Thermal Management in Embedded Systems

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by

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On my honor as a University student, on this assignment I have neither given nor received unauthorized aid as defined by the Honor Guidelines for Papers in TCC Courses.

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Glossary

Convectional Cooling – Process by which heat is transfer from one medium to the air through air currents and temperature gradients

Current (I) - The directed flow of charge in a circuit measure in Amperes (A)

Current Sense Amplifier – A device used to measure slight changes in current

Data Acquisition Board – A PC component used to input data from laboratory equipment

Development Board – A electronic device, containing a processor, that is used to experiment with a processor for prototyping or research

Dynamic Thermal Management System – A system which controls the temperature or power of a microprocessor by actively changing how the processor operates while the processor is running

Embedded Device – A larger device which contains a microprocessor within it

Frequency (f) – the number of cycles per give unit of time measured in Hertz (Hz)

Frequency Scaling – A process by which the clock frequency of a microprocessor is changed to affect the behavior of the chip

Heat Sink – A device which draws heat away from an electronic device and aids in cooling

LabView – A software program for collecting laboratory data

Microprocessor – An electronic device used to perform calculations and instructions

Package – The outer casing on a microprocessor

Performance – A metric used to measure the computational ability, usually given in seconds per program

Power (P) – The measurement of energy produced or consumed per unit time in Watts (W)

Semiconductor – A material used in electronic devices, which has both properties of an insulator and a conductor

Shunt Resistor – A small resistor used to measure current

Thermocouple – A device used to measure temperature

Thermal Management System – A system that controls the temperature or power of an electronic system, include both passive devices and dynamic thermal management systems

Voltage (V) – A measure of the electric potential between two points in Volts (V)

Voltage Scaling - A process by which the voltage of a microprocessor is changed to affect the behavior of the chip

Abstract

By designing a dynamic thermal management system using dynamic frequency scaling, based on the architecture of the Intel 80200 processor, this thesis project shows how thermal management systems can be retrofitted to current embedded devices. In doing so, this thesis project highlights the steps necessary to design a dynamic thermal management system and the components essential in embedded devices for such a thermal management system. Greater use of thermal management techniques will lower the cost of cooling systems and spread the use of embedded devices, impacting society as a whole. The models presented in this thesis could then be used to verify and validate thermal management systems and optimize the thermal management system described in this thesis based on the workload of the processor and the performance of the thermal management system.

1. Introduction

1.1 Project Purpose

The purpose of this project was to design a system for a microprocessor that actively monitors and controls the maximum temperature that the processor reaches by altering how the processor operates. This type of system is called a dynamic thermal management system and is especially important in embedded devices, such as PDAs and cell phones. The project involved choosing an embedded processor currently on the market and designing a dynamic thermal management system that could be implemented to lower the maximum temperature and power.

1.2 Problem Statement

Microprocessors have vastly increased in performance and computational power. Correspondingly, the power consumed by the processors has also vastly increased. As the transistors, which are the building blocks of microprocessors, switch on and off, they heat up. In personal computers and even laptops, this heat is removed using heat sinks and cooling fans, which are passive devices that are always operating. Even the computer case may act as a heat sink, which helps keep the processor cool.

A problem arises with embedded devices because many times conventional cooling techniques are often not feasible. First, space is typically a limiting factor in embedded devices, making large heat sinks and fans not an option. Second, many embedded devices are in direct contact with humans, so the devices can only release so much heat to the outer casing before bothering the user. Third, these devices rely on limited power supplies, often batteries, where every device must be designed to limit the power used; the power consumption penalty of using fans has increased compared to semiconductor device power (Yazawa 786). For these reasons significant research into controlling the power consumption and temperature of embedded devices is underway.

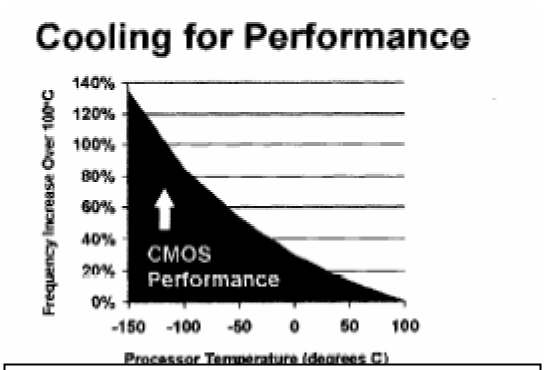


Figure 1: CMOS performance v. processor temperature (Belady 102).

Overheating can have significant detrimental effects on a microprocessor. When transistors heat up, more current is passed through the device. High enough currents will burn out transistors in a processor, ruining the device. Furthermore, transistor performance decays with increasing temperature; figure 1 shows the decay of performance versus temperature (Belady 102).

Processors are typically designed for a certain maximum power intake, i.e. every transistor is operating at the same time, which rarely occurs. The higher the maximum power, the more expensive thermal management is. It has been estimated that for every watt decrease in power consumption correlates to a dollar decrease in device cost. Since this maximum power rarely occurs, it is possible to design a dynamic thermal management system. This system would alter how the processor operates when it reaches a certain temperature or average power consumed so that the chip reduces the power used. If thermal testing shows that the temperature after implementing a thermal management system never rises above a new maximum temperature, then the cooling devices can be designed at this new lower maximum temperature, thereby saving money.

In terms of cooling versus performance, a designer has three options. One is to not consider thermal issues and build a cooling system to handle the maximum temperature of the chip, which we have seen is not always feasible. The second is to choose a processor based on the cooling ability of the design, which limits the performance of the device. The third is to design a thermal management system so that the chip with the performance needed for the application conforms to the cooling ability of the device.

1.3 Practical Applications

Cost, heat, and power reductions will have an impact on the use of embedded devices in the future, and also on our society as a whole. Embedded devices generally offer users more mobility and flexibility in how they lead their lives. For example, the cellular phone has allowed workers to leave the office but still be in contact. Most embedded devices are designed to allow users to perform tasks easier and free up time for other activities. Furthermore, as costs decrease, more people will have access to these devices, allowing more of society to benefit.

Creating devices that produce less heat may help benefit biomedical devices. These devices must maintain a minimum heat transfer to the body to avoid injuring the user, allowing more powerful and more flexible devices to be used while still giving off safe levels of heat. In addition, devices that give off less heat may have benefits to the intelligence community. Devices that give off less heat would be less visible on infrared scans, allowing their concealment, which has definite potentials in the defense and surveillance industries.

The negative social and ethical context might not seem apparent, but there are questions designers must ask themselves while designing new embedded devices. For one, an increase in embedded systems increases our dependencies on these devices. Those devices may seem extravagant at first, but like the cellular phone, they quickly become part of our daily lives. Furthermore, embedded devices tend to decrease human interaction. The bank is a perfect example of an institution that shows how machines have decreased our interaction with actual human beings, through such things as automated teller machines and internet banking. Finally, designers must ensure that the privacy of those using or interacting with these new embedded devices is not being compromised by the information these devices are collecting and their prevalence in new locations and environments. Although privacy and dependence on electrical devices are social and ethical issues that must considered when designing, the benefits of thermal management systems outweigh the drawbacks.

In regards to thermal management, users may not notice the increased thermal performance of their devices, but they would notice if no thermal management plan were implemented. For example, it would be hard to sell a cellular phone to someone if it burned the user’s hand from dissipating all the heat to the outside of the case. Although users rarely think of these ideas when they use a product, there are user considerations that designers must be aware of during design.

1.4 Project Scope and Method

Both academia and device manufacturers have put considerable research into the principles of thermal management because thermal and power constraints will be a future roadblock in the development of smaller, faster devices. While many researchers have focused on laptop computers and larger systems, less work has been concerned with smaller embedded devices. The market demand for small, versatile, high performance embedded devices makes them that much more susceptible to thermal issues. Research thus far into embedded devices has primarily used simulators modeling heat dissipation to show that dynamic thermal management systems can lower the average power. More on current research in the field of thermal management will be discussed in the literature review in chapter two.

This project looked at a specific device, an Intel 80200 embedded processor, and designed a dynamic thermal management for the processor to determine how feasible thermal management techniques are in devices currently on the market. In doing so, this project lays out a method for designing a thermal management system and discusses key architecture components necessary for a successful dynamic scaling thermal management system.

After reviewing the thermal management systems other researchers simulated and evaluating the types of processors available, a frequency scaling system was chosen involving lowering the clock frequency to decrease the power used. The major objectives of this project were then setting up the processor so it runs applications similar to a standard embedded device and developing and choosing a dynamic thermal management technique and method for measuring both the power and temperature measurement.

1.5 Overview of the Technical Report

The second chapter gives background into power and temperature in electronics and covers the thermal management research and its relationship to this project. Chapter three covers the procedures and methods used to develop the dynamic thermal management system and power and temperature measurement systems. Chapter four goes over the specific design of the Intel 80200 thermal management system and discusses the results of the project. Finally, chapter five is the conclusion, which outlines what has been accomplished and the future work that should come out of this project.

2. Background and Literature Review

2.1 Power and Temperature in Microprocessors

Power is a fundamental component of any electrical system. It is a measure of the energy consumed or generated by a device at a given time. The standard metric for power is a watt, the same unit used on an electricity bill. Power can be related to the voltage and current of an electrical system by the formula:

Equation 1: Power = Voltage x Current

Given a voltmeter and ammeter, which measure voltage and current respectively, one can calculate the instantaneous power of any system by multiplying the two values together.

In the case of a microprocessor, the voltage into the chip is usually a known value depending on the chip design. Since the voltage is known, one can measure the current into the chip to find the power consumed by the microprocessor. Chapter three discusses the methods reviewed for measuring current and chapter four details the method chosen for this project.

The temperature of the microprocessor is directly related to the power consumed by the chip. If the processor was lossless, meaning it had no impedance, the temperature of the chip would be the same as the air around it, but the impedance natural to any device causes power to be lost within the chip. Remembering that power is just a measurement of energy over time, one can see that the lost power is released into the processor as thermal energy, causing the temperature of the chip to rise. The power into the chip is directly proportional to the power lost, meaning a chip that is running many instructions and performing more work will release more heat than a processor doing little work. As consumers demand more from their embedded devices in terms of computational performance, the issue of thermal management becomes more important and thermal management systems must be implemented. Given this relationship, it is possible to derive the equation that the power consumed by a processor is proportional to the voltage into the processor squared times the clock frequency the chip is operating at:

Equation 2: $\text{Power} \propto \text{Voltage}^2 \times \text{Clock Frequency}$

From this equation we can recognize that if we were to decrease the frequency or voltage, the power into the chip would decrease, as well as the power released as heat. Therefore, the temperature of the chip is also proportional to the voltage and clock frequency. Looking at the voltage into the chip, we can see it has a quadratic relationship to the power meaning any decrease in voltage has a greater effect on the power than the linear relationship of the clock frequency, which is why thermal management systems that change the voltage level on the processor, called dynamic voltage scaling, are a popular dynamic thermal management system. Some of these systems will be discussed later in this chapter in the literature review.

Lowering the clock frequency has a linear relationship to the power consumed by the chip. As the clock frequency lowers, the processor runs slower, executing fewer instructions in a given time period and therefore decreasing the power needed. Many processors have frequency reducing components built into the architecture, which makes frequency reductions a viable method of dynamic thermal management, especially for processors currently on the market.

As we have seen, power and temperature are related to the voltage, current, and clock frequency, and by changing these values we can reduce the power and temperature of a microprocessor.

2.2 History of Thermal Management

The basis of this project comes out of the work researchers have been working on in the field of thermal management. Past work in the field focused on designing cooling systems to lower the chip temperature and “electrothermal analysis” to determine the thermal behavior of a device (Chiueh 52). As devices become smaller and more powerful, new methods of heat reduction are being developed.

Thermal management for embedded systems began with laptops. Older laptops, like most embedded devices, typically use heat sinks to pull the heat away from the source and spread it across a larger area and micro-fans to blow air across the heat sink to dissipate heat into the air. Although these devices are still used today and provide a good method of dissipating heat, for the faster, smaller devices on the horizon, the “space/volume penalty and the power consumption of the fan have been increasing, relative to the semiconductor device power” (Yazawa 786).

2.3 Other Current Research Areas into Thermal Issues

Many researchers and designers are working to come up with new ways of mitigating the heat problem from the semiconductor to system level. There seems to be an endless possibility of ways to reduce heat. Material scientists are working on developing new materials to use as packages for these chips that provide extremely high thermal conductivity, and lower weight, size and cost (Zweben 360). Researchers have found that the placement of devices on a chip can have an effect on how much heat is produced and whether that heat is evenly spread throughout the chip (Gopinath 117). There is also a vast amount of research being performed at the compiler and OS level to take into account thermal issues when compiling and scheduling instructions. Hardware engineers are designing better systems to control the scaling of frequency and voltage in processors and software engineers are designing the algorithms used to determine when thermal management systems should engage (Pering 76). Although all of these are well out of the scope of a single thesis project, it is important to note that the research is not limited, and there is no single solution to managing heat dissipation.

2.4 Research into Dynamic Thermal Management Systems

More closely related to this project, researchers are working on several methods of dynamic thermal management. One proposed method is called "transient thermal management," which involves using heat storage devices to store the heat produced by the processor during power intensive computations and dissipate it gradually over time. This method is combined with a dynamic thermal management technique to lower the power consumption (Cao 114). Although the transient thermal management system was only simulated, others have developed a prototype for testing a dynamic thermal management system. A research group at Harvard University developed a system that monitored the temperature of the processor and as it reached the set maximum it stalled any power-intensive instructions. This method allows the processor to still run normally for low power instruction, which they felt benefited the user over a system which slowed the processor down for all applications (Rohou 7).

Brooks and Martonosi at Princeton University chose to design a system that did slow down the entire processor. Their research extensively focused on the different techniques that could be used to develop a dynamic thermal management system. They came up with five "response mechanisms" to alter the performance of their simulated processor and tested each one against certain processes to see how each affected temperature and performance (Brooks 176). Other groups are doing similar work simulating voltage and frequency scaling. Figure 2 shows a typical state diagram for dynamic voltage scaling (Hsu 13 and Ma 203).

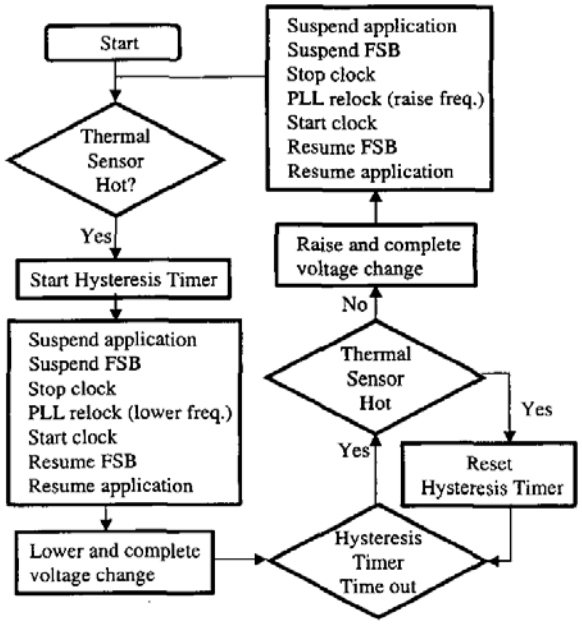


Figure 2: Typical state diagram for a dynamic voltage scaling system (Ma 203).

While most of the dynamic thermal management systems that have been simulated measure the power and temperature and then cause the system to change when the processor is consuming too much power or the temperature is too high, one research group at the University of Illinois is looking at a predictive voltage scaling method. The group has come up with an algorithm that predicts the power to be used and then sets the voltage and frequency accordingly, and they believe their method has a better response time than reactive systems (Srinivasan 109).

A different idea involving voltage and frequency scaling has been developed by a group from the University of Rochester. Their design involves separating the chip into different sections in which the voltage and frequency can be scaled independent of the other sections. Their design would try and minimize the performance loss on those tasks that were not power intensive (Semeraro 12). Other researchers at the Univesity of Waterloo have developed a similar method using a "performance manager" to analyze the power requirements of the next task and then set the voltage and frequency based on values given in a look up table (Elgebaly 155). A performance manager is especially viable in embedded processors because the workload is typically limited to a small range of instructions for which the entire thermal management system can be optimized.

While researchers at universities were developing methods of controlling heat dissipation, chip designers at Intel, and likewise at many other chip manufacturers, were developing chip architectures, like the Xscale processor, such that these thermal management techniques could be implemented. These processors have several built-in features to run at lower power during times when the device is not being used and allow for both dynamic voltage and frequency scaling (Clark 1602). These characteristics made an Xscale processor, like the Intel 80200 processor, an ideal candidate for this project. Research into thermal management is a key process in the design of most modern chips. Designers must ensure "that thermal considerations are a part of the design process rather than an afterthought" (Mahajan 66).

The future of thermal management will be the continuance of current research and the development of new technologies. Researchers have begun combining dynamic thermal management systems to create even more efficient designs for future processors (MA 201). Still, many of these research techniques need to be tested on actual devices to measure their true performance and feasibility. Chip designers will work on developing lower power chips and hardware that has dynamic thermal management techniques built into the architecture. Meanwhile some in the industry are pushing for better ways of judging performance by developing “good, workable thermal requirements” (Luiten 332). Whatever direction the future of the industry leads, the problem of heat dissipation has no magic solution. As the processor density continues to increase, so does the need for better methods of heat dissipation.

2.5 Project Outgrowth

This project is a direct outgrowth of the current research in the field. After researching and reviewing the types of dynamic thermal management systems that have been simulated and current embedded processors, the goal of the project was to design a system that incorporated these dynamic thermal management techniques based on the architecture of the chosen embedded processor. Chapter three will discuss the requirements of the thermal management system and processor and provides a guide for developing a dynamic thermal management system. Chapter four will outline the system design chosen for the project specific architecture.

This project will show the research community that given a processor with even a limited amount of frequency or voltage scaling, one can design a thermal management system to support that particular device. In this way, this project shows that thermal management systems are practical and can even be retrofitted to processors where no such system originally existed.

3. Design Methods and Procedures

3.1 Overview

This chapter discusses the parameters and specifications used to choose an embedded processor, a type of dynamic thermal management system, and power and temperature measuring systems. This chapter can also be used as a guideline for designing a dynamic thermal management system for other embedded processors. Cost and feasibility have been the overriding constraints in choosing a design. The details of the design of each of the above mentioned systems will be described in chapter four.

3.2 Embedded Processor

The heart of any thermal management system is the processor for which it is designed. The goal in choosing a processor for this project was to pick a device that is prevalent in embedded devices and has the capabilities needed to implement a thermal management system, such as dynamic frequency or voltage scaling.

The first step was to create a list of potential processors based on availability and cost. Three alternatives were determined. One was to use an FPGA board, a device commonly used in embedded devices to allow designers to create custom designs. Another approach was to use the Intel 80200 processor, which is a common processor that was available on a development board through Ronald Williams, Associate Professor in the Department of Electrical and Computer Engineering. The third option explored was to purchase a new device.

The advantages of the FPGA were that I had experience using the boards and they were very flexible. The drawback to this approach was that frequency scaling would not have been easy and therefore a thermal management system is not as practical on such a device. The other extreme would have been purchasing a new device that had the best chip features for implementing a thermal management system, but the disadvantages would have been learning how to use the device and also the cost of purchasing the development board. The option chosen was using the 80200 processor. There was no cost associated with the development board and had some features such as dynamic frequency scaling that made it a good choice for designing a thermal management system. The disadvantage associated with the 80200 processor was that I was unfamiliar with the chip and how it operated.

3.3 Thermal Management System

Once the chip was chosen, the second step was to research the chip and the development board to determine what type of thermal management could be developed given the architecture of the board. The two main options were a dynamic voltage scaling method and a frequency scaling method given the limited ability to change the properties of the chip. Voltage scaling has the greatest impact on the power because of the quadratic relationship between voltage and power, and most voltage scaling techniques also involve a frequency scaling as well. While voltage scaling would have been the better thermal management system design, the details of the processor could not be overlooked. Although the 80200 processor did allow for frequency modulation, it did not have the voltage scaling architecture needed to design a dynamic voltage system. Instead, a frequency scaling design was chosen. Unfortunately the 80200 processor does not have on-chip thermal sensors to trigger the thermal management system when the trigger temperature is reached. Because of the absence of thermal sensors, the temperature must be measured by an outside component and triggered externally.

3.4 Power and Temperature Measuring Systems

One of the most difficult tasks in developing thermal management systems is designing on-chip components that accurately measure the heat and power produced. Since these components are not part of the 80200 processor, a device using the thermal management system must be equipped with these external systems.

The method chosen to measure the temperature was to use a thermocouple. It would be more accurate to measure the temperature directly on the chip by removing the packaging and placing the thermocouple directly on the chip, but since the development board was loaned, and thus the temperature had to be measured through the chip's packaging. To measure the temperature changes, LabView and a data acquisition board were chosen because of their availability and flexibility.

Three types of power measurement were possible for this project: non-invasive, invasive, and processor measurement. The non-invasive method for measuring board power was developed by Isci and Martonosi at Princeton University. They chose to use a clamp ammeter around the power cords to measure the current going into the device, and the power is given by P = I*V since the voltage is a known value (Isci 4). The clamp ammeter method is excellent when the system cannot be cut, but since the cost of clamp ammeter could be significant, it was not chosen.

The second method of measuring power is adding a small resistance, called a shunt resistance, into the power cord of the development board, this method has been implemented by both Arun Thomas as a fourth-year thesis project and by Keller, et al., at IBM. Thomas used a current sense amplifier as shown in figure 3 to measure the voltage drop across the resistor to determine the current, using the equation I = V/R. As confirmed by research done at IBM, the invasive shunt resistor method of measuring power works well with LabView and provides reliable power data (Keller 11). The disadvantage of this type of measurement is that it would require cutting the power cord of the development board, which is not an option, given the constraints of using the board. In addition, both the invasive and non-invasive methods given would measure the total power going into the development board, not the processor alone. A method of measuring just the power into the processor would be beneficial, which is the advantage of the third method researched, processor measurment.

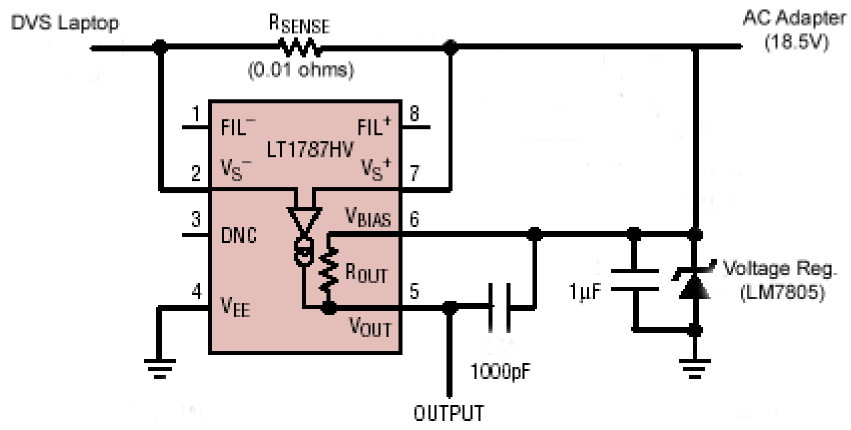


Figure 3: A diagram of the circuit used by Thomas to measure the power into a laptop (Thomas 14).

One of the advantages of the 80200 development board is that it has provisions to measure the power consumption of just the processor. Given these provisions, a hybrid design using the circuit designed by Thomas and the ability to measure just the processor power was chosen. Instead of cutting the power cord, the circuit in figure 3 could be applied directly to the power traces on the board.

4. Project Results

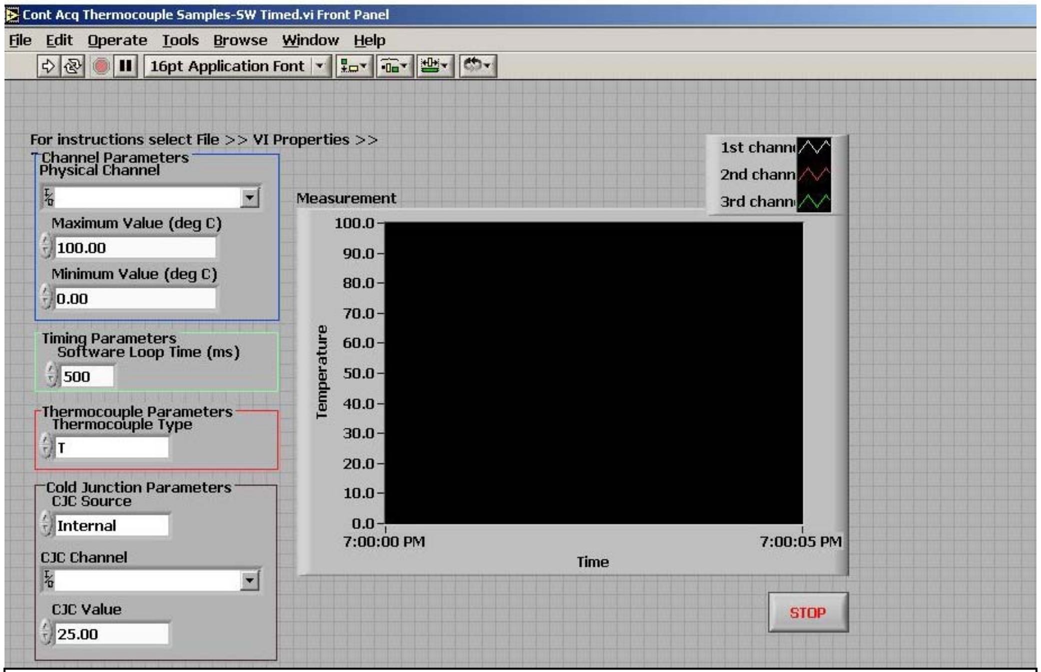
4.1 Dynamic Thermal Management System for the Intel 80200 Processor

Frequency scaling in the Intel 80200 processor may be performed by changing the value of a register on the processor, which is changeable by software. Thus, the next step was to design a program to execute frequency scaling. The chip starts operation at a frequency of 466 MHz. When the processor temperature reaches the trigger temperature, the thermal sensor asserts a high signal. When the frequency scaling software notices a high signal, it lowers the value in the register, thereby lowering the clock frequency. The processor begins operating at this lower speed, and as shown in chapter two, the power and heat will also decrease. Once the temperature has dropped enough, the thermal sensor will stop sending a high signal and the frequency scaling software will restore the clock frequency to 466 MHz. A table of register values and corresponding clock frequencies, as well as the code for changing the clock frequency, is given in appendix A.

4.2 Temperature Measurement System

Because temperature is a fairly stable and easy to measure value, the temperature measurement system is often the device that triggers a dynamic thermal management system, as seen above. To measure the temperature on the 80200 development board, a thermocouple design was chosen. After researching thermocouples and temperature measurement, a 36 AWG ANSI Type T thermocouple was shown to be the most accurate method of measuring processor heat (Shaukatullah 99). Furthermore, researchers recommended attaching the thermocouple with thermally conductive epoxy (Shaukatullah

104). Despite the decrease in accuracy, conductive tape was chosen to attach the thermocouple over epoxy because the tape was not permanent and less invasive. With the thermocouple attached to the board, the other end is connected to LabView by way of the data acquisition board. LabView then records the temperature of the chip as a function of time; figure 4 is a sample version of a LabView template for measuring temperature.



For instructions select File >> VI Properties >>

Channel Parameters
Physical Channel
Maximum Value (deg C) 100.00
Minimum Value (deg C) 0.00

Timing Parameters
Software Loop Time (ms) 500

Thermocouple Parameters
Thermocouple Type T

Cold Junction Parameters
CJC Source Internal
CJC Channel
CJC Value 25.00

Figure 4: A screenshot of a sample temperature measurement program provided by LabView.

4.3 Power Measurement System

The power measuring system designed to validate power consumption for the 80200 development board was an adaptation of the design proposed by Arun Thomas in his thesis proposal, as shown in figure 3, in order to measure just the power into the processor. To modify the design, instead of cutting the power cord the power measurement circuit used the traces on the development board, shown in figure 5, to measure the current. Since the voltage supply entering the processor was too low to power the power measurement circuit, a DC power supply was used to provide the 5 volts necessary. The voltage values given by the power measurement circuit were sent to LabView through the data acquisition board. There the current was calculated using ohms law and the power was product of the current and the initial voltage. LabView then stored the value of the power which could then be displayed as a table or graph for analysis.

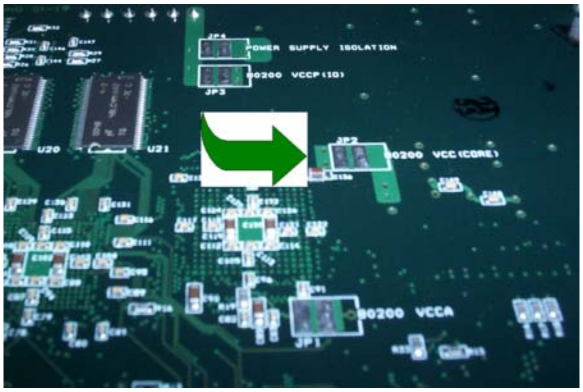


Figure 5: Traces on the 80200 development board to measure power into the processor

4.4 Discussion of Results

This project showed that given a few key architecture components, a thermal management involving frequency and voltage scaling can be designed for a typical embedded processor. The key features necessary for such a thermal management system are a voltage regulator, thermal sensors, a feedback system to control the scaling, and a phase lock loop to

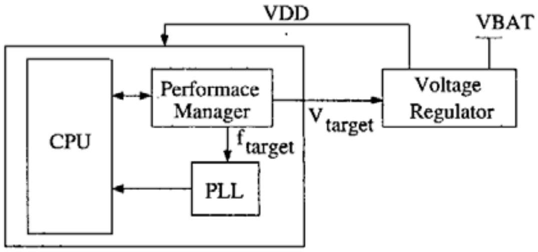


Figure 6: Typical architecture of a dynamic voltage scaling system (Elgebaly 155).

control the clock frequency as seen in figure 6. While the design shown in this technical report only utilized frequency scaling, the quadratic relationship between power and voltage should be exploited to fully gain the benefits of a thermal management system. Furthermore, applications need to have the ability to change the frequency and voltage to best utilize a dynamic voltage scaling system. Thermal sensors are necessary to measure the on-chip temperature so the dynamic thermal measurement system can cause a change in the processor when the temperature reaches the trigger temperature. There are different designs of thermal sensors; many involve thermal resistors in which their resistance changes depending on their temperature. The placement and number of thermal sensors is important in designing a thermal management system. Typically processors have a thermal sensor built into the packaging of the chip above the hottest spot on the processor to detect overheating. While this may work, researchers are continually finding that there can be more than one hot spot and one thermal sensor may not be adequate. Researchers are looking at implementing arrays of thermal sensors on-chip to better measure the temperature on-chip (Clabes 56).

5. Conclusion

5.1 Summary

The purpose of this technical report was to show how a thermal management system can be developed for a typical embedded processor given the proper architecture. It has shown how to design the measurement tools needed to confirm a thermal management system reduces the temperature and power of the chip. A dynamic frequency scaling design was shown for the Intel 80200 processor, and measurement systems designs were provided based on the development board and the availability of LabView. The outcome was a successful design methodology for retrofitting dynamic thermal managements to chips not designed considering thermal management.

5.2 Interpretation of the Results

The original goal of this thesis project was to design a thermal management system and implement that system to show that dynamic thermal management systems work on embedded devices. Due to the constraints imposed on the thesis project by time and cost, and because of difficulties with the development board, the goal was changed to design a dynamic thermal management system that could be implemented on the Intel 80200. Although the original goal was not met, the project still has been successful. Reviewing other researcher's dynamic thermal management systems and designing the system for the 80200 have shown that certain features are necessary for a successful dynamic thermal management system: dynamic frequency and voltage scaling, and thermal sensors. These critical components are important for embedded processor designers to incorporate into the chips they design to allow for greater thermal flexibility.

Furthermore, this project lays out a method for designing a dynamic thermal management system based on the specifications of the processor. The 80200 was not designed with a dynamic thermal management system in mind, but the design method given in this technical report shows how to identify the key features of an embedded processor and design a dynamic thermal management system to take advantage of the architecture to design an efficient thermal management system.

Finally this thesis project provides the design of power and temperature measuring systems, which are necessary to validate any implementation of a dynamic thermal management system. These power and temperature systems are difficult to develop in an accurate manner. This project should offer other researchers a starting point in validating their designs and save them from reinventing the wheel.

The obvious weakness of the results of this project is that it lacks an implementation to prove that the dynamic thermal measurement designed lowers the temperature and power on an actual device. The next section explains how other researchers can take the work done in this project and expand it to further prove the merit of dynamic thermal management systems.

5.3 Recommendations for Future Work

When dealing with power consumption and overheating in processors, there is no one solution; there is always future work that can be done to further mitigate these thermal issues.

With respect to this project, the main area of future work will be the implementation of a thermal management system on an embedded processor. One approach would be to continue using the 80200 processor, and work out the difficulties with the operating system in order to get the dynamic thermal management system working. While continuing to use the 80200 may show improvements in temperature and power, it would be more beneficial to use an embedded processor that allows for dynamic voltage scaling as well. The quadratic relationship between power and voltage makes it difficult to achieve significant gains without changing the voltage, and the method of designing the thermal management system given in this technical report could be applied to another device. Second, since the development board using the 80200 processor was a limited production item, it may be better to choose a platform that is more widely used and has more documentation than what was used in this project.

With a working system, it would be possible to optimize the thermal management system to achieve the greatest power and temperature reductions with the least amount of performance loss. One way to achieve optimization would be to test different trigger temperatures and lengths of time for scaling to determine the optimal settings. Another approach would be to run different applications on the processor and see how different tasks react to the dynamic thermal management. The research from simulations shows that for different tasks, dynamic thermal management systems affect performance differently and that oftentimes an optimal system must be tailored to the tasks performed by the device (Simunic 524). Either way optimization would show the best possible power and temperature reduction for a given performance loss and would allow device designers to determine whether the benefits are worth the costs. Device designers could calculate whether heat dissipation was low enough for the planned embedded environment based on the values given from optimization.

It is hoped that this research will encourage device and processor designers to take thermal issues into consideration for future devices. The long-term benefits would be devises that both save energy and reduce the amount of heat produced. For the consumer, power and heat reduction means less cost associated with running the device, whether it is new batteries or an electricity bill, and less discomfort form the heat produced by embedded devices. As mentioned before, designers will be able to design devices, such as wearable medical equipment that can be implemented in thermally limiting environments, and to retrofit existing designs with thermal management systems to create more thermally flexible devices.

Appendix A: 80200 Frequency Scaling*

Software CCLK Configuration

CCLKCFG[3:0] (Coprocessor 14, register 6)	Multiplier for CLK	Example: CCLK Frequency (MHZ), assuming CLK Frequency of 66MHz
0 (reserved)	Unpredictable	
1	3	200
2	4	266
3	5	333
4	6	400
5	7	466
6	8	533
7	9	600
8	10	666
9	11	733
10-15 (reserved)	Unpredictable	

CCLK Modification Procedure

```
MOV R1, #7; New CCLKCFG value
MCR P14,0,R1,C6,C0,0; Change core clock frequency and wait for PLL to re-lock
```

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*Taken from Intel® 80200 Processor based on Intel® XScale™ Microarchitecture Developer's Manual, page 8-2

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