Implementation and Design of a Low Cost Laser Diode Temperature Controller

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***Abstract*—It has become apparent that many commercial products and military applications require high-endurance laser diodes. Testing the life cycles of laser diodes currently requires large and expensive equipment that is overreaching in terms of the overall goal. Finding a cheap and minimalistic solution will provide a large sample size and allow for rapid testing of hundreds of lasers.**

This paper aims to log the process of designing and implementing a temperature controller system for laser diodes. This system will use a thermoelectric cooler (TEC) to harness control of the Peltier effect to maintain a constant temperature on a laser diode. The system will contain a combination of hardware and software that work intimately to provide an intuitive and simple method of testing the life cycle of a laser diode. The hardware will consist of a cooling fan, heat sink, TEC, and metal plate that constitute the testing apparatus. The software will work with a number of peripherals to provide a steady temperature during testing and rapid transition between different temperature set points. The software will need to control the drive current to the TEC using a software-based PID (Proportional-Integral-Differential) controller and function as a watchdog, capable of giving error messages and raising alarms.

The primary purpose of the temperature controller is to perform endurance testing on laser diodes. It will also free up high cost equipment for precision needs, rather than endurance testing. This system aims to maintain a constant temperature within 0.5°C of the set point. This will guarantee a relatively stable and consistent light-intensity on the laser diode. The basic model of this temperature controller can be scaled and/or modified for applications other than laser diodes. This expands the potential impact of this system to be more consumer-friendly and will provide individuals with their own low cost temperature controller.

Keywords—temperature controller, endurance testing, PID controller, autotuning, feedback, thermoelectric cooler

I. Introduction

A temperature controller is a necessary component to acquire accurate results during endurance testing. Endurance testing means the system is operated for a long period, under strict conditions. The results of the test will reveal the performance of the part as a function of time. The gathered data is used to characterize the reliability of the part, generate a performance curve, and verify the part functions equally well at a variety of prescribed temperatures.

The temperature controller mentioned in this manuscript is required to do several things: manage potential thermal loads of up to 10 Watts, maintain a user-specified temperature anywhere from 15°C to 60°C, and maintain this temperature for long hours. Because it is mainly developed for lab use, there are no power constraints to consider for the temperature controller, although a reasonable amount of discretion was used during the selection of the TEC (Thermoelectric Cooler), a major power consumer.

Several components needed further researching to develop the temperature controller. The correct thermoelectric cooler needs to be selected based on the design constraints. This also meant some basic overview of the Peltier effect was needed. The Peltier effect dictates that when a current is introduced onto a junction of two different materials, one material will release heat while the second material will absorb it. This provides a controllable heater/cooler combination that can be used to manage the temperature of a component. Some of the other major components of the system are the PID controller, the microcontroller, the TEC, the TEC driver, and the LCD (Liquid Crystal Display) [1].

The final design will be low cost and easily implemented using off the shelf parts. Autotuning, which is an automated process for selecting the proper PID values, will not be implemented in the system. This system does not need to respond quickly to many temperature transitions in a short time. Without this feature, the cost of the system will decrease significantly.

II. Design Constraints

A. PID Controller

This basic control loop feedback system may be implemented with hardware using amplifiers or may be implemented through software. A choice between opting to go with the hardware or software implementation will require careful analysis of possible implementation methods and the corresponding engineering effort. Considering that a microcontroller is used, it is probable that a software implementation of the PID Controller will be ideal for this design [5].

B. Microcontroller

The microcontroller is tasked with handling most of the functions supported by the system. Once this part is chosen, much of the other components of the circuit must be checked for compatibility to the microcontroller. First, the microcontroller needs to have enough ports to support the number of peripherals being used. It also needs to have enough memory to store and process a sufficient amount of instructions. Other considerations for the microcontroller include its usability. Is it difficult to code? If the microcontroller supports C, it will be much easier to code

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various functions. Does it support Pulse Width Modulation (PWM) and a Serial Peripheral Interface (SPI)? The added restriction of a financial constraint also provides an additional incentive to maintain minimal expenses. Ideally, the microcontroller should meet the bare minimum requirements without any loss of stability or functionality.

C. *Thermoelectric Cooler*

This device uses the Peltier effect to heat and cool objects. The amount of heating and cooling is controlled by the current going through the device. The major characteristics of a TEC are power rating and ΔT (Maximum Change in Temperature). Picking the correct parameters is critical to the functionality of the entire system. Without a properly selected TEC, the temperature controller will not be stable and will have a very difficult time to produce efficient changes in temperature.

D. *Thermoelcetric Cooler Driver*

This driver is essentially an H-Bridge that will alter the direction of the current depending on whether the TEC needs to be hotter or colder. The main issue here is whether the TEC driver will be able to handle the power load that the TEC needs in order to operate. The TEC can take up to 4 Amps of current to alter the temperature as necessary. Therefore, the TEC driver must be selected to handle the same amount of current.

E. *Temperature Sensor*

The primary concern for the temperature sensor is its accuracy. This system requires an accuracy of 0.5°C over the entire range of applicable temperatures. To meet this goal, a temperature of at least 0.5°C accuracy is necessary. The temperature sensor also needs to support a certain resolution, which brings us to the discussion between digital and analog temperature sensors. Both have their pros and cons; they will be discussed heavily in this manuscript [6].

F. *Liquid Crystal Display*

The LCD needs to provide enough information to the user, while maintaining a simple and sleek graphical interface. A sleek interface will ensure that the user expends a minimum amount of effort to setup and start the system. The LCD will only display temperature readings during normal operation. It will also show various messages signifying mode changes and error messages. The LCD can also be accompanied with a backlight, which will be considered in the design as well.

G. *User Interface*

Producing changes in a system requires the use of stimuli to push it to different states. This system will employ pushbuttons as the primary way for data entry. The major issue with pushbuttons is problems with bouncing signals that need to be rectified with a hardware or software solution. Hardware debouncing is more robust, but requires extra hardware and space. Software debouncing requires no additional hardware, but can cause erroneous results if the software is not configured properly.

III. DESIGN CONSIDERED

For the PID controller, there are two options: hardware or software. Implementing it in hardware would require a series of analog calculations to choose the correct resistors, capacitors, and amplifiers. Its advantage is that the effects of the feedback loop would be almost instantaneous since it is all composed of simple analog parts. Software implementation would be simpler in comparison. Making alterations to the parameters of the PID controller will be much easier since its corresponding variables just have to be changed within the code. But we do have to take into consideration the delay we will get from the microcontroller as it calculates the changed variables and variable temperature [3].

The choice of microcontrollers to use was easily narrowed down to microcontrollers from Atmel. This was because the members of the design team have the most experience in working with microcontrollers from Atmel's ATmega family. The datasheets of various ATmega microcontrollers were used to pick a controller, which would fit the minimum requirements and be the most financially efficient.

TEC's come in two flavors: low voltage and high current output, or high voltage and low current. Picking the right flavor is the primary deciding factor. It is usually easier to use high voltage, low current systems because most power supplies can source higher voltages rather than higher currents. The TEC used in the system is high voltage, low current.

The second factor in selecting a TEC is its power rating. Without a properly selected power rating for the TEC, the system will struggle to alter the temperature of the object. It may become very sluggish and take a long time to produce a significant change it temperature. The system may even become unresponsive and fail completely. It is also important to choose a TEC that will provide the necessary power dissipation without maxing out the TEC. Driving the TEC at its limit puts strain on the TEC and can even be less efficient then driving at a lower current. Therefore having a ratio of roughly 0.5 or less in terms of the part power dissipation ($Part_{PD}$) with respect to the maximum power output of the TEC (TEC_{POmax}) will provide decent results and will require less energy. The efficiency (E) is

$$E = Part_{PD}/TEC_{POmax},\ (E \leq 0.5). \tag{1}$$

This system has an efficiency value of 0.478, which means the TEC uses less than 50% of its potential power output on heating and cooling [4].

As for the TEC driver, the main concern is its ability to push at least 4 Amps to the TEC. However, to compensate for overhead and have a reasonable margin, it may be safer to get an H-bridge rated for currents higher than 4 Amps. This system will never reach the maximum of 4 Amps, because the TEC has the capability to provide efficient cooling of 10 Watts with a lower current.

There are two general implementations of an H-bridge. The first implementation utilizes four independent power MOSEFETs that are pulsed to provide a directional current.

This method allows for greater durability and better heat dissipation. The major issue with this implementation is the need to characterize the H-bridge to provide discrete levels of current. This becomes increasingly difficult when you have to configure four MOSFET's, which all have their own intrinsic impedances. We also need to consider that we need two PMOS and two logic-level NMOS, which will complicate matters even further. Implementing an H-bridge this way is more beneficial when variable currents are not involved, such as driving a motor at one specific level. The addition of two NMOS transistors will be used to drive the PMOS gates. Logic-level PMOS power MOSFET's are expensive and are not manufactured for high supporting levels.

Another solution is to purchase an integrated H-bridge that is configured for pulse width modulation (PWM). This avoids the need to test all the MOSFETs for currents at various levels. Although it may be easier to use at first glance, there are a number of difficulties involved, such as understanding how the part works and writing software that interfaces with the part. Power dissipation will be another major issue that will need to be addressed. This part will drive large currents at times, which means a heat sink will be needed. One possible solution to the power dissipation problem is to attach the part to the main metal assembly, which has a significant metal surface area. Although the integrated H-bridge may seem ideal, it is impractical for this system. These parts are usually supplied in surface mount packages and contain a metal heat pad on the bottom of the part. Hand soldering will not due this part justice, therefore, the standard four discrete power MOSFETs may be a better solution.

Without a temperature sensor, the system would not know how to react. Two types of temperatures sensors are considered for this design. The first type is an analog temperature sensor with a linear output. These are very easy to use and do not require any specific software to read a value from the sensor. They are also very fast and perform thousands of readings every second. The main reason this will not work is that to get a resolution of 0.1°C with the ATmega's 10-bit Analog-to-Digital Converter (ADC) and an analog temperature sensor, would require a 1.024 Volts reference. The temperature change per bit is unstable with this approach. Any noise will likely cause a change of at least 1°C or more. This severely limits the robustness of the temperature sensor and the system as a whole [2].

Another approach is to use a 12-bit ADC. This will bring up the reference voltage to 4.096 Volts, which provides slight better resolution. Although you still have the same voltage per degree Celsius, the larger reference voltage dampens the effects of noise and increases the noise margin. The sampling speed of the sensor is also very fast in this configuration as well. This final design contains additional hardware, which requires custom software to read the temperature.

Of course, both approaches will not produce a stable system. The third solution is to amplify the voltage of temperature sensor output with a low offset operational amplifier (opamp), possibly a chopper opamp. In conjunction with the 12-bit ADC and the 4.096 Volts, the temperature change per bit will be less error prone and more resilient to noise.

The digital solution to this problem can be implemented with a digital thermometer that provides at least 0.1°C resolution. A 12-bit thermometer will provide 0.0625°C resolution, which is more than enough for this system. The disadvantage with digital sensors is that they are very slow. A typical 12-bit conversion can take 750ms; this does not include the time required to extract the data from the temperature sensor. These devices also require many lines of software just to read the register that holds the converted temperature. Although they do not need any additional hardware, they are very slow and software intensive. Not getting enough temperature readings may make the system unstable because it cannot react quick enough to counter quick changes in temperature. The lack of speed offered with a 12-bit temperature sensor will limit the functionality of the system and hamper performance.

An LCD will be used to display information and allow the user to input system parameters. This system will use an LCD with SPI. This method of data transfer is easy to use and implement. It will also feature a backlight, which should aid in the display of the text on the LCD. Other than choosing a manufacturer, there is not much design consideration for the LCD other than cost. The cost of the LCD will be kept at a minimum.

Considerations involving the audio alarm, which is used for alerts, are minimal. The alarm will be driven by a DC voltage. These types of buzzers have an internal resonator that is triggered when power is applied. AC buzzers require an external AC source to creating an alarming sound. The alarm will also be small to conserve on space. Many buzzers have decibel ratings on their datasheets. A good alarm will have a rating of 85dB, which is the equivalent of city traffic inside a car. The alarm used in this system is rated for 100dB.

The pushbuttons in the system will be large enough to press easily with one finger. They will be low profile to minimize accidental presses. The make and bounce times of the pushbuttons will not be considered until the actual building of the system. Either hardware debouncing or software debouncing will be utilized to limit accidental triggers. The design will implement a NAND gate coupled with an interrupt to signify that a pushbutton has been pressed.

IV. Final Design

The system will use a thermoelectric cooler assembly. These assemblies have a fan, heat sink, TEC, and metal plate sandwiched together in a compact package. This type of device is costly and will be used for development purposes only. It has cooling capacities of up to 21 Watts, which is more than enough to handle loads of up to 10 Watts. The ideal solution will be to develop a similar assembly, with off the shelf components, which will benefit the system with lower cost.

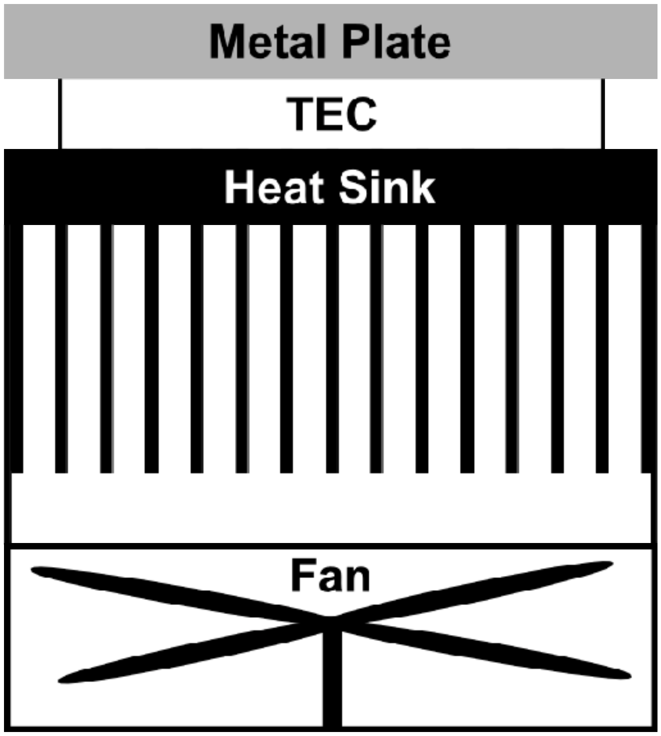

Figure 1. TEC Assembly

The most logical solution for the PID controller is to implement software within the microcontroller. If the controller were hardware implemented, it would require the user to constantly switch out resistors, capacitors, or amplifiers in order to change parameters. This would significantly hinder development and usability. Although it has an advantage of being nearly instantaneous, it is not necessary to instantaneously change its parameters. The microcontroller works at a fast enough frequency that the delay to process the new variables will have minimal effect on the overall functionality of the temperature controller [7].

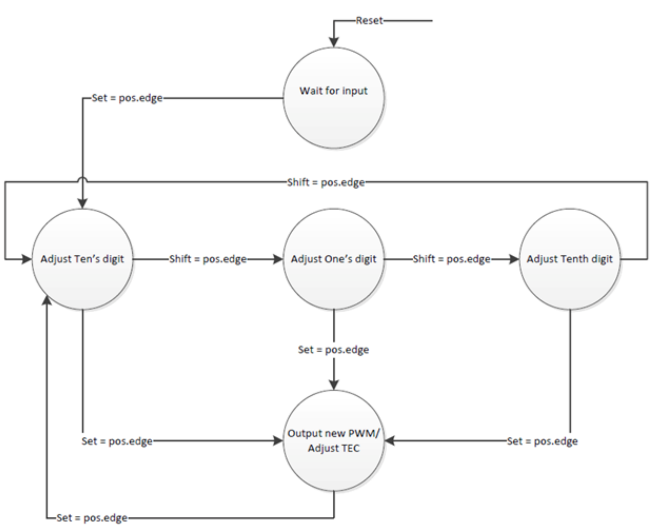

Figure 2. FSM diagram of Temperature Controller

The H-bridge uses four MOSFETs rated for very high current and voltage. These MOSFETs have a small on resistance, which will keep the power down to about 0.15 Watts. This is easily manageable in the TO-220 package. These parts also have a high maximum drain-to-source voltage, in case there are spikes during the switching of the TEC.

There is a specialized chip, the MAX1969, which is developed to be used with TECs. This chip costs more than all of the other parts combined, per unit. The MAX1969 will make it easier to develop the TEC driver but it is too expensive of an option.

The system will be controlled by the ATmega32. There are other options available with bigger memory and more features but efficient software will minimize the physical size of the hardware. It will be a bigger challenge to code with the ATmega32 but the potential benefits may be worth it. The ATmega32 has an SPI interface, several external interrupt ports in addition to an internal counter that can be used to trigger interrupt subroutines and create pulse width modulation. From Atmel's official website, the following parameters can be found for the ATmega32: 32 Kbytes of Flash Memory, 40 Pins, 16 MHz max operating frequency, 32 Max I/O pins, 3 external interrupts, 1 SPI, 8 ADC channels each with 10-bit resolution, and 1024 Bytes of EEPROM. As the design progresses, the ATmega may be replaced with an ATtiny. Using an ATtiny is a cheaper option and will have less unused resources for this application. The ATmega contains a large number of ports that will go unused so switching to a smaller microcontroller is the long-term goal.

Because time constraints for the system are not known yet, an analog temperature sensor along with a 12-bit ADC and an amplifier will be used. The digital temperature sensor will not be considered due to unusually long measuring times.

The following flow chart shows how the feedback loop will work. The laser temperature is read near the laser using a temperature sensor. This data is fed to the PID Controller, along with the binary representation of a set point temperature. The PID Controller will analyze these inputs and decide how to implement the desired temperature change. The PID controller will finally modulate a pulse that is fed to the H-Bridge. The H-Bridge will source a current to the TEC to create a difference in temperature. This process will repeat once again when the temperature sensor reads another value and gives it to the PID Controller.

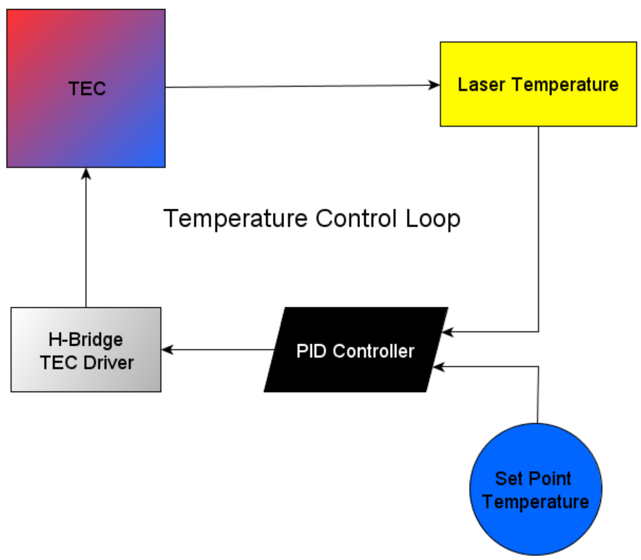

Figure 3. Temperature Control Loop

The LCD will contain be a 16 X 2 LCD display. There will be four temperatures displayed at any given point in time. The first temperature is the set point temperature. The second temperature is the actual temperature of the part placed on the metal plate. The last two temperatures display the high and low values once the set point is reached. This will give the user a quick way to check if the system is operating within bounds.

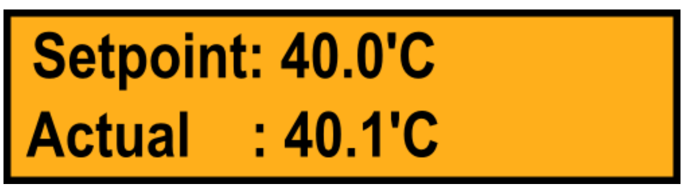

Figure 4. LCD Data Arrangement

The LCD will not display a history of the temperature of the part. The best way to monitor the temperature of the part is to use a data logger. The data logger will record the temperature of the part at a fixed interval and log the result in a spreadsheet or text file on a computer. The results can be graphed instantly using a graphing program or a built-in graph function often found in spreadsheet programs. This simple solution will allow the user to see how the temperature of the part has fluctuated with time.

The pushbuttons will be used to serve as stimuli for the system. The pushbuttons will be connected to a 4-input NAND gate to create an unencoded linear key array. The output will be connected to an interrupt port.

In order to shutdown the system, the user will have the option of pressing a switch rather than pulling out the power cord, or disconnecting the power supply. A rocker type switch will be used to minimize accidental shutoff.

Once the major components of the system are implemented, a fuse will be inserted to prevent excess current from damaging the parts. The maximum current draw of the system will be unknown until it is fully developed.

To minimize the use of several power supplies, the system will use a 5V voltage regulator to power all of the components other than the fan, TEC, and possibly the audio alarm. This will simplify the setup of the system and make it easier to use when only a 12V power source is required.

V. Summary and Conclusion

The low cost temperature controller proposed in this manuscript will contain a mixture of analog and digital subcomponents that will provide stable temperature control in a predefined temperature range. It will use software techniques, hardware, and a feedback loop to provide autonomous control of the temperature. Several peripherals including an LCD and an audio alarm will be used to provide data to the user. The system will be operated with pushbuttons that will control the set point temperature.

This manuscript was compiled to highlight the research, planning, and implementation of the low cost temperature controller. The ultimate goal is to develop a fully functional system as described in this manuscript, and satisfy the specifications needed for its technical and research applications, while maintaining low cost.

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