90	2.02906	2.02978	2.02960
93		2.03107	2.03046
95		2.03186	2.03128
97			2.03186
100	2.03229	2.03325	2.03288
102			2.03335
105		2.03453	2.03411
108			2.03476
110	2.03433	2.03543	2.03533
113			2.03578
115	2.03489		2.03645
117			2.03702
120	2.03481	2.04005	2.03745
123			2.03800
125			2.03853
127			2.03905
130			2.03956
132			2.03988
135			2.04036
137			2.04056
140		2.03944	2.04065

Appendix B:

Cooling Test Measurement Data

Temperature (degrees Celsius)	Trial 1 Frequency (MHz)	Trial 2 Frequency (MHz)	Trial 3 Frequency (MHz)	Trial 4 Frequency (MHz)
-15		1.98550	1.98565	
-14		1.98596	1.98601	
-13		1.98632	1.98650	
-12		1.98667	1.98698	
-11		1.98724	1.98750	
-10		1.98761	1.98804	
-9		1.98799	1.98852	1.98774
-8		1.98854	1.98888	1.98838
-7		1.98901		1.98877
-6		1.98949	1.98995	1.98949
-5		1.99007	1.99053	1.98978
-4				1.99033
-3		1.99054	1.99160	1.99071
-2		1.99096	1.99217	1.99117
-1		1.99138		1.99141
0		1.99187	1.99280	1.99186
1		1.99263	1.99358	1.99256
2				1.99305
3		1.99321	1.99427	
4				1.99371
5	1.99313	1.99447	1.99516	1.99450
6			1.99608	1.99496
7	1.99442			
8	1.99515	1.99563	1.99710	1.99596
10	1.99576	1.99655	1.99818	1.99688
11	1.99622			
12	1.99672	1.99774		
13	1.99720			1.99800
14	1.99791			
15	1.99821	1.99895	2.00028	1.99924
16	1.99878			
17	1.99921			
18	1.99966			
19	2.00018			
20	2.00078	2.00138	2.00257	2.00107
21	2.00105			
22	2.00128			
23	2.00210			2.00261
25				2.00450

Appendix C:
Microchip Oscillator Calibration
and Production Tolerances

[Fwd: RE: Internal Oscillators]

Jonathan Warren <Jonathan.Warren@eldoled.com> **21 August 2009 17:10**

-------- Original Message --------

Subject: RE: Internal Oscillators
Date: Thu, 13 Aug 2009 10:37:02 -0700
From: <Wayne.Freeman@microchip.com>
To: <Jonathan.Warren@eldoled.com>
References: <4A6480C8.2080009@eldoled.com> <FDA12D6045FB8D459028860FB6BD4379046E0977@CHN-CL-MAIL01.mchp-main.com> <4A844BB4.2020806@eldoled.com>

Jonathan:

Yes. It would be 8MHz +/- 1% at 25 degrees C. The oscillators are calibrated during wafer probe, and the packaging process adds a 1% uncertainty factor. They are then rechecked at final test with a 1% tolerance.

From: Jonathan Warren [mailto:Jonathan.Warren@eldoled.com]
Sent: Thursday, August 13, 2009 10:22 AM
To: Wayne Freeman - C13027
Subject: Re: Internal Oscillators

Hi Wayne,

Thanks for your response. I've read that the chips are supposed to be factory calibrated at 25 degrees Celsius - does this mean that the frequency of the HFINTOSC will be nominal at that temperature for all chips? For example, if an assortment of chips were all set to run at 8MHz, would they all run at exactly 8MHz if the environmental temperature was 25 degrees?

Thanks,

Jonathan
