Milestone Report III

Autonomous Thermal Camera EE449

May 7, 2010

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Executive Summary

The purpose of this milestone was to simulate our system with a designed controller. Additionally, we included a brief progress update and modeling on the thermal dynamics. Currently, we have encountered delays due to the attaining parts and modeling the thermal dynamics. However, we have been able to simulate our system using arbitrary values.

Contents

1 Project Update

Our project is currently behind on schedule. The main reason behind this is the delay in time for items ordered to arrive and also the complexity and challenge we had to deal with in figuring out the thermal dynamics of our project. As of this milestone we have received the electrical components to our system and have found a suitable solution to the thermal aspects of our project. For this reason our scheduling has changed to accommodate for these delays. Our first test of the box has been delayed by two weeks and upon receiving the mechanical parts the development of the physical system will be done. As can be seen in 1 we have found the suitable materials and are currently receiving price quotes.

INFRARED CAMERA PARTS

Insurance Information

Personnel Use	Last Name	First Name	Phone	Notes
Team Lead	Alcaide	Ramses		
Electrical Engineering Lead	Thomson	John		
Mechanical Engineering Lead	Haruta	Adrian		

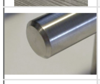
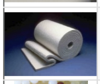
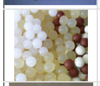
Item	Photo	Quantity	Purchase Date	Place of Purchase	Cost	Total W/O Tax	Description
▼ Electrical Components							
Atmega168		5	4/10/10	Digi-Key	$4.32	$21.60	
IC Driver Dual 15Multiwatt		4	4/10/10	Digi-Key	$4.34	$17.36	$45.30 including tax and shipping for above items
PIR_D203S		8	4/10/10	Futurlec	$1.90	$15.20	
PIR_D203B		8	4/10/10	Futurlec	$1.90	$15.20	
PIR_D202X		8	4/10/10	Futurlec	$1.90	$15.20	$67.60 including tax and shipping for above
Quad Encoder Motor		1	4/10/10	Robotkits	$50.00	$50.00	$58.00 including tax and shipping
Zippy 100mAh 20C Single Cell		8	4/16/10	Hobby King	$2.00	$16.00	
Zippy Flightmax 5800mAh 2S1P		1	4/16/10	Hobby King	$36.18	$36.18	$72.55 including tax and shipping
▼ Mechanical Components							
Haynes 214 Sheet		2246 in.^2	5/6/10	Haynes International	TBD	TBD	If possible 3 ft. x 3 ft. sheets. 1/8 in. thick.
Haynes 214 Billets		2 Cylinders 3 in. Diameter 4 in. Tall	5/6/10	Haynes International	TBD	TBD	
Haynes 214 Bars		4 Bars	5/6/10	Haynes International	TBD	TBD	6 ft. Long 1/2 in. Thick Please Call 800-354-0806 To order. Ship as soon as possible.
Fiberfrax Blanket S		1536 in^2	5/6/10	Fiberfrax	TBD	TBD	1 in. Thickness 8 lb/ft.^3 density Please Call **716-278-3800** To order. Ship as soon as possible.
Solid/Solid PCMs		4 ft.^2 x 1in. Thickness	5/6/10	PCM	TBD	TBD	Please Call **+44(0)1733245511**To order. Ship as soon as possible.
Sapphire Lens		2 lens	5/6/10	Red Optics	$600		3 inch Diameter, 2.5mm Thick, <3in parallelism

Figure 1: Materials and Cost List

Parts will be order promptly and shipping will be expedited to make up for lost time.

2 Thermal Dynamics

2.1 Equations

Table 1: Thermal Dynamics Variables

T	Temperatures inside a plane wall
ρ	Density Of Plane Wall (kg/m^3)
c	Specific Heat $(J/kg * K)$
t	Time in Sec
x	length of individual nodes
N	Number of Nodes
K	Thermal Conductivity $(W/m * K)$
h	Thermal Convection $(W/M^2 * K$

2.2 Mathematics

The thermal dynamics of the our system was one of the most important aspects of our work. Although this task is not fully in the scope of this course due, it is still a difficult task to achieve due to the extreme temperatures we are working with and heat transfer implications. Due to the fact that the system has open loop control the end steady state result will eventually level off at an internal temperature that is dependent on the mechanical properties of the materials we are using as well as the external conditions. This end steady state result is the state at which the phase change material we are incorporating will be all used up. Thus the only thing stopping the heat from entering the box will be the insulation[1]. The open loop control system we are implementing to do this task requires two stages of protection from extreme heat. The two stages are the outer insulation and the phase change material. The outer layers of insulation shield the sensitive equipment inside the box by effectively reducing the cold face surface temperature by more than half the outside temperature. It is physically impossible to keep the temperature inside the box below 50 degrees Celsius by only using insulation[1]. At this point in order to simulate the transient behavior of the temperature distribution, Matlab was used to generate a rudimentary Finite Element Analysis program(FEA) with the help of Dr.Ashley Emery. This FEA program was able to mesh to a desired accuracy although we found that refining the mesh didn't provide much accuracy at the cost of computing time. The programs end result is a temperature vector with the current temperature at each different location throughout the plane wall. The FEA program operated based off of a single principle the law of the conservation of energy in heat transfer form. This principle was implemented at each and every finite element throughout the plane wall. The math for the a matrix is shown below. Were equation 1 is the energy balance of the hot face, equation 2 is energy balance of the of the middle insulation, and equation 3 is the energy balance on the cold face[1].

$$\frac{\rho c \Delta x}{2}\frac{T_1^{n+1}-T_1^{n}}{\Delta t} = (T_\infty^{outside} - T_1)h_{outside} + \frac{(T_2-T_1)k}{\Delta x}[1] \tag{1}$$

$$\frac{\rho c \Delta x}{2}\frac{T_1^{n+1}-T_1^{n}}{\Delta t} = \frac{(T_1-T_2)k}{\Delta x} + \frac{(T_3-T_2)k}{\Delta x}[1] \tag{2}$$

$$\frac{\rho c \Delta x}{2}\frac{T_1^{n+1}-T_1^{n}}{\Delta t} = (T_\infty^{inside} - T_N)h_{inside} + \frac{(T_{N-1}-T_N)k}{\Delta x}[1] \tag{3}$$

The equations consider the conduction of heat through the inner elements. The equations differ when it comes to the outside elements. Namely the first and last row of the A matrix. These two parts need to incorporate the heat transfer by convection into the equation. The convection comes in on both sides of the insulation assuming a fluid layer on each side. Once the A matrix is set up an iteration technique is used to generate corresponding temperatures throughout the material at each interval in time. The increment of time for our case is 1 second thus $\Delta t = 1$ With the FEA program up and running we can do simple calculations of transient conduction through a plane wall. However, at this stage of the program we can only consider a single type of material. In future reports we hope to have a more complete program to help us run simulations on both stages of the heat control process with two types of insulation and a phase change material included.

3 Thermal Dynamics Performance

Once the FEA program was complete for modeling a single plane wall with transient conduction, the simulation needed a contestant. The first type of insulation simulated was Fiberfrax Durablanket S. This material was the type we chose to use as a buffer to essentially take the most heat and drop the temperature down significantly so that another better insulator could be used to stop the majority of the heat from entering the box. This needed to be done in a specific balance because although the Durablanket could handle high temperatures the thermal conductivity wasn't as low as other better insulators. With that said the better insulators couldn't handle the same temperatures as the Durablanket. The reason this type of material was used was due to the fact it was an insulator that could withstand the 1200 degree Celsius forest fire temperatures. Since we have a metal casing the heat would almost immediately equalize the temperature on the side exposed to the fire and the temperature on the inside of the box but before the insulation. The insulator is the main component that will be reducing the temperature on the inside of the box so we needed to know how well it would perform under those conditions[2]. Figure 2 below shows our FEA simulation of a 1 inch thick piece of our insulator. The design constraints of the heat shield designate that the 1200 degree Celsius temperature only needs to be withstood for a two minute interval. We have simulated the durablanket with a six minute interval where the insulation will be exposed to 1200 degrees Celsius. This is effectively a step response since we add a heat source at time t = 0 and take the source away at 360 seconds while monitoring the internal temperature of the box. This shows how well the insulator will do its job with only one inch thick insulation. The peak temperature reaches about 533 degrees Celsius. This represents the temperature in between the two insulations that will be used[2].

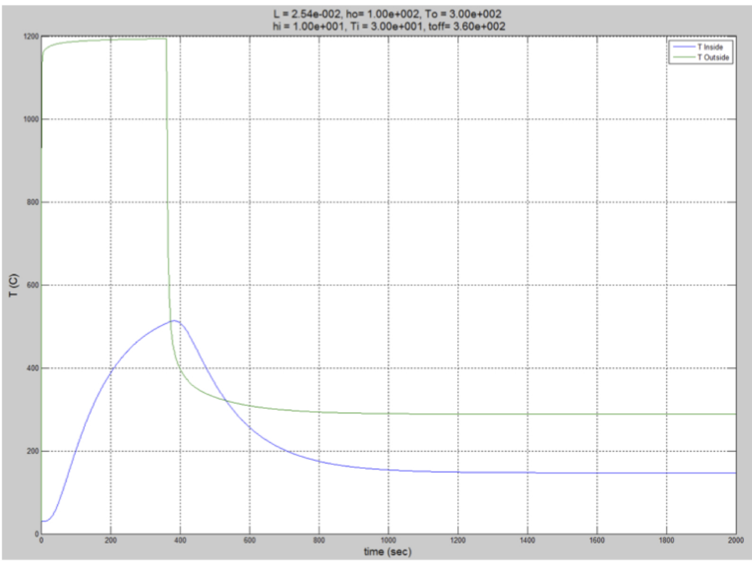


Figure 2: Step response of Dura-blanket S insulation with 1" thickness exposed to a 1200C heat source for 6 min.

From figure 2 after the step response has ended and the 1200 degree Celsius heat source is removed the smoldering process takes over and remains at 300 degrees Celsius for a couple days. The steady state temperature inside the box without any phase change material will be about 150 degrees Celsius. Since we don't yet have the ability to simulate an extra layer of insulation with our phase change material, we can still make estimates of the internal temperature behavior. Since the heat shield design incorporates enough room and we have the ability to control the thickness of a single layer of insulation we decided to see what would happen if we used only the Durablanket S. After lining the interior with 2 inch thick Durablanket S we effectively used all space designated for insulation. The results can be seen in figure 3 below. The temperature on the inside of the box never reaches above 220 degrees Celsius even at peak temperatures. Also the steady state temperature inside the box is lower and is closer to 120 degrees Celsius. This means that the amount of phase change material required to absorb heat energy will be less given thicker insulation.

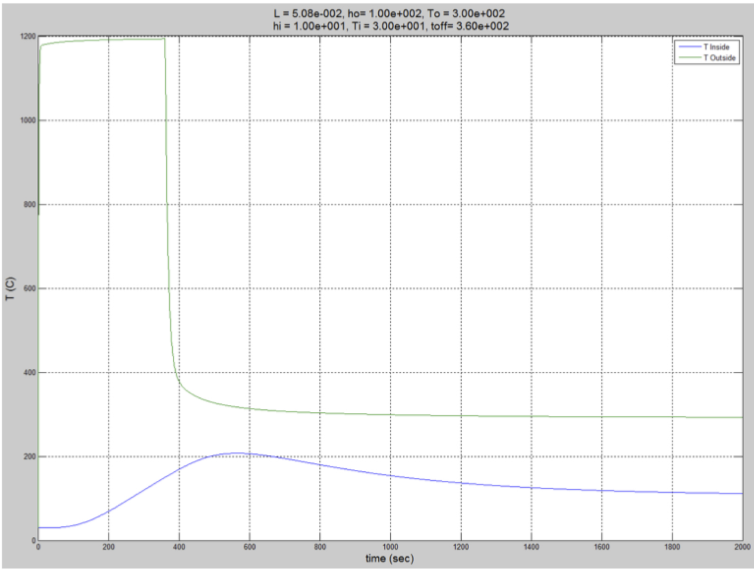


Figure 3: Step response of Durablanket S insulation with 2" thickness exposed to a 1200C heat source for 6 min.

4 Controller Logic and Modeling

4.1 Forward and Disclaimer

In the last milestone presentation, a request was made to prove that the system was able to track a point of interest in a fire reliably. It was not realized that actual purpose of the request was for a controller that utilized a fully linear feedback system as opposed to the current nonlinear comparator based design.

In a meeting with Charlie on the 7th of May, this point of contention was made clear. Now, there exists a fairly well simulated but un-provable controller design that has been fairly well documented and the need for a new design with no time in this milestone to realize it. Subsequently, for the purpose of this milestone report, the controller that will be described is the existing design, while the new design will be outlined in as much detail as is reasonable when starting just before the deadline.

4.2 Controller Requirements

For the purpose of recording footage of wildfires, the customer indicated that accuracy and speed were not considerations for them. Along those lines, the requirements for the controlled system are as follows:

1. The plant must be able to detect and track a hot spot of the fire with an error of 45^o. (Alternatively, the box must face away from "no fire" regions to observe an approaching front of flame.)

2. The settling time must be less than 20 seconds.

3. The controller should remain stable in a noisy environment.

4.3 Overview

In order to isolate complexity to one particular subsystem, the controller logic of the fire tracking system is comprised of two parts: position control and heat tracking. The position controller is comprised of a simple proportional controller. This controller takes an angular position as its command signal and using a quadrature encoder, is able to track any angle with negligible [specify/prove] steady state error. The second stage of the controller acts as an outer loop on the position loop. In order to detect the presence and direction of the fire, thermopiles (also known as Pyrolytic Infrared or PIR sensors) are used in a radiating configuration to detect heat in all directions as shown in figure 4.

Since the values gleaned from the six PIR sensors above do not immediately give an accurate direction of the fire, a method must be used to infer the best direction to point given the known energies incident at each sensor. The previous comparator method used a series of conditional statements to follow the hottest perceived point in the fire. The proposed inferential method would use the non-linear Gaussian behavior of the thermopiles to more accurately derive a theorized "front" of flame that could then be focused upon.

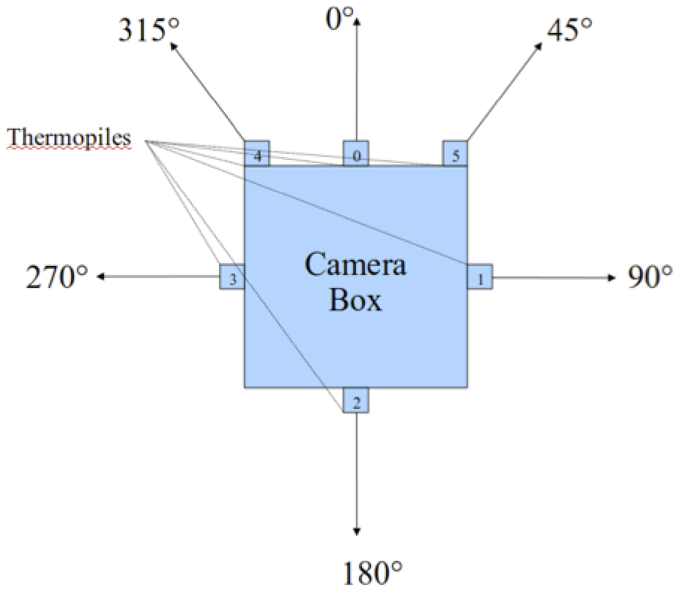


Figure 4: Description of Sensor Layout

4.4 Comparator Logic

The logical description of the comparator method can be broken up into two statements. First, is there a significantly larger heat source than what is currently being looked at by the front sensor? If so, rotate to face the hotter direction. Second, if none of the other faces are significantly hotter than the front face, slew right or left at a constant speed until the center thermopile on the front face of the box reads the highest value. This logic is shown in figure 5 in the visual model of the fire tracking system.

In detail, the functionality can be explained as such: Discovery State: If either sensor 1,2, or 3 has a higher voltage (higher incident heat) than sensor 0, then rotate to that position. This causes the controller to seek its position to either 90, 180 or -90 degrees depending on which sensor reads the highest intensity. Trim State: If none of the sensors 1,2, or 3 have a higher value than sensor 0, then compare the value of sensor 0 with sensors 4 and 5. If either 4 or 5 have a higher value, then track by increments of 5% in the direction of the higher temperature. Do Nothing: If sensor 0 has the highest value, then no action will be taken as that sensor is looking at the highest perceived temperature. Even if there is a section of fire that may be hotter, the camera is recording a substantial section of the flame and is subsequently satisfying the requirements of our customer.

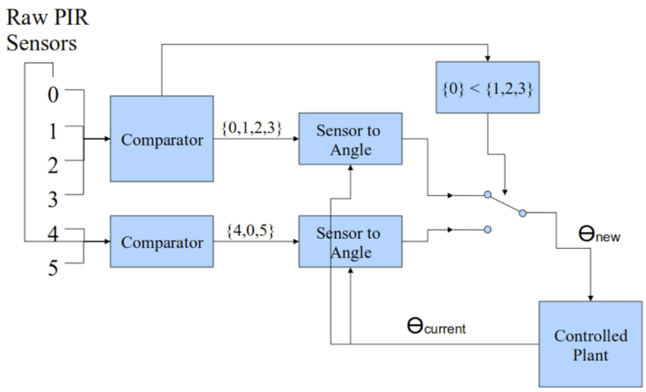


Figure 5: Block diagram of the fire tracking logic

4.5 Thermopile

While very little information is available about the precise characteristics of most thermopiles as manufacturers generally leave the calibration and characterization of such components to the customer, based on experience with similar photoelectric components it might be expected that a PIR sensor will express a roughly Gaussian behavior regarding angle of incidence [3, 4, 5]. By this logic, a purely angular model for the PIR sensor was constructed. The equation for this model, where u is the number of degrees that the camera faces away from the heat source shown in equation 4 when $-180 < u < 180$ degrees[6].

$$y = e^{\frac{5u^2}{2(180)}} [6] \tag{4}$$

Using this equation, a model device was developed for Simulink that behaves as a real thermopile should when being exposed to a heat source from various angles. The response of this model as a function of angle is shown in figure 6.

4.6 Controlled Plant Model

Since the plant has not been constructed yet, its characteristics have not been determined. That said, the basic characteristic curve of a motor can be

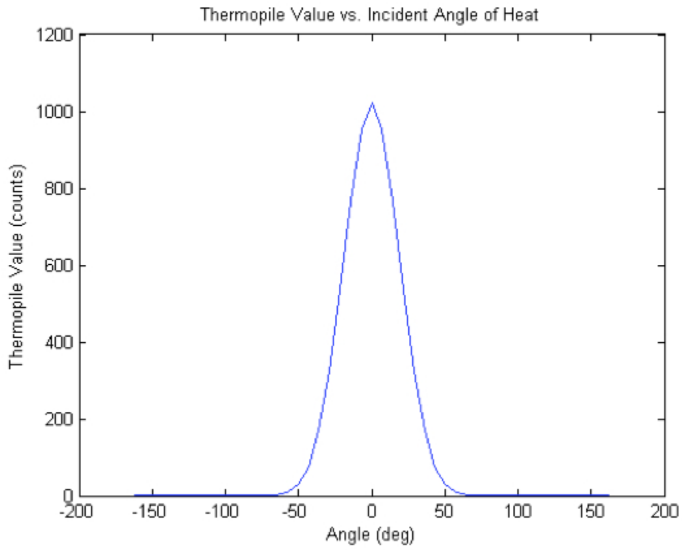


Figure 6: Behavior of the Thermopile over 360 degrees

modeled using the physics derived in EE/AA 448 for the DC motor lab[3]. This consists of the Simulink shown in figure 7.

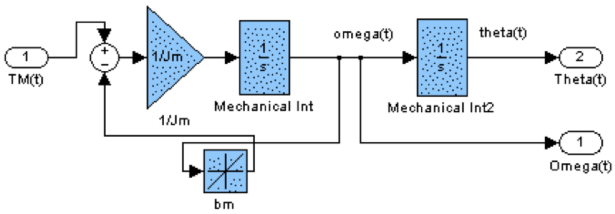


Figure 7: Simulink model describing the behavior of a motor [3]

Where Jm is the mass of the angular load, bm is the damping behavior of the bearings and TM(t) represents the torque applied by the motor. In this configuration, a Jm and bm were chosen as .2 and 1 respectively to obtain a reasonable closed loop response. A value of 1 was chosen for the closed loop gain. These values were chosen to create a motor system with settling time of about five seconds. This response was made intentionally slow to show the ability of the fire tracking controller to settle after 20 seconds even with a slow actuator. This response is shown in figure 8. Currently, arbitrary values have been chosen due to receiving the motor just recently. Full modeling of the motor is goal that will be worked on in the following week.

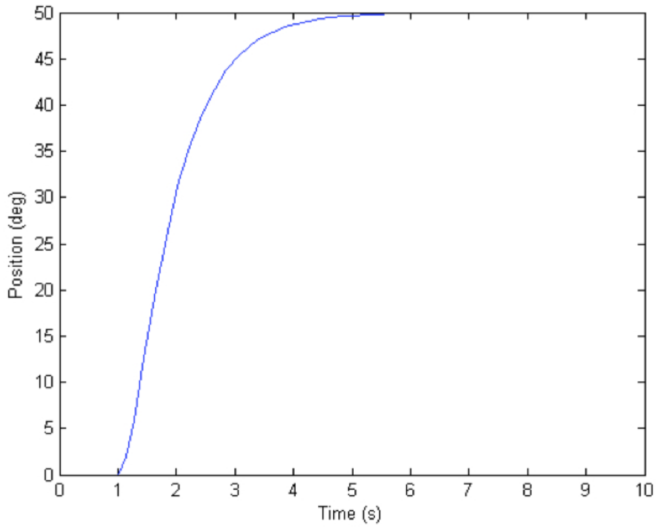


Figure 8: Simulated step response for an arbitrary motor system similar to the expected response of the plant

Once the physical plant is constructed, step perturbations will be used to determine its physical characteristics and subsequently populate this model with accurate parameters.

4.7 Comparator Based Fire Tracking Model

The logic used for the purpose of fire tracking is the same as presented in the Controller Overview. In order to be modeled, this was created in Simulink and linked up with the aforementioned simulated components.

The overall system flow can be seen by looking at the simulated system overview, where the comparator based fire tracking logic lies on the left, the controlled physical plant is to its right and the thermopiles are located to the far right. Looking within the comparator based tracking subsystem, there are three main modules. The top module evaluates if any of the non-front-facing sides are sensing a significantly hotter fire than the front. This result is then used to decide if the tracker uses the "discovery mode" or the "trim mode" command signals to decide where to point the camera this can be seen in figure 10.

The individual Sensor to Angle modules are also shown. The discovery mode module in figure 11 outputs the current angle with either 0, 90, 180 or -90 degrees added, depending on which side is hotter.

The trim mode module shown in figure 12 works in a similar way to the

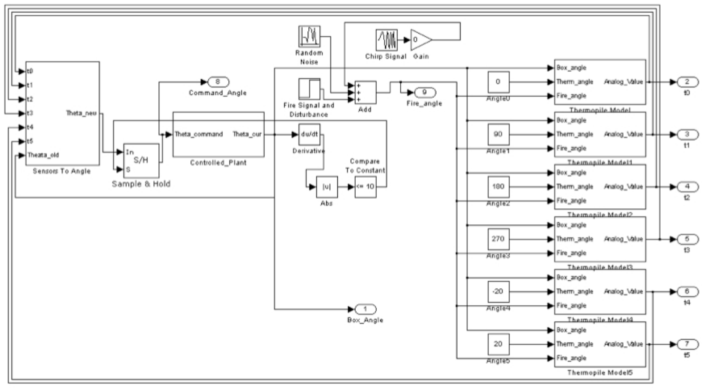


Figure 9: Overview of the simulated system

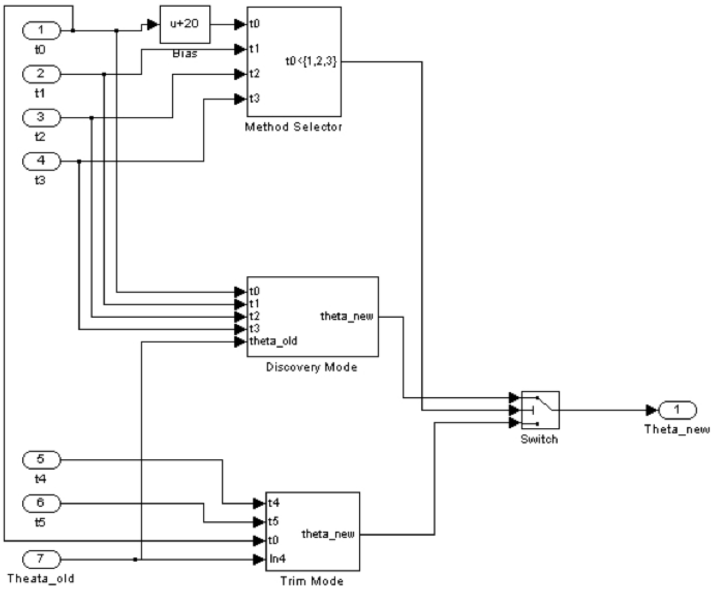


Figure 10: The overview of the Sensor to Angle module showing both modes of control

discovery module, except for the slew rate being a constant one, instead of the box rotating to face the direction of the sensor.

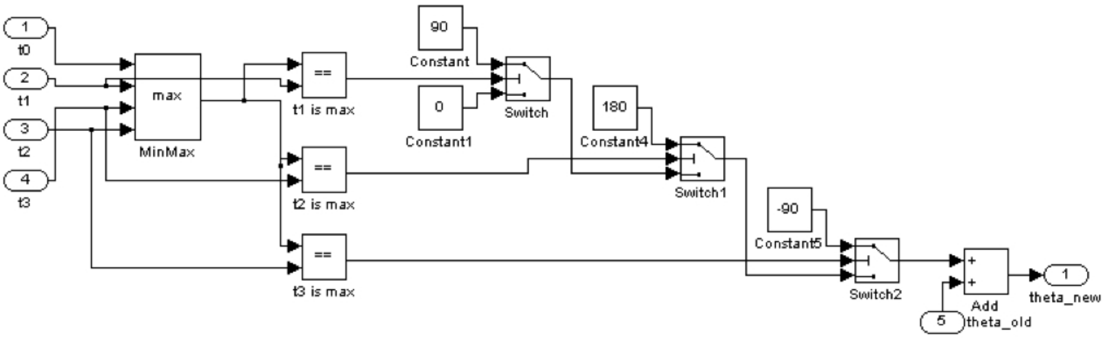


Figure 11: The discovery mode module

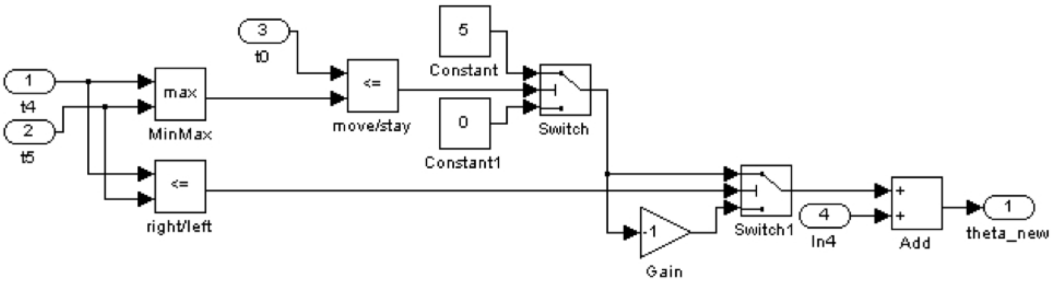


Figure 12: The trimming mode module

5 Comparator Tracking Model Analysis

For the purpose of empirically testing this model, a series of step responses and noise signals were introduced into the value representing the simulated direction the heat of the fire originated from. From these responses, it was determined that for all angles, the controller was able to track and settle well within 4 seconds to a steady state error of less than 20^o. This can be shown in figure 13.

5.1 Comparator Tracking Noise Robustness

In order to determine the robustness of this controller design against noise, some assumptions were made. The first assumption was that the noise exhibited by a fire could be roughly approximated by Gaussian noise added to the "hot spot" angle. The next assumption was that the noise generated by

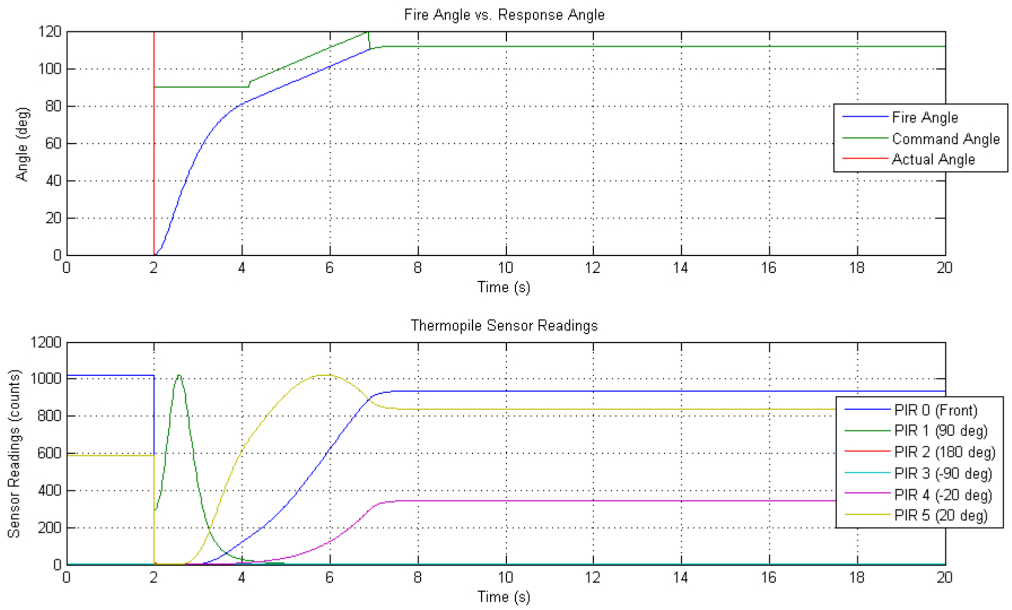


Figure 13: Testing multiple step responses showed the system always turned towards the fire

a fire on the thermopile sensors would be constrained to around ±20 to 40 degrees. These values were chosen based on the size of burning objects from 5 to 10 feet away. Characteristic objects, such as trees, would generate ±33 degrees of noise at 5 feet away and with a 2 foot trunk. This can be seen in equation 5.

$$cos^{-1}(\frac{2ft}{5ft} = 33^o) \tag{5}$$

When introducing noise into the fire position, the thermopile measurements seemed to generally amplify that noise, due to their steep fall-off behavior away from a hot spot. However, even with ±40 degrees of noise, the controller exhibited a stable behavior and was not perturbed. This can be seen in figure 14.

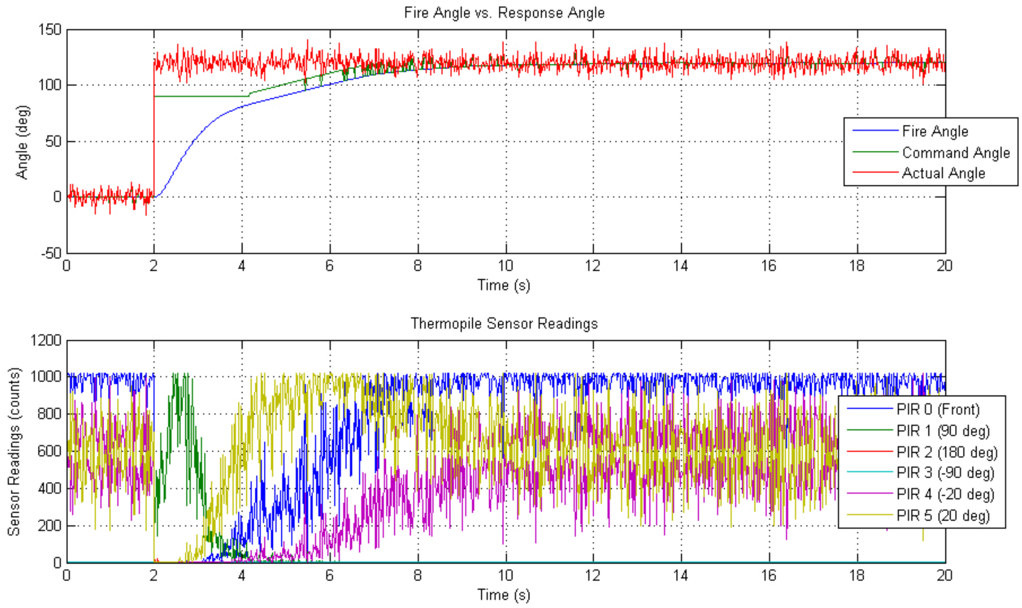


Figure 14: Testing multiple step responses showed the system always turned towards the fire

5.2 Outline of the Sensor-Fusion-Driven Fire Tracking System

During a conversation with Charlie the TA, the assertion was made that the current controller can not be proven to have the ability to stably track a noisy fire. While it is believed that the fire tracking algorithm should work for the purpose of ensuring the camera faces something "interesting", the difficulty of proving this functionality outside of empirical simulation makes it unusable for the purpose of a controls capstone. Along these lines it is recognized that a new controller design is needed. The proposed modification, as suggested by Charlie, makes several assumptions about the fire. First, it assumes that the fire front can be treated like a line producing heat along its length. This line would have a varying intensity of infrared light along its length in a pseudorandom manner. Using the values from the six thermopiles, an approximation of this line would be created within the controller. Using this line, an optimal direction to point the camera could be calculated. This can be seen in figure 15

To determine this line model, only two points of data need to be known if a few assumptions are made. First, the fire-line must be uniform with a known intensity and height. While it may be possible to characterize a fire with

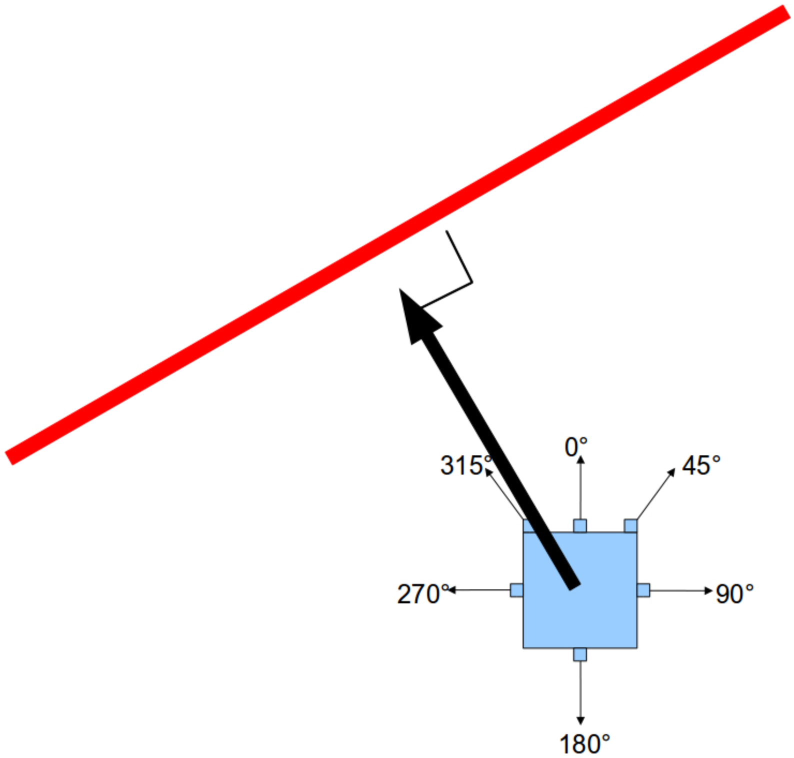


Figure 15: The sensor fusion system should determine the location of the fire as a line and then look at its closest point

non-uniform characteristics, such an algorithm is not currently known. With the line defined as uniform, two thermopile's could be used to determine its location and angle. One way this would be accomplished would be by creating vertical slit blinders for each thermopile and subsequently calibrating each with a known light source of given area at various distances. This would allow for the sensing of the distance of the fire-line from the box by the virtue of its uniform intensity and height. With this information, the incident light can be converted directly to an angle and subsequently to a distance using trigonometry. This is shown in equation 6 and 7 and figure 16[7].

$$\Theta_{fire} = intensityToAngle(i)[7]$$

$$dist_{fire} = \frac{(height_{fire} - height_{cam}}{cos(\Theta_{fire})}[7]$$

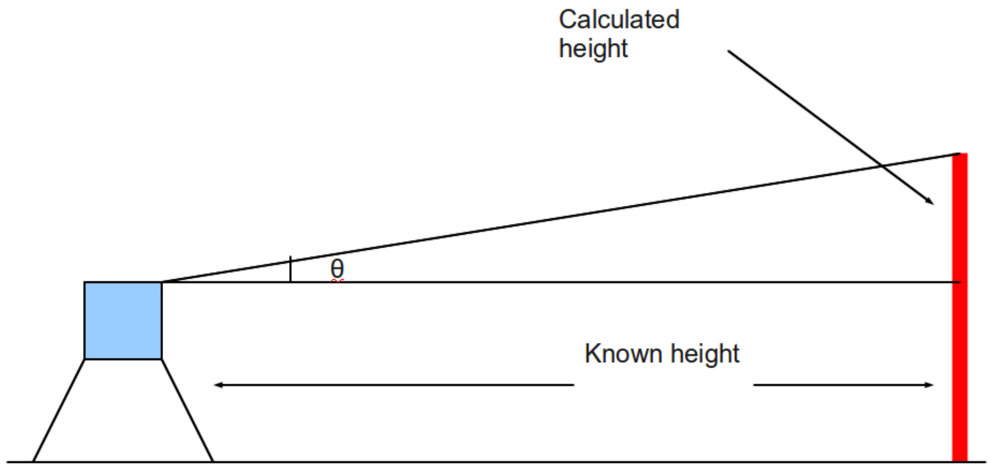


Figure 16: Fire location determination using trigonometry

6 General Remarks

The controller section of this report discusses two controller designs. Specifically, there exist two methods that have been, or are, being considered for the purpose of reliably facing the camera housing towards the oncoming front of a wildfire. The existing method does not use linear control and subsequently cannot be proven to track the fire under noisy conditions. The proposed method would use the optical properties of the thermopiles to infer properties about the location and angle of the fire, subsequently creating a model and calculating an ideal direction for the camera to face. While enabling the use of a linear controller, the proposed controller / sensor fusion method would make many assumptions about the fire that aren't necessarily accurate and may need more information than just the sensor values of the flame-oriented side of the box. To provide this additional information, it may be necessary to create a memory of all angles surrounding the box in order to decide the hottest direction to point. One other possibility, which was not explored in this report but is attractive in its simplicity, is the idea of simply avoiding "cold spots." Instead of trying to find the hottest point in the fire, it has been proposed to simply not look at any place that "isn't hot." In order to make such a system provably functional however, an accurate model of the fire must still be created. At this point in the project, it is evident that much work still needs to be done on the controller design to meet the course requirements.

7 List of Figures

8 List of Tables

References

[1] Inc John Wiley Sons, editor. *Introduction to Heat Tranfer*. Incropera/DeWitt/Bergman/Lavine, 2007.

[2] Yorkshire Refactory Products Limited. Fiberfrax durablanket s.

[3] Dr. Uy-Loi Ly. Dc motor control system: Modeling and control design. February 2010.

[4] Futurlec. Pir sensors, 2010.

[5] Melexis. Thermopile infrared sensor mlx90247. 2006.

[6] Carl Friedrich Gauss. *Disquisitiones Arithmeticae*. 1798.

[7] Gene Mosca Paul A. Tipler. *Physics for Scientists and Engineers*. Freeman Custom Publishing (C) 2008, 2008.